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Effects of dam construction and increasing pollutants on the ecohydrological evolution of a shallow freshwater lake in the Yangtze floodplain

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Abstract:

Large river-floodplain systems which provide a variety of societal, economic and biological benefits are undergoing extensive and intensive human disturbance. However, floodplain lakes responses to multiple stressors are poorly understood. The Yangtze River and its floodplain which provide water and food resources for more than 300 million people are an important region in China. Hydrological regulation as well as socio-economic development have brought profound negative influence on this ecologically important area. To improve understanding of decadal-scale responses of floodplain lakes to multiple stressors, lake sediment proxies including particle size, geochemical elements, diatoms and chironomids were analyzed in a lead-210 dated core from Futou Lake. The analyses show that dams constructed in 1935 and the early 1970s stabilized hydrological conditions in Futou Lake and impeded the interaction with the Yangtze River, resulting in a decrease in major elements (e.g. Mg, Al, Fe) transported into the lake and an increase of macrophyte-related chironomids (*C. sylvestris*-type, *P. penicillatus*-type and *Paratanytarsus* sp.). After the late 1990s, further decreases of major elements and increases in median grain size are attributed to the erosion of the Yangtze riverbed and declining supply of major elements-enriched sediments from the upper Yangtze caused by the impoundment of the Three Gorges Dam. Chironomid and diatom assemblages indicate that hydrological stabilization caused by dam constructions stimulated the growth of macrophytes, which may be important in buffering against an ecosystem state change towards a phytoplankton-dominated and turbid state with ongoing eutrophication. However, a recent increase in Zn, TP and the emergence of eutrophic diatom and chironomid species indicate initial signs of water quality deterioration which may related to the combined effects of hydrological stabilization and aquaculture. Over all, the sediment record from Futou Lake emphasizes the importance of interactions between hydrological change and pollutant loads in determining floodplain lake ecosystem state.

Key words: Lake sediments; Paleohydrology; Multiple proxies; Ecosystem state change; Yangtze floodplain

1 Introduction

Floodplains which receive uninterrupted nutrients, sediments and water from both the river channel and terrestrial sources are among the most productive and diverse landscapes on earth (Tockner and Stanford, 2002). High productivity combined with other societal and economic benefits, such as water supply, flood control, irrigation, navigation and recreation, make floodplains appealing for human habitation and, consequently, many floodplains are densely-populated (Fang et al., 2006; Tockner et al., 2010). Due to multiple stressors including changing hydrology, climate warming and human disturbance, shallow lakes within floodplain areas are suffering from environmental deterioration (Tockner et al., 2010). Eutrophication is one of the most widespread and severe problems of freshwater ecosystems (Smith et al., 1999; Paerl and Huisman, 2008) and is thought to play a critical role in determining ecosystem states in shallow lakes, altering the likelihood of transitions between macrophyte-dominated clear water state and algae-dominated turbid state (Scheffer et al., 2001). While these states are known to exist in floodplain lakes, their existence appears to be linked to flood frequency and therefore hydrological connectivity (Van Geest et al., 2007; Bhattacharya et al., 2016).

In a river-floodplain system, the river and its lateral floodplain are an inseparable unit in terms of water, sediment, nutrients, and organisms (Junk et al., 1989). Natural hydrological regimes which stimulate lateral interaction and nutrient cycling between the floodplain and the main channel maintain the diversity of river-floodplain systems (Junk et al., 1989). Hydrological connectivity is one of the main factors that influences the nutrient cycle, light conditions and ecosystem function of these shallow freshwater floodplain lakes (Sokal et al., 2010; Bayley, 1995; Chen et al., 2017). For example, phytoplankton production shows a unimodal response to hydrological conditions due to the trade-off between light availability and nutrients in the Peace-Athabasca Delta (McGowan et al., 2011). As well as eutrophication, anthropogenic modification of the natural flow regime of a river-floodplain system for the benefits of flood control, hydroelectricity and agriculture also influences floodplain lakes (Chen et al., 2016; Kattel et al., 2016).

The Yangtze floodplain, an important economic, cultural and societal zone in China, provides homelands and water resources for more than 300 million people (Dong et al., 2012). Over the last several decades, with the intensification of industrial and agricultural activities and rapid population expansion, lakes in this area have suffered from problems such as lake area shrinkage for land reclamation (Fang et al., 2006; Du et al., 2011), hydrological regulation (Yang et al., 2011; Kattel et al., 2016), eutrophication (Yang et al., 2008; Chen et al., 2011) and declines in biodiversity (Fang et al., 2006). Surveys of 49 lakes and reservoirs in the middle and lower reaches of the Yangtze River revealed that 48 are in a eutrophic or hyper-eutrophic state resulting from nutrient enrichment due to the development of agricultural and industrial activities since the 1950s (Yang et al., 2008). Over the past five decades, more than 50000 dams and levees have been established in the Yangtze floodplain (Yang et al., 2011), but their effects on floodplain lakes are not well established. Sustainable management of this ecological important zone needs a better understanding of the historical trajectory of the river-floodplain system and how lakes in floodplain areas respond to multiple stressors (Wolfe et al., 2012). Instrumental records in this region exist only for the past few decades, so information pre-dating the major period of anthropogenic/economic growth state is limited. However, lake sediments which provide fruitful information about lake history have been widely used to determine hydrological change and its ecological effects (McGowan et al., 2011; Bhattacharya et al., 2016; Kattel et al., 2016). Past paleolimnological studies in Yangtze floodplain lakes have mainly focused on the effects of anthropogenic pollutants and climate change (Yang et al., 2008; Chen et al., 2011), but little attention had been paid to hydrological modifications through damming. Futou Lake, the fourth largest lake in Hubei Province, was freely connected with the Yangtze River before the 1930s but experienced hydrological modification (e.g., dam construction) and human disturbance thereafter, providing an ideal case study of how floodplain lakes respond to multiple stressors. In this study we aim to (1) reconstruct the paleohydrology of Futou Lake and (2) assess individual and synergistic effects of hydrological alteration and increasing pollutants on floodplain freshwater ecosystems.

2 Materials and methods

2.1 Study area

Futou Lake (114°10′~114°15′E，29°56′~30°07′N), which has a water surface area of 126 km^2 and a mean water depth of 2.9 m, is located in the middle reaches of the Yangtze River. This area is characterized by a subtrophical monsoonal climate with a mean annual temperature of 17.4 ^{o}C and a mean annual precipitation of 1400 mm. Before 1935, Futou Lake was freely connected with the Yangtze River. Water flowed into Futou Lake through the Jinshui River during the wet season when the water level in the Yangtze River was higher than that of the lake and flowed out during the dry season. In 1935, a local dam named Jinshui was established at the confluence of the Jinshui and Yangtze rivers for flood control (Fig. 1). Since then the lake has changed into a restricted drainage basin. In 1973, after the impoundment of Xinhe Dam at the confluence of Jinshui River and Futou Lake, hydrological conditions of Futou Lake were modified again (Fig. 1). With the construction of Three Gorges Dam (TGD) in Yichang in the late 1990s, hydrological conditions were further modified. At certain times of the year, depending on the relative water levels of the Yangtze River and Futou Lake, gates of both dams are opened for water exchange.

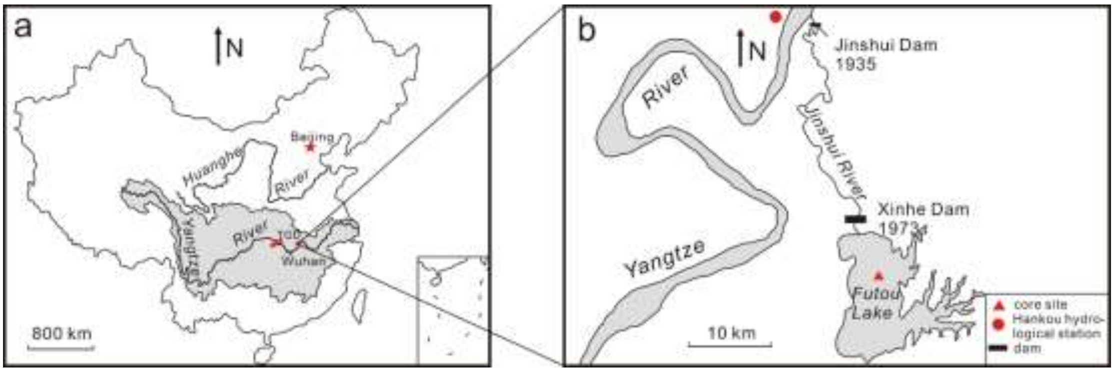

Fig. 1 Location of Futou Lake and core site

Futou Lake is one of the few lakes with rich macrophytes covers in the Yangtze floodplain. Between the 1970s and the early 1990s, observations suggest that Futou Lake was abundant in aquatic plants (e.g., *Pistia stratiotes*, *Vallisneria natans*, *Potamogeton crispus*, *Ceratophyllum demersum*), and also noted declines in aquatic plants in recent years (Hai Zeng, fisherman on Futou Lake, personal communication, July 30, 2017). In recent years, more than 70% of its water area has been used for aquaculture. Each year more than 930 tons of total phosphorus and 2800 tons of total nitrogen generated from aquaculture has been emitted into the lake (Committee for Lake Records Compilation of Hubei Province, 2014). Aquaculture production in Futou Lake increased from <10 million Yuan (RMB) in the early 1990s to ca. 60 million Yuan (RMB) in 2008 (Committee for Lake Records Compilation of Hubei Province, 2014). Water-quality monitoring data revealed that total phosphorus (TP) in Futou Lake increased from 0.027 mg L^{-1} in the 1990s to 0.04 mg L^{-1} in 2014 and slightly decreased to 0.037 mg L^{-1} in 2017 (Table 1). Chl *a* sharply increased from 4.27 to 23.47 μg L^{-1} between the early 2000s and the 2014, followed by a slight decrease to 20.58 μg L^{-1} in 2017.

Table 1 Variation of total phosphorus and Chl a in Futou Lake over the last two decades

Age	TP (mg L^{-1})	Chl *a* (μg L^{-1})	Source

1990s	0.027	-	Wang and Dou, 1998
2001-2003	0.035	4.27	Yang et al., 2008
2014	0.040	23.47	Wu et al., 2017
2017	0.037	20.58	This study

2.2 Sediment core

In 2014, a sediment core (ca. 85 cm) was collected from the central part of Futou Lake using a gravity corer (Fig. 1). The water-sediment interface was well preserved. The sediment core was sectioned at 1 cm intervals in the field and samples were stored at 4 ^{o}C until analysis. Particle size and geochemical proxies were selected because they have been shown to be useful indicators of hydrological change (Chen et al., 2016). Biological proxies were also analysed because chironomids can indicate macrophyte coverage in Yangtze Delta lakes (Cao et al., 2016; Zhang et al., 2012) and diatoms are sensitive to nutrient pollution (Battarbee 2001).

2.3 Chronology

Radio activities of ^{210}Pb, ^{137}Cs and ^{226}Rn was measured by a direct gamma spectrometry using the Ortec HPGe GWL series of well-type, coaxial, low background and intrinsic geranium detectors at an interval of 2 cm (a total of 44 samples). Reference material of ^{210}Pb was supplied by University of Liverpool. Sedimentary chronology was calculated using the constant rate of supply (CRS) model (Appleby et al., 2001).

2.4 Particle size

Particle size spectra of samples were measured at 1-cm intervals (a total of 82 samples) using a Malvern automated laser optical particle-sizer analyser (Mastersizer-2000) after the removal of carbonates by 10% HCl and organic matter by 30% H_2O_2.

2.5 Geochemical elements

Metal elements (Al, Fe, Li, K, Mg, Cr, Cu, Zn, Sr) and total phosphorus (TP) were analysed using an inductively coupled plasma-atomic emission spectrometry (ICP-AES) after digesting sediments in a mixture of HF, HCl, HNO_3 and $HClO_4$ (3:0.5:6:0.5). After being weighed out (ca. 0.125 g), samples were transferred into a Teflon beaker for acid digestion and dilution before analysis (see details in Liu et al., 2007). Reference materials (GSD-9, GSD-11) were supplied by the Chinese Academy of Geological Sciences. One duplicate sample was analysed for every fifteen samples. The reproducibility of the duplicated sediment samples was >90% for all elements. Blank digestion solution results were <5% for all samples and elements and all standard deviations in prepared samples were <7% of documented certified values. Subsampling intervals for elemental analysis were at 2-cm resolution. 41 samples were used for geochemical analysis.

2.6 Chironomids

Sediment samples for chironomid analysis were prepared according to standard methods by Brooks et al. (2007) at 2-cm intervals in the upper 30 cm and at 4-cm intervals at lower levels. 27 chironomid samples were analysed. Samples were deflocculated in 10% KOH in a water bath at 75 ºC for 15 minutes and then sieved through 212 and 90 μm meshes. The residue was transferred to a grooved Perspex sorting tray and examined manually under a setero-zoom microscope at 25× magnification with fine forceps. Head capsules were permanently mounted on slides using Hydromatrix®. Chironomid species were identified using an Olympus CX31 microscope (magnification×100/×400). Chironomid taxonomy mainly followed Wiederholm (1983), Rieradevall and Brooks (2001) and Brooks et al. (2007). At least 50 head capsules were counted for each sample in the upper 52 cm and between 70 and 82 cm. Between 53 and 69 cm, at least 45 head capsules were counted, expect for samples at the depth of 57, 61 and 69 cm where chironomids were poorly preserved.

2.7 Diatom

Diatom analysis followed standard procedures by Battarbee et al. (2001), and samples were counted at 1 cm intervals. The diatom suspension was mounted on slides with Naphrax® after the removal of carbonates by HCl and organic matter by H_2O_2. Diatom valves were identified using an Olympus CX31 microscope with an oil immersion objective (magnification×1000). Diatom taxonomy mainly followed Krammer and Lange-Bertalot (1986-1991). As diatoms were poorly preserved in the bottom of the sediment core, only subsamples in the upper 40 cm were enumerated. A total of 40 diatom samples were analysed. A minimum of 300 valves were counted for each sample in the upper 22 cm. Between 23 and 27 cm, 200 to 300 valves were counted. Between 28 and 40 cm, 100 to 200 valves were counted where preservation was suboptimal. As relative abundances of some epiphytic and benthic diatoms species such as *Achnanthes, Amphora*, *Caloneis*, *Cymbella*, *Epithemia*, *Eunotia*, *Gomphonema*, *Navicula*, *Nitzschia* and *Pinnularia* were low, they were summed and presented at genus level.

2.8 Historical archives

Annual sediment load data from the main channel was collected to evaluate the quantity of sediments being transported by the Yangtze River. Hankou Hydrological Station (Fig.

1), the nearest hydrological station located downstream of the Three Gorges Dam (TGD), has long-term instrumental measurements of water discharge (started in 1865) in the middle Yangtze River. Since the 1950s, sediment load data has also been measured. Wang et al. (2008) used the established relationship between annual water discharge and annual sediment load from the 1950s to 2005 to reconstruct the sediment load of the middle Yangtze River before the 1950s.

2.9 Numerical analysis

Stratigraphic diagrams of particle size and elements were plotted using Grapher 7 (Golden Software Inc.). In order to summarize the most important gradients of variation in elemental concentrations, principal component analysis (PCA) was performed. PCA was performed on log(x+1)-transformed data analysis using Canoco v. 4.5 (ter Braak and Smilauer, 2002). Analysis of non-parametric statistics were perform using R language to test the significance level of elements between sample groups (R core team, 2016).

Only diatom and chironomid taxa occurring in at least two samples and with an abundance ≥2% were used in the diagrams and analyses. Stratigraphic diagrams of the major taxa of diatoms and chironomids were plotted using C2. Detrended correspondence analysis (DCA) was performed on square-root transformed diatom and chironomid data using Canoco v. 4.5 (ter Braak and Smilauer, 2002).

3 Results

3.1 Chronology

As observed in ^{137}Cs profiles of other Yangtze floodplain lakes (Xiang et al., 2002), ^{137}Cs activities in Futou Lake were low and fluctuated in the sediment core profile. ^{137}Cs peaks in the year 1963, corresponding with atomic weapons testing, and peak activity is recorded in the Futou Lake core at 13 cm (Fig. 2a). Excess ^{210}Pb activity in the sediment core showed an exponential declining trend (R^2=0.862, p<0.01) (Fig. 2b) and the chronology derived from the ^{210}Pb profile dates the sediments at 13 cm to ca. 1995. Eroded soil particles carrying ^{137}Cs can be transported and deposited in lakes from the catchment (Ritchie and McHenry, 1990). In floodplain lakes, hydrological connectivity could influence the activity of ^{137}Cs by mediating the concentration of suspended particles transported into them. Hence, the ^{137}Cs profile in Futou Lake may be influenced by hydrological regulation and soil erosion processes. Therefore, in this study, the chronology is mainly based upon the ^{210}Pb activities. The CRS model gave a mean sediment rate of 0.41 cm yr^{-1} with the upper 65 cm representing ca. 157 years of sediment accumulation at which depth the detection limit of ^{210}Pb dating was reached. The chronology below 65 cm was established using a linear regression equation derived from the mean sediment rate in the upper 65 cm (Fig. 2c). Based on the linear regression equation, the age of sediments at the bottom of the sediment core was estimated to be ca. 1815.

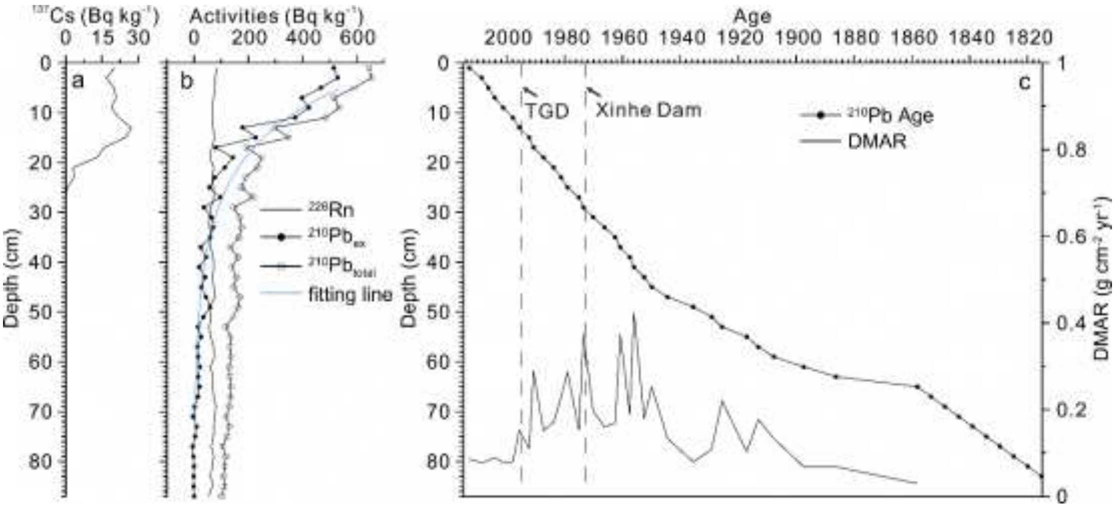

Fig. 2 ^{137}Cs (a), ^{210}Pb activity profiles (b) and age-depth model and dry mass accumulation rate (DMAR) (c) in Futou sediment core

The dry mass accumulation rate (DMAR) sequence of the upper 65 cm was calculated using the established chronology (Fig. 2c). Before the 1970s, DMAR in Futou Lake gradually increased to the maximum of about 0.4 g cm^{-2} yr^{-1}. Since then, DMAR showed a declining trend with a mean value of 0.21 g cm^{-2} yr^{-1} between 1973 and 1995 and 0.09 g cm^{-2} yr^{-1} after 1995.

3.2 Particle size and geochemical elements

The sediments were mainly composed of fine particles (<64 μm) (Fig. 3). Before the early 1970s, proportions of clay (<4 μm) and silt (4-64 μm), which were inversely correlated, fluctuated around 45% and 50%, respectively. Percentage of clay increased from ~ 25% in the early 1970s to 50% in the late 1990s, while proportions of silt decreased from ~ 70 to ~ 50% during the same period. As a result, median grain size of samples decreased from 8.3 to 4 μm. Since the late 1990s, proportions of sand increased markedly from <1 to >15% and percentage of clay decreased from ~ 50 to ~ 25%. Consequently, median grain size increased from 4 to 8 μm.

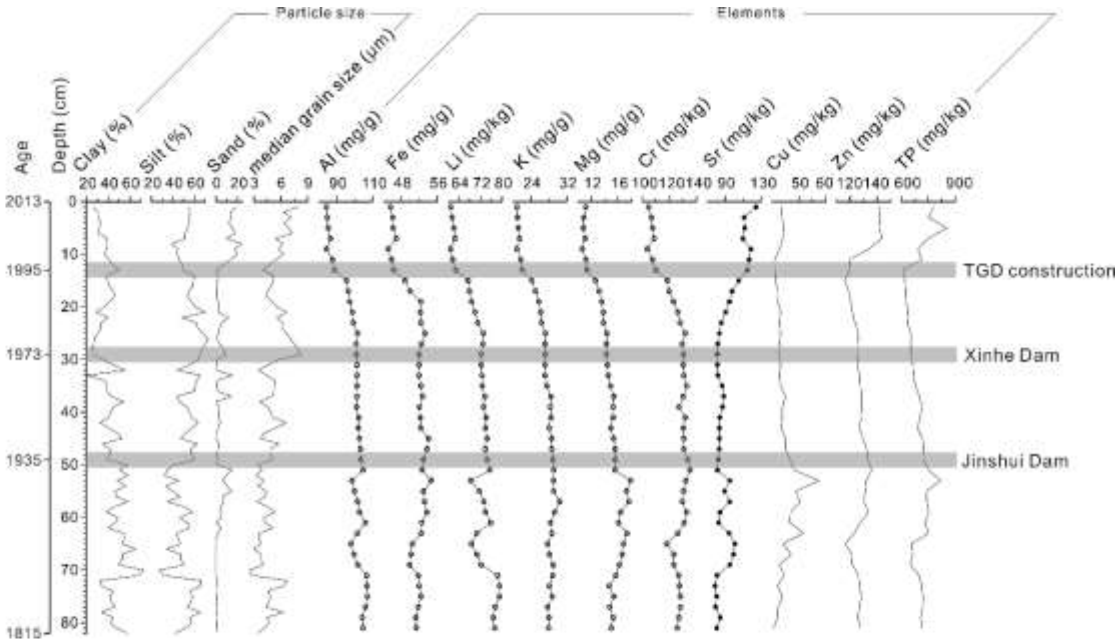

Fig. 3 Sedimentary profiles of particle size and elements in Futou sediment core (the grey bar indicates the time of dam construction with the depth of the bar accounting for dating error)

Three distinctive patterns of changes in elements were observed. Al, Fe, Li, Mg, K and Cr exhibited similar vertical trends (Fig. 3) wherein they fluctuated before 1935, gradually decreased until the late 1990s, followed by a more pronounced decline after 1995. In contrast, Sr concentrations increased gradually between 1935 and the early 1970s and rapidly from the early 1970s to the late 1990s. Trends in concentrations of Cu, Zn and TP differed from the other elements; concentrations fluctuated before 1935, declined gradually between 1935 and the late 1990s and increased thereafter. After 1995, concentrations of Zn and TP increased from ca. 120 and 610 mg kg^{-1} to more than 140 and 800 mg kg^{-1}, respectively.

3.3 PCA of elemental data

PCA of elemental geochemistry showed that axis 1 and axis 2 explained 74.3% and 14.2% of variance in elemental concentrations, respectively (Fig. 4). The first PCA axis ($PC1_{elements}$) was negatively correlated with Al, Fe, Mg, K, Cr and Li (R^2>0.75, p<0.001) and positively correlated with Sr (R^2>0.72, p<0.001). Cu, Zn and TP were positively correlated with axis 2 ($PC2_{elements}$). Four stages divided by the damming events are distinguished in the ordination plot (analysis of non-parametric statistics, p<0.05) (Fig. 4). Before 1935, samples were placed at the left of the ordination plot, and they then shift between the mid-1930s and early 1970s, towards high abundances of Sr. Between the early 1970s and the late 1990s samples move towards the right of the plot (high Sr).

After 1995, samples sustained high Sr concentrations and low concentrations of Al, Fe, Li, Mg, K and Cr.

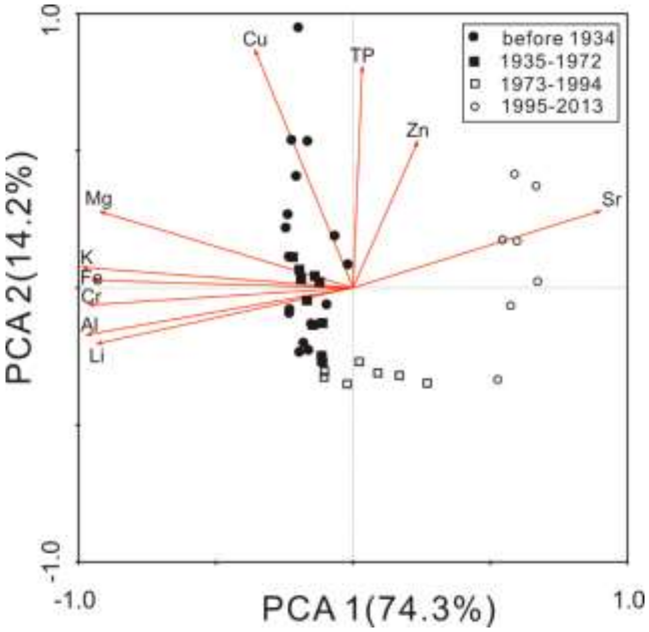

Fig. 4 Principle component analysis (PCA) ordination plot of metal elements and TP

3.4 Chironomids

A total of 42 chironomid species were identified in the sediment core. Chironomid assemblages were dominated by *Microchironomus tener*-type, *Cricotopus sylvestris*-type, *Paratanytarsus penicillatus*-type and *Paratanytarsus* sp., which had an average abundance of ca. 27.9%, 9.7%, 16.8% and 10.7%, respectively (Fig. 5). Over the last 200 years, there was a major assemblage shift from *M. tener*-type to *C. sylvestris*-type, *P. penicillatus*-type and *Paratanytarsus* sp. Before 1935, chironomid assemblages were dominated by *M. tener*-type (average ca. 38.9%), accompanied by *Clinotanypus* (average ca. 9.2%) and *Procladius* (about 5.0%) with few *C. sylvestris*-type, *P. penicillatus*-type and *Polypedilum nubifer*-type. Between 1935 and the early 1970s, the abundance of *Paratanytarsus* sp., *P. penicillatus*-type and *C. sylvestris*-type increased to 7.3%, 3.3% and 12.8%, respectively. The transition period from the early 1970s to 1995 was characterized by the decline in *M. tener*-type (from ≥50 to ≤10%) and increases in *C. sylvestris*-type (from 3.4 to ca. 15%), *Paratanytarsus* sp. (from ca. 13 to ca. 23%) and *P. penicillatus*-type (from ≤15 to ca. 30%). Since 1995, chironomid assemblages were co-dominated by *C. sylvestris*-type, *Paratanytarsus* sp. and *P. penicillatus*-type, with *P. penicillatus*-type having an average abundance of ≥32% whilst *M. tener*-type declined to ≤5%. In this zone, *Glyptotendipes severini*-type, *Chironomus plumosus*-type and *Propsilocerus akamusi*-type appeared, whilst species which were present at lower strata (e.g., *Clinotanypus*, *Cryptotendipes*, *Cryptochironomus* and *Harnischia*) disappeared.

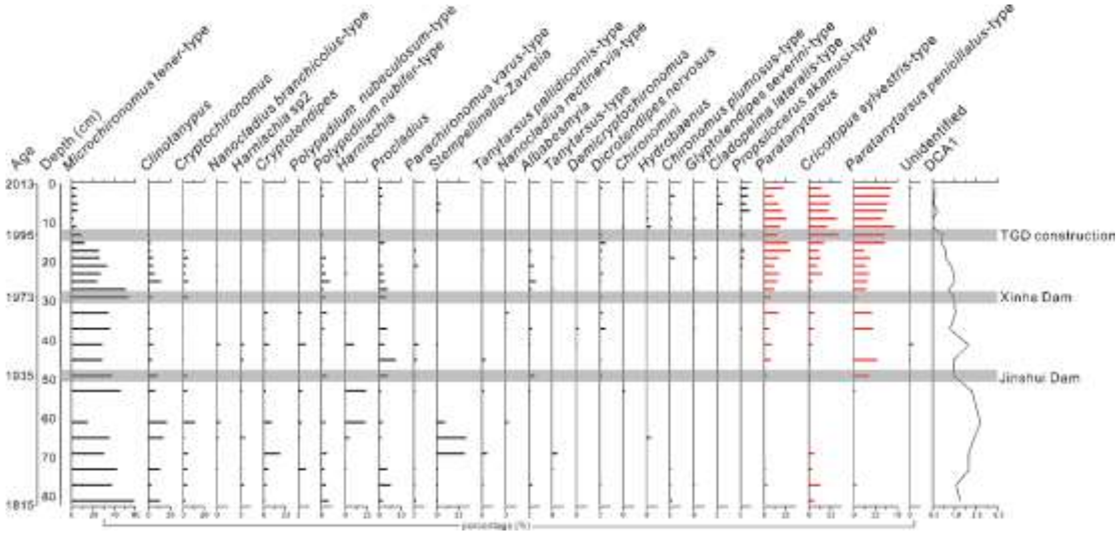

Fig. 5 Sedimentary profile of chironomids in Futou sedimentary core (the grey bar indicates the time of dam construction with the depth of bar accounting for dating error)

3.5 Diatoms

A total of 145 diatom taxa were identified in the sediment core. Diatom assemblages were characterized by planktonic species like *Aulacoseira granulata* with a few *Aulacoseira ambigua*, *Aulacoseira alpigena*, *Cyclotella bodanica* and *Cyclotella. meneghiniana* (Fig. 6). Between 1956 and the early 1970s, *A. granulata* which had an average abundance of over 60% was the dominant species and concentrations of other planktonic taxa such as *A. ambigua*, *A. alpigena* and *Cyclotella* sp. were low. The abundance of epiphytic and benthic diatoms (e.g., *Eunotia* sp., *Cymbella* sp., and *Navicula* sp.) fluctuated around 25%. From the early 1970s to the late 1990s, diatom assemblages were still dominated by planktonic species, especially *A. granulata*, but the relative abundances started to decline whilst the proportion of epiphytic and benthic diatoms increased (*Cocconeis placentula* and *Gyrosigma acuminatum* increased to ca. 6% and $\geq$ 8%, respectively).Since the late 1990s, *A. granulata* had a percentage of about 60% and relative abundances of *A. ambigua*, *A. alpigena* and *Cyclotella* sp. increased compared with the lower strata (for example, the percentage of *A. ambigua* increased to more than 9%). During this period, concentration of *F. construens* var. *venter* increased to an average abundance of about 11%.

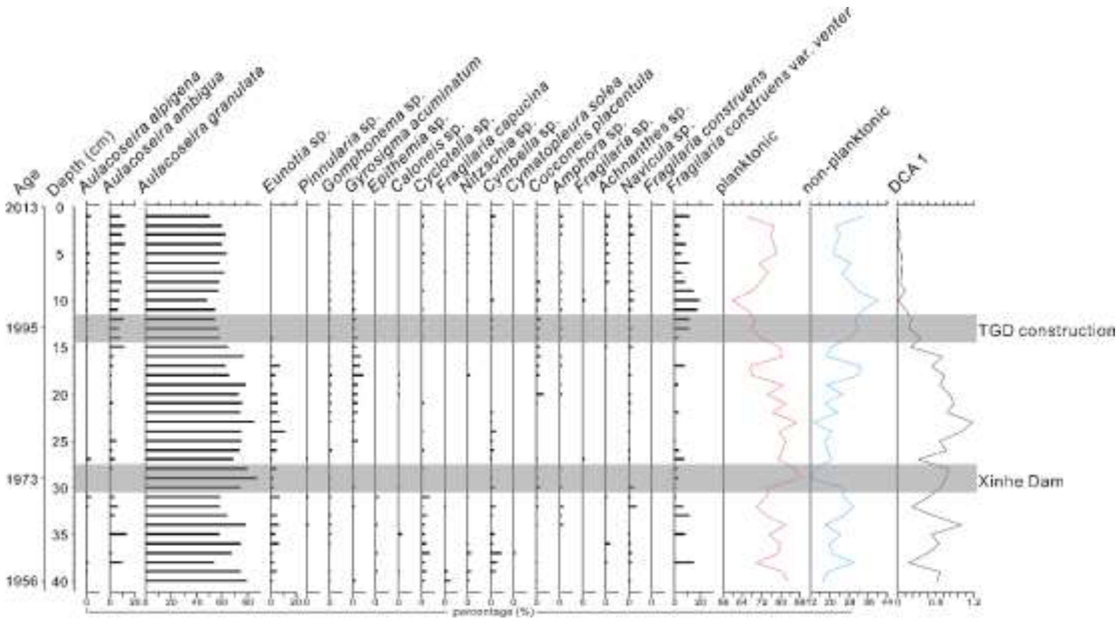

Fig. 6 Sedimentary profiles of diatoms in Futou sedimentary core (the grey bar indicates the time of dam construction with the depth of bar accounting for dating error)

3.6 Relationship between geochemical elements and diatoms and chironomids

Comparisons of the PCA1 axis scores from the elements (as indicators of hydrological condition) with biotic assemblages (Fig. 7) demonstrate that diatoms and chironomids responded clearly to dam construction. Chironomid assemblages in Futou Lake were successively characterized by *M. tener*-type and *C. sylvestris*-type, *P. penicillatus*-type and *Paratanytarsus* sp. In lakes of Europe and the Yangtze floodplain, *Paratanytarsus* is found in lakes with dense macrophytes (Zhang et al., 2012; Langdon et al., 2010; Cao et al., 2014). *C. sylvestris*-type which feed on the epiphytes attached to aquatic plants is also associated with macrophytes in Yangtze floodplain lakes (Cao et al., 2014, 2016). The increase of macrophyte-related chironomid species (*C. sylvestris*-type, *P. penicillatus*-type and *Paratanytarsus* sp.) since 1935, and especially after the early 1970s, suggested the development of aquatic plants in Futou Lake. An increase of benthic and epiphytic diatoms (e.g., *G. acuminatum*) further suggest the growth of macrophytes under more stable hydrological conditions (Liu et al., 2012).

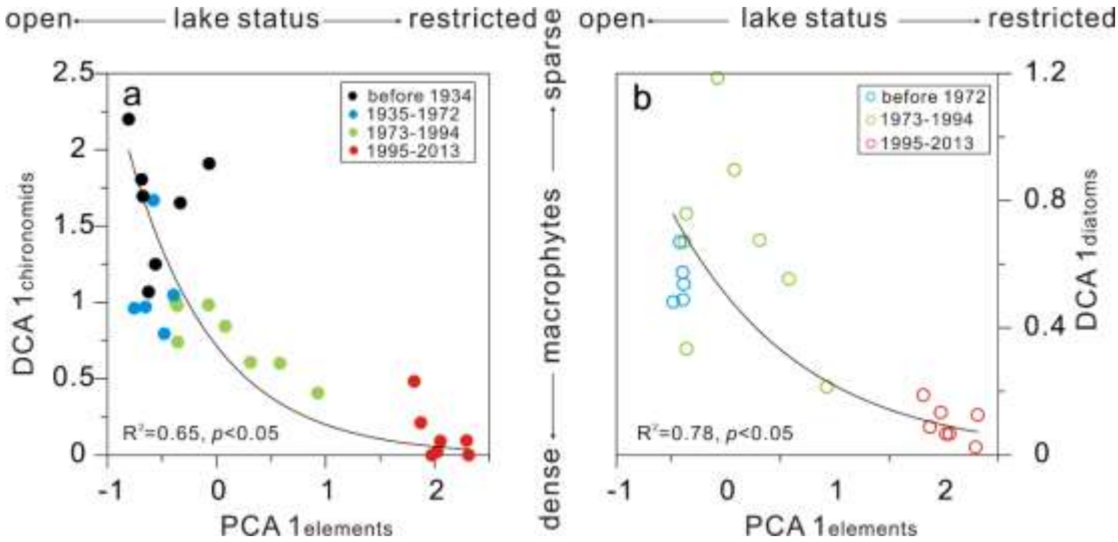

Fig. 7 Scatter plots of first DCA axis of chironomids (a) and diatoms (b) against first PCA axis of elements

4 Discussion

4.1 Effects of dam constructions on natural hydrology

Geochemical compositions of lake sediments provide fruitful information for tracking past changes in hydrological conditions (Rippey et al., 1982; Chen et al., 2016). In closed basin lakes, metal elements mainly come from the erosion of topsoil and bedrock from the lake catchment (Rippey et al., 1982), while sediment influxes from inflows are the main sources of elements in open lakes (Chen et al., 2016). In a river-floodplain system, the main channel is a major source of elements being transported into floodplain lakes (Junk et al., 1989; Chen et al., 2016). The upper reaches of the Yangtze River sequentially cross through the evaporates of the Tibetan Plateau, the Jurassic Red sandstone of the Sichuan Basin and the carbonatite in the Three Gorges Region (Müller et al., 2008). After weathering, large amounts of major elements (e.g., Mg, Al, Fe) are attached on the suspended particles in the Yangtze River and transported into the middle and lower reaches. Once entering the floodplain lakes, these elements are deposit in the lake bottom with the suspended particles (Chen et al., 2016). In contrast, the floodplain in the middle reaches of the Yangtze River is characterized by unconsolidated fluvial deposits with scarce major elements (Müller et al., 2008; Wang et al., 2011). Therefore, it is assumed that variations in sedimentary major elements in Futou Lake should be closely related to the influx from the Yangtze River. Sr which is closely related to Ca, exists as Sr^{2+} in a dissolved form due to the strong chemical carbonate weathering in the Yangtze Basin and relatively low pH of the waters (Chen et al., 2002). However, prolonged water retention time enhances Sr deposition, resulting in elevated sedimentary Sr. PCA1 of elements which strongly correlated with major elements and Sr therefore appears to reflect hydrological connectivity between the lake and the Yangtze River.

Under natural hydrological conditions, rainfall is the main factor influencing the water discharge and sediment load in the Yangtze River (Chen et al., 2014), affecting water exchange intensity between the lake and the Yangtze River. In a wet year, high water discharge transports more sediments into the lake while the strong hydrologic flushing decreases Sr concentrations. Conversely, the weak hydrological connection in a dry year decreases the concentration of major elements while increases the concentration of Sr. Hence, the fluctuations of major elements and Sr before 1935 reflected the variation of sediments being transported into Futou Lake under natural hydrological conditions (Fig. 3).

Since 1935, the steady decrease of major elements indicates declining sediments being transported into Futou Lake (Fig. 8a), alongside a longer water retention time (increasing Sr concentrations), associated with impeded interactions between Futou Lake and the Yangtze River, and the stabilization of hydrological conditions due to dam construction. After the Xinhe Dam established in 1973, lower quantities of element-enriched sediments from the Upper Yangtze River were transported into Futou Lake, resulting in a further decrease of major elements between the early 1970s and the late 1990s (Fig. 8a). The decline of DMAR during this period further reflects the decreasing sediment transport into Futou Lake (Fig. 2c). At the same time, finer particles and Sr were deposited in the lake due to prolonged water retention time, resulting in the decrease of median grain size and the increase of Sr (Fig. 8b).

As hydrological conditions in Futou Lake stabilized due to the establishment of local dams, the increase of median grain size reflects an increasing input of coarse particles after the late 1990s. Since the closure of the TGD in 1998, about 150 million tons of sediment enriched in major elements which comes from the upper reaches of the Yangtze River has been trapped in the reservoir (Yang et al., 2014), resulting in a decrease of sediment load in water released from the dam. Observational records from Hankou Hydrological Station show that annual sediment load decreased from 323.12 Mt (1991-1998) to 157.57 Mt (1999-2013) (Wang et al., 2008) (Fig. 8c). As a result, DMAR in Futou Lake declined after the closure of the TGD (Fig. 2c). When released from the dam, the sediment-starved water possesses more energy to erode the downstream riverbed, resulting in the coarsening of the riverbed substrate. Studies along the Yangtze River revealed that the main channel between Yichang and Hankou changed from a deposition rate of 78 Mt/yr (1956-2000) to an erosion rate of 47 Mt/yr (2003-2012) and the riverbed sediment which was characterized by primarily medium sized sands prior to the TGD closure is now dominated by gravels (Yang et al., 2014). Therefore the coarsening of particle size and further decreasing of major elements can be attributed to the change of material source from the fine-grained, major element-enriched sediments from the upper reaches of the Yangtze River prior to the TGD closure to the coarse-grained, major element-depleted sediments from the downstream riverbed. This suggests that sedimentation and geochemistry in Futou Lake have been influenced by proximal and distal dam structures.

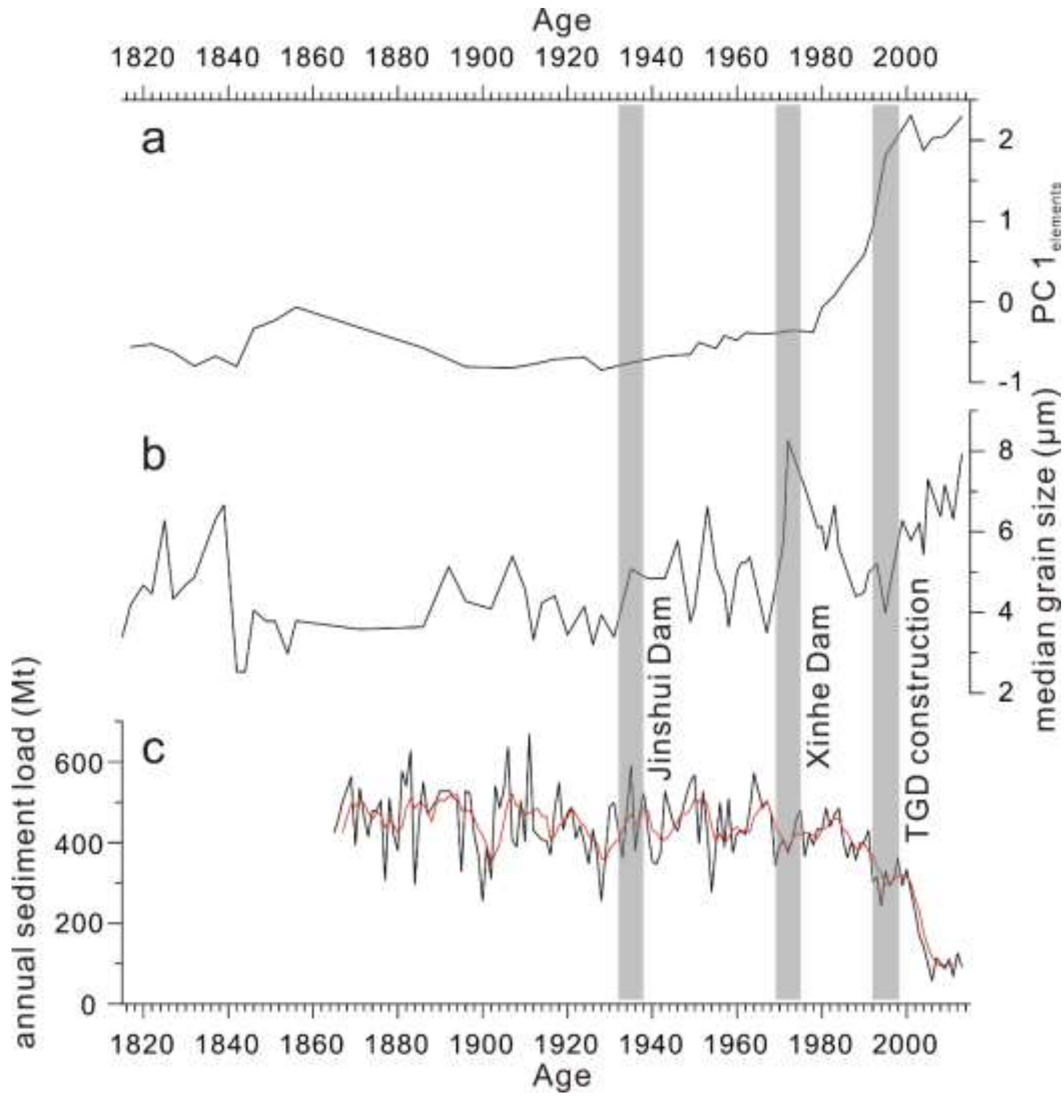

Fig. 8 Comparison between sample score on the first PC axis of elements (a) and median grain size (b) and annual sediment load (the red line indicates five year running average) in Hankou Hydrology Station (cited from Wang et al., 2008) (c) during the last 200 years (the grey bar indicates the time of dam construction with the bar width accounting for dating error)

4.2 Ecological responses to altered hydrology

Macrophyte cover, an important structuring component of aquatic ecosystems, may be mediated by water depth, water level fluctuation, light conditions and nutrient concentrations in floodplain lakes (Sokal et al., 2010; Van Geest et al., 2007). Hydrological connectivity with the main channel influences macrophyte growth by changing the light conditions through turbidity and thus closed-drainage lakes generally have high macrophyte densities because of lower suspended sediment concentrations and transparent waters (Sokal et al., 2010; Squires et al., 2002). Conversely, macrophyte cover in open-drainage lakes is usually sparse (Sokal et al., 2010; McGowan et al., 2011). Accordingly, macrophyte biomass may vary temporally between flood (low biomass) and non-flood (high biomass) years (Sokal et al., 2010; McGowan et al., 2011). In addition, as shallow lakes are susceptible to sediment resuspension which can enhance water turbidity (Blindow et al., 1993), stable hydrological conditions should prevent erosion of the lake margins and resuspension of sediments, enhancing water transparency and benefiting the development of macrophytes (Egertson et al., 2004). Water level stabilization may also promote the germination and establishment of macrophytes (Van Geest et al., 2005). Since Jinshui Dam established in 1935, the hydrologically open lake changed into a restricted-drainage lake, which probably increased the water transparency. An increase in macrophyte-related chironomid species document the spread of macrophytes at this time. After the impoundment of Xinhe Dam in the early 1970s, light and hydrological conditions became increasingly favorable for macrophytes. Sustained increases of macrophyte-related chironomids and non-planktonic diatoms indicate further expansion of macrophytes cover in Futou Lake, which is coincident with the dense macrophytes cover during this period (Hai Zeng, fisherman on Futou Lake, personal communication, July 30, 2017). Similar biotic responses to reduced hydrological connectivity have been reported in the Yangtze floodplain, Peace-Athabasca Delta, Slave River Delta and lower Rhine floodplain (Liu et al., 2012; McGowan et al., 2011; Sokal et al., 2010; Van Geest et al., 2007).

4.3 Increased pollutants since the late 1990s

Accompanied with the stabilization of hydrological conditions resulting from dam and levee constructions is a blocked lateral exchange between the lake and the main channel, resulting in a lower water exchange ratio and a prolonged water retention time of floodplain lakes (Chen et al., 2016). For example, after the closure of the TGD, prolonged water retention time accompanied with increasing nutrient loads from the catchment resulted in algal proliferation in Dongting Lake. Since the 1990s, Futou Lake has experienced the intensification of aquaculture with more than 70% of its water area being used for aquaculture in recent years. The increase of TP and Chl *a* in the water column (Table 1) and declining of macrophytes (Hai Zeng, fisherman on Futou Lake, personal communication, July 30, 2017) since the middle 1990s suggest increased nutrients and habitat disturbance pressures in Futou Lake. Despite the relatively low abundances, frequent occurrence of nutrient-tolerant diatom species (e.g. *A. alpigena* has an TP optima of about 130 μg L^{-1} in the Yangtze floodplain lakes) (Yang et al., 2008) and chironomid species (e.g. *C. plumosus*-type, *G. severini*-type and *P. akamusi*-type) after the late 1990s, together with the sharp increase of Zn and TP concentrations, indicate pollutant enrichment in Futou Lake, which may be attributed to the development of aquaculture and exacerbated sedimentation by hydrological isolation. Even though the high abundance of macorphyte-related chironomids denoted abundant macrophyte cover in Futou Lake, the emergence of nutrient-tolerant chironomid and diatom species indicate initial signs of lake deterioration. We can expect that this hydrologically restricted system may become more and more vulnerable to a state change towards algal dominance and loss of aquatic plants with the continuously development of aquaculture and increase in nutrients (Bhattacharya et al., 2016). Once in a turbid state, there are well known challenges with restoring macrophyte communities unless human disturbance can be restricted to an extremely low level, which is unlikely in this densely populated region (Scheffer et al., 1993; McGowan et al., 2005).

4.4 Implications for floodplain lake protection

The dominance of macrophyte-related chironomids (*C. sylvestris*-type, *Paratanytarsus* sp. and *P. penicillatus*-type) and high concentrations of non-planktonic diatoms revealed the development of aquatic macrophytes after the establishment of the proximal Jinshui Dam (in 1935) and Xinhe Dam (in the early 1970s) and the distal TGD in the late 1990s. Macrophytes play an important role in buffering shallow freshwater ecosystems against regime shifts into the turbid algae-dominated state (Scheffer et al., 2001). Our study provides clear evidence that anthropogenic hydrological regulation which stimulates the growth of macrophytes may buffer against a lake shift into an algae-dominated state caused by eutrophication. Therefore, whilst dam structures undoubtedly alter the ‘natural’ functioning of floodplain lakes, their effects may not be entirely detrimental for ecological and conservation value.

Multiple sedimentary proxies demonstrated by our sediment core suggest that the interactions between increasing nutrients and hydrology both should be considered simultaneously for effective lake management in the future. Because sedimentation in floodplain and shallow lake basins can be spatially variable, further multi-coring studies on Futou Lake and other sites might further understanding of whole lake basin responses, and help to assess how representative single cores are for floodplain lake paleolimnology. Besides, ongoing water monitoring is urgently needed to provide lake ecosystem information for the sustainable management of these important floodplain lakes.

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