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HUI ZENG[1, 2, 4], LIRONG SONG*[, 1], ZHIGANG YU[3] and HONGTAO CHEN[3]

[1]State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology,
The Chinese Academy of Science, Wuhan 430072, P. R. China; e-mail: lrsong@ihb.ac.cn
[2]Graduate School of Chinese Academy of Science, Beijing 100049, P.R. China
[3]Ocean University of China, Qingdao 266003, P. R. China
[4]Environmental Protection Institute of Guangxi, Nanning 530022, P.R. China

Post-Impoundment Biomass and Composition of Phytoplankton in the Yangtze River

key words: hydrodynamics, blooms, eutrophication

Abstract

Damming, and thus alteration of stream flow, promotes higher phytoplankton populations and encourages algal blooms (density $>10^6$ cells L^{-1}) in the Three Gorges Reservoir (TGR). Phytoplankton composition and biomass were studied in the Yangtze River from March 2004 to May 2005. 107 taxa were identified. Diatoms were the dominant group, followed by Chlorophyta and Cyanobacteria. In the Yangtze River, algal abundance varied from 3.13×10^3 to 3.83×10^6 cells L^{-1}, and algal biomass was in the range of 0.06 to 659 mg C m^{-3}. Levels of nitrogen, phosphorus and silica did not show consistent longitudinal changes along the river and were not correlated with phytoplankton parameters. Phytoplankton abundance was negatively correlated with main channel discharge (Spearman $r = -1.000$, $P < 0.01$). Phytoplankton abundance and biomass in the Yangtze River are mainly determined by the hydrological conditions rather than by nutrient concentrations.

1. Introduction

The Changjiang (Yangtze) River, the third longest river in the world, originates in the Qinghai-Tibet Plateau and flows east about 6300 km to the East China Sea. The drainage basin lies between 91°–122° E and 25°–35° N and covers 1.81×10^6 km^2 (CHEN *et al.*, 2001), which is equivalent to approximately 20% of the total area of China. The Yangtze River and some of its 700 tributaries have been key navigable waterways and important sources of irrigation water since ancient times. Dams on the Yangtze have also made it a source of hydroelectric power.

Three-Gorges Dam (TGD), the largest dam in the world, is located in the upper reaches of the Yangtze River. The total length of the dam axis is 2309 m, the crest elevation is 185 m and the maximum height is 181 m. The Three Gorges Project (TGP) includes three stages, with completion scheduled for 2009. While the current level of the Three Gorges Reservoir (TGR) is approximately 135 m, the level at completion will fluctuate between 145 m (rainy season) and 175 m (dry season). The dam's turbines will generate tremendous electric power and the reservoir is designed to help control flooding. In addition, TGR will allow large ships to penetrate China's interior and will provide irrigation and drinking water. However, large scale dams are seldom constructed without associated environmental problems (SNOW *et al.*, 2000; VÖRÖSMARTY *et al.*, 2003). Damming alters the characteristics of a water body, replac-

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* Corresponding author

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ing riverine conditions with those of a lake and affecting not only the hydrology but also physical, chemical and biological nature of the system. These changes include increases in residence time, stratification, decrease in particles and sometimes an increase of primary production (JICKELLS, 1998; FRIEDL and WÜEST, 2002; CHENG and LI, 2001). Not only can large dams affect characteristics of individual rivers, but might also have a cumulative effect on the phytoplankton composition and biogeochemical cycling in coastal seas (HUMBORG *et al.*, 1997).

Phytoplankton species are often used as biological indicators because they have a short life cycle and rapid growth, and respond quickly to changes in environmental conditions (IBELINGS *et al.*, 1998). However, while other large rivers around the world have been extensively studied, there are a limited number of studies on the phytoplankton populations of the Yangtze River (BORUZKIJ *et al.*, 1959; WANG and LIANG, 1991). The goals of our study were to assess (1) the impacts of TGD on ecosystem structure and biogeochemistry of the Yangtze River and estuary and (2) fluctuations in TGR water quality through a long-term study of the phytoplankton community and biomass (STEVENSON and WHITE, 1995; BÜSING, 1998; O'FARRELL *et al.*, 2002).

2. Materials and Methods

2.1. Sample Collection

Sampling was performed at 29 stations along the Yangtze River in March, May, July–August and October 2004, and May 2005 (Fig. 1). These stations are listed in the Table 1. Samples for phytoplankton and chemical analysis were taken by using 1 L water-sampler at the surface.

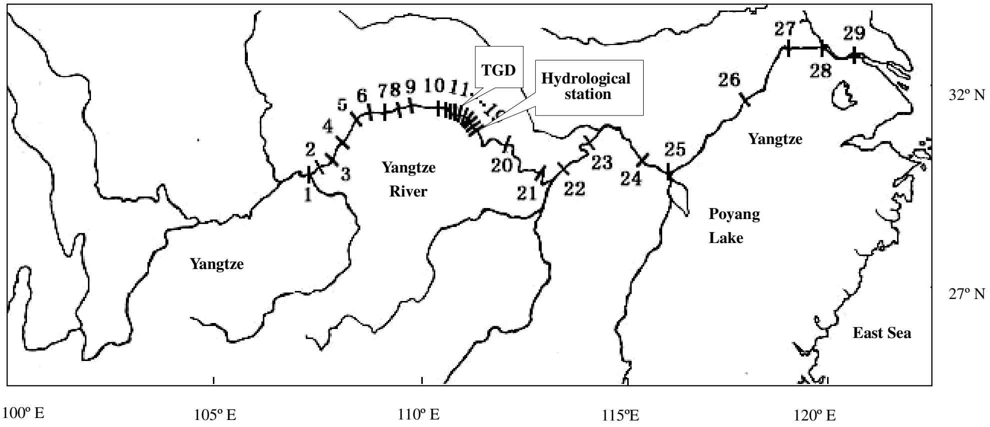

Figure 1. Sampling sites along the Yangtze River during surveys: 1. FL – Fuling, 2. FD – Fengdu, 3. ZX – Zhongxian, 4. WZ – Wanzhou, 5. YY – Yunyang, 6. YZ – Yunyangzhen, 7. FJ – Fengjie, 8. WS – Wushan, 9. BD – Badong, 10. XX – Xiangxi, 11. XT – Xintaizhen, 12. LL – Liulan, 13. TP – Taipingxi, 14. ZG – Zigui (TGD), 15. SD – Sandouping, 16. TX – Tianxizhen, 17. SP – Shipai, 18. NG – Nanjinguan, 19. GZ – Gezhoubaxia (Hydrological station), 20. JZ – Jingzhou, 21. JL – Jianli, 22. HH – Honghu, 23. HY – Hanyang, 24. HS – Huangshi, 25. HK – Hukou, 26. DT – Datong, 27. NJ – Nanjing, 28. ZJ – Zhenjiang, 29. JY – Jiangyin.

Table 1. The sampling sites in the Yangtze River.

Sample sites in upstream of the TGD	Sample sites in downstream of the TGD
1. Fuling (29°44′ N, 107°21′ E)	15. Sandouping (30°59′ N, 111°04′ E)
2. Fengdu (29°50′ N, 107°36′ E)	16. Tianxizhen (30°51′ N, 111°08′ E)
3. Zhongxian (30°12′ N,107°58′ E)	17. Shipai (30°47′ N, 111°09′ E)
4. Wangzhou (29°44′ N, 107°21′ E)	18. Nanjinguan (30°45′ N, 111°17′ E)
5. Yunyang (30°55′ N, 108°33′ E)	19. Gezhoubaxia (30°41′ N, 111°17′ E)
6. Yunyangzhen (30°56′ N, 108°47′ E)	20. Jingzhou (30°18′ N, 112°10′ E)
7. Fengjie (31°00′ N, 109°27′ E)	21. Jianli (29°47′ N, 112°51′ E)
8. Wushan (31°03′ N, 109°49′ E)	22. Honghu (29°51′ N, 113°32′ E)
9. Badong (31°02′ N,110°20′ E)	23. Hanyang (30°19′ N, 114°06′ E)
10. Xiangxi (30°58′ N,110°43′ E)	24. Huangshi (30°23′ N, 115°05′ E)
11. Xintanzhen (30°56′ N, 110°48′ E)	25. Hukou (29°43′ N, 115°57′ E)
12. Liulan (30°53′ N, 110°54′ E)	26. Datong (30°47′ N, 117°38′ E)
13. Taipingxi (30°52′ N, 110°58′ E)	27. Nanjing (31°56′ N, 118°34′ E)
14. Zigui (30°51′ N, 110°59′ E)	28. Zhenjiang (32°16′ N, 119°26′ E)
	29. Jiangyin (31°91′ N, 120°26′ E)

Note: TGD is located at Zigui, and the Hydrologic station is located at Gezhoubaxia.

2.2. *Qualitative and Quantitative Investigation of Phytoplankton*

Phytoplankton samples were preserved immediately with 1% Lugol's solution. In the lab, a sedimentation method was used for taxa identification and counting (ZHANG and HUANG, 1991; EKER *et al.*, 1999). The sample was gently agitated before a subsample was withdrawn for counting under a standard light microscope (OLYMPUS C41) using a Fuchs-Rosental slide. Most phytoplankton were identified to species, especially the dominant algae (ZHANG and HUANG, 1991). The volume of each taxa was calculated by measuring morphometric characteristics (diameter or length and width) (MONTAGNES *et al.*, 1994) and converted to carbon biomass (STRATHMANN, 1967):

$$\log_{10} \mathrm{C} = 0.758 \log_{10} \mathrm{V} - 0.422 \quad \text{(for diatoms)}$$

$$\log_{10} \mathrm{C} = 0.866 \log_{10} \mathrm{V} - 0.460 \quad \text{(for other algae)}$$

Where: C is cell carbon in picograms and V is cell volume in μm^3.

2.3. *Chemical Analysis*

After collection, water samples were filtered immediately through pre-cleaned, 0.45-μm pore-size, acetate cellulose filters presoaked in diluted hydrochloric acid ($pH < 2$) overnight, then rinsed with Milli-Q water. The filtrates for nitrate, nitrite, ammonia and phosphate determination were kept frozen (–20 °C), whereas those for silicate were kept cool (4 °C) in the dark until analysis within one month. Nutrients were analyzed photometrically using an AutoAnalyzer (Bran and Luebbe AA3) and according to the Methods for the Chemical Analysis of Water and Wastes (MCAWW) (EPA/600/4–79/020) U. S. EPA National Exposure Research Laboratory). The analytical detection limits were 0.08 $\mu mol\ L^{-1}$ for NH_4, 0.05 $\mu mol\ L^{-1}$ for NO_3, 0.003 $\mu mol\ L^{-1}$ for NO_2, 0.009 $\mu mol\ L^{-1}$ for phosphate and 0.07 $\mu mol\ L^{-1}$ for silicate. The precision of nutrient analysis was estimated by repeated determinations of selected samples, and was better than 3% in this study.

2.4. Statistical Analysis

Spearman correlation analysis was conducted to evaluate relationships between algal abundance and nutrient concentrations. Analysis was completed using the SPSS 11.5 package.

3. Results

3.1. Phytoplankton Composition and Relative Abundance

From all locations, 107 taxa were identified. Diatoms (55 taxa) were the dominant group, accounting for 51% of all phytoplankton taxa, followed by Chlorophyta (32 taxa) and Cyanobacteria (12 taxa). Only a few representative taxa of Perrophyta (3), Euglenophyta (3), Chrysophyta (1) and Cryptophyta (1) were identified. The most common species in the Yangtze River were *Cyclotella meneghiniana, Cryptomonas erosa*, *Melosira varians*, *Microcystis aeruginosa*, *Synedra acus*, *Scendesmus quadricauda* and *Peridinium bipes*.

At most stations, diatom relative abundance was over 80%; however, proportional abundance of different algal groups did change over time. In March 2004, which is during spring and dry season, Cryptophyta and Chlorophyta were also abundant. At Zigui, the site of TGD, Pyrrophyta (*Peridiniopsis* sp.) accounted for 35% of the taxa collected in March 2004 (Fig. 2a), higher much than other sites. In May 2004, diatoms were dominant at all stations. Diatoms once again dominated the samples during July–August 2004 (rainy season). This group accounted for 100% of the taxa at 23 stations (Fig. 2c). Cryptophyta, however, accounted for 100% of the abundance at Shipai, and 70% of the taxa at Honghu were Cyanobacteria during this same time period. In October 2004, while diatoms were still dominant, other groups were present in several samples (Fig. 3a). At Wanzhou, approximately 50% of the abundance was due to Cyanobacteria (*Microcystis aeruginosa*). At Sandouping, approximately 25% were Pyrrophyta (*Peridiniopsis* sp.). In the May 2005 sample, diatoms were the only group observed at several locations. At Yunyang only Cynophyta were identified; this group was also dominant at Yunyangzhen and Badong (Fig. 3b). While diatoms were generally the most abundant group throughout the study, the dominance of this group was greater during the rainy season (July–August); in some cases, only diatoms were identified.

There were substantial temporal and spatial changes in phytoplankton abundance. In all sample periods, densities were higher in the downstream sites of the TGD, particularly from Jingzhou to Huangshi. In March 2004, for example, five of the six sites with the highest density ($1.02 \times 10^6 \sim 3.83 \times 10^6$ cells L^{-1}) belonged to the downstream; the sixth site was Zigui, the location of TGD with the value of 2.73×10^6 cells L^{-1}. The highest densities were observed in the March 2004 sampling (Fig. 4a); in May, July–August and October 2004, densities decreased dramatically (Figs. 4b, 4c, Fig 5a). In May 2005 phytoplankton densities were higher again, although not to the level observed in March 2004 (Fig. 5b).

3.2. Phytoplankton Carbon Biomass

The phytoplankton biomass in downstream locations was generally higher than in upstream locations (Table 2). But there was an exception in the March 2004 data. The biomass was very high at Zigui (TGD location) (659 mgC m^{-3}) due to the bloom of Pyrrophyta (*Peridiniopsis* sp.) (Fig. 6a). Maximum biomass for the remaining sampling periods was less than 100 mgC m^{-3}; the downstream sites continued to have the highest values (Figs. 6b–7b).

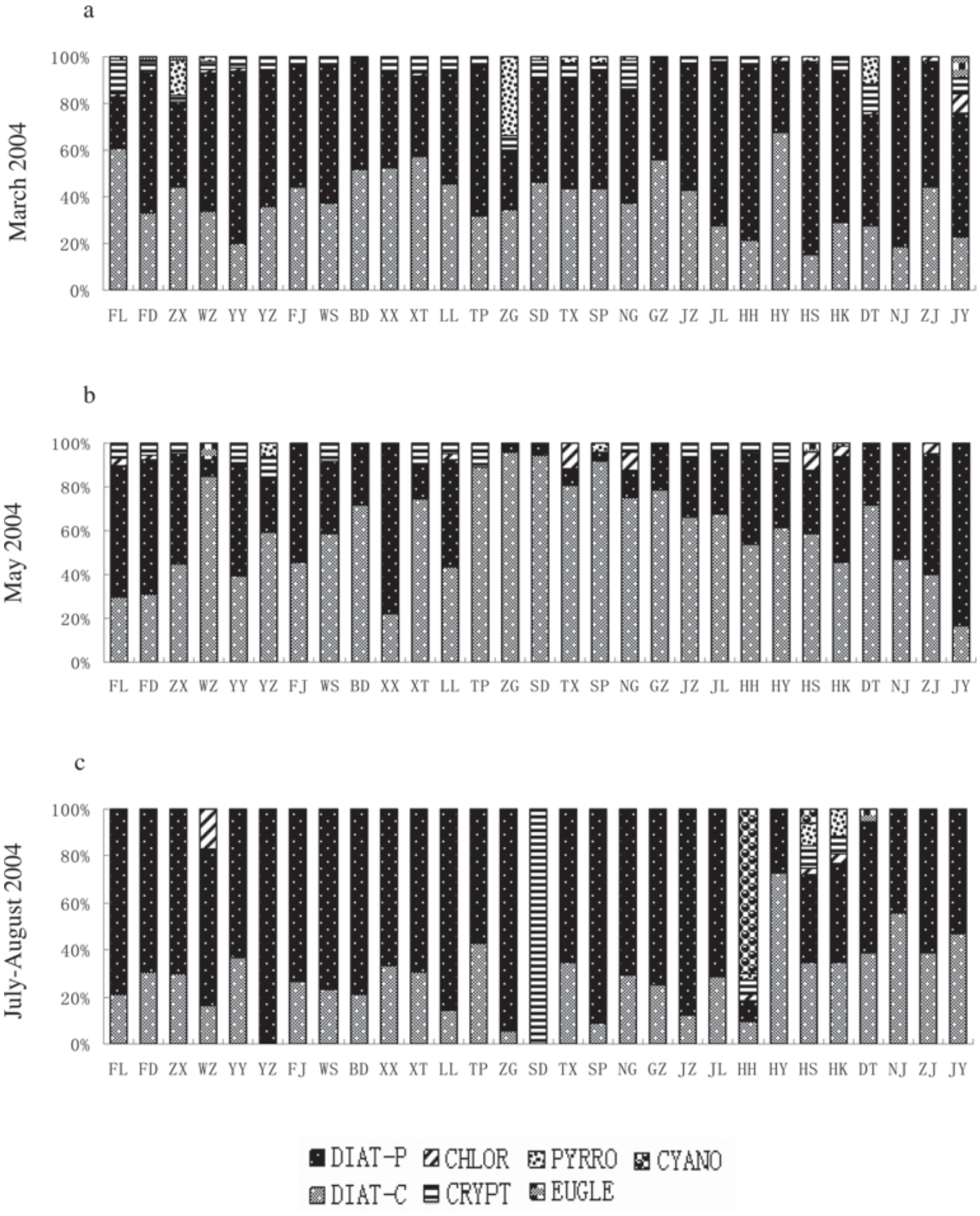

Figure 2. Relative abundance of phytoplankton in the Yangtze River during March (a), May (b) and July–August 2004 (c) (Diat-P: Pennatae; Diat-C: Centricae). Sample sites are listed from upstream to downstream. These sample sites can be referred to Figure 1.

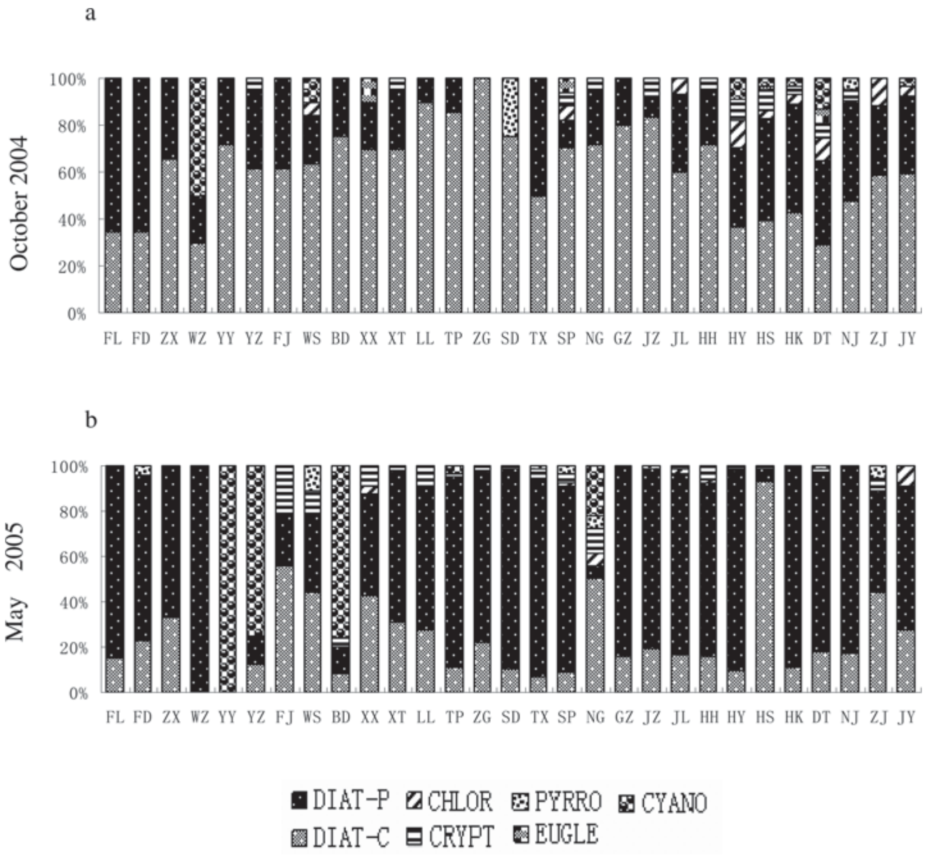

Figure 3. Relative abundance of phytoplankton in the Yangtze River during October 2004 (a) and May 2005 (b).

3.3. Nutrient Chemistry of the Yangtze River

Although there was variability in the concentrations of nutrients, including silica, at the different sampling locations, there did not appear to be any consistent spatial trends, for example, the nitrogen, phosphate and silicate concentration in upstream of TGD were in the range of 63.16 to 160.77, 0.31 to 2.05 and 78.90 to 163.78 μmol L^{-1}; in downstream the values were in the range of 65.54 to 152.77, 0.32 to 2.83 and 73.24 to 163.78 μmol L^{-1}, respectively (Table 3).

3.4. Correlation Analysis

There was no correlation between the concentrations of the main soluble nutrients (NO_3^--N, PO_4^{3-}-P, SiO_3^{2-}-Si) and phytoplankton abundance (Spearman, $r = 0.166$; $r = -0.186$; $r = 0.166$, respectively, $n = 29$). However, the average algal abundance and biomass in the upstream and downstream locations did demonstrate significantly negative correlations with

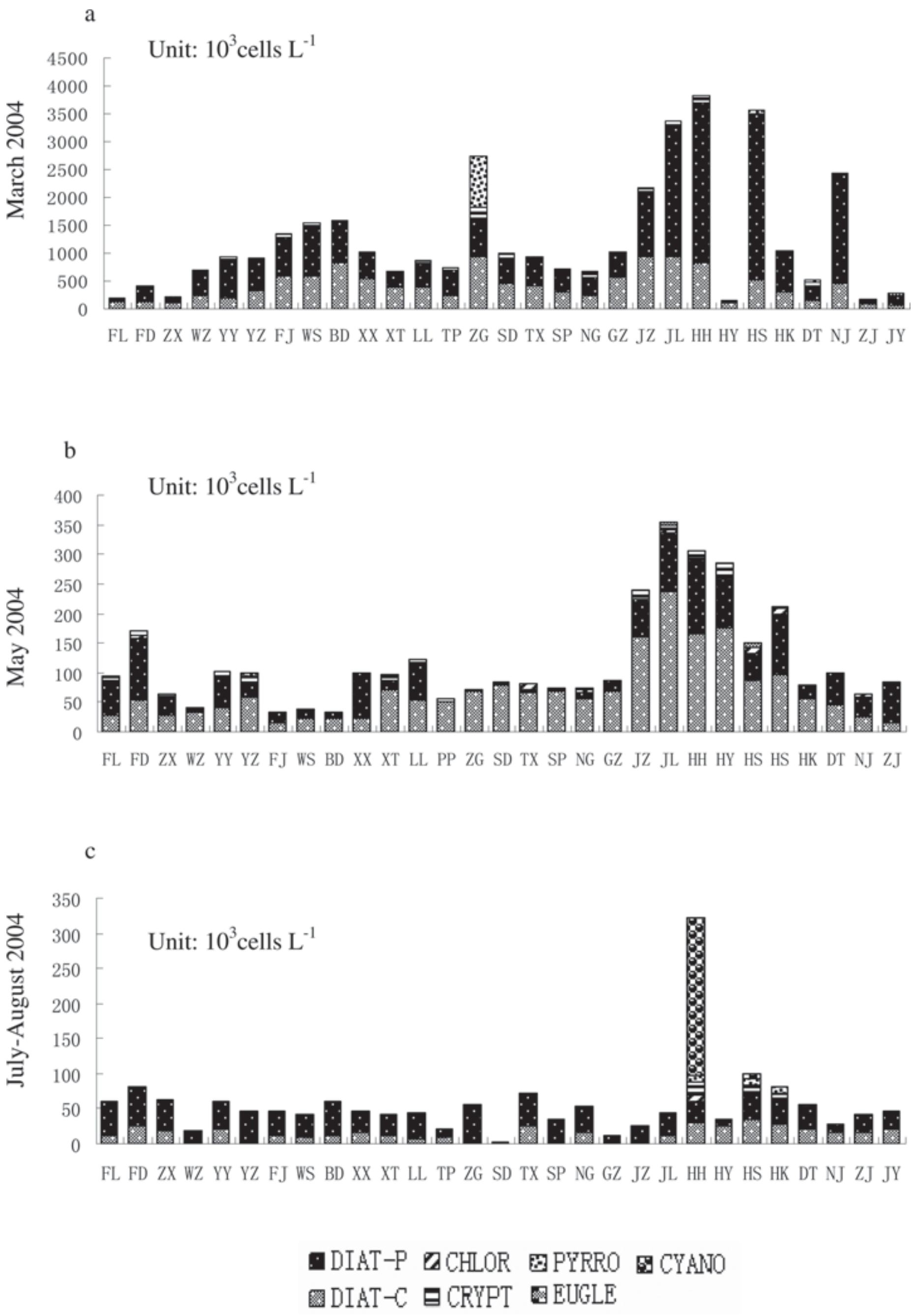

Figure 4. Density of phytoplankton in the Yangtze River during March (a), May (b) and July–August 2004 (c).

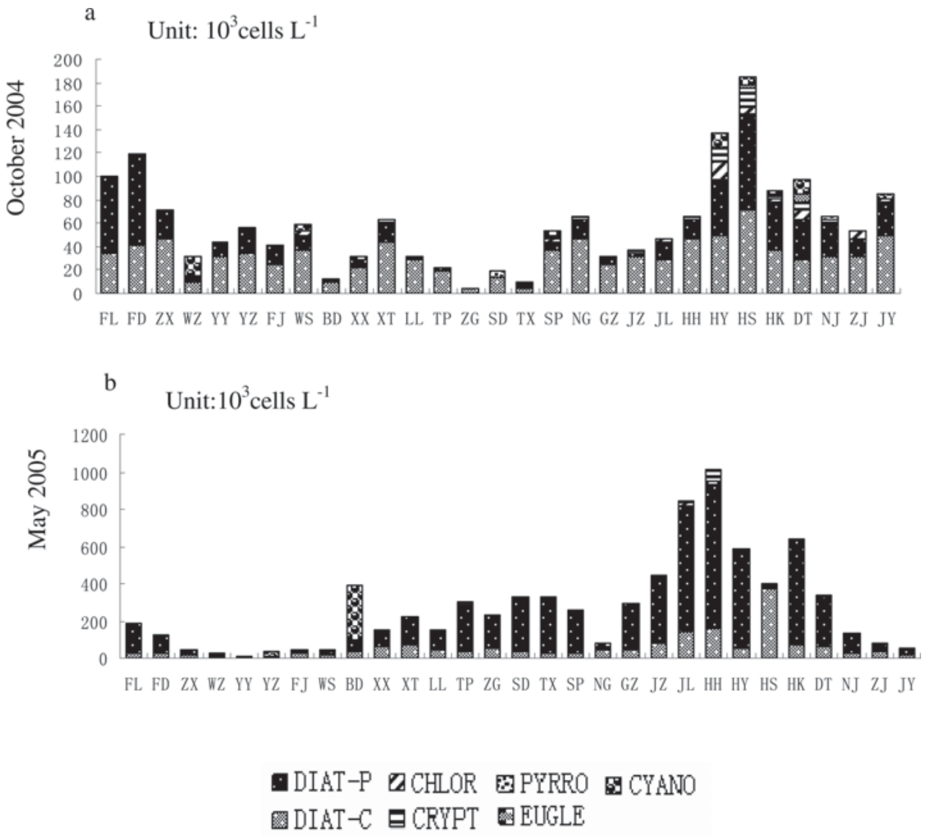

Figure 5. Density of phytoplankton in the Yangtze River during October 2004 (a) and May 2005 (b).

Table 2. Average abundance and biomass in upstream and downstream of TGD and flow discharge during surveys.

Period	Upstream of the TGD		Downstream of the TGD		Gezhoubaxia
	Algal density cells L^{-1}	Algal biomass mg C m^{-3}	Algal density cells L^{-1}	Algal biomass mg C m^{-3}	Discharge $m^3\ s^{-1}$
03/2004	992×10^3	140.5	1460×10^3	137.5	5.45×10^3
05/2004	80.0×10^3	13.8	152×10^3	24.1	11.6×10^3
07–08/2004	48.9×10^3	6.3	63.5×10^3	8.9	22.8×10^3
10/2004	49.1×10^3	7.2	69.3×10^3	12.4	15.9×10^3
05/2005	140×10^3	12.0	3.89×10^5	33.2	7.9×10^3

Note: Discharge data were provided by the Changjiang Hydrological Bureau.

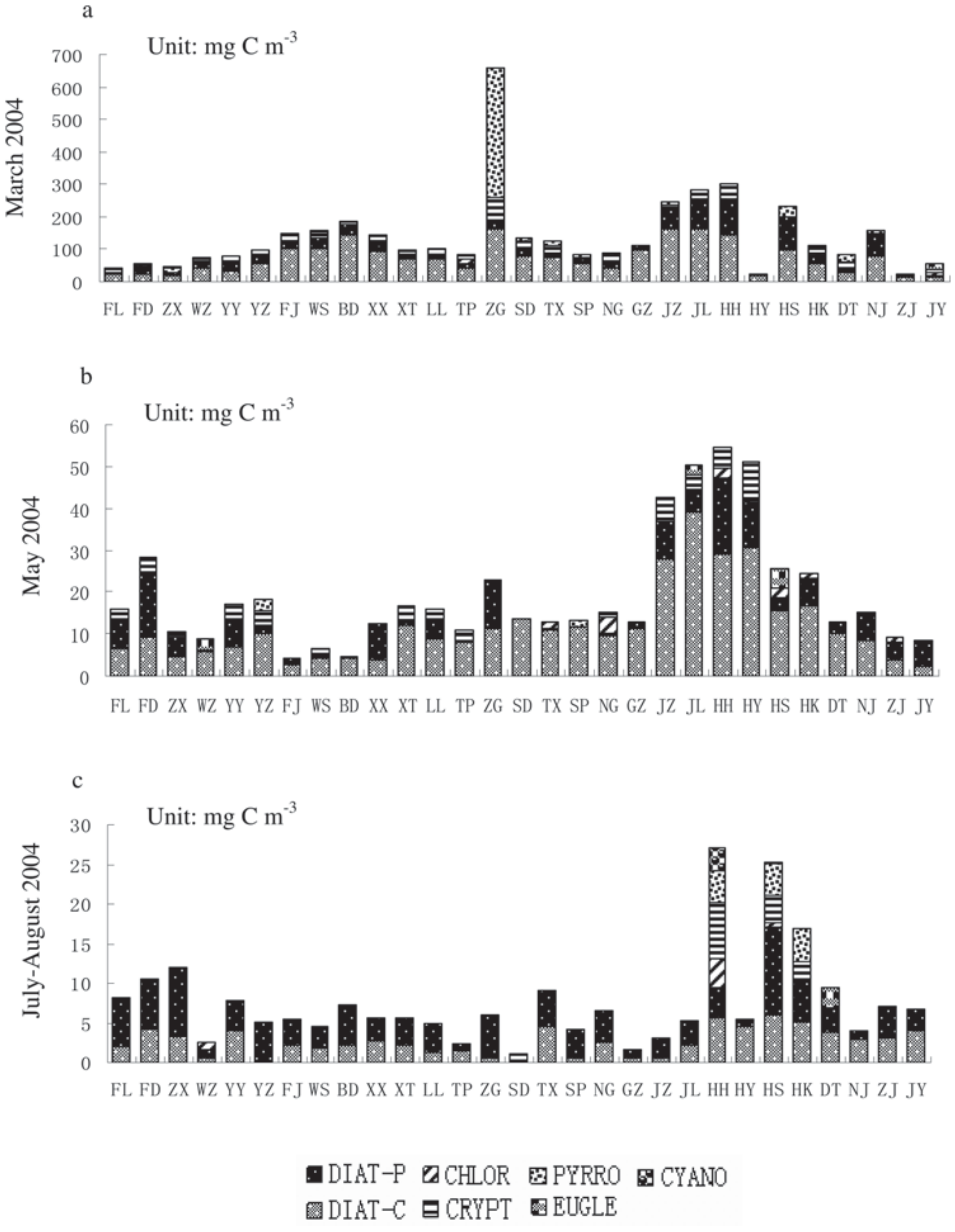

Figure 6. Biomass of phytoplankton in the Yangtze River during March (a), May (b) and July–August 2004 (c).

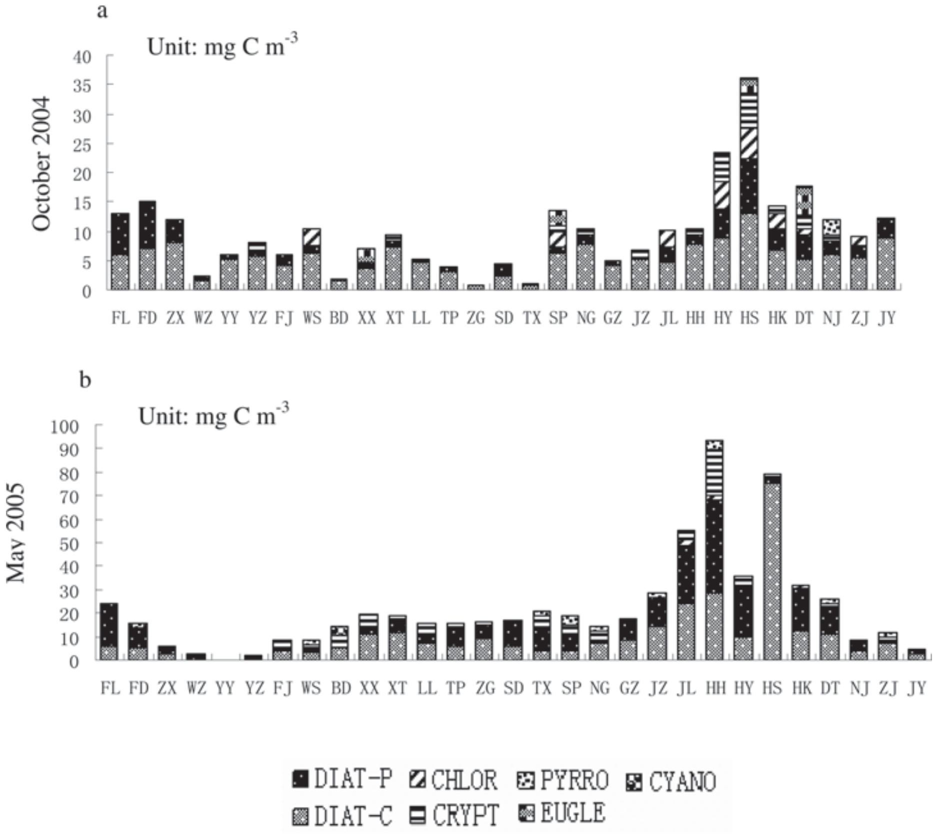

Figure 7. Biomass of phytoplankton in the Yangtze River during October 2004 (a) and May 2005 (b).

discharge (Spearman, $r = –1.000$, $P < 0.01$; $r = –0.900$, $P < 0.05$, respectively) (Table 2, Fig. 8).

4. Discussion

The original Yangtze River ecosystem has been greatly modified by the Three-Gorges Project (Wu *et al.*, 2003). Hydrologic conditions of the Yangtze River have changed remarkably since TGR impoundment in July 2003. The backwater reach of TGR has pushed upstream to Chongqing (650 km from the dam), and the width of the main channel has increased to 1.10 km from the average pre-damming value of 0.39 km. Average water velocity in the main channel has decreased from 0.85 m s^{-1} to 0.20 m s^{-1} (Li *et al.*, 2002). In the backwater reach of Chongqing, the average water velocity has decreased from 2.68 m s^{-1} to 0.38 m s^{-1}. The average concentration of suspended solids in TGR has decreased from 0.81 kg m^{-3} to 0.56 kg m^{-3}. Despite the decrease in water velocity, total discharge of the Yangtze has not yet been altered demonstrably in recent years. In July and August 2004 discharge was lower at Yichang station than in 2003, however, in 2005 discharge was higher during these same two months (Fig. 8).

Table 3. Average chemical data (mean ± standard deviation) for sampling stations during surveys ($n = 29$).

Station	NO_3^-–N µmol L^{-1}	NO_2^-–N µmol L^{-1}	NH_4^+–N µmol L^{-1}	PO_4^{3-}–P µmol L^{-1}	SiO_3^{2-}–Si µmol L^{-1}
Fuling	95.20 ± 36.50	2.36 ± 2.12	4.75 ± 4.03	1.48 ± 1.04	123.69 ± 32.67
Fengdu	106.35 ± 31.80	2.42 ± 2.13	3.81 ± 2.85	1.38 ± 0.77	121.2 ± 34.23
Zhongxian	105.73 ± 30.55	2.61 ± 2.47	4.14 ± 4.19	1.32 ± 0.77	120.9 ± 35.63
Wanzhou	105.52 ± 27.25	1.64 ± 0.87	3.46 ± 2.45	1.21 ± 0.41	118.04 ± 37.96
Yunyang	101.62 ± 20.21	1.34 ± 0.77	3.10 ± 1.30	1.33 ± 0.47	117.64 ± 37.18
Yunyangzhen	106.89 ± 27.57	1.67 ± 1.12	4.34 ± 3.47	1.5 ± 0.65	118.14 ± 38.60
Fengjie	107.43 ± 20.79	2.00 ± 1.59	2.17 ± 1.35	1.4 ± 0.91	116.64 ± 37.93
Wushan	106.7 ± 21.33	1.72 ± 1.89	2.16 ± 1.58	1.44 ± 0.82	122.68 ± 37.92
Badong	101.33 ± 18.63	1.09 ± 1.32	3.01 ± 3.23	1.19 ± 0.53	124.54 ± 38.34
Xiangxi	89.13 ± 27.28	0.51 ± 0.93	3.20 ± 4.2	1.38 ± 0.75	124.87 ± 37.52
Xintanzhen	98.74 ± 19.86	0.58 ± 1.04	5.42 ± 4.29	1.39 ± 0.61	123.95 ± 37.16
Liulan	101.02 ± 23.23	0.54 ± 0.73	2.17 ± 2.05	1.17 ± 0.59	125.34 ± 36.42
Taipingxizhen	107.51 ± 22.23	0.57 ± 0.83	1.75 ± 1.76	1.18 ± 0.41	125.03 ± 38.65
Zigui	98.74 ± 26.35	0.55 ± 0.75	2.26 ± 2.79	1.04 ± 0.53	124.45 ± 37.86
Sandouping	104.14 ± 24.32	1.04 ± 1.12	2.79 ± 2.63	1.02 ± 0.55	126.25 ± 39.70
Tianxi	104.19 ± 25.19	0.56 ± 0.72	3.24 ± 2.89	1.02 ± 0.59	124.30 ± 37.23
Shipai	105.42 ± 25.93	0.58 ± 0.68	0.69 ± 0.50	1.1 ± 0.58	124.08 ± 37.04
Nanjinguan	109.82 ± 26.0	0.63 ± 0.81	2.87 ± 2.50	1.04 ± 0.56	123.22 ± 37.57
Gezhouba	94.45 ± 37.81	0.69 ± 0.71	4.55 ± 4.38	1.16 ± 0.47	124.56 ± 37.49
Jingzhou	96.82 ± 32.22	0.49 ± 0.42	2.56 ± 3.17	1.02 ± 0.41	124.85 ± 37.46
Jianli	99.97 ± 31.82	0.82 ± 0.64	6.04 ± 3.92	0.98 ± 0.40	123.73 ± 38.43
Honghu	103.71 ± 22.74	2.19 ± 1.51	5.66 ± 5.00	1.26 ± 0.64	125.15 ± 39.42
Hanyang	106.53 ± 28.55	2.26 ± 1.17	5.78 ± 5.81	1.39 ± 0.87	123.13 ± 40.26
Huangshi	111.34 ± 20.46	2.16 ± 1.70	6.28 ± 6.11	1.23 ± 0.57	123.38 ± 40.19
Hukou	117.08 ± 24.42	2.20 ± 1.80	5.98 ± 6.33	1.21 ± 0.54	124.56 ± 40.13
Datong	113.73 ± 19.46	1.61 ± 2.12	5.56 ± 6.00	1.06 ± 0.19	126.7 ± 35.46
Nanjing	105.8 ± 26.58	1.05 ± 1.74	6.27 ± 5.90	1.06 ± 0.21	126.69 ± 35.02
Zhenjiang	99.67 ± 22.31	1.03 ± 1.78	6.71 ± 7.30	1.11 ± 0.19	125.73 ± 36.01
Jiangyin	112.80 ± 14.83	0.74 ± 1.38	6.63 ± 7.71	1.04 ± 0.23	124.80 ± 36.20

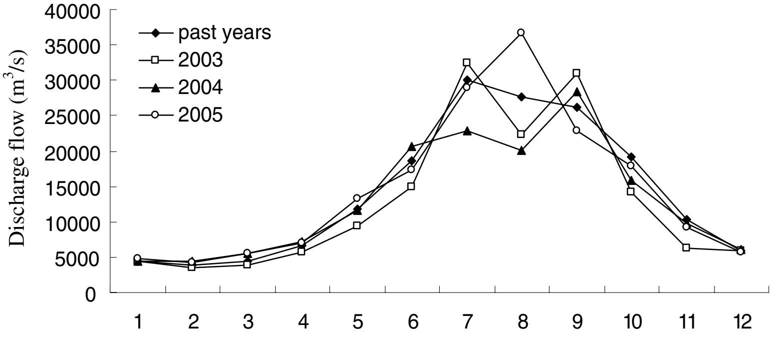

Figure 8. Average monthly discharge at Yichang hydrologic station. Past years means the average discharge of the time from 1993 to 2002.

Damming of the Yangtze has altered the mainstream and tributaries feeding into TGR by creating more lake-like hydrologic conditions. This alteration is reflected in the increased TGR water retention, which is now as long as 77 d (DU *et al.*, 2004). The diversity, abundance and biomass of algal species have increased greatly in backwater regions of tributary branches (MENG *et al.*, 2005; ZENG *et al.*, 2006; HU and CAI, 2006).

Prior to dam closure, algal blooms were unknown, or at least not documented, upstream of TGD. However, in March 2004, blooms (algal density $>10^6$ cells L^{-1}) were observed at five stations within TGR. A maximum density of 2.73×10^6 cells L^{-1}, measured at Zigui (the site of TGD), was much higher than the density of $0.25 \sim 32.70 \times 10^4$ cells L^{-1}, which was reported before damming. However, the concentrations of the main soluble nutrients in March 2004 (dry season) in the Yangtze were significantly lower than those in May 2004 ($P < 0.001$). Increases in phytoplankton abundance in upstream locations following dam closure have been reported in other rivers (KAWARA *et al.*, 1998; SULLIVAN *et al.*, 2001). Such increases are not surprising considering the decreased flow rates and longer retention times that would promote algal growth. While damming might be expected to affect water chemistry within a reservoir, such overt changes where not seen in this study, and there were no significant correlations between phytoplankton parameters and measured water chemistry. However, the average phytoplankton density and biomass in the upstream and downstream locations was significantly correlated (negative) with the main channel discharge. Similar correlations between algal biomass and flow discharge were observed in the Mississippi River (BAKER and BAKER, 1981), Danube River (SCHMIDT, 1994) and some Dutch rivers (IBELINGS *et al.*, 1998). Based on these data, therefore, algal biomass in the Yangtze River (at least under current conditions) is determined by hydrodynamics rather than by nutrient levels, a finding which is consistent with that derived from other large rivers (BAHNWART *et al.*, 1999; LUIGI, 2000). Although nutrient concentrations in the Yangtze were very high before damming (LIU, 2000), algal blooms were not reported. The data gathered in the current study, as well as those reported by ZHANG *et al.* (2005) indicate relatively few changes in overall nutrient levels. It is likely that the substantial modifications in hydrological conditions in TGR are a major contributor to the appearance of algal blooms. Variations in hydrology have been shown to trigger algal blooms in many backwater regions (CAI and HU, 2006; ZENG *et al.*, 2006). In TGR, the proportion of chlorophyta has increased dramatically and algal composition is more consistent with lacustrine, rather than riverine, systems (KUANG *et al.*, 2005).

In TGR, discharge was significantly lower during the dry season than during the rainy season ($P < 0.01$) (Fig. 8). Water levels in TGR will be controlled to 1) allow for increased storage capacity from flooding during the rainy season and 2) maintain sufficient hydraulic head for generation of hydroelectric power during the dry season. The maintenance of a more constant reservoir level during the dry season through prolonged water retention will promote the increase of the phytoplankton biomass, accelerate the eutrophicaiton in the dam and threaten the usage of human water (SØBALLE and KIMMEL, 1987; NOGUEIRA, 2000; HA *et al.*, 2002). On the contrary, during flooding, rapid water inflows and concomitant releases will decrease retention, discourage high levels of phytoplankton and finally avoid the occurrence of algal blooming (BAKER and BAKER, 1979; TRAIN and RODRIGUES, 1998).

5. Acknowledgements

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