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Effects of riverine suspended particulate matter on the post-dredging increase in internal phosphorus loading across the sediment-water interface☆

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ABSTRACT

Dredging is frequently used in the river mouths of eutrophic lakes to reduce internal phosphorus (P) loading from the sediment. However, the accumulation of P-adsorbed suspended particulate matter (SPM) from the inflowing rivers negatively affects the post-dredging sediment-water interface and ultimately increases internal P loading. Here, a 360-d experiment was carried out to investigate the influence of riverine SPM on the efficacy of dredging in reducing internal P loading. SPM was added to dredged and undredged sediments collected from the confluence area of Lake Chaohu. Several parameters related to internal P loading, including oxygen profile, soluble reactive P, and ferrous iron across the sediment-water interface, organic matter, alkaline phosphatase activity, and P fractions, were measured throughout the experimental period. The results showed that the P content (especially mobile P) in the sediment increased to the pre-dredging level with the accumulation of SPM in the dredged sediment. In addition, the P flux across the sediment-water interface increased with the accumulation of SPM. Several characteristics of SPM, including high organic matter content, mobile P, high activity of alkaline phosphatase, and high biological activity, were considered correlated with the post-dredging increase in internal P loading. Overall, this study showed that the heavily contaminated riverine SPM regulates the long-term efficacy of dredging as a nutrient management option in the confluence area. Management is needed to avoid or reduce this phenomenon during dredging projects of this nature.

1. Introduction

Phosphorus (P) plays an important role in freshwater lake eutrophication and is usually the limiting element for phytoplankton blooms (Havens and Schelske, 2001; Lau and Lane, 2002; Søndergaard et al., 2001). The reduction of external P loading can immediately control P concentration in some lakes (Søndergaard et al., 2003), while it is not effective in others due to internal P loading from the sediment (Köhler et al., 2005; Nürnberg et al., 2012; Søndergaard et al., 1999, 2003). Various factors may influence the release of internal P across the sediment-water interface (SWI), including oxygen (O_2) saturation, redox conditions, pH, iron: P ratio, bioturbation, bacterial activity, and resuspension (Hupfer and Lewandowski, 2008; McQueen et al., 1986; Nürnberg, 1988; Petticrew and Arocena, 2001; Søndergaard et al., 2003). O_2 acts as a key factor for the dissolution of redox sensitive iron-bound P (Fe—P) in the surface sediment. The microbial degradation of organic matter and the respiration of organisms in the sediment are generally responsible for the consumption of O_2 across SWI (Kristensen, 2000; Rabalais et al., 2002). The depletion of O_2 might promote the dissolution of Fe—P and increase the P flux across SWI (Hupfer and Lewandowski, 2008; Loh et al., 2013; Nürnberg et al., 2013). Even in oxic conditions, the microbial solubilization of Fe—P also contributes to internal P loading (Boström et al., 1988). In addition, the high organic content in the surface sediment of hypereutrophic lakes increases the activity of alkaline phosphatase (Wang et al., 2012). The increased alkaline phosphatase activity

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(APA) might consequently enhance the availability of phosphates from both organically-bound P (Org-P) and Fe–P and lead to the release of bioavailable P from the sediment (Zhou et al., 2008). These complex mechanisms make the internal P loading difficult to be quantified or even to be disregarded (Nürnberg, 2005, 2009). Therefore, the reduction of internal P loading is crucial for the control of P in water environments.

Various techniques have been studied for the reduction of internal P loading, including capping (Xu et al., 2012; Yin and Kong, 2015), dredging (Annadotter et al., 1999; Kleeberg and Kohl, 1999; Lohrer and Wetz, 2003), and phytoremediation (Wu et al., 2009). Of these techniques, dredging can permanently reduce the high internal P loading, and it has been widely applied in many lakes and bays (Annadotter et al., 1999; Kleeberg and Kohl, 1999; Wasserman et al., 2013). Dredging projects are frequently implemented in some estuarine or confluence areas (the 'confluence area' in this study mainly refers to the river mouth area where a river flows into a lake), where large amounts of P ultimately end up in the sediment transported from inflowing rivers (Johnston, 1981; Wilber and Clarke, 2001).

The transportation and accumulation of P by polluted inflowing rivers are usually responsible for the high internal P loading in confluence areas (Liu et al., 2015; Sutula et al., 2004). The suspended particulate matter (SPM), which adsorbs high levels of P during the transportation process (Lebo, 1991; Sutula et al., 2004), is concentrated in river waters and transported into confluence areas. According to previous studies (Faul et al., 2005; Sutula et al., 2004), P in riverine SPM is usually in mobile forms (labile P, iron-bound P, and organic P). The continuous accumulation of riverine SPM may adversely affect the post-dredging SWI and lead to the increased internal P loading in confluence areas. However, information on these adverse effects is limited. This study investigated the influence of riverine SPM on the post-dredging SWI in the hypereutrophic confluence area of Lake Chaohu, China, and the increase in internal P loading with the accumulation of SPM. The results might provide useful information for improving dredging projects and reducing internal P loading in similar confluence areas.

2. Materials and methods

2.1. Field sampling

Lake Chaohu, the fifth largest freshwater lake in China with an area of 770 km^2 and a mean depth of 2.69 m, is characterized by hyper-eutrophication and harmful algal blooms (Yang et al., 2006). Three heavily polluted urban rivers (Nanfei River, Shiwuli River, and Tangxi River), located northwest of the lake, cause the formation of a heavily polluted confluence area (Fig. 1) (Liu et al., 2012). Dredging has been considered as the preferred technique to reduce internal P loading. However, the surrounding rivers are still being polluted, and they transport P that is adsorbed to SPM.

In order to investigate the effects of riverine SPM on the post-dredging increase in internal P loading, one of the most heavily polluted sites (31°42′ 4.76″ N and 117°21′ 43.49″ E; Fig. 1) was selected for this study. In January 2014, about 150 *in situ* sediment cores were collected from this site using a gravity corer (110 mm diameter, 500 mm length; Rigo Co., Ltd., Japan). The depth of the cores was 40–45 cm. All the sediment cores were carefully transferred to the laboratory within 3 h to ensure that SWI remained undisturbed. The physical shape, porosity, and density of SWI were the same as those in the lake. The chemical character of SWI was the same as that in the lake, except for the depletion of O_2 that might occur during transportation. All the sediment cores were dredged and incubated with aeration immediately after their arrival at the laboratory. *In situ* lake water was sampled on a monthly basis from January 2014 to December 2014 to conduct a 360-d laboratory incubation experiment.

2.2. Sampling of SPM

SPM was sampled monthly from January 2014 to December 2014 from the river mouth of the Nanfei River (31°41′43.88″ N and 117°24′19.24″ E; Fig. 1), which is the most heavily polluted urban river around the lake. The transportation of contaminants by the Nanfei River contributes greatly to the heavy pollution in the northwest area of Lake Chaohu. A series of 16-channel sediment traps (110 mm diameter, 350 mm length) was used for sampling. From January 2014 to December 2014, sediment traps were placed at the sampling site (3.5–4 m water depth) at the beginning of each month and retrieved at the end of the same month. The influence of bacterial activity in SPM on internal P loading was studied throughout the experimental period. Therefore, SPM in the trap was not contaminated during the sampling period. Bacterial activity in SPM might be relatively high, because of the decomposition of materials in the trap. The trapped SPM was transferred to the laboratory and treated within 24 h.

2.3. Experimental design

In January 2014, simulated dredging operations were performed using the *in situ* sediment cores as soon as they were transported to the laboratory. Dredging at a depth of 25 cm (the upper 25 cm of the sediment core was removed by simulated dredging) was applied. Internal P loading can be mostly reduced at this dredging depth, according to our previous study in the same area (Liu et al., 2015). The upper 25 cm and the remaining sediment layers (about 15–20 cm) were transferred to two separated empty columns (110 mm diameter, 350 mm length), corresponding to undredged and dredged sediment cores. All the sediment cores were incubated in a water tank filled with *in situ* lake water at *in situ* water temperature ±2 °C (Fig. S1). Water in the tank was replaced monthly with fresh *in situ* lake water. *In situ* lake water was filtered through a 20-μm net to remove most of the plankton and large particulate matter before adding to the water tank. Aeration was used to maintain the O_2 saturation of the overlying water during the incubation. The O_2 saturation of the studied area was 214.4–339.2 μmol L^{-1} throughout the experimental period, similar to that of the water tank in the laboratory, whereas the O_2 penetration depth (OPD) of the *in situ* sediment was usually approximately 2 mm or lower (Fig. S2 of the Supplementary material).

Six treatments were performed as follows: (1) U, undredged sediment without the addition of SPM; (2) U + DP, undredged sediment with the addition of sterile SPM; (3) U + FP, undredged sediment with the addition of non-sterile SPM; (4) D, dredged sediment without the addition of SPM; (5) D + DP, dredged sediment with the addition of sterile SPM; and (6) D + FP, dredged sediment with the addition of non-sterile SPM. Sterile SPM was obtained by drying fresh SPM at 60 °C for 24 h and then sterilizing it at 121 °C for 30 min. Previous studies demonstrated that organisms in SWI have a significant influence on the internal P release from the sediment (Jiang et al., 2008; Pettersson, 1998). Therefore, sterile SPM was used to study whether the biological activity in SPM affects the P flux across the post-dredging SWI. This might be helpful to explain the increase in internal P loading with the accumulation of riverine SPM. Both the non-sterile and sterile SPM were separately mixed with *in situ* lake water and then added to sediment columns. The addition of SPM-lake water mix was took out every month, following the *in situ* sedimentation rate (about 6 mm yr^{-1}) of the studied area (Tu et al., 1991).