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ORIGINAL ARTICLE

Spatial analysis for spring bloom and nutrient limitation in Xiangxi bay of three Gorges Reservoir

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Abstract The spatial and temporal dynamics of physical variables, inorganic nutrients and phytoplankton chlorophyll *a* were investigated in Xiangxi Bay from 23 Feb. to 28 Apr. every six days, including one daily sampling site and one bidaily sampling site. The concentrations of nutrient variables showed ranges of 0.02–3.20 mg/L for dissolved silicate (Si); 0.06–2.40 mg/L for DIN ($NH_4N + NO_2N + NO_3N$); 0.03–0.56 mg/L for PO_4P and 0.22–193.37 μg/L for chlorophyll *a*, respectively. The concentration of chlorophyll *a* and inorganic nutrients were interpolated using GIS techniques. The results indicated that the spring bloom was occurred twice in space during the whole monitoring period (The first one: 26 Feb.–23 Mar.; the second one: 23 Mar.–28 Apr.). The concentration of DIN was always high in the mouth of Xiangxi Bay, and PO_4P was high in the upstream of Xiangxi Bay during the whole bloom period. Si seems no obvious difference in space in the beginning of the spring bloom, but showed high heterogeneity in space and time with the development of spring bloom. By comparing the interpolated maps of chlorophyll *a* and inorganic variables, obvious consumptions of Si and DIN were found when the bloom status was serious. However, no obvious depletion of PO_4P was found. Spatial regression analysis could explained most variation of Chl-*a* except at the begin of the first and second bloom. The result indicated that Si was the factor limiting Chl-*a* in space before achieved the max area of hypertrophic in the first and second bloom period. When Si was obviously exhausted, DIN became the factor limiting the Chl-*a* in space.

Daily and bidaily monitoring of Site A and B, representing for high DIN: PO_4P ratio and low DIN:PO_4P ratio, indicated that the concentration of Si was decreased with times at both site A and B, and the dramatically drop of DIN was found in the end monitoring at site B. Multiple stepwise regression analysis indicated that Si was the most important factor affect the development of spring bloom both at site A and B in time series.

Keywords Chlorophyll *a* · Dissolved silicate · DIN · Spatial analysis · Spring bloom · Xiangxi Bay · Three Gorges Reservoir

1 Introduction

The Xiangxi Bay, which had been the former Xiangxi River prior to the construction of the Three Gorges Reservoir (TGR), is located in the north-west of Hubei

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Province, P.R. China. After the TGR had been filled into the altitude of 135 m above sea level in year 2003, a long bay in length of 25 km was formed in the downstream of the Xiangxi River. Xiangxi River is one of the longest rivers (94 km long) in the TGR region with a watershed area of 3099km^2 (Ye *et al.*, 2003). Since the current velocity was dramatically reduced and an abundance of nutrients were carried into Xiangxi Bay, a phytoplankton bloom was observed during the first spring after TGR was filled.

The phytoplankton bloom was one of the worst water quality problems in the world, and it will cause a variety of problems including toxin production, odors, scum and possibly unsafe drinking water (Paerl, 1988; Paerl *et al.*, 2001). Many current works in China were always focusing on the problems of lakes (Xu *et al.*, 2001; Xie *et al.*, 2003; Hou *et al.*, 2004; Wang *et al.*, 2005), seldom studies were carried out in TGR region. TGR is the biggest freshwater source in China. It has 3.93×10^{11} m^3 in reservoir capacity, and the average yearly inflow is 4.51×10^{12} m^3.

Understanding the bloom status and determining which nutrients limiting algae growth are an important step in the development of effective watershed and reservoir water resource management strategies. In this study, the basic physical and chemical variables of water samples were measured during the spring bloom period in Xiangxi Bay in year 2005. The main aim of this study was to access the development of the spring bloom in Xiangxi Bay, determine the limiting factors and provide advices for the water resource management.

2 Materials and methods

2.1 Field sampling

The field survey was carried out from Feb. 23 to Apr. 28 in year 2005, except for the malfunction of boat engine on 11 Mar. According to the Regulation for Water Environmental Monitoring of Ministry of Water Resources, P.R. China (1998), a total of 31 sites were sampled in the Xiangxi Bay (Fig. 1) every six days, including one daily sampling site (Site A) and one bidaily sampling site (site B). Site A represented the habitat with high DIN:PO_4P ratio, with the average DIN:PO_4P ratio of 13.14, during the spring bloom period. Site B represented the habitat with low DIN:PO_4P ratio (2.68). The position of each site was recorded using a hand held GPS (Topcon, Japan). Water samples were collected at a depth of 0.5 m beneath the water surface using the Van Dorn sampler. The physical parameters: pH, DO and water temperature (WT) were measured using the Horiba W-23XD multi-probes (Horiba, Japan) *in situ*. And 300 to 600ml water sample was filtered through a micro-filter (0.8 μm) for chlorophyll *a* (Chl-*a*) determination. The filter was immediately placed in a sealed plastic container and held on ice until measurement of Chl-*a* was made according to Observation and Analysis in Chinese Ecosystem Research Network (Huang *et al.*, 1999). Another 300ml water sample was stored in a pre-cleaned plastic bottle for phosphate-phosphorus (PO_4P), ammonium-nitrogen (NH_4N), nitrite-nitrogen + nitrate-nitrogen (NO_2N+NO_3N) and dissolved silicate (Si) measurement. The above chemical variables were analyzed according to the user manual of Skalar on the segmented flow analyzer (Skalar SAN^{++}, Netherlands).

2.2 Date analysis

2.2.1 Spatial analysis

GIS is a useful technique in environmental modeling and assessment (Xu *et al.*, 2001; Maidment, 2002; Goodchild, 2003). In this study, the outline of water surface in Xiangxi Bay was extracted from the Xiangxi River Watershed Digital Elevation Model (DEM, 1: 50,000) under ArcGIS (ArcGIS 8.3, ESRI). Because the sampling sites are limited, the spatial distribution maps of Chl-*a* and nutrient (Si, PO_4P, DIN [NH_4N + NO_2N + NO_3N]) were interpolated using the IDW method referenced from the work of Xu *et al.*, (2001) and Newton *et al.*, (2003) with a spatial resolution of 30m × 30m. The concentration of Chl-*a* was scaled according to different eutrophication scales (Wang *et al.*, 2005): ultra-oligotrophic ($<= 1.00$ μg/L), oligotrophic (1.00–2.50 μg/L); mesotrophic (2.5–8.0 μg/L), eutrophic (8.0–25.0 μg/L) and hypertrophic ($>=25$ μg/L).

Spatial regression were performed in order to examine possible nutrient factors affecting the spatial heterogeneity of Chl-*a*. It was performed on the GeoDa software (http://geog55.geog.uiuc.edu/). There are three algorithms in GeoDa: OLS, LM-Error, LM-Lag. The appropriate algorithm was selected based on the LM diagnostics (Anselin *et al.*, 2005, 2006).

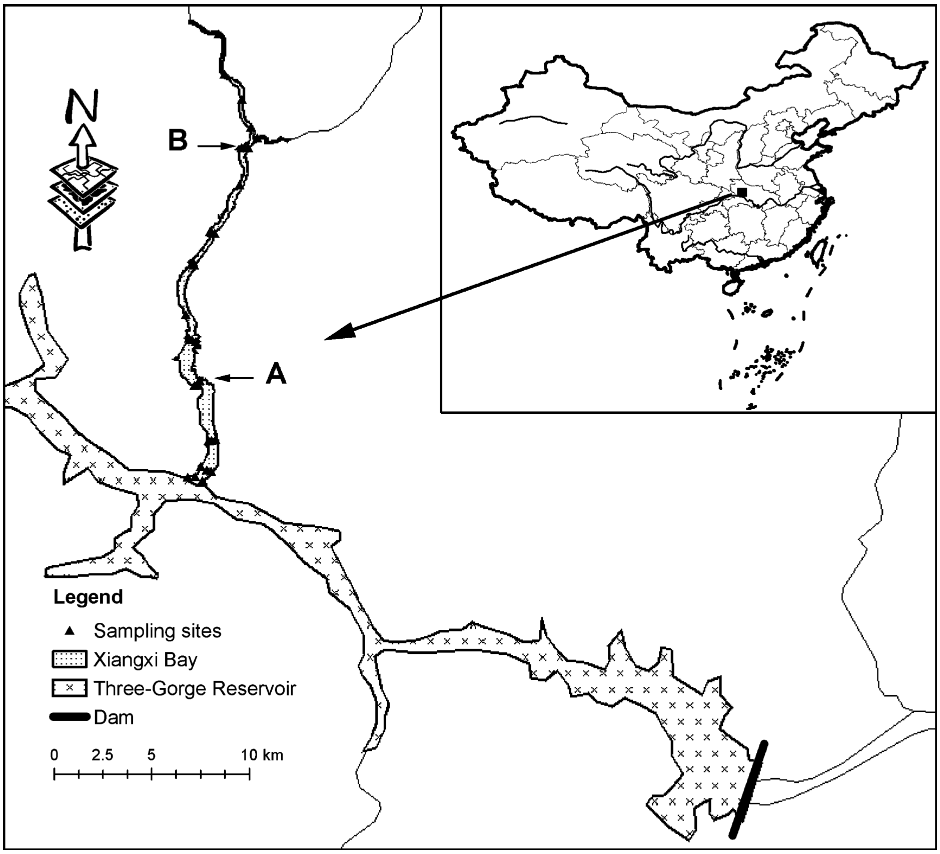


Fig. 1 Spatial distribution of sampling sites in Xiangxi Bay, Three Gorges Reservoir region. A: Sampling site A (daily sampling site); B: Sampling site B (bidaily [every two day] sampling site).

2.3 Stepwise regression analysis

Stepwise regression analysis (using Statistica 6.0) was performed individually for each site with Chl-*a* concentration as the dependent variable and DIN, PO_4P, and Si as independent variables to determine what factors controlling the development of spring bloom in Xiangxi Bay (Kocum *et al.*, 2002; Iriarte *et al.*, 2004).

3 Results

3.1 Physical characteristics

Results of conventional statistical analysis showed that pH was ranged from 7.36 to 9.50, with a mean value of 8.64. DO was ranged from 6.08 to 19.99 mg/L, and its mean value was 11.81 mg/L. Water temperature was ranged from 9.77 to 25.00°C, with a mean value of 14.94°C. Correlation analysis indicated that the concentration of Chl-*a* has a good correlation with pH ($r = 0.75$, $p < 0.001$), DO ($r = 0.73$, $p < 0.001$), WT($r = 0.43$, $p < 0.001$) in the whole spring bloom period.

It is well known that temperature can enhance phytoplankton growth rate, and plays a critical role in the timing of bloom initiation (Eppley, 1972; Iriarte *et al.*, 2004). When the first major bloom events occurred (17, Mar.), the average temperature of surface water was more than 13°C. However, the spring bloom seems to disappear temporarily in the following week because of the drop of air temperature and the precipitation (Fig. 2). According to the related studies, the good relationship with pH and DO can be understood as the result of the spring bloom. Algal photosynthesis is usually the major supplier of oxygen to slow flowing water body (Wehr *et al.*, 1998). In natural water, pH is principally related with photosynthesis. pH is affected by the water chemistry, particularly the concentration of some of the CO_2-system components (CO_2, HCO_3^- and CO_3^{2-})

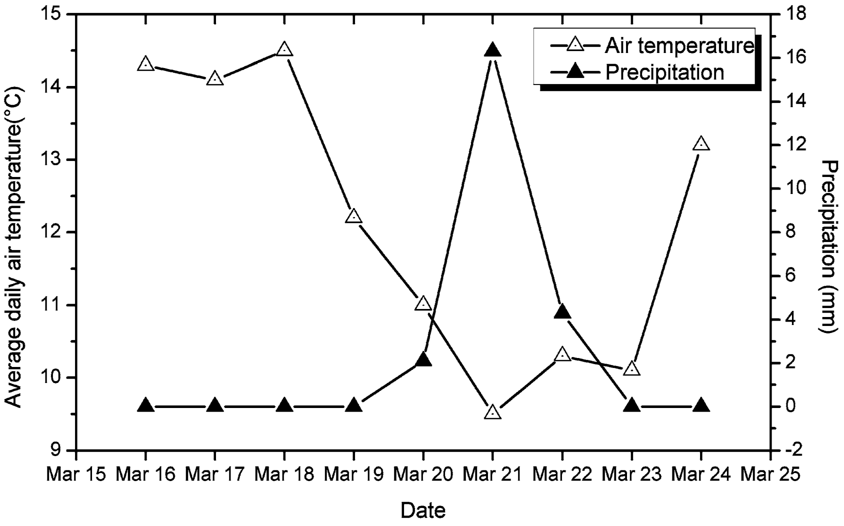


Fig. 2 The average daily air temperature and precipitation during 16 Mar.–24 Mar. Recorded from Xianshang weather station, about 18km north from the Xiangxi Bay (110°44′ E, 31°21′ N).

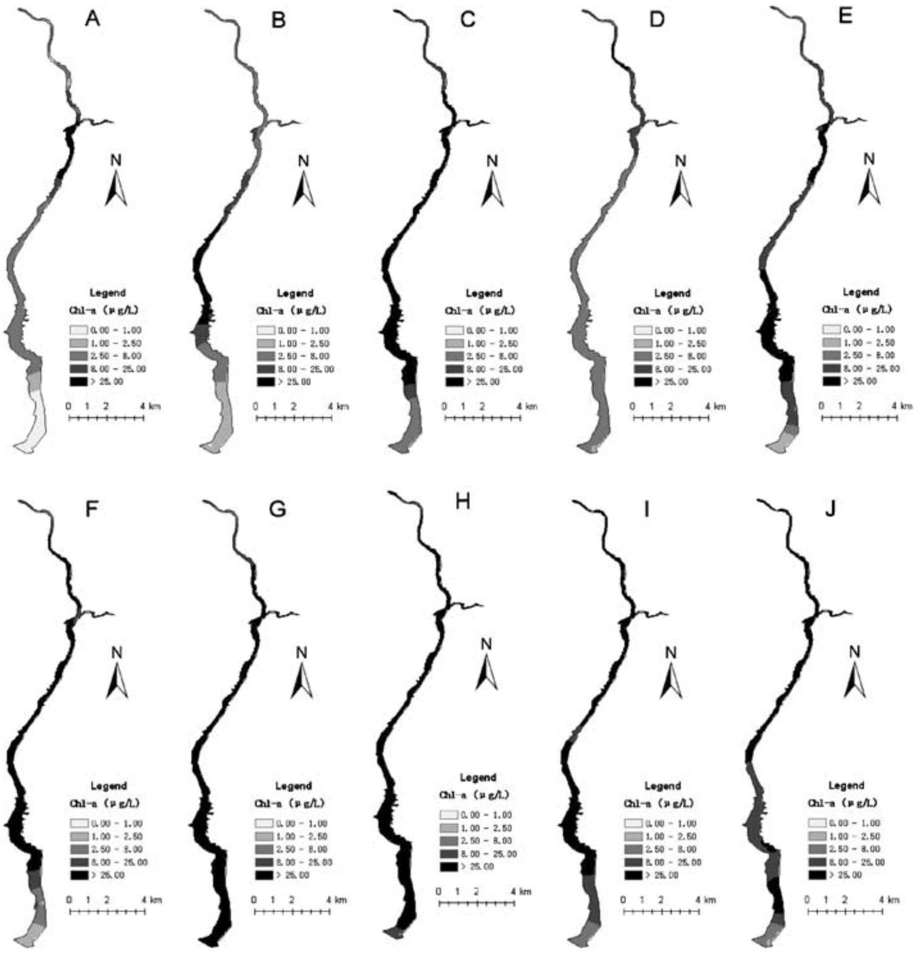
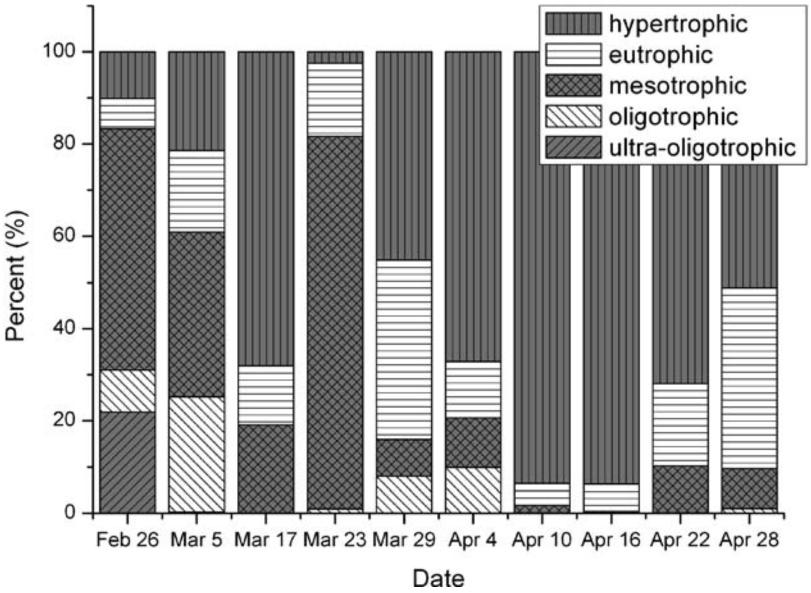


Fig. 3 The spatial distribution of Chl-*a* in the Xiangxi Bay at different time: A. 26 Feb. B. 5 Mar. C. 17 Mar. D. 23 Mar. E. 29 Mar. F. 4 Apr. G. 10 Apr. H. 16 Apr. I. 22 Apr. J. 28 Apr.

Fig. 4 Percent of the area of different eutrophication types in Xiangxi Bay during the spring bloom period.



according to the equilibrium reactions (Stumm *et al.*, 1981; Wehr *et al.*, 1998).

3.2 Spatial analysis

Calculated spatial and temporal variations of Chl-*a* with different eutrophication scales are presented in Fig. 3. From the figure, the spring bloom was occurred twice in the study area during the whole monitoring period. The first bloom occurred during 26 Feb–23 Mar, and the second one occurred during 23 Mar–28 Apr. It can be found that the first bloom was originated in the upstream of the Xiangxi Bay, and had a tendency to develop and diffuse toward the river mouth. The second bloom was originated in the middle reach of Xiangxi Bay and developed quickly to almost all the bay. The spatial statistic under GIS revealed that the areas of eutrophic and hypertrophic regions had achieved about 80.85% of the whole area of Xiangxi Bay in the first bloom period, and in the second bloom period, these areas had achieved more nearly 99.55% (Fig. 4).

The spatial and temporal variations of dissolved silicate (Si) in Xiangxi Bay are presented in Fig. 5. The initial concentration of Si seems no obvious difference in space (Fig. 5A, 5B). However, it showed high heterogeneity in space with the development of the spring bloom. Obvious consumptions of Si were found when the bloom status was serious (i.e., 17 Mar., 16 Apr., 22 Apr., 28 Apr.).

Figure 6 shows the spatial distribution of DIN in Xiangxi. It can be found that the region in the mouth of Xiangxi Bay has a high concentration of DIN and the upstream area of the bay has a low concentration of DIN. By comparing with the distribution of Chl-*a*, it can be found that DIN was consumed remarkably in the end of the second bloom period in the upstream of Xiangxi Bay. The lowest value of DIN achieved to 0.06 mg/L on 28 Apr.

Figure 7 represents the spatial and temporal distribution of PO_4P in Xiangxi Bay. It can be found that the region with high concentration of PO_4P occurred in the upstream of Xiangxi Bay, and the area with low concentration of PO_4P occurred in the mouth of Bay. By comparing with the spatial distribution of Chl-*a*, no obvious depletion of PO_4P was found in the whole monitoring period.

Spatial regression analysis was carried out to determine what factors cause the spatial heterogeneity of Chl-*a*. According to the results of LM diagnostics performed by the software GeoDa, OLS algorithm and Lag algorithm were selected in the analysis (Table 1). It can be found that the nutrient variables could explain most variations of Chl-*a* in space, except at the beginning of the first and second bloom period (26 Feb., 23 Mar. and 29 Mar.). The results also indicated that Si was negative correlated with Chl-*a* both at the first and second

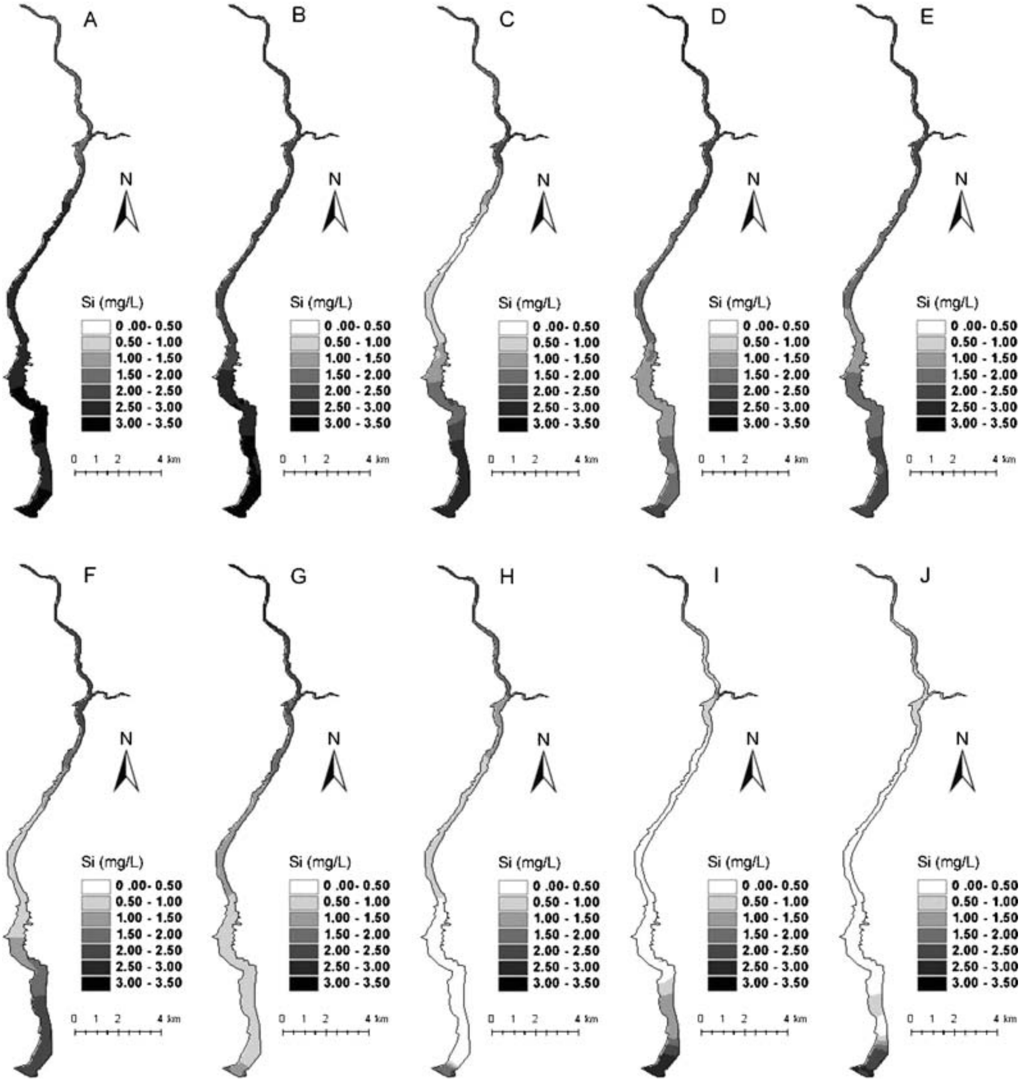


Fig. 5 The spatial distribution of dissolved silicate (Si) in Xiangxi Bay at different time: A. 26 Feb. B. 5 Mar. C. 17 Mar. D. 23 Mar. E. 29 Mar. F. 4 Apr. G. 10 Apr. H. 16 Apr. I. 22 Apr. J. 28 Apr.

bloom period before achieved the maximum hypertrophic area. And after that DIN was negative correlated with Chl-*a* when Si was obviously depleted during the second bloom period.

3.3 Time series analysis

The concentration of Chl-*a* was ranged from 1.65 to 101.40 μg/L at site A, and 1.62–193.37 μg/L at site B. The results of conventional statistical analysis showed that the mean values of Chl-*a* was 26.82 μg/L at site A, and 45.20 μg/L at site B. The respective coefficients of variation (CV) were 86% and 98%. According to the dynamics of Chl-*a* at site A and B, the spring bloom had three pulses (Fig. 8): the first peak appeared around 1 March, the second one appeared around 15 March, and the third one appeared around 5 April.

The concentration of Si decreased with times at site A and B, and this change was more dramatically at site A (Fig. 8). At site A, the concentration of Si was ranged from 0.02 to 3.20 ml/L, and achieved the minimum values on 14 April. At site B, it was ranged from 0.32 to 2.66 mg/L, and achieved the lowest values on 20 April. The concentration of DIN was ranged from 0.71 to 2.40 mg/L at site A, and 0.06 to 0.83 mg/L at site B.

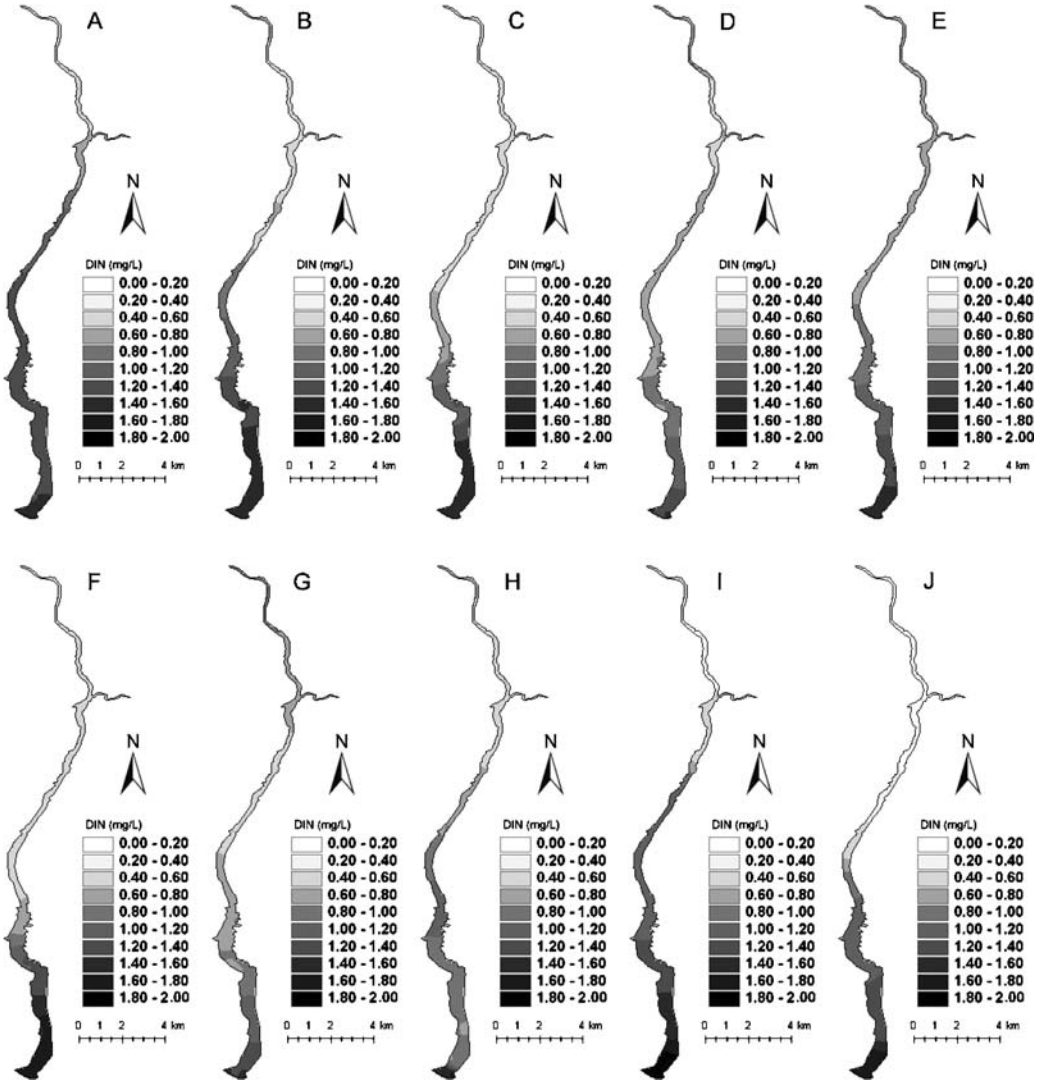


Fig. 6 The spatial distribution of DIN in Xiangxi Bay at different time: A. 26 Feb. B. 5 Mar. C. 17 Mar. D. 23 Mar. E. 29 Mar. F. 4 Apr. G. 10 Apr. H. 16 Apr. I. 22 Apr. J. 28 Apr

Table 1 Spatial regression analysis between Chl-*a* and nutrient variables during the spring bloom in Xiangxi Bay

	Constant	DIN	PO4P	Si	R^2	Model
26/02	193.16	15.63	−233.00	−62.50	0.13	OLS
05/03	160.67**	33.10**	−90.17**	−65.44**	0.88	OLS
17/03	141.21**	−19.59	−66.43	−35.40**	0.77	OLS
23/03	−8.53	−2.47	30.86	6.49	0.28	OLS
29/03	67.25**	−18.99	−34.66	−11.71	0.34	Lag
04/04	74.69**	−10.65	38.75	−23.85**	0.79	OLS
10/04	111.29**	−24.85	−107.79	−18.68**	0.94	OLS
16/04	168.11**	−88.71**	−336.13**	8.09	0.62	Lag
22/04	113.37**	−64.87**	6.71	0.95	0.85	Lag
28/04	70.43**	−45.90	9.27	5.98	0.81	Lag

*$p < 0.05$, **$p < 0.01$.

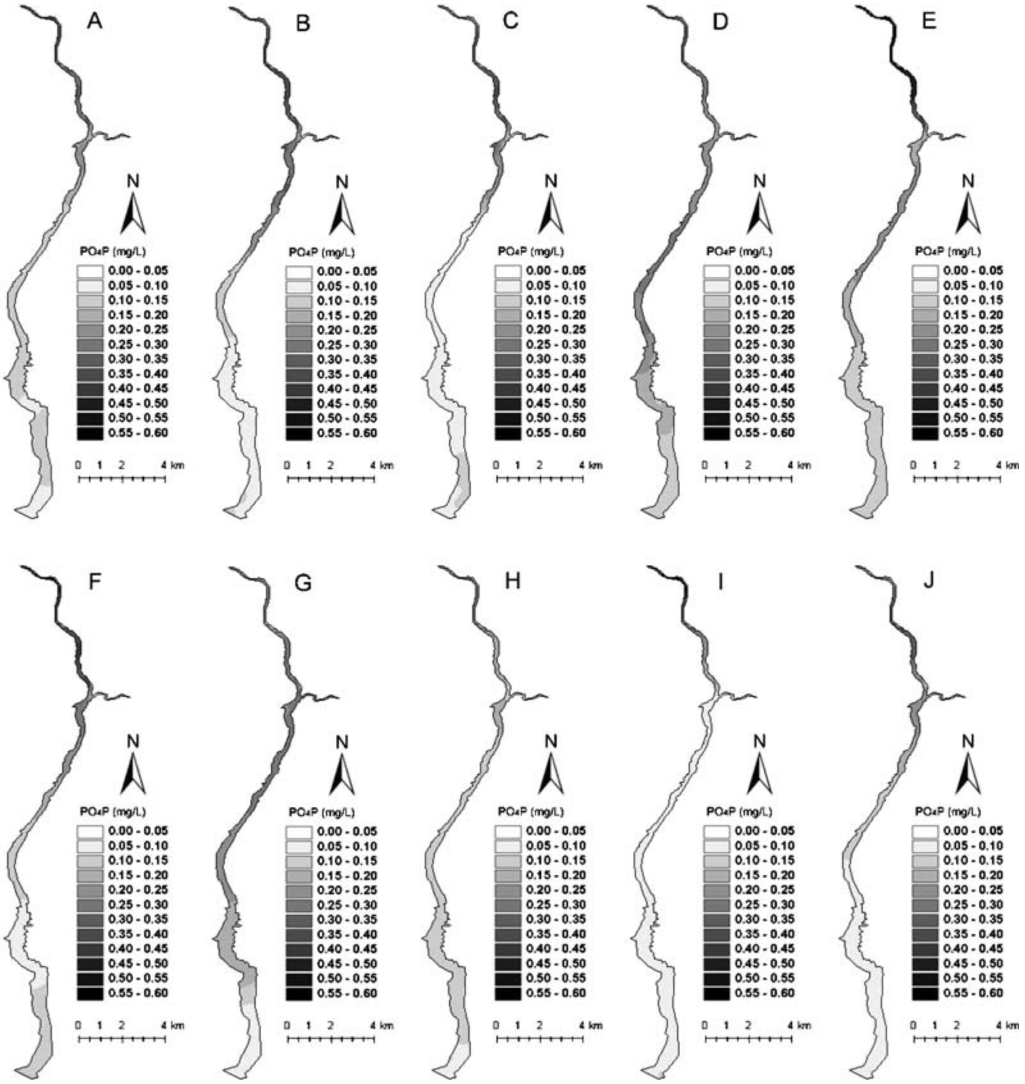


Fig. 7 The spatial distribution of PO_4P in Xiangxi Bay at different time: A. 26 Feb. B. 5 Mar. C. 17 Mar. D. 23 Mar. E. 29 Mar. F. 4 Apr. G. 10 Apr. H. 16 Apr. I. 22 Apr. J. 28 Apr.

The dynamics of DIN were dissimilar between site A and B, and dramatically drop of DIN was found in the end of the field monitoring at site B (Fig. 9). The dynamics of PO_4P were also dissimilar between site A and B (Fig. 9). The concentration of PO_4P was ranged from 0.05 to 0.16 mg/L at site A, and 0.08 to 0.42 mg/L at site B.

Multiple stepwise regression analysis indicated that Si was the most important factor affect the development of spring bloom both at site A and B (Table 2). At site A, the concentration of Si could explain 48% variation of Chl-*a*, however, only 23% variation of Chl-*a* was explained by the concentration of Si.

4 Discussion

Historically, phosphorus has been considered to be the primary nutrient limiting phytoplankton growth in freshwater ecosystem (Schindler, 1977; Hecky *et al.*, 1988). This study found that PO_4P was not the primary factor limiting the spatial and temporal dynamics of Chl-*a* in Xiangxi Bay of Three Gorges Reservoir. The spatial regression analysis indicated that Si was the primary limiting the spatial herterogeneity Chl-*a* in Xiangxi Bay before achieved the max area of hypertrophic. When Si was exhausted, spatial regression analysis indicated that DIN would become the factor

Fig. 8 Time series plot for the concentration of Chl-*a* and dissolved silicate (Si) in Xiangxi Bay from 23 Feb. to 28 Apr. A: Sampling site A (Daily sampling site), B: Sampling site B (Bidaily sampling site).

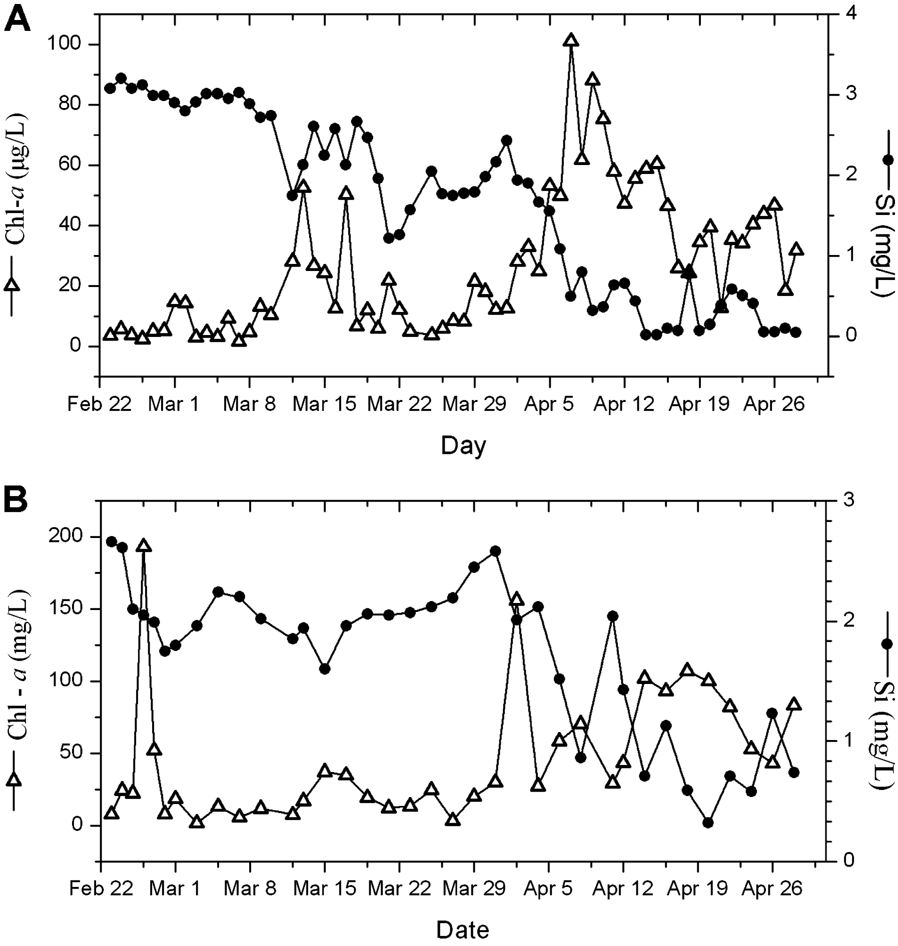


Table 2 Multiple stepwise regression analysis between the Ch-*a* and nutrient variables (DIN, PO_4P and Si) during the spring phytoplankton bloom in Xiangxi Bay

	Coefficient	Standardized coefficient	*p*
Site A			
Constant	50.62	3.77	<0.001
Si	−14.56	1.92	<0.001
Site B			
Constant	105.50	19.15	<0.001
Si	−34.86	10.41	0.002

$^{*}p < 0.05$, $^{**}p < 0.01$.

effluence the spatial pattern of Chl-*a*. Time series monitoring at two sites, representing the high N:P ratio and low N:P ratio region, indicated that Si was the most important factor influenced the dynamics of Chl-*a* in Xiangxi Bay in time series.

The effects of Si and DIN to the phytoplankton bloom are well-known in the estuarine and marine ecosystem (Brzezinski *et al.*, 2001; Bode *et al.*, 2005). The present study indicated that the Si was the most important factor limiting the development of spring bloom in Xiangxi Bay. The dominant species in Xiangxi Bay were diatoms. Si was an important factor to diatoms when forming their silica shells (Turner *et al.*, 1998). From the figures (Fig. 5, 6), it can be found that Si was exhausted in the downstream of the bay at the end of the second bloom period, and DIN was depleted in the upstream of the bay. This may be understood that different phytoplankton taxa have different individual nutrient consumption, to further understand the inner development of the spring bloom and the nutrient limitation, research should focus on the responses of individual taxon to specific nutrient listed above (Elser *et al.*, 1990; Lagus *et al.*, 2004).

Many studies indicated that hydrologic parameters are a major factor controlling phytoplankton blooms in estuaries and reservoirs (Martines *et al.*, 2001; Ha *et al.*, 2003; Iriarte *et al.*, 2004). According to the spatial analysis of the nutrient variables, DIN, PO_4P and Si

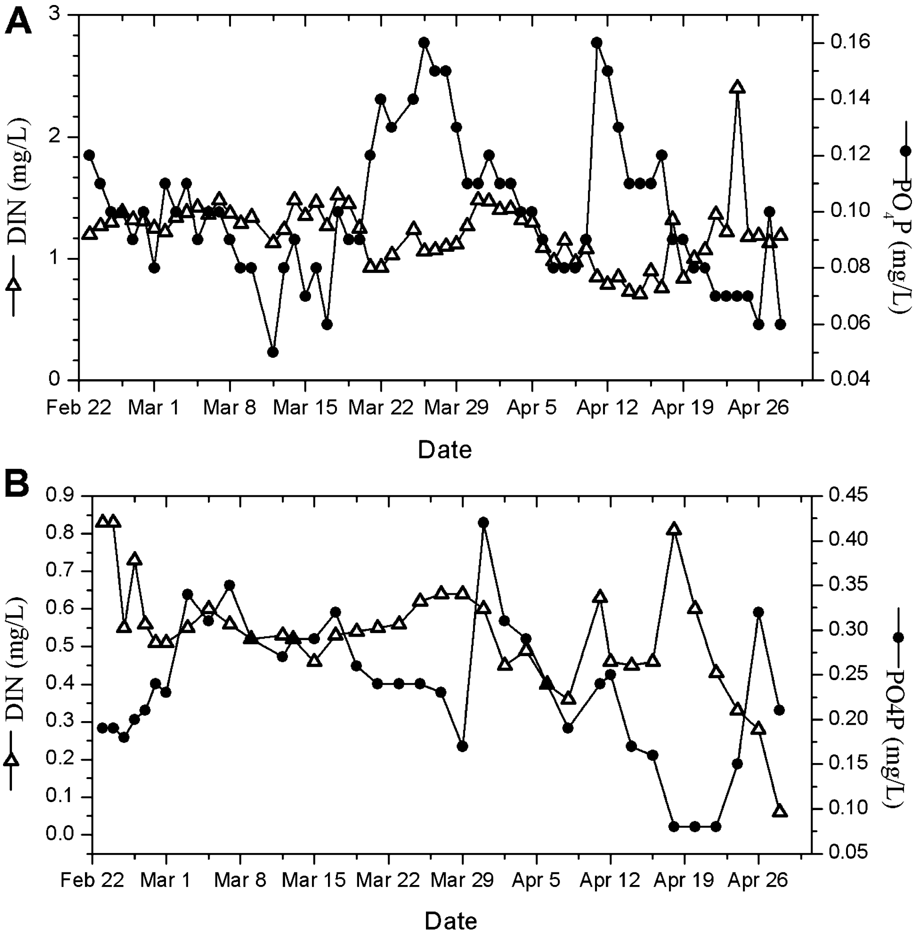


Fig. 9 Time series plot for the concentration of DIN and PO$_4$P in Xiangxi Bay from 23 Feb. to 28 Apr. A: Site A (Daily sampling site); B: Site B (Bidaily sampling site).

had clear spatial distributions in Xiangxi Bay. The area in the mouth of the Xiangxi Bay has a high concentration of DIN and Si. Efforts to use hydrologic measures to control the spring bloom should consider different nutrients needed by the phytoplankton. For example, if the bloom is limited by Si or DIN, measures to store water would accelerate the movement of water from the river mouth into the bay, and this would not be appropriate because it would bring water with a high concentration of DIN and Si into the bay to boost the growth of algae.

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