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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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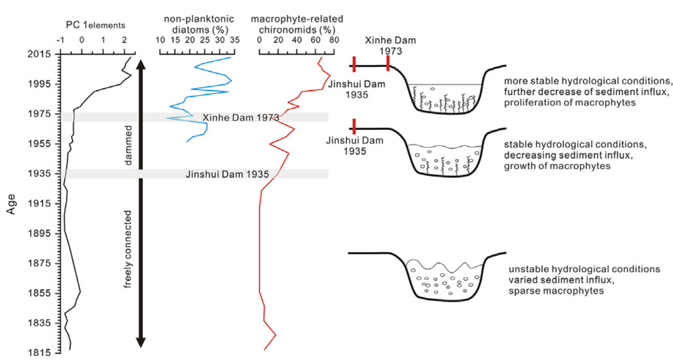
HIGHLIGHTS

- Effects of hydrological modification on a floodplain lake were examined.
- Dam constructions stabilized hydrological condition of floodplain lakes.
- Stabilized hydrological condition may stimulate the growth of macrophytes.
- Macrophytes may buffer aquatic stable state transition caused by eutrophication.

GRAPHICAL ABSTRACT



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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 analysed 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 in 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 be related to the combined effects of hydrological stabilization and aquaculture. Over all, the sediment record from Futou Lake

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emphasizes the importance of interactions between hydrological change and pollutant loads in determining floodplain lake ecosystem state.

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 the 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 Mackenzie Delta (Squires and Lesack, 2002). 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 50,000 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 ecologically 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 °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.

Futou Lake is one of the few lakes with rich macrophytes coverage in the Yangtze floodplain. Between the 1970s and the early 1990s, observations suggest that Futou Lake had abundant 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, >70% of its water area has been used for aquaculture. Each year >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.

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