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Diatom succession dynamics controlled by multiple forces in a subtropical reservoir in southern China

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A B S T R A C T

Investigating how freshwater ecosystems respond to multiple environmental stresses provides important references for catchment management and model prediction. Here we compared the pre- and post-impoundment diatom and geochemical records from the subtropical Liuxihe Reservoir in South China, attempting to demonstrate the diatom succession dynamics during the reservoir maturation process under climate-human interaction. The Nonmetric Multidimensional Scaling (NMDS) and Redundancy Analysis (RDA) revealed a clear trajectory of diatom assemblage succession in the context of multiple stressors on Liuxihe Reservoir. Right after damming (1956–1958), the reservoir underwent a rapid shift from lotic into lentic conditions with abrupt decreases in sediment grain size and magnetic susceptibility, and increases in diatom planktonic/benthic (P/B) ratios and valve concentrations. The reservoir then entered a lengthy, lake-forming process with decreasing C/N ratios and $\delta^{13}C$ values. This process was interrupted by a combination of climate changes and anthropogenic activities since the 1990s, and the resulting limnological conditions appeared to favor the planktonic *Cyclotella hubeiana* and *Discostella stelligera*. In the long term, the diatom biomass seemed to respond sensitively to hydrodynamic regulations in this artificially hydraulic-controlled reservoir ecosystem.

1. Introduction

Freshwater ecosystems are generally influenced by multiple stressors including natural forces, climate change and anthropogenic disturbances (Ormerod et al., 2010), and their joint force drives the ecological succession of aquatic systems through time. Consequently, it has remained a key topic in ecology to determine and quantify the driving factors controlling community structure and succession in response to environmental change (Zhou et al., 2014). However, due to the increasingly intensive anthropogenic activities (e.g., damming, fish farming, and urbanization) coupled with climatic changes (e.g., global warming and anomalous precipitation) in recent decades, the succession patterns of many freshwater ecosystems have become intricate and unpredictable, and therefore more difficult to understand the underlying operation mechanisms (Battarbee et al., 2012), which necessitates reconstruction of past ecological processes in relatively pristine systems to obtain a long-term perspective. As primary producers, diatoms occupy a significant position in the food chain and are an indispensable component in the freshwater ecosystem (Bouchard et al., 2004; Smol and Stoermer, 2010). Previous studies have shown that diatoms are excellent indicators of water quality degradation (Hawryshyn et al., 2012), land-use change (Cooper, 1995), hydrological change (Liu et al., 2012a) and climate variability (Tapia et al., 2003; Karst-Riddoch et al., 2005; Stephens et al., 2012). In particular, their siliceous cell walls are readily preserved in sediments and resistant to alteration, offering abundant subfossil records to study the interaction of multiple forces in a freshwater ecosystem from a historical/geological perspective.

Since the 1950s, a great number of reservoirs have been constructed in Guangdong Province, South China as well as nationwide. Today these reservoirs still play an increasingly important role in water supply under rapid social-economic development, supplying approximately one third of the total water consumption of Guangdong (Han and Liu, 2012). As semi-manmade water bodies built for water management, reservoirs are inherently impacted by both natural processes and hydrological regulation (Wang et al., 2013), and the increasing human disturbance and changing climate over the past several decades have not only accelerated water quality degradation in many of these reservoirs (Wang et al., 2012), but complicated the variation pattern of the reservoir ecosystems, adding to the difficulty of water management under a multiple-stress context. This highlights the need for ecosystem

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reconstruction from the sediment record to supplement reservoir monitoring, which was launched in only a few reservoirs from the early 2000s. Despite the little attention received historically due to sediment disturbance and the relatively short time coverage (Shotbolt et al., 2005), reservoir sediments have proved to be a significant tool to track the environmental changes of a reservoir (Filstrup et al., 2010; Winston et al., 2013; Fontana et al., 2014; Carnero-Bravo et al., 2015). Especially in China, reservoir sediments provide a unique high-resolution record to study the ecosystem response to rapid social-economic development since China's Reform and Open-up in the 1980s, during which period the environment has undergone the most rapid and severe changes but with little effort in environmental monitoring, resulting in widespread eutrophication in most reservoirs (Han, 2010).

Liuxihe Reservoir (LXH Reservoir) is one of the few oligo-mesotrophic impoundments, and its large catchment and subtropical location have fueled high sedimentation rates, which provide fine-resolution sediment records to investigate how relatively pristine ecosystems respond to multiple stresses. By comparing the pre- and post-impoundment diatom assemblages, we attempt to: 1) establish a high-resolution record of diatom succession dynamics in a subtropical freshwater ecosystem in South China; and 2) distinguish the influences of various stresses (hydrological, climatic and anthropogenic forces) on the diatom succession, and determine their relative contributions. This case study will undoubtedly benefit the sustainable management of water quality in subtropical Chinese water bodies.

2. Study area

Liuxihe Reservoir (23°45′N, 113°46′E; Fig. 1), a canyon-type reservoir built in 1958, is located in Guangdong Province, South China, and has a dendritic morphology with a surface area of 14.9 km^2 and a storage capacity of 0.325×10^9 m^3. Its dam lies 240 m and the normal water level is 235 m above sea level. The maximum water depth is 73 m with an average of 21.3 m. Its catchment covers an area of 539 km^2 mostly formed by the inflowing Lütian and Yuxi Rivers, and is strongly influenced by a subtropical monsoonal climate; the mean annual precipitation reaches up to 1300 mm with 80% rainfall occurring in the wet season (April to September), and the annual air temperature is 22 °C. The water residence time averages about 170 days and varies greatly between wet and dry seasons. The mean annual water discharge is 693×10^6 m^3. A nearby meteorological station provides historical temperature and precipitation data for comparison and calibration to the reconstructed record (detailed in next section).

3. Materials and methods

3.1. Sediment coring and physical properties

A 96-cm-long sediment core was taken using the UWITEC universal sampling platform with a piston corer in July 2012 (Core S3; Fig. 1). The coring site had a water depth of 43 m, and was surveyed by a high-resolution sub-bottom profiler to determine the spatial distribution and thickness of sediments prior to coring. The sub-bottom profiler uses an acoustic wave generating source and an array of hydrophones to receive the signals reflected by the various interfaces, and provides continuous, real-time seismic reflection profiles for determining the thickness of sediments. The sub-bottom acoustic profile revealed that the coring site was located within the original river channel, and the coring was designed to drill into the fluvial deposits formed before damming (Xia et al., 2013). When the core was pulled out from the core barrel, a clear sediment-water interface was observed. Another 3 cores (Core S4, S6, S8; Fig. 1) were taken from various parts within the reservoir to find out a complete and representative sediment record for this study (Wang et al., 2015b). The core was sectioned at 2 cm intervals, freeze dried and stored in black plastic bags until needed.

Grain size distribution was measured with a laser particle size analyzer (Malvern Mastersizer 2000) with a measurement range of 0.02–2000 μm. Triplicate measurements were made with a relative

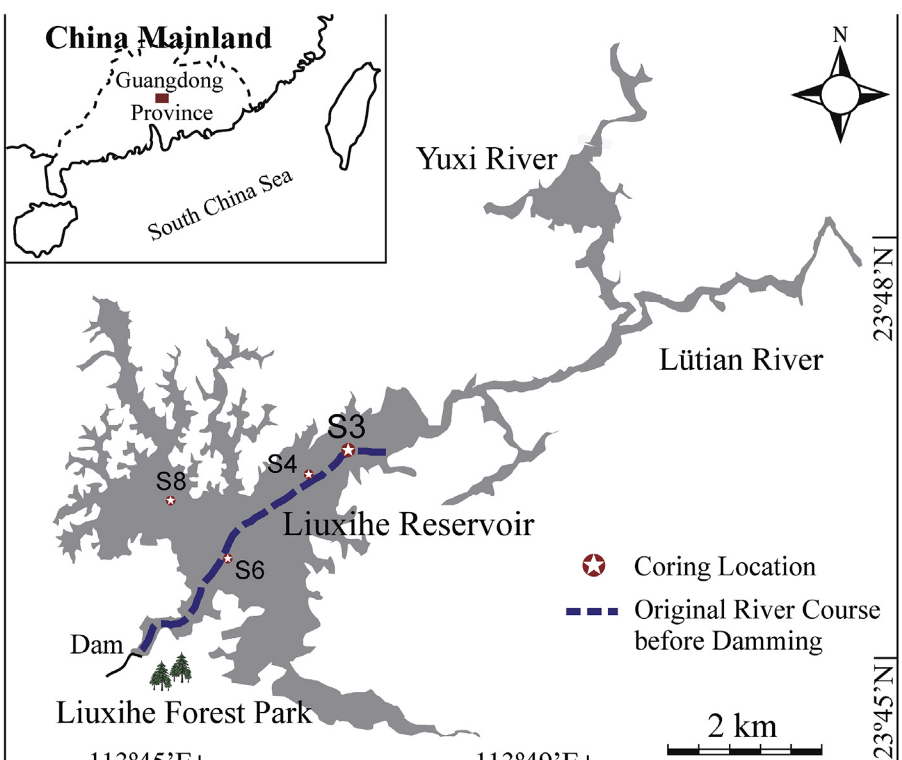

Fig. 1. Map of Liuxihe Reservoir showing the location of the sediment cores. Core S3 located within the original river channel is the key core for this study. Another 3 cores (Core S4, S6, S8) were taken synchronously from various parts within the reservoir.