Changes in benthic algal communities following construction of a run-of-river dam

Author(s): Naicheng Wu, Tao Tang, Shuchan Zhou, Xinghuan Jia, Daofeng Li, Ruiqiu Liu, and Qinghua Cai
Source: Journal of the North American Benthological Society, 28(1):69-79. 2009.
Published By: North American Benthological Society
DOI: 10.1899/08-047.1
URL: http://www.bioone.org/doi/full/10.1899/08-047.1

J. N. Am. Benthol. Soc., 2009, 28(1):69–79

DOI: 10.1899/08-047.1

Changes in benthic algal communities following construction of a run-of-river dam

Naicheng Wu[1], Tao Tang[2], Shuchan Zhou[3], Xinghuan Jia[4], Daofeng Li[5], Ruiqiu Liu[6], AND Qinghua Cai[7]

State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, Hubei 430072, People's Republic of China

Abstract. Ecological responses to dam construction are poorly understood, especially for downstream benthic algal communities. We examined the responses of benthic algal communities in downstream reaches of a tributary of the Xiangxi River, China, to the construction of a small run-of-river dam. From February 2003 to August 2006, benthic algae, chemical factors, and habitat characteristics were monitored upstream and downstream of the dam site. This period spanned 6 mo before dam construction and 37 mo after dam construction. Benthic algal sampling yielded 199 taxa in 59 genera that belonged to Bacillariophyta, Chlorophyta, and Cyanophyta. Some physical factors (flow velocity, water depth, and channel width) and 3 algal metrics (diatom species richness, Margalef diversity, and % erect individuals) were significantly affected by the dam construction, whereas chemical factors (e.g., NH_4-N, total N, SiO_2) were not. Nonmetric multidimensional scaling (NMS) ordinations showed that overall algal assemblage structure downstream of the dam sites was similar to that of upstream control sites before dam construction and for 1 year after dam construction ($p > 0.05$). However, sites belonging to upstream and downstream reaches were well separated on NMS axis 1 during the 2nd and 3rd years after dam construction. Our results suggest that impacts of dam construction on benthic algal communities took 2 to 3 y to emerge. Further development of a complete set of indicators is needed to address the impact of small-dam construction. Our observations underscore the need for additional studies that quantify ecological responses to dam construction over longer time spans.

Key words: run-of-river, dam construction, benthic algal communities, BACI.

Run-of-river dams impede the flux of water, sediments, biota, and nutrients, and can strongly alter the structure and dynamics of upstream and downstream aquatic and riparian habitats and biota (Ward and Stanford 1979, Petts 1984, Thomson et al. 2005). Eventually, dams disturb ecological connectivity, which underpins the transfer of materials and products of ecological functions and processes (Jenkins and Boulton 2003).

Many studies have investigated the impacts of large dams (>15 m high) and reservoirs on water chemistry, fish, zoobenthos, and cladocerans in streams and rivers (e.g., Garnier et al. 1999, 2000, Gunkel et al. 2003, Shao et al. 2006, Xue et al. 2006), but few investigations have focused on the effects of small human-made dams. Benthic assemblages in downstream habitats might be strongly influenced by such dams, but only a few studies have examined the responses of macroinvertebrates and stream chemistry to small dams (Stanley et al. 2002, Velinsky et al. 2006) and, to our knowledge, even fewer have evaluated the responses of algae.

Benthic algae are the main primary producers in stream ecosystems; they are ubiquitous, ecologically important, sensitive to a broad range of stressors, and they respond rapidly to changes in water quality (Hambrook 2002). Diatoms, the algal division pre-

---

[1] Present address: Department of Hydrology and Water Resource Management, Christian-Albrechts-Universität zu Kiel, 24118 Kiel, Germany. E-mail: wunaicheng2003@yahoo.com.cn

[2] E-mail address: tangtao@ihb.ac.cn

[3] Present address: Institute of Biodiversity Science, Fudan University, Shanghai 200433, People's Republic of China. E-mail: shuchanzhou@yahoo.com.cn

[4] E-mail addresses: jiaxh@ihb.ac.cn

[5] dfli@ihb.ac.cn

[6] liuruiqiu@ihb.ac.cn

[7] To whom correspondence should be addressed. E-mail: qhcai@ihb.ac.cn

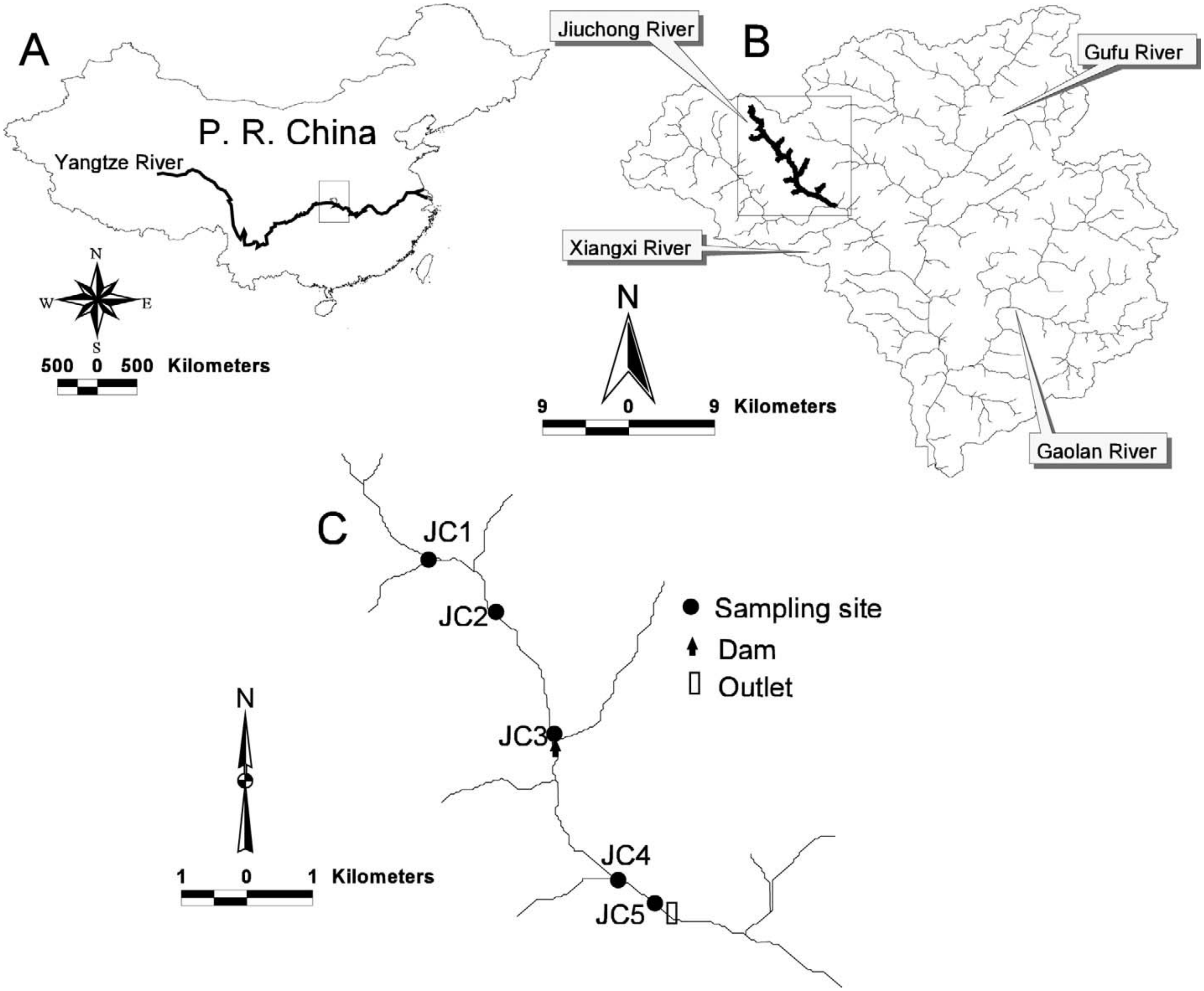

FIG. 1. Jiuchong River within the Xiangxi River watershed in the People's Republic (P. R.) of China and locations of sampling sites. A.—Yangtze River. B.—Xiangxi River watershed. C.—Jiuchong (JC) River.

dominant within periphyton of the Xiangxi River system (Tang et al. 2002), have a long history of use for environmental monitoring in Europe, North America, and elsewhere (Stevenson and Smol 2002). We investigated the effect of a run-of-river dam on benthic algal communities. Our specific goal was to assess downstream effects within the first 3 y after dam construction. We hypothesized that dam construction would change benthic algal communities by changing the hydrology and hydraulics of the stream. Our study was one component of a large research program designed to assess damage to river ecosystems caused by construction of series of cascading dams for production of hydropower and to investigate mechanisms of recovery from the damage.

Methods

Study site and sampling design

The Xiangxi River is a 6th-order stream that originates from Shennongjia Mountain (Fig. 1A, B). Average annual precipitation within its watershed is 988 mm (Fig. 2). It has a watershed area of 3099 km^2 and a natural fall of 1540 m from the headwaters to its confluence with the Yangtze River (Tang et al. 2006). As the biggest tributary of the Three Gorges Reservoir (TGR) in Hubei province, the Xiangxi River can strongly influence water quality in the TGR. The Xiangxi River has 3 main tributaries: the Jiuchong, Gufu, and Gaolan rivers. Many small hydropower

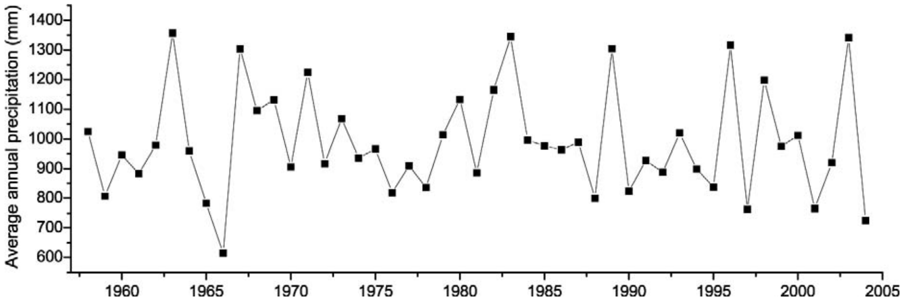

FIG. 2. Average annual precipitation of the Xiangxi River from 1958 to 2004. The data were obtained from the Xingshan Hydrological Survey gauging station located ~4 km downstream from the confluence of the Gufu River.

stations have been built within the watershed of the Xiangxi River. The small dam (1.5 m high, 20 m across) that we studied was constructed in August 2003 on the Jiuchong River (Fig. 1B).

We sampled monthly at 5 sites (JC1–JC5; Fig. 1C) from February 2003 to August 2006. Our sampling approach was based on a modified Before-After-Control-Impact (BACI; Green 1979) design for assessment of disturbance (Bushaw-Newton et al. 2002). We sampled benthic algae at 3 upstream control sites (JC1–JC3) and 2 downstream impact sites (JC4 and JC5) (Fig. 1C). Samples were collected 6 times before dam construction (before sites) and 37 times after dam construction (after sites). We made an effort to select sites that were as similar as possible with respect to surrounding land use, but differences in riparian vegetation and water depth did occur among sites. The BACI study design is based on replicated sampling before and after dam construction, and it enabled us to test the impact of construction by comparing patterns of difference between control and impact sites before dam construction with those after construction. Thus, initial biotic differences between control and impact sites caused by relatively static factors, such as riparian cover or urbanization, do not prevent detection of construction impacts (Underwood 1991).

Algal sampling and identification

We sampled benthic algae on 3 to 5 randomly selected rocks (diameter <25 cm) from each site on each date. We scrubbed rock surfaces thoroughly with a brush and rinsed them several times with distilled water. We composited samples from each set of rocks into a single sample, which was preserved in 4% formalin for identification. We recorded the total volume of each sample. After removing the algae from each rock, we estimated the surface area of the rock by measuring the area of plastic wrap required to cover each rock. We assumed that the surface area on which algae grew was 70% of the measured area of plastic wrap (Naiman and Sedell 1980).

Identification of benthic algae involved 2 steps. First, we analyzed soft algae with a 0.1-mL counting chamber and an inverted microscope at 400×. Second, we prepared permanent diatom slides after oxidizing the organic material with acid. We counted a minimum of 300 valves at 1000× under oil immersion. We identified algae to the lowest taxonomic level possible with keys in Anonymous (1992), Hu et al. (1980), Zhang and Huang (1991), and Zhu and Chen (2000). We based all analyses on algal numbers.

Measurement of physicochemical factors

We collected monthly water samples in the middle of each month. We excluded data obtained during runoff events (i.e., July 2004) from the final analysis. At each site, we measured altitude (Global Positioning System 315; Thales Navigation, Carquefou, France), water depth, channel width, and current velocity (LJD-10 water current meter; Chongqing Hydrological Machines Manufactory, Chongqing, China). We used a Hydrolab Minisonde (Hach Environmental, Loveland, Colorado) to measure in situ variables that included pH, conductivity, salinity, total dissolved solid, and water temperature.

We collected ~1 L of water in precleaned plastic containers to measure chemical variables, including SiO_2, Ca^{2+}, alkalinity, NH_4-N, total P, and total N. We stored samples in the dark at 4°C until we processed them in the laboratory. We measured all chemical variables according to standard methods (Chinese Environmental Protection Bureau 1989) as soon as possible after collection (generally within 24 h). SiO_2, Ca^{2+}, and alkalinity were measured using molybdosilicate (GB8647.3–2006), ethylene-diamine-tetraacetic-acid titration (GB15452–95), and titration (GB15451–95) methods, respectively. We used Nessler's reagent colorimetric method (GB7497–87) to measure NH_4-N concentrations at 420 nm. We measured total P and total N using the ammonium molybdate spectrophotometric method (at 700 nm; GB11893–89) and the alkaline potassium persulfate digestion ultraviolet spectrophotometric method (at 220 and 275 nm; GB11894–89), respectively.

Calculation of algal metrics

Based on van Dam et al. (1994), Wang et al. (2005), and Tang et al. (2006), we compiled a large pool of diatom attributes that were classified into 11 categories: pollution-tolerance index, pH index, salinity index, N-uptake metabolism, O_2 requirements, saprobity, trophic state, moisture, diversity indices (Shannon–Wiener, Margalef, Pielou evenness, Simpson's dominance, richness, and number of genera), growth form (% prostrate individuals, % erect individuals, % stalked individuals, % unattached individuals, and % mobile individuals), and taxonomic composition. We eliminated metrics with medians of 0 before data analyses because low values could have prevented identification of differences among groups (Wang et al. 2005).

Data analyses

We used a combination of univariate analyses of algal community metrics and multivariate ordinations to examine benthic algal responses to dam construction. We used factorial analysis of variance (ANOVA) models to examine the effects of dam construction on the algal metrics. Preconstruction (before) samples were from February to August 2003 and postconstruction (after) samples were from February to August 2004, 2005, and 2006. We excluded samples from June 2003 and May 2005 because biological samples were lost. Heavy precipitation 2 d before our sampling on July 2004 caused stream discharge to increase from 3 to $\sim$12 m^3/s, and algal samples could be obtained only on one side of the river. Therefore, we excluded data collected on this date from the statistical analyses.

We examined changes in benthic algal metrics with a 2-factor ANOVA model with location (upstream and downstream) and stage (before and after dam construction) as fully crossed, fixed factors, and site (fixed) and date (random) as nested factors. Significant location × stage interactions indicated possible dam impacts (Underwood 1991), and were followed by simple main effects tests (stage means compared within each location; Quinn and Keough 2002) to determine how temporal patterns differed between upstream and downstream sites. We attributed an effect to dam construction when before differences between locations differed from after differences between locations. We ran the ANOVA with SPSS (version 11.5; SPSS, Chicago, Illinois).

We evaluated changes in benthic algal community structure (species present and relative abundances) after dam construction with nonmetric multidimensional scaling (NMS) ordinations. NMS is an ordination method that is suited to data that are not normally distributed or are on arbitrary, discontinuous, or otherwise questionable scales. Ordination stress is a measure of departure from monotonicity in the relationship between the dissimilarity (distance) in the original p-dimensional space and distance in the reduced k-dimensional ordination space. To avoid the problem of local minima, we ran the NMS analysis in autopilot mode and allowed the program to choose the best solution at each dimensionality (McCune and Mefford 1999). We used the Sørenson (Bray–Curtis) coefficient as the distance measure in the analysis.

We tested the significance of between-group differences at each group with a multiresponse permutation procedure (MRPP), a nonparametric method for testing multivariate differences among predefined groups (Zimmerman et al. 1985). We used the Sørenson coefficient of $\log_{10}(x + 1)$ abundance data as the distance measure in the MRPP. We tested the significance of the null hypothesis that groups were not different with a Monte Carlo randomization procedure with 10,000 permutations.

We used the indicator value method (IndVal) (Dufrêne and Legendre 1997) to detect how strongly each species discriminated among NMS groups. The indicator value of a taxon varied from 0 to 100, and the indicator value attained its maximum value when all individuals of a taxon occurred at all sites within a single group. We tested the significance of the indicator value for each species with a Monte Carlo randomization procedure with 1000 permutations. We ran IndVal, NMS, and MRPP analyses with PC-ORD (version 4; MjM Software Design, Gleneden Beach, Oregon).

Results

Environmental characteristics and taxonomic composition

Sites varied widely in water quality and habitat characteristics. The altitude of the 5 study sites ranged from 534 to 916 m. During the sampling period, water temperature averaged 11.4°C (3.5–19.0°C), mean total dissolved solids was 109.8 mg/L (68.1–142.1 mg/L), mean conductivity was 192 μS/cm (128–293 μS/cm), and median pH was 8.46 (7.31–8.74).

Benthic algal sampling yielded 199 taxa in 59 genera that belonged to Bacillariophyta, Chlorophyta, and Cyanophyta. The most abundant taxa during each of

TABLE 1. Species with relative abundance >1% collected from sites in the Xiangxi River before and after run-of-river dam construction. Numbers in parentheses are relative abundances (%).

	After		
Before	Year 1	Year 2	Year 3
Chlorophyta			
Stigeoclonium sp. (2.24)		*Stigeoclonium* sp. (5.20)	
Bacillariophyta			
Achnanthes biasolettiana (1.06)	*Achnanthes biasolettiana* (2.25)	*Achnanthes linearis* (42.11)	*Achnanthes linearis* (48.80)
Achnanthes lanceolata (1.33)	*Achnanthes lanceolata* (1.24)	*Achnanthes minutissima* (5.04)	*Achnanthes microcephala* (1.45)
Achnanthes linearis (14.40)	*Achnanthes linearis* (37.44)	*Cocconeis placentula* (12.62)	*Achnanthes minutissima* (7.32)
Cocconeis pediculus (4.44)	*Cocconeis placentula* (16.73)	*Eunotia* sp. (4.39)	*Cocconeis placentula* (18.30)
Cocconeis placentula (12.73)	*Cyclotella bodanica* (1.01)	*Stephanodiscus minutulus* (3.21)	*Gomphonema* sp. (2.16)
Diatoma vulgare (1.22)	*Gomphonema olivaceum* (4.10)	*Synedra ulna* var. *contracta* (3.41)	
Gomphonema angustatum (1.04)	*Gomphonema parvulum* (2.25)		
Gomphonema olivaceum (5.16)	*Synedra ulna* (1.24)		
Gomphonema parvulum (3.64)			
Synedra ulna (2.85)			
Cyanophyta			
Oscillatoria princeps (1.22)	*Oscillatoria* sp. (16.04)	*Oscillatoria* sp. (13.77)	*Oscillatoria* sp. (13.59)
Oscillatoria sp. (33.27)	*Phormidium* sp. (1.97)	*Phormidium* sp. (2.63)	
Phormidium sp. (1.17)	*Stigonema* sp. (3.80)		
Stigonema sp. (3.41)			

the 4 sampling periods were *Oscillatoria* sp. (33.27%; before), *Achnanthes linearis* (37.44%; after, year 1), *A. linearis* (42.11%; after, year 2), and *A. linearis* (48.80%; after, year 3), respectively (Table 1). The relative abundance of *A. linearis* increased from 14.40 to 48.80%, whereas the relative abundance of *Oscillatoria* sp. decreased from 33.27 to 13.59% over the 4-y sampling period. The mean algal density over the entire sampling period was 2.93×10^9 ind./m^2 (5.44×10^6–4.81×10^{10} ind./m^2).

Hydraulic characteristics

Mean channel width was significantly smaller at all sites after dam construction than before dam construction, but the average decrease was significantly greater at downstream than at upstream sites (Table 2, Fig. 3A). Water depth and current velocity did not differ between upstream and downstream sites before dam construction (Table 2, Fig. 3B, C). In contrast, water depth and current velocity were significantly lower at downstream than at upstream sites after dam construction (2004 to 2006) (ANOVA, $p < 0.05$). Dam construction did not affect any water-chemistry variables (ANOVA, $p > 0.05$).

Algal metrics

Forty-one algal metrics were selected after removing metrics with medians of 0. Three metrics, diatom species richness, Margalef diversity, and % erect individuals, were significantly affected by dam construction. Diatom species richness was significantly greater at downstream than at upstream sites before dam construction ($p < 0.05$; Table 3, Fig. 4A). In contrast, diatom species richness was significantly lower at downstream than at upstream sites after dam construction ($p < 0.05$). Margalef diversity downstream and % erect individuals did not differ significantly between upstream and downstream sites

TABLE 2. Mean (±1 SE) values of habitat variables at sites upstream and downstream of the dam before and after dam construction.

			After		
Response variable	Location	Before	Year 1	Year 2	Year 3
Channel width	Upstream	10.46 ± 1.47	9.01 ± 1.16	9.62 ± 1.73	6.08 ± 0.98
	Downstream	8.38 ± 1.63	5.05 ± 0.32	5.91 ± 1.10	3.97 ± 0.26
Water depth	Upstream	0.47 ± 0.08	0.54 ± 0.14	0.35 ± 0.07	0.36 ± 0.09
	Downstream	0.57 ± 0.08	0.30 ± 0.02	0.24 ± 0.02	0.25 ± 0.05
Flow velocity	Upstream	0.91 ± 0.16	0.86 ± 0.20	0.80 ± 0.14	0.55 ± 0.12
	Downstream	0.96 ± 0.17	0.51 ± 0.11	0.67 ± 0.09	0.44 ± 0.08

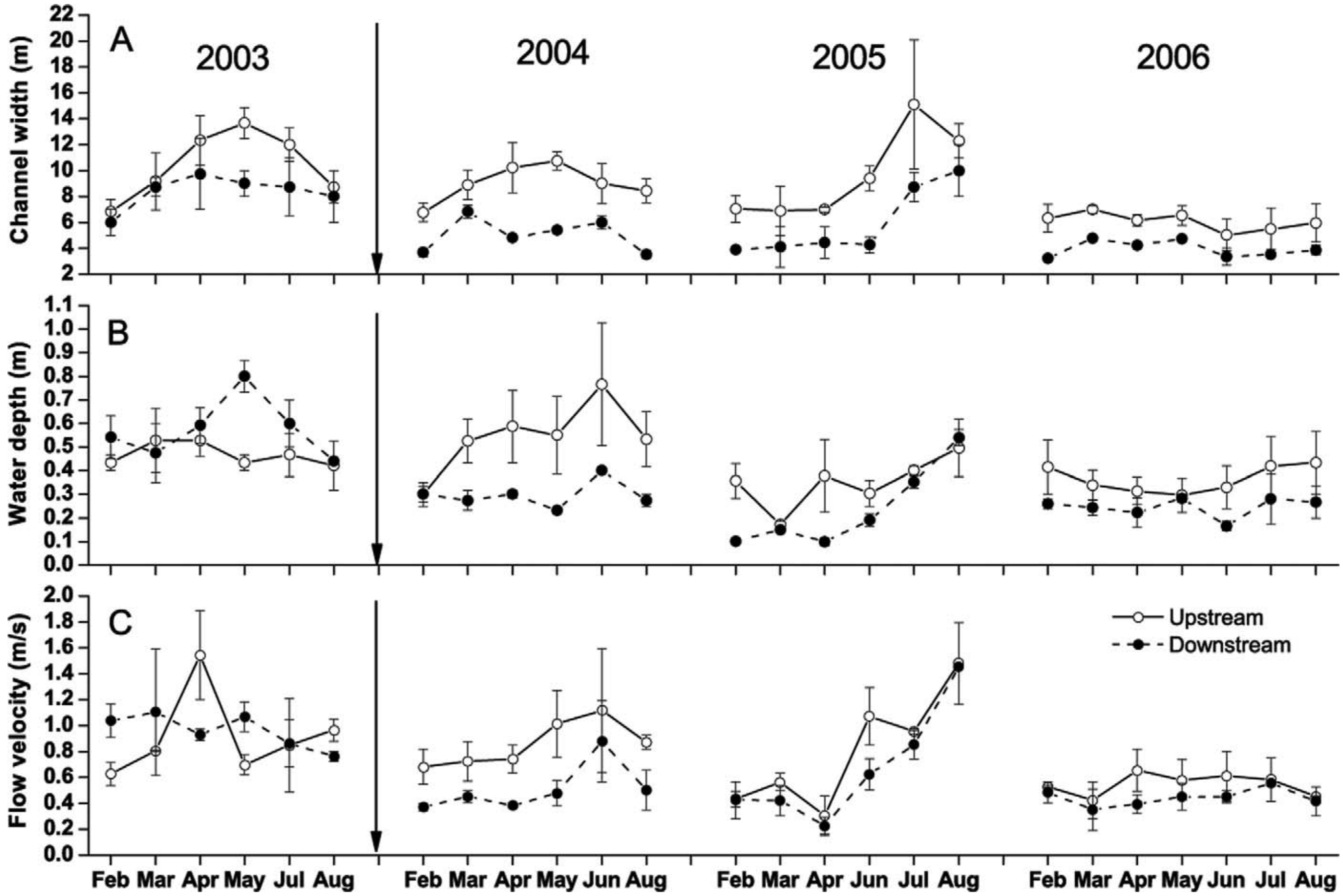

Fig. 3. Mean (±1 SE) channel width (A), water depth (B), velocity (C) at upstream and downstream sites over the study period. Dam construction is indicated by the vertical solid line.

before dam construction ($p > 0.05$; Table 3, Fig. 4B, C). However, Margalef diversity downstream and % erect individuals were significantly lower at downstream than at upstream sites after dam construction ($p < 0.05$).

NMS ordination

Before dam construction and for 1 y after dam construction, upstream and downstream sites were not separated along NMS axes 1 or 2 (Fig. 5A, B), and MRPP analysis indicated no significant differences in algal community composition between upstream and downstream locations ($p > 0.05$). During years 2 and 3 after dam construction, upstream and downstream sites were separated along NMS axis 1 (Fig. 5C, D), and MRPP analysis indicated significant differences in algal community composition between upstream and downstream sites ($p < 0.05$).

Table 3. Mean (±1 SE) values of benthic algal metrics at sites upstream and downstream of the dam before and after dam construction.

			After		
Response variable	Location	Before	Year 1	Year 2	Year 3
Diatom species richness	Upstream	17.44 ± 2.38	16.28 ± 2.64	22.31 ± 2.57	22.31 ± 2.33
	Downstream	22.42 ± 3.08	13.08 ± 2.75	21.00 ± 2.67	19.86 ± 2.25
Margalef diversity	Upstream	0.60 ± 0.08	0.55 ± 0.09	0.70 ± 0.08	0.70 ± 0.06
	Downstream	0.71 ± 0.09	0.45 ± 0.09	0.67 ± 0.08	0.60 ± 0.07
% erect individuals	Upstream	2.50 ± 1.34	0.78 ± 0.72	1.23 ± 0.6	0.23 ± 0.12
	Downstream	2.68 ± 1.78	0.11 ± 0.11	0.30 ± 0.15	0.18 ± 0.08

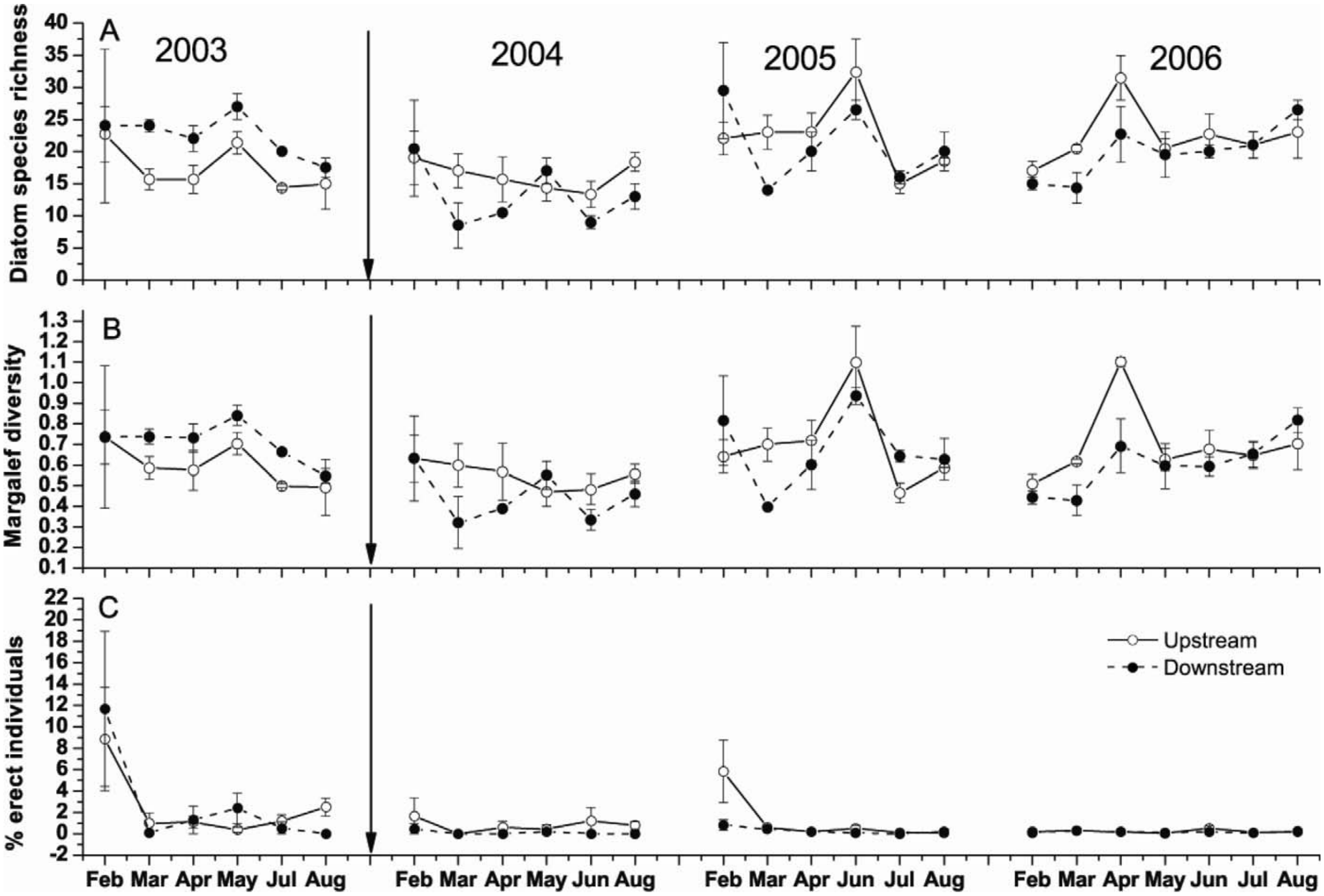

FIG. 4. Mean (±1 SE) diatom species richness (A), Margalef diversity (B), and % erect individuals (C) at upstream and downstream sites before and after dam construction. Dam construction is indicated by the vertical solid line.

During years 2 and 3 after dam construction, NMS site groups were characterized by different sets of indicator taxa (Table 4). Ten taxa, including *Stigeoclonium* sp., *Fragilaria vaucheriae*, and *Amphora perpusilla*, were significant indicators for group 1 (upstream sites, 2 y after dam construction). *Cymbella hustedtii*, *Oedogonium* sp., and *Merismopedia elegans* were significant indicators for group 2 (downstream sites, 2 y after dam construction). Eight taxa, including *Fragilaria virescens* and *Navicula notha*, were significant indicators for group 3 (upstream sites, 3 y after dam construction). Only 1 taxon, *Navicula cryptocephala*, was a significant indicator for group 4 (downstream sites, 3 y after dam construction).

Discussion

Hydraulic changes

Construction of a run-of-river dam in the Xiangxi River study area created physical and ecological conditions that were distinctly different from those in free-flowing lotic reaches despite the constrained channel and small size of the dam. As expected, dam construction significantly reduced channel width, water depth, and current velocity in the downstream reach. These results were consistent with those reported by Almodóvar and Nicola (1999) and Parasiewicz et al. (1998) and suggest that water abstraction led to hydraulic changes. Flow regulation can adversely affect the structure and function of benthic algal communities. Water depth and flow velocity are important factors for algal growth (Moreau et al. 1998, Tang et al. 2004), and algal biomass and flow velocity are significantly negatively related (Thomson et al. 2005). Moreover, changes in channel width could influence distributional patterns of benthic diatom assemblages indirectly by changing water depth and flow velocity (Brandt 2000, Tang et al. 2006).

We expected upstream–downstream differences in water chemistry after dam construction and hypothesized that the physical changes, such as altered hydraulic residence time caused by the impoundment and sedimentation caused by dam construction, would

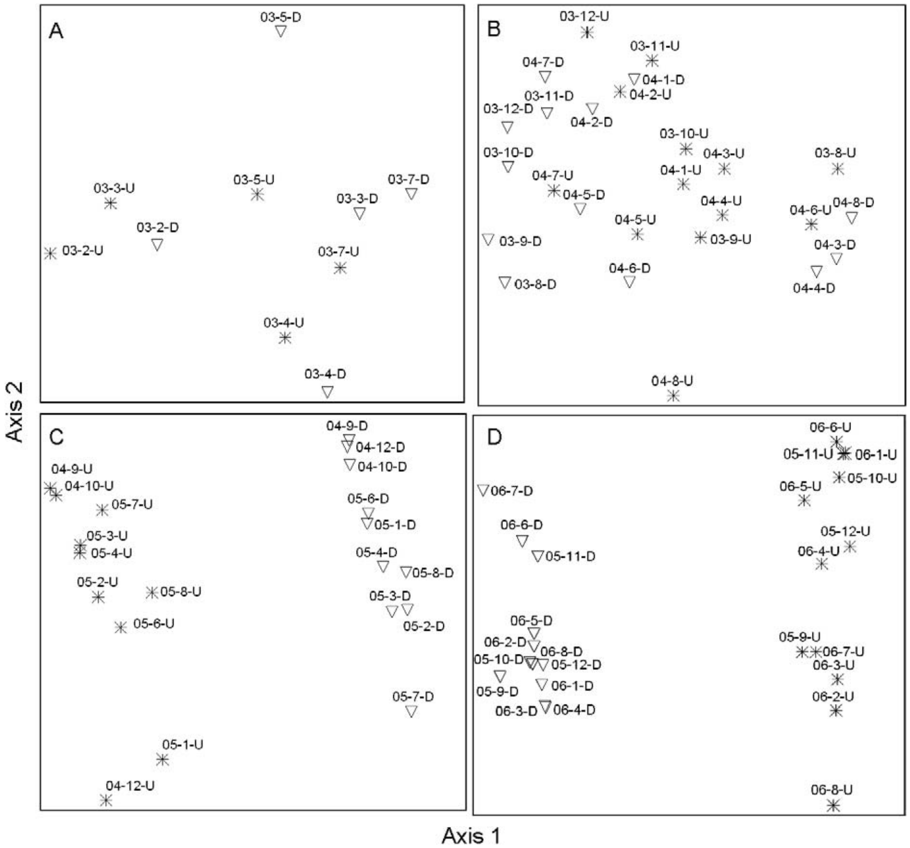

FIG. 5. Nonmetric multidimensional scaling (NMS) ordination of benthic algal assemblages at sites upstream (U) and downstream (D) of the dam before (February 2003–July 2003) (A) and 1 y (September 2003–August 2004) (B), 2 y (September 2004–August 2005) (C), and 3 y (September 2005–August 2006) (D) after dam construction. Ordination stress, final instability, and number of iterations were (respectively): before—1.24, 0.00008, 101; year 1—8.57, 0.00007, 45; year 2—6.28, 0.00004, 58; year 3—8.72, 0.00001, 75. Legends in the figure are in the format: year (last 2 digits only)-month-upstream (U)/downstream (D). For example, 04–6-U = 2004 June upstream site.

alter water chemistry. Stanley and Doyle (2002) observed reduced concentrations of inorganic N and P leaving the impoundments of 5 small dams in the upper midwestern US. However, in our study, dam construction had no significant effect on chemical factors. This absence of a dam effect probably was related to dam size, impoundment residence time, wetted-perimeter area, and nutrient uptake–release rates (Velinsky et al. 2006). Water residence time, determined mostly by dam size, is a useful system-level index that has similar ecological implications for rivers, lakes, and reservoirs (Soballe and Kimmel 1987). Where water has a long hydraulic residence time (e.g., Kilickaya Dam with residence time ~264 d; Kurunc et al. 2006), uptake of elements by aquatic organisms or populations could have significant effects on water-quality constituents. However, the dam in our study is a run-of-river structure with a relatively small impoundment area, and water flows directly into the dam intake with a very low residence time.

Changes in algal metrics

Biodiversity indices, including Shannon diversity index, Margalef diversity index, Pielou evenness index, species richness, and number of diatom genera, are used commonly in bioassessments (Wang et al. 2005). The effects of disturbance on diatom species richness and Margalef diversity are unpredictable and depend on the type of stressors (Stevenson 1984). However, in our study, these 2 metrics and % erect individuals did respond to dam construction.

Diatom growth form represents a morphological adaptation to environmental conditions, such as current velocity and disturbance timing (Peterson and Stevenson 1992), and diatom species with erect growth forms are susceptible to hydraulic disturbance (Wang et al. 2005). The reduction in % erect individuals at downstream sites after dam construction might reflect frequent hydraulic disturbances after dam construction. On the other hand, reduced current

TABLE 4. Summary of indicator species analysis showing indicator taxa, relative abundance, relative frequency, and indicator value (IV) for each nonmetric multidimensional scaling group during the 2nd and 3rd years after dam construction. Bold font indicates significant indicator values ($p < 0.05$, Monte Carlo permutation test). U = upstream sites, D = downstream sites.

	Relative abundance				Relative frequency				IV			
	Year 2		Year 3		Year 2		Year 3		Year 2		Year 3	
Taxon	U	D	U	D	U	D	U	D	U	D	U	D
Achnanthes lanceolata var. *elliptica*	53	47	0	0	80	60	0	0	**43**	28	0	0
Amphora perpusilla	100	0	0	0	50	0	0	0	**50**	0	0	0
Ceratoneis arcus	78	17	2	3	40	10	8	8	**31**	2	0	0
Cocconeis placentula var. *euglypta*	86	0	14	0	30	0	8	0	**26**	0	1	0
Diatoma vulgare var. *vulgare*	93	5	2	0	50	10	8	0	**47**	0	0	0
Eunotia sp.	54	46	0	0	60	60	8	0	**32**	28	0	0
Fragilaria vaucheriae	67	15	10	8	80	50	67	33	**54**	8	7	3
Nitzschia dissipata	87	0	7	5	50	10	17	17	**44**	0	1	1
Stigeoclonium sp.	94	6	0	0	70	40	8	8	**65**	2	0	0
Synedra rumpens var. *meneghiniana*	100	0	0	0	30	0	0	0	**30**	0	0	0
Cymbella hustedtii	26	67	5	3	50	50	8	8	13	**33**	0	0
Merismopedia elegans	0	98	2	0	0	30	8	0	0	**30**	0	0
Oedogonium sp.	2	98	0	0	10	30	0	0	0	**29**	0	0
Characium sp.	6	17	77	0	10	10	33	0	1	2	**26**	0
Cymbella minuta	0	0	100	0	0	0	33	0	0	0	**33**	0
Diatoma anceps	4	0	76	20	10	0	42	17	0	0	**32**	3
Fragilaria virescens	0	0	90	10	0	0	50	8	0	0	**45**	1
Gomphonema dichotomum var. *dichotomum*	2	0	61	37	10	0	58	25	0	0	**35**	9
Navicula notha	21	7	49	23	70	40	92	58	15	3	**45**	13
Nitzschia fonticola	0	5	76	19	0	10	42	8	0	1	**31**	2
Oscillatoria princeps	3	8	54	35	10	10	75	50	0	1	**40**	18
Navicula cryptocephala	20	12	23	45	60	60	92	100	12	7	21	**45**

velocity at downstream sites can increase deposition of fine sediments, which generally have negative effects on benthic communities (Wood and Armitage 1997). Sediments deliberately or accidentally released from reservoirs can cause pronounced reductions in benthic densities and diversity (Gray and Ward 1982, Marchant 1989). Increased sedimentation might be the reason that diatom species richness and Margalef diversity decreased at downstream sites following dam construction. Therefore, changes in algae-based metrics probably reflect the effects of deposition of fine sediments and hydraulic disturbances, and might indicate a potential long-term effect of dam construction on primary production.

Erect individuals made up a very small percentage of the total algal community, and the significant differences in richness and diversity were very small. Thus, the observed changes in % erect individuals, diatom species richness, and Margalef diversity probably had very little ecological influence on the algal community.

NMS ordination

Changes in benthic algal community structure following dam construction appear to reflect dam-induced changes in sedimentation and hydraulic disturbances (Thomson et al. 2005, Wu et al. 2007). Theory suggests that increased downstream sediment deposition will continue until a relatively stable channel is formed and that particle sizes of bed sediments in downstream reaches will gradually decrease as excess fine sediment accrues (Thomson et al. 2005). Our study showed that algal community structure at downstream sites remained similar to community structure at upstream sites throughout the 1st year after dam construction. Significant changes to community structure were not observed until years 2 and 3 after completion of the dam. It is possible that postconstruction deposition of fine sediments might not have been sufficient during the 1st year after construction to induce a significant change in the overall algal assemblage, although several individual metrics were influenced by dam construction.

Long-term effects of dam construction

Few studies have been published on the influence of dam construction on aquatic organisms; as a consequence, we compared our results with the opposite process of dam removal. Dam removal caused relatively small and transient geomorphic and ecological changes in downstream reaches in a Wisconsin river and induced no changes in macroinvertebrate assemblage structure or condition metrics (Stanley et al. 2002). Diatom species richness in downstream reaches changed significantly following the removal of a small run-of-river dam in Manatawny, Pennsylvania, but overall assemblage structure (as indicated by NMS ordinations) remained similar to that of upstream control sites throughout the 1-y study (Thomson et al. 2005). The same 2-m-high dam on Manatawny Creek, Pennsylvania, had no effect on instream C, N, or P concentrations and, consistent with our results, removal of the dam had no effect on instream water chemistry (Velinsky et al. 2006). Velinsky et al. (2006) suggested that geomorphic adjustment and, therefore, biological changes following removal or construction of small run-of-river dams could take many years to manifest. In our study, the effects of dam construction on benthic algal communities took 2 to 3 y to emerge (Fig. 5C, D). The probable reason for the lag in algal community response is that overall algal community composition was more resistant to hydraulic disturbance than were individual metrics.

We conclude that dam construction in the Xiangxi River system might not significantly influence benthic algal assemblages through the 1st year after dam construction, but that changes could become evident 2 or 3 y later. Other studies have confirmed long-term influences of dams on aquatic organisms. For example, the zooplankton community downstream of a small 21-y-old dam in the Xiangxi River differed significantly from the community upstream of the dam (Zhou et al. 2008). A series of 5 small cascade dams that ran for many years in the Xiangxi River dramatically altered many characteristics of river phytoplankton and some characteristics of macroinvertebrates in tailwater reaches (Wu et al. 2007, Fu et al. 2008).

The area we studied remains a dynamic system, and the differences we observed might increase, dampen, or remain unchanged with time. Further development of a complete set of indicators is needed to address the impact and potential harm of small-dam construction. Our observations underscore the need for additional studies that quantify ecological responses to dam construction over longer time spans.

Acknowledgements

Special thanks should be expressed to 2 anonymous referees for their constructive comments on the manuscript. We thank Ming Cao, Xiaodong Qu, and Meiling Shao for their assistance in the field sampling and Jun Li of Fudan University for figure processing. This study was supported financially by the National Natural Science Foundation of China (30330140), the Key Project of Knowledge Innovation Program of the CAS (KSCX2-YW-427), and the National Basic Research Priorities Program (973 Programme, 2002CD412310).

Literature Cited

Almodóvar, A., and G. G. Nicola. 1999. Effects of a small hydropower station upon brown trout *Salmo trutta* L. in the River Hoz Seca (Tagus Basin, Spain) one year after regulation. Regulated Rivers: Research and Management 15:477–484.

Anonymous (The Comprehensive Scientific Expedition to the Qinghai-Xizang Plateau, Academia Sinica). 1992. The algae of the Xizang Plateau. Science Press, Beijing, China (in Chinese).

Brandt, S. A. 2000. Classification of geomorphological effects downstream of dams. Catena 40:375–401.

Bushaw-Newton, K. L., D. D. Hart, T. E. Johnson, J. Pizzuto, J. Egan, M. Keeley, J. Lawrence, J. Thomson, J. T. Ashley, R. J. Horwitz, D. Charles, C. Gatenby, D. A. Kreeger, T. Nightengale, R. L. Thomas, and D. J. Velinsky. 2002. An integrative approach towards understanding dam removal: the Manatawny Creek study. Journal of the American Water Resources Association 38:1581–1600.

Chinese Environmental Protection Bureau. 1989. Monitoring and analyzing methods for water and sewage. China Environment Science Press, Beijing, China.

Dufrêne, M., and P. Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67:345–366.

Fu, X. C., T. Tang, W. X. Jiang, F. Q. Li, N. C. Wu, S. C. Zhou, and Q. H. Cai. 2008. Impacts of small hydropower plants on macroinvertebrate communities. Acta Ecologica Sinica 28:45–52 (in Chinese with English abstract).

Garnier, J., G. Billens, N. Sanchez, and B. Leporcq. 2000. Ecological functioning of the Marne Reservoir (Upper Seine Basin, France). Regulated Rivers: Research and Management 16:51–71.

Garnier, J., B. Leporcq, N. Sanchez, and X. Philippon. 1999. Biogeochemical mass balances (C, N, P, Si) in three large reservoirs of the Seine Basin (France). Biogeochemistry 47:119–146.

Gray, L. J., and J. V. Ward. 1982. Effects of sediment releases from a reservoir on stream macroinvertebrates. Hydrobiologia 96:177–184.

Green, R. H. 1979. Sampling design and statistical methods for environmental biologists. Wiley Interscience, New York.

Gunkel, G., U. Lange, D. Walde, and J. W. C. Rosa. 2003. The environmental and operational impacts of Curuá-Una, a reservoir in the Amazon region of Pará, Brazil. Lakes and Reservoirs: Research and Management 8:201–216.

Hambrook, J. A. 2002. Bioassessment of stream-water quality using benthic and planktonic algae collected along an urban intensity gradient in the Eastern Cornbelt Plains Ecoregion, Ohio, USA. Journal of Phycology 38:14–15.

Hu, H. J., R. Y. Li, Y. X. Wei, H. Z. Zhu, J. Y. Chen, and Z. X. Shi. 1980. Freshwater algae in China. Shanghai Science and Technology Press, Shanghai, China (in Chinese).

JENKINS, K. M., AND A. J. BOULTON. 2003. Connectivity in a dryland river: short-term aquatic microinvertebrate recruitment following floodplain inundation. Ecology 84:2708–2723.

KURUNC, A., K. YUREKLI, AND C. OKMAN. 2006. Effects of Kilickaya Dam on concentration and load values of water quality constituents in Kelkit Stream in Turkey. Journal of Hydrology 317:17–30.

MARCHANT, R. 1989. Changes in the benthic invertebrate communities of the Thomson River, southeastern Australia, after dam construction. Regulated Rivers: Research and Management 4:71–89.

MCCUNE, B., AND M. J. MEFFORD. 1999. PC-ORD. Multivariate analysis of ecological data. Version 4. MjM Software Design, Gleneden Beach, Oregon.

MOREAU, S., G. BERTRU, AND C. BUSON. 1998. Seasonal and spatial trends of nitrogen and phosphorus loads to the upper catchment of the river Vilaine (Brittany): relationship with land use. Hydrobiologia 373/374:247–258.

NAIMAN, R. J., AND J. R. SEDELL. 1980. Relationships between metabolic parameters and stream order in Oregon. Canadian Journal of Fisheries and Aquatic Sciences 37:834–847.

PARASIEWICZ, P., S. SCHMUTZ, AND O. MOOG. 1998. The effect of managed hydropower peaking on the physical habitat, benthos and fish fauna in the River Bregenzerach in Austria. Fisheries Management and Ecology 5:403–417.

PETERSON, C. G., AND R. J. STEVENSON. 1992. Resistance and resilience of lotic algal communities: importance of disturbance timing and current. Ecology 73:1445–1461.

PETTS, G. E. 1984. Impounded rivers: perspectives for ecological management. John Wiley and Sons, New York.

QUINN, G. P., AND M. J. KEOUGH. 2002. Experimental design and data analysis for biologists. Cambridge University Press, Cambridge, UK.

SHAO, M. L., Z. C. XIE, L. YE, AND Q. H. CAI. 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).

SOBALLE, D. M., AND B. L. KIMMEL. 1987. A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes, and impoundments. Ecology 68: 1943–1954.

STANLEY, E. H., AND M. W. DOYLE. 2002. A geomorphic perspective on nutrient retention following dam removal. BioScience 52:693–701.

STANLEY, E. H., M. A. LUEBKE, M. W. DOYLE, AND D. W. MARSHALL. 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. Journal of the North American Benthological Society 21:172–187.

STEVENSON, R. J. 1984. Epilithic and epipelic diatioms in the Sandusky River, with emphasis on species diversity and water quality. Hydrobiologia 114:161–175.

STEVENSON, R. J., AND J. P. SMOL. 2002. Use of algae in environmental assessment. Pages 775–804 *in* J. D. Wehr and R. G. Sheath (editors). Freshwater algae of North America: ecology and classification. Academic Press, New York.

TANG, T., Q. H. CAI, AND J. K. LIU. 2006. Using epilithic diatom communities to assess ecological condition of Xiangxi River system. Environmental Monitoring and Assessment 112:347–361.

TANG, T., Q. H. CAI, R. Q. LIU, AND Z. C. XIE. 2002. Distribution of epilithic algae in the Xiangxi River system and their relationships with environmental factors. Journal of Freshwater Ecology 17:345–352.

TANG, T., X. D. QU, D. F. LI, R. Q. LIU, Z. C. XIE, AND Q. H. CAI. 2004. Benthic algae of the Xiangxi River, China. Journal of Freshwater Ecology 19:597–604.

THOMSON, J. R., D. D. HART, D. F. CHARLES, T. L. NIGHTENGALE, AND D. M. WINTER. 2005. Effects of removal of a small dam on downstream macroinvertebrate and algal assemblages in a Pennsylvania stream. Journal of the North American Benthological Society 24:192–207.

UNDERWOOD, A. J. 1991. Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. Australian Journal Marine and Freshwater Research 42:569–588.

VAN DAM, H., A. MERTENS, AND J. SINKELDAM. 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Netherlands Journal of Aquatic Ecology 28:117–133.

VELINSKY, D. J., K. L. BUSHAW-NEWTON, D. A. KREEGER, AND T. E. JOHNSON. 2006. Effects of small dam removal on stream chemistry in southeastern Pennsylvania. Journal of the North American Benthological Society 25:569–582.

WANG, Y. K., R. J. STEVENSON, AND L. METZMEIER. 2005. Development and evaluation of a diatom-based index of biotic integrity for the Interior Plateau Ecoregion, USA. Journal of the North American Benthological Society 24:990–1008.

WARD, J. V., AND J. A. STANFORD. 1979. The ecology of regulated streams. Plenum Publishing, New York.

WOOD, P. J., AND P. D. ARMITAGE. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21:203–217.

WU, N. C., T. TANG, S. C. ZHOU, X. C. FU, W. X. JIANG, F. Q. LI, AND Q. H. CAI. 2007. Influence of cascaded exploitation of small hydropower on phytoplankton in Xiangxi River. Chinese Journal of Applied Ecology 18:1091–1096 (in Chinese with English abstract).

XUE, J. Z., L. YE, AND Q. H. CAI. 2006. Variation of cladocerans from Maoping to Guizhou in the Three Gorges Reservoir before and after impoundment. Acta Hydrobiologica Sinica 30:113–115 (in Chinese with English abstract).

ZHANG, Z. S., AND X. F. HUANG. 1991. Research methods for freshwater plankton. Science Press, Beijing, China (in Chinese).

ZHOU, S. C., T. TANG, N. C. WU, X. C. FU, AND Q. H. CAI. 2008. Impacts of a small dam on riverine zooplankton. International Review of Hydrobiology 93:297–311.

ZHU, H. Z., AND J. Y. CHEN. 2000. Bacillariophyta of the Xizang Plateau. Science Press, Beijing, China (in Chinese).

ZIMMERMAN, G. M., H. GOETZ, AND P. W. MIELKE. 1985. Use of an improved statistical method for group comparisons to study effects of prairie fire. Ecology 66:606–611.

Received: 18 March 2008
Accepted: 15 August 2008