



Effects of sediment dredging on internal phosphorus: A comparative field study focused on iron and phosphorus forms in sediments



Liandong Jing^a, Xingli Liu^a, Song Bai^a, Chenxi Wu^{b,*}, Hongyi Ao^b, Jiantong Liu^{b,*}

^a College of Chemistry and Environmental Protection Engineering, Southwest University for Nationalities, 610041 Chengdu, PR China

^b State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, PR China

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ABSTRACT

Sediment dredging is a controversial technology for eutrophication control. Its effects on phosphorus (P) cycling are still unclear. In this study, a long term 3 year field investigation was conducted at Dongqian Lake, China, following a sediment dredging project. The amount of iron (Fe) and P forms presented in the sediment from a dredged region (Y region) and a nearby un-dredged region (N region) were monitored and compared. The results showed that soon after the sediment dredging, there were no significant differences in NH₄Cl extractable P (NH₄Cl-P), NaHCO₃/Na₂S₂O₄ extractable P (BD-P) and residual P (Res-P) levels between the Y and N region. However, NaOH extractable reactive P (NaOH-rP) and non-reactive P (NaOH-nrP) were higher, and HCl extractable P (HCl-P) was lower, in the N region than in the Y region. Three years after dredging, considerable reduction in Fe ($P < 0.01$) was observed in the surface sediment from the N region, contrarily the amount of Fe ($P < 0.05$) accreted in the newly formed surface sediment from the Y region. Compared with the first year after the sediment dredging, TP increased by 35.2 and 42.3 mg/kg in the sediment of Y and N regions in the third year, respectively. The increased amount of TP in sediments may result from external loadings and existed primarily in two bioavailable forms (BD-P and NaOH-rP) in both the Y region and the N region. This result indicated that it is better to conduct dredging after external P loading has been blocked. In addition, more BD-P and NaOH-rP accumulated in the N region than the Y region. The observed increase in BD-P and NaOH-rP in the N region may result from Fe- and aluminum-adsorbed P from the water column. Our study suggests that Fe cycling in lakes following sediment dredging is an important factor for understanding the environmental effects of sediment dredging.

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1. Introduction

Among the methods used in the control of lake eutrophication, sediment dredging is a controversial countermeasure (Pu et al., 2000; MACTEC, 2008). On the one hand, it can permanently remove internal nutrient loadings from a lake system (NRC and Council, 2007). On the other hand, it destroys the sediment–water interface which is known to play a key role in the stabilization of lake systems (Søndergaard et al., 2003). Previously, many dredging projects generated positive effects on nutrient control in lake systems in short term, but negative effects were observed in a long run (Ruley and Rusch, 2002; Zhong and Fan, 2007; MACTEC, 2008). Additionally, effects of dredging can be affected by the dredging depth (Liu et al., 2015). The mechanisms underlying the observed effects on nutrients cycling remained puzzling. Understanding

these processes is critical for project design and decision making. To understand the environmental effects of sediment dredging and the mechanisms underlying these effects, it is important to monitor the spatial and temporal patterns of nutrients in the lake, especially in the lake sediment after dredging.

Phosphorus (P) was the primary consideration in many research works about studying the dredging effects (Reddy et al., 2007; Zhong and Fan, 2007), as it is a limiting factor in primary production in fresh water ecosystems (Carpenter 2008; Conley et al., 2009). Cycling of P in a lake is affected by iron (Søndergaard et al., 2003). P can be adsorbed by oxide iron and settle down into sediments. When amount of iron is reduced, adsorbed P can be released into water column. Sediments can function both as a source and sink in controlling P cycling in lakes (Bostrom et al., 1988; Tang et al., 2014). Studying various P forms in lake sediments is a useful approach for assessing P bioavailability, potential P loading, and the biogeochemical cycling of P in a lake (Penn et al., 1995; Ribeiro et al., 2008; Zaaboub et al., 2014). Sediment dredging can directly and extensively alter the physical, chemical, and

* Corresponding authors. Tel.: +86 27 68780710; fax: +86 27 68780712.

E-mail addresses: chenxi.wu@ihb.ac.cn (C. Wu), jtliu@ihb.ac.cn (J. Liu).

biological conditions at the sediment–water interface in dredged regions, and can also indirectly affect un-dredged regions. Therefore, it is important to monitor the P forms in sediment and to follow the changes over time in both dredged and un-dredged regions.

In this paper, we report results from a three-year field study of Dongqian Lake in which sediment dredging was carried out. We performed sequential extraction of P from sediments in dredged and un-dredged regions. The aim of this study was to investigate the effects of sediment dredging on P cycling. The differences in P forms and bioavailability between freshly dredged and un-dredged regions were characterized. How and why P forms changed over time after dredging in both dredged and un-dredged regions were studied.

2. Materials and methods

2.1. Study area

Dongqian Lake is a shallow freshwater lake in eastern China (29°46'N, 121°39'E). A suction dredging project was conducted to protect the lake from further eutrophication. About 33.1% of the surface sediments in area were removed. Suction dredging is a common environmental dredging method. It is effective in the controlling of internal nutrient loadings (Zhong and Fan, 2007; Chen et al., 2013). The top 50 cm sediments were removed from region Y and region N was not dredged during the monitoring period. Aluminum potassium sulfate was used in the dredging projects for flocculating abundant suspended solids and leaked sediments.

2.2. Sampling and analysis

The top 5 cm of sediment samples were collected quarterly with a sediment core sampler (height 500 mm, diameter 70 mm) during April 2009–January 2012 from region Y (at 29°45'54.30"N; 121°38'27.90"E) and region N (at 29°45'36.40"N; 121°38'46.10"E), respectively. The two sampling sites were 734 m apart. Sediments were sampled three times from each site every time, combined and stored in airtight plastic bags, and transported to the laboratory in a portable ice chest.

In the laboratory, the TP and Fe in sediments were detected following the methods of Ruban et al. (2001) and Kan (2011), respectively. P forms in sediment samples were analyzed according to a sequential extraction scheme (Rydin, 2000). In this scheme, P in sediment was separated into NH_4Cl extractable P (NH_4Cl -P), $\text{NaHCO}_3/\text{Na}_2\text{S}_2\text{O}_4$ extractable P (BD-P), NaOH extractable reactive P (NaOH-rP) and no-reactive P (NaOH-nrP), HCl extractable P (HCl-P) and residual P (Res-P). Res-P was calculated by calculating the difference between TP and the sum of the extracted P.

2.3. Data analysis

One way ANOVA was used to analyze the differences of iron and phosphorus content in the three years in both the dredged and the un-dredged regions. Independent *t*-tests were performed to compare the differences between the dredged region and un-dredged region each year. Statistical analysis was performed using SPSS 16.0 and figures were prepared with Origin 8.0.

3. Results and discussion

3.1. Iron patterns in sediments

Fe is a key factor that impacts P cycling in lakes (Søndergaard et al., 2003). As shown in Fig. 1A, total Fe (TFe) content in the

sediments of region Y showed an increasing trend over time. Region Y had a significantly higher TFe content ($P < 0.05$) in sediment during the third year than in the first year after dredging. However, TFe content in the sediment from region N decreased, and was lower than the TFe from region Y ($P < 0.01$) in the third year. Our previous study showed that the average TFe contents in both lake water (0.211 mg/L) and in the outflow river (0.302 mg/L) were higher than that in the inflowing streams (below 0.03 mg/L) (Jing, 2013). Additionally, TFe content in lake water before the dredging project was below 0.03 mg/L (Report from local government). These results suggested that dredging may have caused the release of Fe from the sediments of N region and Fe may be transported to and settled into the sediment of region Y.

In theory, as Fe was released from sediment into the water column, two parallel but opposite results would occur: (1) Fe-bound P released into the water and/or the Fe/P ratio in the sediment would decrease, which is not beneficial in the control of internal P loadings; (2) Fe compound would absorb P in the water column, and this material could subsequently settle into sediments. We observed that the Fe/P ratio decreased significantly in the sediment from the region N in the third year, and it was significantly lower than that from the region Y (Fig. 1). However, there was no significant change in the Fe/P ratio in region Y over time. The Fe/P ratio in sediment is considered to be an important factor that influences the release of internal P loadings. Søndergaard et al. (2003) proposed a key Fe/P ratio of 15, lower than which P may be released significantly. Although the Fe/P ratio decreased in region N, it was still 3 times higher than the key ratio, suggesting that no extensive release of P likely occurred in the sediments from either the region Y or the region N. However, as a management consideration, Fe release should be carefully monitored in dredged lakes. This is especially important when the Fe/P ratio in sediment is close to or below 15.

Few studies have addressed Fe cycling in a lake following the dredging of sediment. However, some reports have indicated that Fe in the water column increased dramatically during and/or after sediment dredging projects (Ohimain et al., 2008; Zhang et al., 2009; Umunnakwe JohnBosco et al., 2011). The reasons for the Fe released from the un-dredged sediment but not in the dredged region in this work may be explained as follow. First, the pH of the water column decreased from 8.35 to 6.59 (Jing, 2013), which might lead to the desorption and/or dissolving of Fe from the suspended sediment. Second, the sediments from the region N could be more easily suspended by wind as compared with the region Y due to a lower water depths and higher water contents in sediments. Third, there might be lower Fe-reducing bacterial activity in the sediments from the region Y compared with the region N. Fe-reducing bacteria are anaerobic microorganisms that can reduce and dissolve Fe-oxides (Kan, 2011). Therefore, Fe reduction by Fe-reducing bacteria can be inhibited by the presence of nitrate and oxygen. Many previous studies showed that denitrification in dredged regions is typically weak, which may result in accumulation of nitrate, and the sediment–water interface in dredged regions is more likely to be in oxidizing condition (Ryding, 1982; Zhang et al., 2009,b; Zhong et al., 2010a,b; Jing et al., 2013). Since Fe content in lakes can change dramatically after dredging of sediment, and Fe is known to be a key factor that impacts P cycling, we proposed that it is of critical importance to monitor Fe cycling in lakes for dredging projects.

3.2. Temporal and spatial variations of phosphorus in sediments

Patterns of TP content in the sediments are presented in Fig. 1B. It showed that the TP in region N was higher ($P < 0.05$) than in region Y during each of the three years. When compared with the first year, the TP content in the sediments increased by 35.2 and

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