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Fifteen-year study of environmental dredging effect on variation of nitrogen and phosphorus exchange across the sediment-water interface of an urban lake☆

Cheng Liu [a, b], Jicheng Zhong [a], Jianjun Wang [a], Lu Zhang [a], Chengxin Fan [a, *]

[a] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, PR China

[b] University of Chinese Academy of Sciences, Beijing 100049, PR China

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ABSTRACT

Environmental dredging has been applied widely in Chinese lakes to reduce their internal nutrient loads. However, the efficacy of dredging to reduce internal loading of nitrogen (N) and phosphorus (P) and to improve water quality has been questioned by some researchers. In this study, the long-term (~15 years) effects of dredging to reduce internal N and P loading in a closed, polluted urban lake were investigated. The results showed that the release of soluble reactive phosphorus (SRP) could be suppressed quickly after dredging, and that the dredging effect was sustained for about 18 months. A significant release of NH_4^+-N was discovered during the first 2–8 months after dredging, followed by maintenance of low-level release rates for about 21–32 months. The continuous inflowing of external pollution loading led to the increase in the release rates of SRP and NH_4^+-N. The external pollution loading was therefore reduced three years after dredging to strengthen the remediation effect. After that, high diffusive flux from the sediment was observed for both NH_4^+-N and SRP during summer seasons for about six years, followed by a decreasing trend. The NH_4^+-N concentration in the overlying water was reduced after the reduction of external loading, while a high concentration of SRP in the overlying water was still observed during summer seasons. In conclusion, the mid-term (<3 years) reduction of internal N and P loading could be achieved by dredging if the external pollution loading were not reduced. Achieving long-term control would require modification of external loading.

1. Introduction

Environmental dredging is used worldwide to reduce internal pollution loads in sediments (Annadotter et al., 1999; Wasserman et al., 2013). It has been reported that about 10.7–21.4 million m^3 of sediment are dredged annually in the United States (Ravikrishna et al., 2002). However, a series of negative effects of sediment dredging, including re-suspension, residuals, and release of contaminants (Bridges et al., 2008), makes it a controversial technology for the remediation of contaminated sediments. In some areas, controversial results have been reported. Zhong et al. (2008) believed that dredging can reduce labile phosphorus (P) content in sediments and therefore reduce the internal P loading. Annadotter et al. (1999) found that P continued to be released from the sediment after dredging operations in Lake Finjasjön in Sweden. In China, dredging has also been used widely in numerous hyper-eutrophic lakes for the main purpose of reducing internal nutrient loading (Cao et al., 2007; Jing et al., 2015; Zhang et al., 2010). Nitrogen (N) and phosphorus (P) were usually the primary concerns in these dredging projects because they were the dominant factors affecting algal blooms and eutrophication issues in many shallow lakes in China (Jin et al., 2005; Shang and Shang, 2005; Xu et al., 2010). Previous work (Liu et al., 2015; Zhong et al., 2008, 2009) revealed that there are some different reduction effects for internal N and P loading by sediment dredging over the short term (<two years). The release of P is usually suppressed shortly or immediately after dredging (Liu et al., 2015; Zhong et al., 2008). In contrast, the release of N cannot be controlled shortly after dredging, and may even increase just after dredging (Liu et al.,

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* Corresponding author. Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, No. 73 East Beijing Road, Nanjing 210008, PR China.
E-mail address: cxfan@niglas.ac.cn (C. Fan).

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2015; Zhong et al., 2009). The main reason for this phenomenon might be the usually high concentration of NH_4^+-N and low concentration of soluble reactive P (SRP) in the pore water of deep layer sediment (Liu et al., 2015). However, the existing literature on the reduction effects of internal N and P loading by dredging were mostly short-to mid-term indoor studies or field investigations (Jing et al., 2013; Zhong et al., 2008). The long-term effects of efforts to control both N and P might be more significant for eutrophication control in lakes, and for evaluating the efficiency of dredging projects, while are seldom reported (Ruley and Rusch, 2002).

Previous literature showed that the long-term effects of dredging were usually influenced by the external pollution loading (Annadotter et al., 1999; Kleeberg and Kohl, 1999). Kleeberg and Kohl (1999) suggested that dredging without reduction of external P loading leads to temporary improvement followed by a slow return to the pre-dredging conditions. The long-term effects of dredging projects in the field, with and without external pollution loading, is crucial to settling the long-standing controversy about whether dredging is effective for reducing N and P concentrations in eutrophic waters. However, information on these long-term effects of dredging projects with and without external pollution loading is limited.

In this study, a fifteen-year-long investigation was carried out to assess the short-to long-term effects of controlling the internal N and P loading in a formerly heavily polluted bay (now a closed lake) of Lake Taihu in China. Dredging was implemented in the lake first, followed by reduction of external pollution loading a few years after dredging. Thereby, the long-term variation of N and P exchange across the sediment-water interface (SWI), with and without external pollution loading, was investigated for about 15 years. In addition, the control of N and P concentration in the overlying water was also investigated to study the effect of dredging on the control of N and P. Our results are expected to provide a new practical basis for long-term effects of dredging on reduction of internal N and P loading, and to inform the debate about whether dredging is favorable for reducing internal nutrient loading.

2. Materials and methods

2.1. Study sites and field sampling

Lake Wuli, covering an area of 5.6 km^2, is a hyper-eutrophic bay area located north of Lake Taihu (Fig. 1). In addition, it is also an urban lake near the city of Wuxi.

It is a typical, unstratified lake with a mean depth of ~2.5 m. The water residence time is about 400 d. The rapid development of Wuxi City gave rise to heavy sewage, industrial, and non-point pollution (Qin et al., 2007) of the bay. Our previous study of the bay in 1998 determined that the sediment in the bay released about 80.7 t of NH_4^+-N and 0.507 t of PO_4^{3-}-P to the overlying water during summer (Fan et al., 1998). Moreover, serious algal blooms have been observed in the lake every year since the 1990s. In order to recover the aquatic ecosystem, environmental dredging and pollution interception were introduced to reduce internal and external pollution loading, respectively. From June 2002 to November 2002, and September 2003 to November 2003, environmental dredging projects (cutter-suction dredging) were implemented in the eastern (D1) and western (D2) parts of the lake (Fig. 1), respectively, covering an area of about 5.3 km^2. The dredging depth was 30 cm according to our study of the lake (Fan et al., 2004). About three years after the dredging projects (2006), a water gate was completed to separate Lake Wuli from the larger, shallow Lake Taihu (Fig. 1). Therefore, the Lake Wuli was isolated from the serious algal blooms that occur in Lake Taihu during summer, to decrease the algal concentration in Lake Wuli. In addition, the external pollution sources from inflowing rivers were mostly intercepted until 2006. During 1998 to 2015, the exchange of N and P across the SWI, and the water quality of sites D1 and D2 were investigated to study the long-term effects of dredging.

The investigation began in 1998 (four years before dredging). While frequent investigation was carried out shortly after dredging. From 2002 to 2008, the investigation was carried out bi-monthly or quarterly. After 2008, the investigation frequency was decreased to once or twice a year. During each investigation period, three in-situ sediment cores were collected from each site using a gravity corer (110 mm diameter, 500 mm length; Rigo Co., Ltd., Japan). The area of each sampling site was about 10 m × 10 m during the long-term investigation to avoid repeatedly sampling at the same position. After capture, the sediment–water interface of the core sample was maintained as it was in the lake (Fig. S1). Each sediment core was sealed with a rubber stopper and sealing film immediately after sampling. All of the cores were transported to laboratory and treated under anoxic conditions within 4 h. Simultaneous with sampling of the sediment, the bottom water (about 10–20 cm above the SWI) was sampled using a deep water sampler (DS-800, Dasen, China). The in situ sampling of pore water began in 2003 and was carried out quarterly between 2006 and 2009. Passive sampling devices (peeper) were used for the sampling of pore water. Each peeper has 36 vertically disposed dialysis cells (6 cm length, 0.65 cm width, and 1.5 cm thickness), with 0.35 cm space between the cells (Fig. S2 in the Supplementary material). On the day of each sampling of the pore water, three peepers were deployed at the SWI of each sampling site and were retrieved 15 days after deployment. The distance between the triplicate peepers was ~2 m to avoid the disturbance of the SWI during deployment. The pore water was sampled immediately after the peeper was retrieved, and preserved at 4 °C. The sampled pore water was then transported to the laboratory immediately for analysis within 4 h.

2.2. Methods for the investigation of N and P exchange across the SWI

Two methods were used to investigate the N and P exchange across the SWI during the long-term study:

(1) Static release method: This method was used between March 1998 and January 2006. The in situ sediment cores sampled from the two sites were transported to the laboratory without disturbance. The integrity of the SWI was kept as long as the sample was in the lake (please see Fig. S1 in the Supplementary materials). After being transported to the laboratory, the overlying water in the column was removed carefully with a siphon. Then, 20 cm of in situ lake water (about 1135 mL) was carefully added to the column. A siphon was used during this process to avoid disturbance of the sediment. The column was incubated at the in situ temperature of ±2 °C for 72 h. Fifty milliliter water samples were collected from the middle of the water column at the following intervals: 0, 12, 24, 36, 48, 60, and 72 h. In situ lake water was added to the column immediately after sampling to maintain the water volume. The release rates of NH_4^+-N and SRP were calculated using the following formula (Fan et al., 2002):

$$F = \left[V(C_n - C_0) + \sum_{n-1}^{n} V_{j-1}\left(C_{j-1} - C_a\right) \right] \Big/ (A \cdot t) \quad (1)$$

where F represents the exchange rate of NH_4^+-N or SRP (mg m^{-2} d^{-1}). A positive F value shows the release of a substance from the sediment to water, and vice versa. Here, V represents the volume of overlying water in the sediment column (L); C_0, C_n, and