Quaternary International 244 (2011) 280–288

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Longitudinal patterns of phytoplankton distribution in a tributary bay under reservoir operation

Lan Wang [a,b], Qinghua Cai [a,*], Min Zhang [a,b], Lu Tan [a,b], Linghui Kong [a,b]

[a] State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, PR China
[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, PR China

ARTICLE INFO

Article history:
Available online 15 October 2010

ABSTRACT

To investigate longitudinal patterns of phytoplankton distribution influenced by reservoir operation, weekly surveys were carried out in the mainstream of the Yangtze River and Xiangxi Bay of the TGR from February, 2008 to February, 2009. Using cluster analysis based on chlorophyll *a*, transparency, and relative water column stability, the longitudinal patterns in different water level fluctuations periods were identified. The mainstream zone, lacustrine zone, transitional zone and riverine zone could be successively distinguished from the mouth to the end of Xiangxi bay, but distinct differences existed in different periods, including the location and extent of each zone. In Periods I (spring) and II (summer and early autumn, flood season), the mainstream zone was relatively short, while in Periods III and IV (autumn and winter seasons), it became longer. At the end of Xiangxi Bay, it presented characteristics of a transitional zone in Periods I, III, and IV, while in Period II it could be recognized as the riverine zone. The correlations among chlorophyll *a*, transparency, and relative water column stability differed from the Yangtze River to longitudinal zones of Xiangxi Bay, influenced by various features of these regions.

1. Introduction

In reservoirs, the spatial and temporal heterogeneity of limnological characteristics influences the ecological structure and functioning of these ecosystems fundamentally (Nogueira et al., 1999). The temporal variations of aquatic ecosystems in tropical and subtropical areas are induced by the seasonal pattern of precipitation and wind action (Nogueira et al., 1999). Along with the transport and sedimentation of influent materials, the important hydrodynamic characteristics dominating the reservoirs' spatial distribution such as river inputs, advective flow regimes, and regulated outflow provide a physical setting that fosters the establishment of physical, chemical, and biological longitudinal spatial gradient from headwaters to dam in the main axis of the reservoir (James et al., 1987). The physical and chemical gradients imposed by a river flow is a typical feature in deep valley reservoirs (Vašek et al., 2004), whereas the advective flow regimes and regulated outflow are obviously under the impact of reservoir operation. The reservoir operation distinguishes the reservoir from other natural aquatic systems, intended to guide real-time operation management so that the releases made are in the best interests of the system's objective consistent with certain inflow and existing storage levels (Malekmohammadi et al., 2009). The setting conditions changed by reservoir operation, together with natural forces, cause the heterogeneous distribution of the organisms in the environment (Zanata and Espíndola, 2002). The water level fluctuations are inevitably brought about by reservoir operation, affecting plankton biomass and species composition (Naselli-Flores and Barone, 1997; Donagh et al., 2009).

In large river systems, the complicated interactions among channel geomorphology, nutrients, water retention time, light availability, and herbivores affect the longitudinal pattern of planktonic communities (Sabater et al., 2008). The responses of phytoplankton to physical and chemical factors in the surrounding environment affect the structure and function of the entire planktonic community (Burić et al., 2007). The longitudinal pattern of phytoplankton is more complex because the dynamics of phytoplankton are altered by human activities and hydrological dynamics of the reservoir when the systems are highly regulated (Sabater et al., 2008).

The prevailing theory of reservoir longitudinal zonation focuses on the main axis of reservoir, i.e., three longitudinal zones can be distinguished in a typical reservoir: riverine zone, transitional zone and lacustrine zone in the direction of inflow (Straškraba and Tundisi, 1999; Wetzel, 2001). However, longitudinal zonation in

---

[*] Corresponding author. Fax: +86 27 68780123
E-mail address: qhcai@ihb.ac.cn (Q. Cai).

1040-6182/$ – see front matter © 2010 Elsevier Ltd and INQUA. All rights reserved.
doi:10.1016/j.quaint.2010.09.012

reservoir bays is poorly documented (Shao et al., 2010). The tributary bay has smaller annual discharge and catchment area compared to the mainstream of reservoir, so the chlorophyll *a* concentration is higher, indicating the higher frequency of algal bloom and level of eutrophication (Cai and Hu, 2006). So, research of longitudinal patterns of phytoplankton distribution in tributary bays is of great theoretical and practical importance for reservoir operation and management. There is no dam in a tributary bay, so a typical bay contains one more zones than a reservoir (Shao et al., 2010). This newly distinguished zone lying along the mouth stretch of a tributary bay is disturbed by the reservoir mainstream and named as a mainstream zone by Shao et al. (2010). In a bay under the influence of reservoir water level fluctuations, rising water level in the reservoir may cause longer retention time of water in the bay, higher phytoplankton biomass in the upper parts of the bay and a stronger influence of the mainstream on the lower part of the bay. Nevertheless, studies of longitudinal patterns of phytoplankton distribution in such tributary bays are still scarce in China.

The Three Gorges Reservoir (TGR) is a warm monomictic, typically subtropical canyon-shaped reservoir in China. As it is the largest hydropower project in the world, TGR is a highly dynamic ecosystem due to the enormous water level fluctuations from human operation. Until now no study about the characteristics of phytoplankton longitudinal distribution in tributary bays of the TGR has been reported. The present study aims to examine the following hypotheses: (1) longitudinal zonation exists in a reservoir bay, and there is one more mainstream zone than the prevailing theory; (2) the location and extent of each zone varies in different water level fluctuations periods; (3) the correlations among chlorophyll *a*, transparency and relative water column stability are different between the Yangtze River and longitudinal zones of Xiangxi Bay. Firstly, spatial zones were distinguished for different water level fluctuations periods based on the similarity analysis of sampling sites, and then the temporal variations and numerical relationships of the characteristic parameters for different zones were analyzed, to recognize the different responses of phytoplankton longitudinal patterns to the reservoir operation.

2. Investigation area, data and methods

The Three Gorges Reservoir (TGR) is located at 29°16′–31°25′ N, 106°–110°50′ E (Huang et al., 2006), with a subtropical monsoon

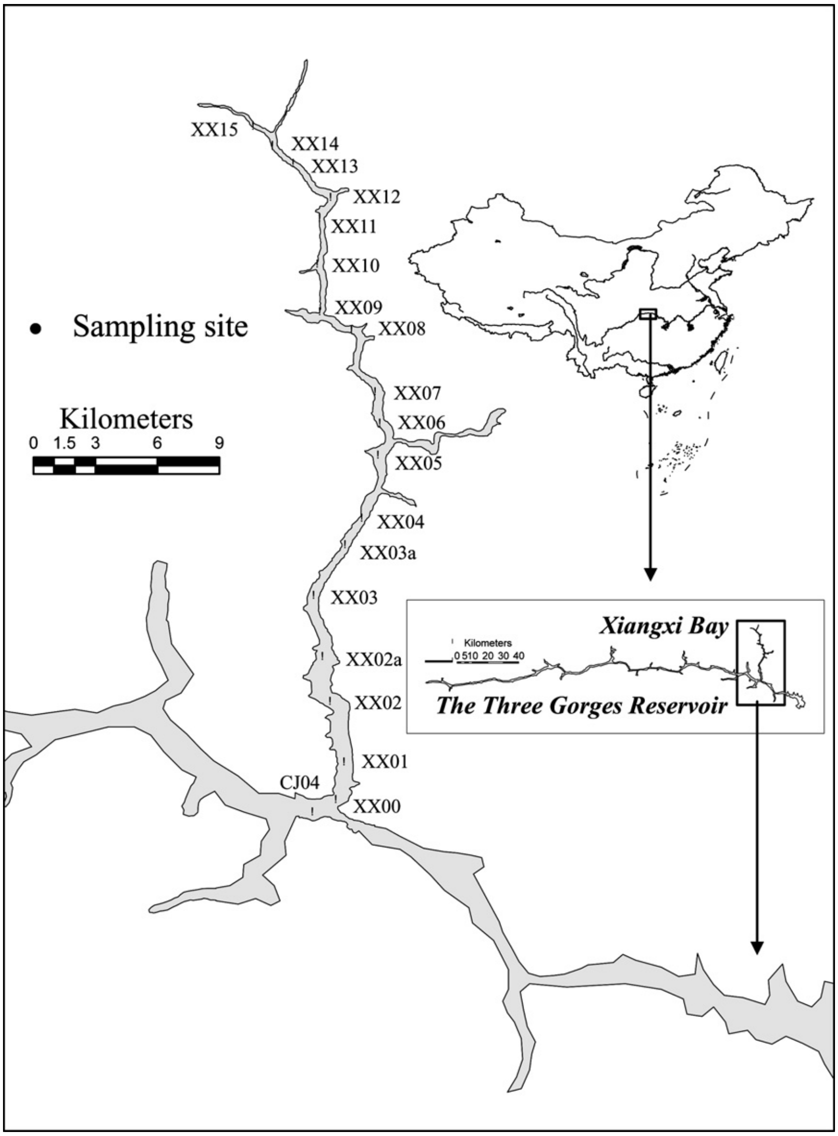


Fig. 1. Location of the sampling sites in the mainstream of the Yangtze River and Xiangxi Bay.

climate prevailing (Jiang et al., 2006), and average annual rainfall of 1000–1300 mm. When finally completed, TGR will have a water level of 175 m and a surface area of 1080 km^2, with a capacity of 3.93×10^{10} m^3 (Huang et al., 2006). There are 40 large reservoir bays formed, and the total area of these bays accounts for 1/3 of the whole surface area of the TGR (Cai and Hu, 2006; Huang et al., 2006). The water level regime of TGR has varied drastically since the first experimental storage in 2008, with the highest water level of 172.8 m on November 10, 2008, and the lowest of 144.7 m on June 9, 2008.

The Xiangxi River is the largest tributary of the TGR in Hubei Province, with a length of 94 km in the mainstream and a watershed area of 3099 km^2, located 38 km upstream of the Three Gorges Dam. The lower 20–40 km stretch of the river flows slowly, similar to a natural lake, after the impoundment of TGR, and it is now called Xiangxi Bay, where many aspects in this ecosystem have been studied (Han et al., 2006; Shao et al., 2006; Ye et al., 2006; Zhou et al., 2006). In the present study, one sampling site (CJ04) was set up in the mainstream of the Yangtze River, just upstream from the mouth stretch (XX00) of Xiangxi Bay. Simultaneously, several sites along the longitudinal axis of Xiangxi Bay were surveyed, from XX00 to the last site located very near the end of the bay, depending on the water level of the TGR. XX15 was reached only once in all the surveys, so it was excluded in the following data analysis. The map of sampling sites is shown in Fig. 1.

Weekly surveys were performed from February 23, 2008 to February 20, 2009. Water samples were collected at a depth of 0.5 m beneath the water surface using a 5-L Van Dorn sampler. The chlorophyll *a* concentrations were determined with a spectrophotometer according to the standard method of APHA (1999). The value of Secchi depth was determined with a 20-cm Secchi disc. Vertical profiles of water temperature were recorded with Environmental Monitoring Systems (YSI Model 6600EDS, Yellow Springs).

Multivariate statistical techniques have been widely applied in environment researches for characterizing and evaluating the surface and freshwater quality (Boyacioglu and Boyacioglu, 2007; Shrestha and Kazama, 2007; Iscen et al., 2008; Sojka et al., 2008), and are useful in verifying temporal and spatial variations caused by natural and anthropogenic factors (Singh et al., 2004; Shrestha and Kazama, 2007). Cluster analysis is an unsupervised pattern recognition method, which makes it possible to detect similarities or dissimilarities within a large group of objects characterized by a number of variables (Li et al., 2007a; Zhou et al., 2007), and is an ideal technique for classifying the types of samples according to

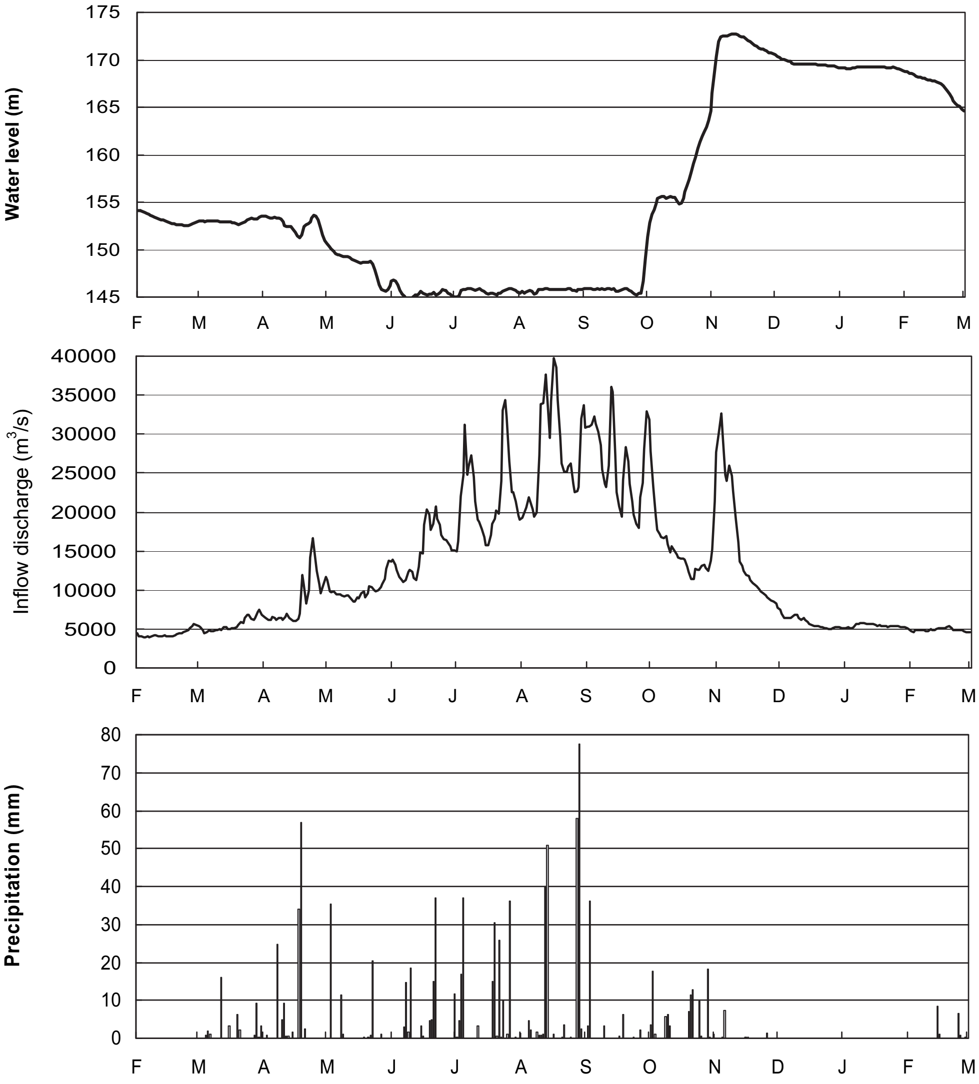


Fig. 2. Water level fluctuation (top), inflow discharge (middle) of the TGR and the precipitation of Xiangxi Bay (bottom).

their sampling time and sites (Ismail and Ramadan, 1995). It assembles objects based on the characteristics they possess (Boyacioglu and Boyacioglu, 2007; Iscen et al., 2008), and the resulting clusters of objects exhibit high internal (within-cluster) homogeneity and high external (between cluster) heterogeneity (Shrestha and Kazama, 2007). Hierarchical agglomerative clustering is the most common approach, which provides intuitive similarity relationships between any one sample and the entire data set, and is typically illustrated by a dendrogram (tree diagram) (McKenna, 2003). In this study, hierarchical agglomerative cluster analysis was performed on the standardized data using Ward's method (Ryberg, 2006; Zhou et al., 2007; Sojka et al., 2008), and with Euclidean distance as a measure of similarity (Panda et al., 2006). The monitored parameters for cluster analysis covered chlorophyll *a*, transparency and relative water column stability. The cluster analysis was performed using the software Statistica 6.0.

Chlorophyll *a* (Chl*a*) is the most common substitute for phytoplankton biomass, and a good indicator for algal blooms (Phillips et al., 2008; Xu et al., 2009). Transparency is one of the core variables recommended for the detection and monitoring of aquatic ecosystem changes (Tegler et al., 2001), and is used as a first spot-check of eutrophication (Tilzer, 1988). Transparency, most commonly measured with a Secchi depth (Sd), is a simple measure of the concentration of light attenuating factors in the waterbody, such as phytoplankton cells, inorganic suspended solids and color dissolved organic matter (Borkman and Smayda, 1998; Morrison et al., 2006; Swift et al., 2006). Relative water column stability (RWCS) reflected the thermal stratification conditions of waterbody by the density differences in the water column (Padisák et al., 2003). 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):

$$\mathrm{RWCS} = \frac{D_b - D_s}{D_4 - D_5},$$

where D_b, D_s, D_4, and D_5 are the density of the bottom waters, the density of the surface water, and the densities of 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 water depth of sampling site was bigger than 10 m, and the greatest depth was considered as "bottom" when water depth of sampling site was smaller than 10 m.

The data of water level and inflow discharge of the TGR were obtained from the China Three Gorges Corporation. The precipitation data was provided by the Weather Station of Xingshan County. The capacity of the TGR and Xiangxi Bay in the given water level was obtained from Huang et al. (2006). The residence time for each period was calculated as (modified from George and Hurley, 2003):

$$\tau = \frac{V}{Q},$$

where τ is water residence time for each period, V is the average volume, and Q is the average inflow discharge for each period.

The Mann–Whitney *U* test was employed on hydrodynamic parameters between different water level periods. Differences between the conditions of different zones in each period were tested for three parameters (chlorophyll *a*, transparency and relative water column stability) with Wilcoxon Signed Ranks Test. The regression equation $\mathrm{Log(Sd)} = a0 + a \times \mathrm{Log(Chl}a)$ was used to examine the relationship between transparency and chlorophyll *a*, and the equation $\mathrm{Chl}a = a0 + a \times \mathrm{RWCS}$ was used to determine the relationship between chlorophyll *a* and relative water column stability. They were all performed using the software SPSS 16.0.

Table 1
Basic hydrodynamic parameters of the Yangtze River and Xiangxi Bay for 4 periods (different letters indicated significantly different, $p < 0.05$).

	Period I	Period II	Period III	Period IV
	February 23–June 5, 2008	June 6–September 28, 2008	September 29–November 11, 2008	November 12, 2008–February 23, 2009
Averaged water level of the Yangtze River (m)	151.2 ± 2.4 (145.6–153.6)^a	145.6 ± 0.3 (144.7–145.9)^b	160.3 ± 7.4 (146.7–172.8)^c	169.5 ± 1.3 (166.0–172.7)^d
Average range of water level (m)	0.22 ± 0.19 (0.06–0.96)^a	0.21 ± 0.11 (0.05–0.70)^b	0.66 ± 0.61 (0.07–2.35)^c	0.13 ± 0.07 (0.04–0.36)^d
Averaged inflow discharge of the Yangtze River (m^3/s)	8066.8 ± 2871.0 (4487.5–16700.0)^a	23124.3 ± 6783.8 (11000.0–39750.0)^b	18582.8 ± 6494.0 (11375.0–32950.0)^c	6318.1 ± 2097.6 (4650.0–13575.0)^d
Retention time of the Yangtze River (d)	28	8	16	62
Averaged inflow discharge of Xiangxi Bay (m^3/s)	36.06	63.22	34.20	9.60
Retention time of Xiangxi Bay (d)	131	64	181	814

3. Results and discussion

3.1. Water level fluctuations, inflow discharge, reservoir storage capacity, and residence time

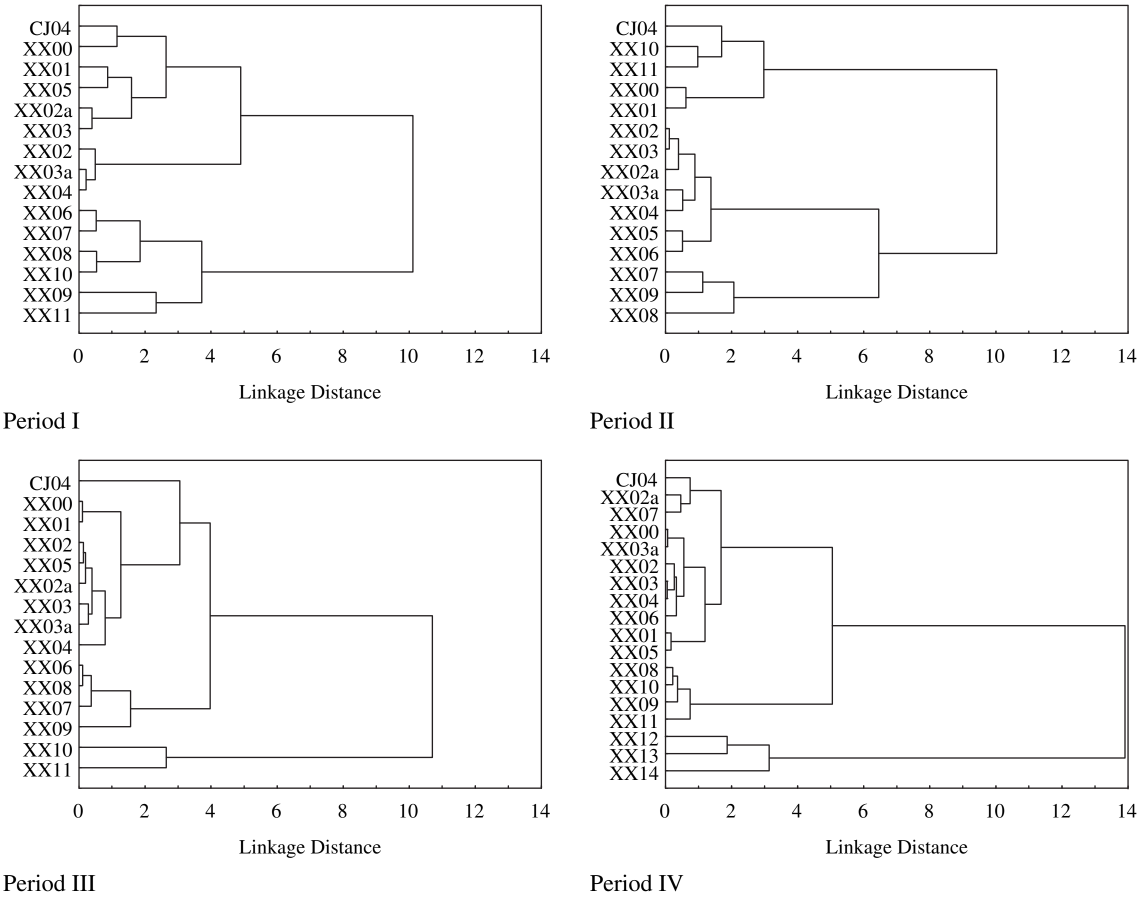
Water level fluctuations of TGR from February 2008 to February 2009 are shown in Fig. 2. The lowest water level is near the flood control level (145 m) from June to September, ascends rapidly from October to November, and gradually falls in other months. Four different periods were distinguished according to water level variations of TGR (Table 1): Period I (February 23–June 5, 2008), Period II (June 6–September 28, 2008), Period III (September 29–November 11, 2008), and Period IV (November 12, 2008–February 23, 2009). The hydrodynamic parameters of the 4 periods were shown in Table 1. It was spring in Period I when the water level began at the median water level and then fell to the lowest water level rapidly, with an average fall of 0.07 m per day over the whole period, and average fall of 0.24 m per day from April 27 to May 27 in 2008. Period II was in the flood season (summer to early autumn) when the water level remained lowest, with the variation range not more than 1.2 m. The water level went up most rapidly in Period III, with an average rise of 0.60 m per day for the entire period. The average fall was 1.24 m per day from September 29 to October 6, and 0.92 m per day from October 17 to November 5, 2008. It fell slowly in Period IV, with an average fall of 0.06 m per day.

The inflow discharge of TGR was 8066.8, 23124.3, 18582.8 and 6318.1 m^3/s for the respective periods (Table 1). It often rained in summer, and the winter was low water season in Xiangxi catchment, according to observations of the Weather Station of Xingshan County and Hydrological Station of Xiangxi River from 1999 to 2006, resulting in high inflow discharge in summer and low in winter in Xiangxi catchment (Li et al., 2007b). The precipitation of Xiangxi Bay was shown in Fig. 2. The estimated inflow charge of Xiangxi was 36.06, 63.22, 34.20 and 9.60 m^3/s, respectively (Table 1). In both the mainstream of the Yangtze River and Xiangxi Bay, the maximal inflow discharge and the minimal residence time appeared in Period II, while Period IV had the minimal inflow discharge and the maximal residence time. Additionally, the inflow discharge of the Yangtze River was much higher than Xiangxi Bay in each period, so the residence time in the Yangtze River was shorter (Table 1).

3.2. Longitudinal distribution of phytoplankton based on chlorophyll *a*, transparency and relative water column stability

Cluster analysis was performed for sampling sites in the mainstream of the Yangtze River and longitudinal axis of Xiangxi Bay in four different water level variation periods based on chlorophyll *a*, transparency and relative water column stability (Fig. 3). The results of cluster analysis were as follows.

All the sampling sites in Period I could be divided into 4 groups. The first group was CJ04, the second group was XX00, the third group was XX01–XX05, and the fourth group was XX06–XX11. The site of CJ04 could be taken as a single group, implying the mainstream of the Yangtze River (coded as MS). The agglomeration schedule indicated that XX00 was more likely to be disturbed by the mainstream of the Yangtze River, with low values of chlorophyll *a* concentration and relative water column stability, and could be regarded as mainstream zone (coded as MZ). Within the lacustrine



Period I

Period II

Period III

Period IV

Fig. 3. Cluster dendrogram of the sampling sites for different periods.

zone, characteristics become more similar to lake ecosystems, i.e., the lacustrine zone often stratifies thermally and assumes many of the properties of natural lakes in regard to planktonic production, limitations by nutrients, sedimentation of organic matter, and decomposition in the hypolimnion (Wetzel, 2001). The values of chlorophyll *a*, transparency and the relatively water column stability ascended in the zone of XX01–XX05, which could be considered as the lacustrine zone (coded as LZ). The transitional zone functions as an intermediate river–lake ecosystem (Matsumura-Tundisi and Tundisi, 2005), with increasing photosynthetic productivity (Wetzel, 2001). The zone from XX06 to XX11 had high values of chlorophyll *a* and low transparency, and high values of relative water column stability quite different from the riverine zone, so it could possess the characteristics of the transitional zone (coded as TZ).

The sampling sites in Period II could be divided into 5 groups. The first group was CJ04, the second group was XX00–XX01, the third group was XX02–XX06, the fourth group was XX07–XX09, and the last group was XX10–XX11. Group XX00–XX01 could be regarded as the mainstream zone. The chlorophyll *a* concentration, transparency and relative water column stability were relatively high in XX02–XX06, termed the lacustrine zone. Group XX07–XX09 could be regarded as the transitional zone, with the highest values of chlorophyll *a* concentration and relative water column stability. The zone of XX10–XX11 was located near the end of the bay, with much lower values of chlorophyll *a* concentration and relative water column stability, designated the riverine zone (RZ). Wetzel (2001) pointed out that high particulate turbidity commonly reduces light penetration and limits primary production within the water of the riverine zone. The low value of chlorophyll *a* in the riverine zone was presumed to be related to the inflow discharge of upstream, accordant with some related studies. The freshwater discharge had important effects on the longitudinal distribution of chlorophyll *a* concentrations in the Neuse River Estuary-Pamlico Sound system, USA, for example, the elevated runoff during relatively high rainfall months prevented accumulation of chlorophyll *a* in the upper regions (Paerl et al., 2007). In the eutrophic Taw Estuary, SW England, the algal bloom dynamics were regulated by two important factors, ammonia inhibition and the flow regime of the River Taw, and the influence of the River Taw was strongest in the upper reaches of the estuary (Maier et al., 2009). In Xiangxi Bay, the riverine zone could only be sampled in Period II of 4 water level periods, indicating a relationship to high inflow from the upper area in the flood season.

The sampling sites in Period III could be divided into 4 groups. The first group was CJ04, the second group was XX00–XX05, the third group was XX06–XX09, and the fourth group was XX10–XX11. Group XX00–XX05 could be regarded as the mainstream zone. Group XX06–XX09 could be regarded as the lacustrine zone. Group XX10–XX11 could be regarded as the transitional zone.

The sampling sites in Period IV could be divided into 4 groups. The first group was CJ04, the second group was XX00–XX07, the third group was XX08–XX11, and the fourth group was XX12–XX14. Group XX00–XX07 could be regarded as the mainstream zone. Group XX08–XX11 could be regarded as the lacustrine zone. Group XX12–XX14 could be regarded as the transitional zone.

Mean value, standard deviation and the variation range of each parameter for different zones were listed in Table 2. The comparisons among the 4 periods suggested that there was one more zone (the riverine zone) in Period II than the other periods. Along the longitudinal direction of Xiangxi Bay, the zone near the end of Xiangxi Bay was the transitional zone in Periods I, III and IV, with the relatively high values of chlorophyll *a* concentration and relative water column stability, revealing good conditions of thermal stratification. However, it took on the riverine features related to flood

Table 2
Mean value, standard deviation and the variation range of Chl*a* (chlorophyll *a*), Sd (transparency) and RWCS (relative water column stability) of 4 periods (different letters indicated significantly different, $p < 0.05$).

		MS	MZ	LZ	TZ	RZ
Period I	Sites	CJ04	XX00	XX01–XX05	XX06–XX11	
February 23–June 5, 2008	Chl*a*	4.36 ± 6.38 (0.16–20.30)^{b}	21.05 ± 35.54 (0.35–141.85)^{a}	41.54 ± 111.56 (0.05–610.91)^{c}	42.37 ± 58.05 (1.23–424.73)^{a}	
	Sd	236.00 ± 78.45 (100–390)^{ab}	208.67 ± 63.90 (130–310)^{ab}	245.72 ± 110.83 (50–500)^{a}	123.56 ± 68.68 (30–340)^{b}	
	RWCS	2.83 ± 5.41 (−0.13 to 20.28)^{a}	13.12 ± 15.36 (0.16–49.34)^{b}	30.70 ± 20.98 (0.64–87.09)^{c}	58.60 ± 53.09 (0.99–230.90)^{d}	
Period II	Sites	CJ04	XX00–XX01	XX02–XX06	XX07–XX09	XX10–XX11
June 6–September 28, 2008	Chl*a*	1.15 ± 1.89 (0.05–8.18)^{a}	18.65 ± 24.16 (0.05–104.02)^{b}	24.50 ± 21.04 (2.15–137.55)^{c}	34.81 ± 33.59 (0.05–152.07)^{d}	7.39 ± 15.26 (0.05–59.93)^{e}
	Sd	39.41 ± 23.78 (15–90)^{b}	95.29 ± 48.32 (30–230)^{a}	124.91 ± 70.76 (10–330)^{c}	82.06 ± 45.98 (0–210)^{a}	75.00 ± 42.80 (25–180)^{a}
	RWCS	1.32 ± 3.58 (−0.31 to 14.53)^{a}	32.30 ± 24.34 (−1.01 to 87.86)^{b}	64.24 ± 31.22 (2.56–157.46)^{c}	115.41 ± 80.39 (−0.50 to 278.22)^{d}	17.52 ± 45.84 (−1.67 to 179.66)^{e}
Period III	Sites	CJ04	XX00–XX05	XX06–XX09	XX10–XX11	
September 29–November 11, 2008	Chl*a*	0.43 ± 0.29 (0.05–0.76)^{a}	1.23 ± 2.56 (0.05–18.01)^{a}	2.88 ± 3.64 (0.34–13.93)^{b}	13.26 ± 22.92 (1.25–83.97)^{c}	
	Sd	70.00 ± 29.66 (40–110)^{a}	97.71 ± 34.47 (50–170)^{b}	112.08 ± 26.04 (70–170)^{c}	126.67 ± 28.39 (70–170)^{d}	
	RWCS	0.26 ± 1.07 (−0.74 to 2.25)^{a}	0.11 ± 5.92 (−38.72 to 7.25)^{a}	5.54 ± 4.45 (0–13.98)^{b}	71.27 ± 55.14 (4.45 to 156.62)^{c}	
Period IV	Sites	CJ04	XX00–XX07	XX08–XX11	XX12–XX14	
November 12, 2008–February 23, 2009	Chl*a*	1.30 ± 1.85 (0.05–7.30)^{a}	2.36 ± 3.58 (0.16–16.27)^{a}	3.53 ± 4.13 (0.38–18.74)^{b}	8.59 ± 7.00 (0.50–24.14)^{c}	
	Sd	260.67 ± 84.64 (140–390)^{abc}	265.10 ± 61.97 (130–395)^{a}	250.00 ± 47.16 (170–370)^{b}	232.61 ± 73.49 (100–500)^{c}	
	RWCS	0.41 ± 1.61 (−0.91 to 4.31)^{a}	1.14 ± 2.95 (−1.44 to 16.65)^{a}	4.29 ± 4.66 (−0.39 to 21.01)^{b}	26.88 ± 26.36 (0.37–114.80)^{c}	

MS: the mainstream of the Yangtze River; MZ: the mainstream zone; LZ: the lacustrine zone; TZ: the transitional zone; RZ: the riverine zone.

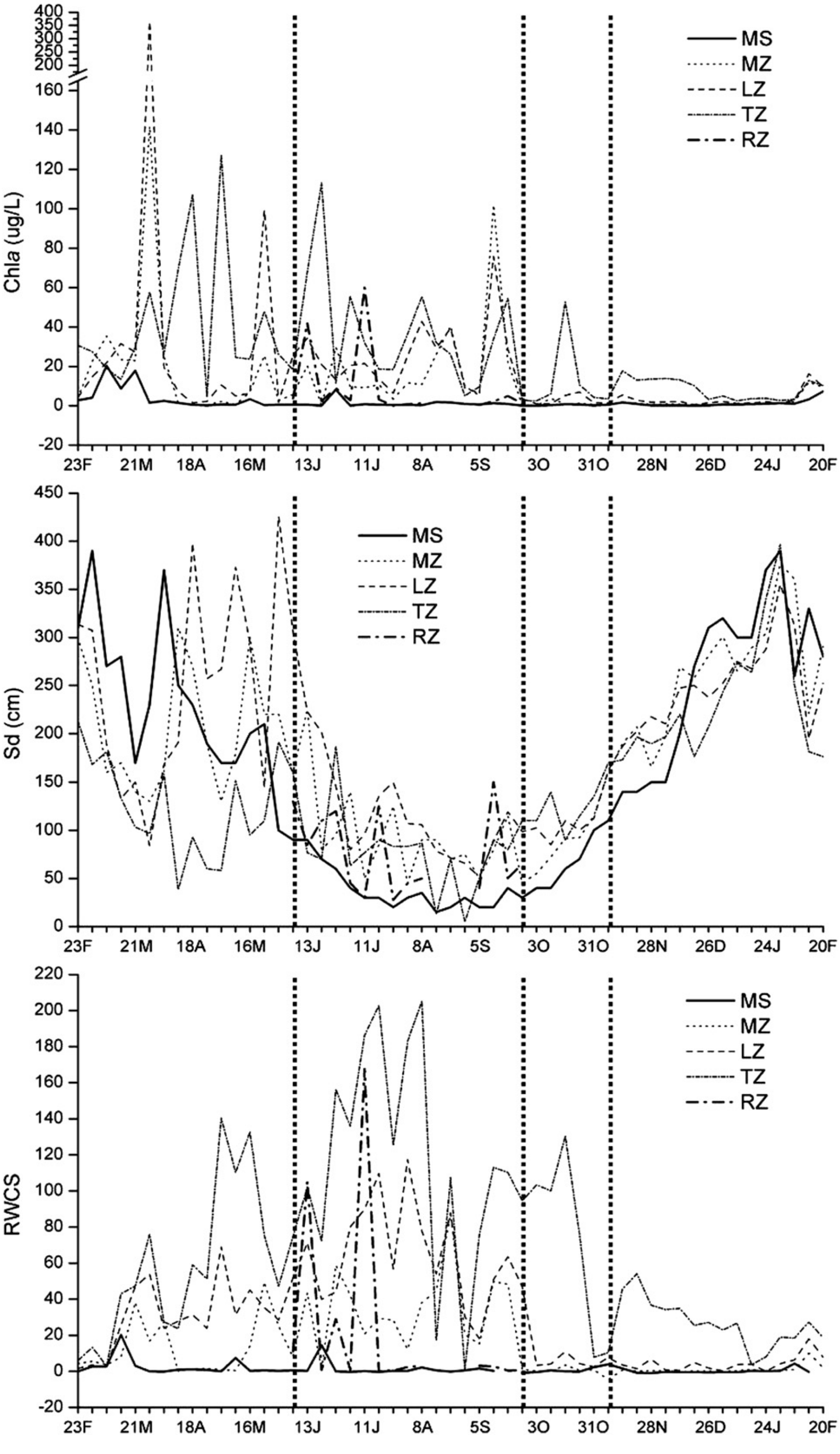


Fig. 4. Temporal variations of mean Chl*a* (chlorophyll *a*), Sd (transparency) and RWCS (relative water column stability) in different zones. MS: the mainstream of the Yangtze River; MZ: the mainstream zone; LZ: the lacustrine zone; TZ: the transitional zone; RZ: the riverine zone.

season near the end of the bay in Period II, with lower values of chlorophyll *a* concentration and relative water column stability. The scale of the mainstream zone was enlarged from XX00 (or XX00–XX01) in Period I (or Period II) to XX00–XX05 in Period III and XX00–XX07 in Period IV, indicating that the range of influencing regions due to the jacking of the mainstream of the TGR became larger following the rising water level of TGR, and the region near the end of Xiangxi Bay had the highest phytoplankton biomass.

In general, there were distinct longitudinal distributions under different water level regimes, i.e., the mainstream zone, lacustrine zone, transitional zone and riverine zone, successively from mouth stretch to the end of Xiangxi Bay (riverine zone only detected in Period II), but the differences existed among the longitudinal zones of Xiangxi Bay. Straškraba and Tundisi (1999) expounded that the size of a horizontal zone varies in each individual reservoir, and depends upon morphometry, retention time, thermal stratification, season, and geographical location. Meanwhile, the hydrodynamic conditions cause horizontal variability in most reservoirs. For instance, in Jurumirim, a large tropical reservoir of Brazil with remarkable spatial gradients, the spatial patter is not static, i.e., it becomes more defined during the dry season and less evident during the rainy period (Nogueira et al., 1999). It can be assumed that water level regime, inflow and outflow have complex interactions to the longitudinal patterns of phytoplankton distribution in Xiangxi Bay. Additionally, the differences between the mainstream of the Yangtze River and the longitudinal zones of Xiangxi Bay can be regarded as the interactions between them, under the influence of water level fluctuations in the reservoir.

3.3. Temporal variations of chlorophyll a, transparency, and relative water column stability in the mainstream of the Yangtze River and longitudinal zones of Xiangxi Bay

Temporal variations of average chlorophyll *a*, transparency, and relative water column stability of every group in the mainstream of the Yangtze River and longitudinal zones of Xiangxi Bay are displayed in Fig. 4. As a whole, the levels of chlorophyll *a* concentration in Periods III and IV were lower than those in Periods I and II. In contrast to Xiangxi Bay, the mainstream of the Yangtze River retained very low values of chlorophyll *a*. In Xiangxi Bay, the transitional zone had the highest value of chlorophyll *a* in most times of the investigation year. It was very similar to relative water column stability variations: the mainstream of the Yangtze River was totally mixed, with the lowest relative water column stability values. In Xiangxi Bay, relative water column stability reached high values in Period II (flood season), implying strong stratification, but nevertheless the strongest mixed period was Period IV. In the spatial distribution, the highest relative water column stability appeared in the transitional zone, implying mostly stable stratified status. The temporal variations of transparency had a decreasing trend and then ascended both in the mainstream of the Yangtze River and Xiangxi Bay. The transitional zone reached the lowest transparency in Period I, linked to phytoplankton growth in spring. The transparency of the mainstream of the Yangtze River in Periods II and III was lower than in Xiangxi Bay, mostly due to the large inflow discharge to the Yangtze River in the flood season. Seasonal dynamics of transparency were very well explained by inflow discharges in the mainstream of the Yangtze River, but not in Xiangxi Bay (Xu et al., 2010). In Period IV, transparency was lower in Xiangxi Bay than in the mainstream of the Yangtze River, implying phytoplankton development in Xiangxi bay.

Table 3
Relationships between Sd (transparency) and Chl*a* (chlorophyll *a*), expressed as $\text{Log(Sd)} = a0 + a \times \text{Log(Chl}a)$.

	$a0$	a	R^2	p
MS	2.063	0.185	0.070	0.055
MZ	2.190	−0.031	0.009	0.505
LZ	2.359	−0.168	0.198	0.001
TZ	2.313	−0.236	0.127	0.009
RZ	1.789	0.067	0.045	0.446

MS: the mainstream of the Yangtze River; MZ: the mainstream zone; LZ: the lacustrine zone; TZ: the transitional zone; RZ: the riverine zone.

Table 4
Relationships between Chl*a* (chlorophyll *a*) and RWCS (relative water column stability), expressed as $\text{Chl}a = a0 + a \times \text{RWCS}$.

	$a0$	a	R^2	p
MS	1.080	0.719	0.436	<0.001
MZ	4.775	0.552	0.206	0.001
LZ	7.301	0.438	0.070	0.056
TZ	15.008	0.175	0.118	0.012
RZ	1.089	0.359	0.989	<0.001

MS: the mainstream of the Yangtze River; MZ: the mainstream zone; LZ: the lacustrine zone; TZ: the transitional zone; RZ: the riverine zone.

3.4. Relationships among chlorophyll a, transparency, and relative water column stability in the mainstream of the Yangtze River and longitudinal zones of Xiangxi Bay

The relationships among chlorophyll *a*, transparency, and relative water column stability in the mainstream of the Yangtze River and longitudinal zones of Xiangxi Bay were exhibited in Tables 3 and 4. Good correlation relationships between log-transformed transparency and chlorophyll *a* were detected in the lacustrine zone and the transitional zone of Xiangxi Bay, indicating high influence of chlorophyll *a* concentration on water transparency, and co-variation of phytoplankton and other suspended particles. In the mainstream of the Yangtze River and the riverine zone of Xiangxi Bay, the relationships might be affected by the inflow discharge, rainfall and other factors, and the mainstream zone of Xiangxi bay was under the influence of the mainstream of the Yangtze River, so inorganic suspended matter might become a more important parameter affecting the transparency variations in these regions.

In the mainstream of the Yangtze River, there were good correlation relationships between chlorophyll *a* and relative water column stability ($R^2 = 0.436$, $p < 0.001$). In the upper reach (riverine zone) and the downstream (mainstream zone) of Xiangxi Bay, high correlation could be also detected ($R^2 = 0.989$, $p < 0.001$ and $R^2 = 0.206$, $p = 0.001$, respectively), but not in the middle part of the bay including the lacustrine zone and the transitional zone. Variations in composition, abundance, and biomass of the phytoplankton community are largely due to changes in water column stability, which is significantly influenced by meteorological factors such as rainfall, wind and temperature (da Silva et al., 2005). In Xiangxi Bay, the relative water column stability was influenced by the additional factors such as water level fluctuations and inflow and outflow of the reservoir. In the inflow and outflow regions of Xiangxi Bay, the values of chlorophyll *a* concentration were sensitive to the changes of water column stratification conditions, where it could be suitable for forecasting the chlorophyll *a* variations by the changes of relative water column stability.

4. Conclusion

Characteristics of phytoplankton longitudinal distribution in the mainstream of the Yangtze River and Xiangxi Bay in different water level fluctuations periods were studied before and after the first experimental storage of the Three Gorges Reservoir in 2008. Longitudinal zones including the mainstream zone, the lacustrine zone, the transitional zone, and the riverine zone (only in Period II) were distinguished towards the inflow of Xiangxi Bay, according to the traditional longitudinal zonation as well as the new "mainstream zone" proposed by Shao et al. (2010). The length of the mainstream zone was quite short when the water level declined gradually in spring (February–May) and fluctuated gently in the flood season (summer and early autumn, i.e., June–September). In contrast, the mainstream zone became much longer when the water level ascended quickly and then fell down slowly in autumn and winter (October to the next February). There was one more zone – the riverine zone – in the flood season than the other periods, and in the other periods the end of Xiangxi Bay could be recognized as a transitional zone. The correlation relationships among chlorophyll *a*, transparency and relative water column stability were quite different between the Yangtze River and longitudinal zones of Xiangxi Bay. There were good correlation relationships between chlorophyll *a* and relative water column stability in the mainstream of the Yangtze River. In Xiangxi Bay, good correlation relationships between log-transformed transparency and chlorophyll *a* were found in the lacustrine zone and the transitional zone. There was a high correlation between chlorophyll *a* and relative water column stability in the inflow and outflow regions of Xiangxi Bay, implying favorable applicability of forecasting chlorophyll *a* variations by relative water column stability in these regions.

Acknowledgments

We are grateful to Qiande Yuan, Yaoyang Xu, Xingzhong Wang and Shunyi Yang for their contributions in the field sampling. We also thank the anonymous reviewers for their useful comments on the manuscript. This study was financially supported by National Natural Science Foundation of China (No. 40671197), the Key Project of Knowledge Innovation Program of CAS (No. KZCX2–YW–427), and the Key Project of the National Eleventh-Five Year Research Program of China (No. 2006BAC10B02).

References

American Public Health Association (APHA), 1998. Standard Methods for Examination of Water and Wastewater (20th). APHA, Washington DC.

Borkman, D.G., Smayda, T.J., 1998. Long-term trends in water clarity revealed by NUS Secchi-disk measurements in lower Narragansett Bay. ICES Journal of Marine Science 55, 668–679.

Boyacioglu, H., Boyacioglu, H., 2007. Surface water quality assessment by environmetric methods. Environmental Monitoring and Assessment 131, 371–376.

Burić, Z., Cetinić, I., Viličić, D., Mihalić, K.C., Carić, M., Olujić, G., 2007. Spatial and temporal distribution of phytoplankton in a highly stratified estuary (Zrmanja, Adriatic Sea). Marine Ecology 28 (Suppl. 1), 169–177.

Cai, Q., Hu, Z., 2006. Studies on eutrophication problem and control strategy in the Three Gorges Reservoir. Acta Hydrobiologica Sinica 30, 7–11 (in Chinese with English abstract).

da Silva, C.A., Train, S., Rodrigues, L.C., 2005. Phytoplankton assemblages in a Brazilian subtropical cascading reservoir system. Hydrobiologia 537, 99–109.

Donagh, M.E.M., Casco, M.A., Claps, M.C., 2009. Plankton relationships under small water level fluctuations in a subtropical reservoir. Aquatic Ecology 43, 371–381.

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, 21–26.

Han, X., Ye, L., Xu, Y., Cai, Q., 2006. Analysis of the spatial and temporal changes of Chlorophyll *a* concentration in Xiangxi Bay in spring and its impact factors. Acta Hydrobiologica Sinica 30, 89–94 (in Chinese with English abstract).

Huang, Z., Li, Y., Chen, Y., Li, J., Xing, Z., Ye, M., Li, J., Lü, P., Li, C., Zhou, X., 2006. Water Quality Prediction and Water Environmental Carrying Capacity Calculation for Three Gorges Reservoir. China WaterPower Press, Beijing (in Chinese with English abstract).

Iscen, C.F., Emiroglu, Ö., Ilhan, S., Arslan, N., Yilmaz, V., Ahiska, S., 2008. Application of multivariate statistical techniques in the assessment of surface water quality in Uluabat Lake, Turkey. Environmental Monitoring and Assessment 144, 269–276.

Ismail, S.S., Ramadan, A., 1995. Characterisation of Nile and drinking water quality by chemical and cluster analysis. Science of the Total Environment 173/174, 69–81.

James, W.F., Kennedy, R.H., Montgomery, R.H., 1987. Seasonal and longitudinal variations in apparent deposition rates within an Arkansas reservoir. Limnology and Oceanography 32, 1169–1176.

Jiang, T., Zhang, Q., Zhu, D., Wu, Y., 2006. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). Quaternary International 144, 29–37.

Li, R., Dong, M., Zhao, Y., Zhang, L., Cui, Q., He, W., 2007a. Assessment of water quality and identification of pollution sources of Plateau Lakes in Yunnan (China). Journal of Environmental Quality 36, 291–297.

Li, F., Ye, L., Liu, R., Cao, M., Cai, Q., 2007b. Investigation on aquatic environmental factors in Xiangxi river watershed. Ecological Science 26, 199–207.

Maier, G., Glegg, G.A., Tappin, A.D., Worsfold, P.J., 2009. The use of monitoring data for identifying factors influencing phytoplankton bloom dynamics in the eutrophic Taw Estuary, SW England. Marine Pollution Bulletin 58, 1007–1015.

Malekmohammadi, B., Kerachian, R., Zahraie, B., 2009. Developing monthly operating rules for a cascade system of reservoirs: application of Bayesian Networks. Environmental Modelling & Software 24, 1420–1432.

Matsumura-Tundisi, T., Tundisi, J.G., 2005. Plankton richness in a eutrophic reservoir (Barra Bonita reservoir, SP, Brazil). Hydrobiologia 542, 367–378.

McKenna, J., 2003. An enhanced cluster analysis program with bootstrap significance testing for ecological community analysis. Environmental Modelling & Software 18, 205–220.

Morrison, G., Sherwood, E., Boler, R., Barron, J., 2006. Variations in water clarity and chlorophyll a in Tampa Bay, Florida, in response to annual rainfall, 1985–2004. Estuaries and Coasts 29, 926–931.

Naselli-Flores, L., Barone, R., 1997. Importance of water level fluctuation on population dynamics of cladocerans in a hypertrophic reservoir (Lake Arancio, south-west Sicily, Italy). Hydrobiologia 360, 223–232.

Nogueira, M.G., Henry, R., Maricatto, F.E., 1999. Spatial and temporal heterogeneity in the Jurumirim Reservoir, São Paulo, Brazil. Lakes & Reservoirs: Research and Management 4, 107–120.

Padisák, J., Barbosa, F., Koschel, R., Krienitz, L., 2003. Deep layer cyanoprokaryota maxima in temperate and tropical lakes. Archives of Hydrobiology Special Issues in Advanced Limnology 58, 175–199.

Paerl, H.W., Valdes-Weaver, L.M., Joyner, A.R., Winkelmann, V., 2007. Phytoplankton indicators of ecological change in the eutrophying Pamlico Sound system, North Carolina. Ecological Applications 17, 88–101.

Panda, U.C., Sundaray, S.K., Rath, P., Nayak, B.B., Bhatta, D., 2006. Application of factor and cluster analysis for characterization of river and estuarine water systems – a case study: Mahanadi River (India). Journal of Hydrology 331, 434–445.

Phillips, G., Pietiläinen, O.P., Carvalho, L., Solimini, A., Solheim, A.L., Cardoso, A., 2008. Chlorophyll–nutrient relationships of different lake types using a large European dataset. Aquatic Ecology 42, 213–226.

Ryberg, K.R., 2006. Cluster Analysis of Water-quality Data for Lake Sakakawea, Audubon Lake, and McClusky Canal, Central North Dakota, 1990–2003. U.S. Geological Survey. Scientific investigations Report 2006–5202.

Sabater, S., Artigas, J., Durán, C., Pardos, M., Romaní, A.M., Tornés, E., Ylla, I., 2008. Longitudinal development of chlorophyll and phytoplankton assemblages in a regulated large river (the Ebro River). Science of the Total Environment 404, 196–206.

Shao, M., Xie, Z., Ye, L., Cai, Q., 2006. Monthly change of community structure of zoobenthos in Xiangxi Bay after impoundment of Three Gorges Reservoir. Acta Hydrobiologica Sinica 30, 64–69 (in Chinese with English abstract).

Shao, M., Xu, Y., Cai, Q., 2010. Effects of reservoir mainstream on longitudinal zonation in reservoir bays. Journal of Freshwater Ecology 25, 107–117.

Shrestha, S., Kazama, F., 2007. Assessment of surface water quality using multivariate statistical techniques: a case study of the Fuji river basin, Japan. Environmental Modelling & Software 22, 464–475.

Singh, K.S., Amrita, M., Dinesh, M., Sartia, S., 2004. Multivariate statistical technology for the evaluation of spatial and temporal variations in water quality of Gomti River (India) – a case study. Water Research 38, 3980–3992.

Sojka, M., Siepak, M., Zioła, A., Frankowski, M., Murat-Błażejewska, S., Siepak, J., 2008. Application of multivariate statistical techniques to evaluation of water quality in the Mala Welna River (Western Poland). Environmental Monitoring and Assessment 147, 159–170.

Straškraba, M., Tundisi, J.G., 1999. Guidelines of Lake Management. In: Reservoir Water Quality Management, vol. 9. International Lake Environment Committee.

Swift, T.J., Perez-Losada, J., Schladow, S.G., Reuter, J.E., Jassby, A.D., Goldman, C.R., 2006. Water clarity modeling in Lake Tahoe: linking suspended matter characteristics to Secchi depth. Aquatic Sciences 68, 1–15.

Tegler, B., Sharp, M., Johnson, M.A., 2001. Ecological monitoring and assessment network's proposed core monitoring variables: an early warning of environmental change. Environmental Monitoring and Assessment 67, 29–55.

Tilzer, M.M., 1988. Secchi disk-chlorophyll relationships in a lake with highly variable phytoplankton biomass. Hydrobiologia 162, 163–171.

Vašek, M., Kubečka, J., Peterka, J., Čech, M., Draštík, V., Hladík, M., Prchalová, M., Frouzová, J., 2004. Longitudinal and vertical spatial gradients in the distribution of fish within a canyon-shaped reservoir. International Review of Hydrobiology 89, 352–362.

Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems, third ed. Academic Press.

Xu, Y., Wang, L., Cai, Q., Ye, L., 2009. Temporal coherence of chlorophyll a during a spring phytoplankton bloom in Xiangxi bay of Three-Gorges Reservoir, China. International Review of Hydrobiology 94, 656–672.

Xu, Y., Shao, M., Cao, M., Zhou, S., Cai, Q., 2010. Using temporal coherence to determine the responses of water clarity to hydrological processes in a giant subtropical canyon-shaped reservoir. Quaternary International 226 (1–2), 151–159.

Ye, L., Xu, Y., Cai, Q., 2006. The spatial and temporal distribution of nitrate and phosphate in the Xiangxi Bay, Three Gorges Reservoir region during the spring bloom period. Acta Hydrobiologica Sinica 30, 75–79 (in Chinese with English abstract).

Zanata, L.H., Espíndola, E.L.G., 2002. Longitudinal processes in Salto Grande Reservoir (Americana, SP, Brazil) and its influence in the formation of compartment system. Brazilian Journal of Biology 62, 347–361.

Zhou, S., Huang, X., Tang, T., Cai, Q., 2006. Primary studies on plankton rotifers and water quality assessment in Xiangxi Bay of the Three Gorges Reservoir. Acta Hydrobiologica Sinica 30, 52–57 (in Chinese with English abstract).

Zhou, F., Liu, Y., Guo, H., 2007. Application of multivariate statistical methods to water quality assessment of the watercourses in Northwestern New Territories, Hong Kong. Environmental Monitoring and Assessment 132, 1–13.