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SEDIMENT ENVIRONMENT, POLLUTION AND REMEDIATION

Dredging method effects on sediment resuspension and nutrient release across the sediment-water interface in Lake Taihu, China

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Abstract

Environmental sediment dredging is one of the most common methods for the remediation of contaminated sediments in lakes; however, debate continues as to whether the effectiveness of dredging methods contributes to this phenomenon. To determine sediment resuspension and nutrient release following dredging with a variety of dredging methods, four dredging treatments at wind speeds of 0–5.2 m/s were simulated in this study, namely suction dredging (SD), grab dredging (GD), ideal dredging with no residual sediments (ID), and non-dredging (ND). Field sediments from suction and grab dredging areas (including post-dredged and non-dredged sediments) of Lake Taihu were used to assess the release abilities of soluble reactive phosphorus (SRP) and ammonia nitrogen (NH_4^+-N) from the sediment-water interface. The effects of residual sediments on nutrient concentrations in water were also evaluated. The results reveal that inhibition of resuspension of particulate matter and nutrients released through sediment dredging decreases with increasing levels of residual sediment. Total suspended particulate matter content in the mean water columns of ID, SD, and GD under wind-induced disturbance (1.7–5.2 m/s) decreased by 67.5%, 56.8%, and 44.3%, respectively; total nitrogen and total phosphorus in ID (SD) treatments were 19.8% (12.9%) and 24.5% (11.2%) lower than that in ND treatment. However, there were ~ 1.6 and 1.5 times higher SRP and NH_4^+-N in the GD treatment compared with the ND treatment at the end of the resuspension experiment (0 m/s). A significant increase in the SRP and NH_4^+-N release rates at the sediment-water interface was also observed in field sediments from a grab dredging area, indicating that GD may pose a short-term risk of nutrient release to the water body. Hence, dredging methods with less residual sediments both during and after dredging improves the dredging quality.

Keywords Lake Taihu · Sediment dredging · Dredging methods · Sediment resuspension · Nutrient release

Introduction

The removal of contaminated sediments from waterbodies by environmental dredging is commonly used worldwide as an engineering approach to sediment remediation. However, field experience gained in recent years has shown that not all sediment dredging can successfully decrease internal nutrients (especially biogenic N and P) to manage lake eutrophication (Hu et al. 2010; Yenilmez and Aksoy 2013; Weng 2017). Sediment characteristics, dredging method, dredging season, and the hydrological conditions of the lake itself are key factors affecting sediment dredging and internal nutrient loading (Kleeberg and Kohl 1999; Liu et al. 2015).

Determining the vertical distributions of the physicochemical properties of sediments is vital for accurately removing targeted contaminated sediments, determining sediment cleanup levels (CULs), and decreasing nutrient flux at the sediment-water interface (Oldenborg and Steinman 2019; Bridges et al. 2010).

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Dredging sediments over reasonable periods of time (cool seasons) can successfully inhibit nutrient release, while inappropriate dredging seasons may stimulate, rather than prevent, the formation of black odorous substances (Zhong et al. 2018; Chen et al. 2016). The physical characteristics of the water body (water depth, current, slope, etc.) affect the transportation and resuspension of residual sediments produced during dredging processes, resulting in increasing dissolved N and P concentrations in the water column with the release of particulate-associated contaminants (Zhu et al. 2007; Choppala et al. 2018); however, previous studies have suggested that the resuspension of sediments should be a sink of inorganic phosphorus under wind disturbance, since it increases oxygen in the overlying water and the contact probability between P and P reactants, resulting in adsorption (Li et al. 2011). Thus, resuspension of residual sediments under post-dredging wave disturbance, which varies between 2 and 20% of total dredged volume depending on dredging methods (e.g., suction dredging and grab dredging; Gustavson et al. 2008; Palermo and Hays 2014; Bridges et al. 2006), should be one reason for the inconsistent dredging outcomes observed in field studies.

Lake Taihu is a typical eutrophic lake with high nutrient concentrations in its sediments. Approximately 35,000,000 m^3 of sediments have been dredged for the purpose of decreasing the internal nutrient loading of the lake, with both suction dredging and grab dredging widely used (Liu et al. 2018; Fan and Zhang 2009). Resuspension of sediments is typical of Lake Taihu, since the mean depth is ~ 2.0 m and it frequently suffers wave disturbance at wind speeds of 1–6 m/s (Qin et al. 2006). Hence, wind-induced waves may drive the prolonged suspension of residual sediments of post-dredging in the water column, resulting in the different release patterns of nutrients, hindering improvements to water quality, and providing nutrients for algal blooms (Wang et al. 2017). Moreover, the nutrient cycling process and nutrient flux at the sediment-water interface are affected by new sediment interfaces, which differ greatly between suction dredging and grab dredging (Yu et al. 2016). Hence, determining the nutrient release and particulate resuspension for the typical wind-induced wave conditions of Lake Taihu following dredging with various dredging methods is important for the development of a suitable dredging plan.

Unfortunately, insufficient research has been carried out to determine the nutrient release and particulate resuspension responses of Lake Taihu to dredging with different dredging methods under typical wind speed conditions. In this study, sediment cores from seriously contaminated areas of Lake Taihu were used to simulate particulate resuspension and nutrient release after different sediment dredging methods. Nutrient flux at the sediment–water interface and interstitial water nutrients were also analyzed in suction-dredging and grab-dredging areas of Lake Taihu, and the effects of residual sediments on nutrient concentrations in the water column were also evaluated.

Materials and methods

Study site and sampling

Lake Taihu is a typical eutrophic lake with high nutrient concentrations in its sediments, particularly within Meiliang Bay, Zhusan Bay, Lvjiang Port, the Western Coastal Zone, and Yueliang Bay. Thus, both suction dredging and grab dredging have been used in these areas to control internal nutrient loading (Fan and Zhang 2009). A total of 24 sediment cores were collected from the non-dredged area of Bafang Port (31° 13′ 33″ N and 119° 54′ 41″ E) to simulate the effects of different dredging methods and residual sediment on nutrient release and particulate resuspension. Two sample sites were selected for suction-dredging (Bafang Port) and grab-dredging (Lvjiang Port) areas, namely a non-dredged region and a post-dredged region. Six sediment cores were collected from each sample site for the nutrient concentration analysis of interstitial water and to assess nutrient release. All sediment cores were collected in May 2013 and transported to the laboratory within 24 h. The overlying water was carefully removed by siphoning for further experiments.

Experimental design

The effect of different dredging methods on nutrient release and particulate resuspension Twelve sediment cores collected from Bafang Port were used to simulate four treatments (each in triplicate). Moreover, the vertical distributions of the physicochemical properties of sediments showed that mostly, nutrients were enriched in the top 25 cm; accurately removing these parts can successfully decrease nutrient flux at the sediment–water interface (Liu et al. 2015).

A non-dredged control group (ND) and a group in which the top 25 cm of sediment was removed using a cutting blade to produce a new smooth sediment interface devoid of residual sediments (ideal dredging, ID) were analyzed. The next group had the top 20-cm surface sediments removed, after which the next 5 cm of sediment was removed using a small grab dredger; the new sediment interface was wedge-shaped (grab dredging, GD, residual sediments ~ 10%). The last group had the top 25 cm of sediment removed using a small suction pump (suction dredging, SD, residual sediments ~ 3%). Each treatment group was placed into a Y-shaped apparatus to simulation wind-induced resuspension following dredging (see Supplementary Material for details; He et al. 2013) at a water depth of ~ 1.6 m. Previous studies have shown that accumulative frequency of wind speed in Lake Taihu can be divided into four segments (mean values; You et al. 2007): background wind (1.7 m/s), light wind (3.2 m/s), moderate wind (5.1 m/s), and strong wind (8.7 m/s). The mean duration of moderate winds in Taihu Lake was 120 min. Thus, wind conditions in this study were set to 1.7 m/s for 1 h (W_1), 5.2 m/s for 3 h (W_2), and 1.7 m/s for 1 h (W_3). Water samples were collected at heights of 25, 75, and 150 cm above the water–sediment interface, and the sampling times were divided into four periods (W_1 0 h, 0.5 h, and 1 h; W_2 2 h, 4 h; W_3 5 h; and period four 8 h, 10 h, and 12 h) to completely simulate the resuspension and settlement processes.

Unfiltered water samples were used to determine the concentration of total phosphorus (TP) and total nitrogen (TN). Another water samples were filtered through a GF/C membrane; the filtrate was used for nutrient analysis (soluble reactive phosphorus, SRP; ammonia nitrogen, NH_4^+-N), while the membranes were used to measure the total suspended particulate matter (TSS).

The TSS, TN, TP, SRP, and NH_4^+-N contents in the water column of experiment a were calculated using the same equation, as provided for TSS:

$$TSS = \sum_{i=1}^{n} C_{ssi} \cdot h_i$$

where TSS represents total suspended particulate matter in the water column (mg/m^2) and C_{ssi} and h_i are the concentration of suspended particulate in layer i and the depth of layer i, respectively. Data were then averaged over each period.

Effect of residual sediment on nutrient release Twelve sediment cores from Bafang Port had the top 25 cm of their surface sediments removed before being mixed in a steel barrel to serve as residual sediments. The remaining ~ 20 cm of each bottom sediment was transferred into a separate plexiglass tube and carefully injected with 20 cm of filtered lake water following siphoning, after the sample was incubated at room temperature (25 ± 2 °C) to serve as dredged sediments. Residual sediments were added to the dredged sediments. Four series of samples were used in these experiments, with 3%, 5%, 10%, and 15 % of the mass of the removed sediments added.

After standing for 1 day, water samples were collected on a daily basis over 7 days to determine the concentrations of SRP and NH_4^+-N.

Nutrient released after suction dredging and grab dredging Each of three replicate sediment cores collected from non-dredged and post-dredged areas of Zhusan Bay and Lvjiang Port, which were subjected to grab dredging and suction dredging in November 2012, respectively, were used for experimental static release simulations (see Supplementary Material for details; Zhong et al. 2018). Water samples (50 mL) were collected at 0, 12, 24, 36, 48, and 72 h, for SRP- and NH_4^+-N-concentration analysis and to calculate their release rates at the water–sediment interface. Another three sediment cores were sliced at 2-cm intervals over 0–22 cm to obtain pore water samples, which were used to determine SRP and NH_4^+-N contents.

The release rates of SRP and NH_4^+-N were calculated according to equations described by Fan et al. (Fan et al. 2002). The concrete calculation equation is described in detail in the supplementary material.

Sample analyses

Concentrations of NH_4^+-N and SRP were determined using Nessler's reagent and the molybdenum blue method (Chinese 2002), respectively. Water samples were digested with alkaline potassium persulfate, and the digestion solutions were subjected to colorimetry in order to determine the TP and TN concentrations. Filtered membranes were dried to constant weight at 105 °C in order to determine the TSS content.

Data analysis

Differences between the various treatment groups were assessed using one-way analysis of variance (ANOVA) using the SPSS 19 software, and a significance level of $p < 0.05$ was used in each test. All graphs were created using the Origin 8.5 software.

Results

Effect of dredging methods on sediment resuspension and nutrient release (experiment a)

Total suspended particulate matter content in water column

Mean water-column TSS content in the ND treatment group varied between 202.4 and 424.4 g/m^2 at wind speeds between 1.7 and 5.2 m/s, while the highest content following grab dredging treatment was found to be 55.4 g/m^2 at a wind speed of 5.2 m/s. These results indicate that dredging effectively inhibits the resuspension of particulate matter in the water column under different wind conditions. SD treatment was found to better inhibit the resuspension of particulate matter compared with GD, since the inhibition rates of SD and GD at a wind speed of 5.2 m/s were 67.4 and 52.4%, respectively; however, no significant difference ($p > 0.05$) in the TSS content was found between the treatment groups in the settlement stage (0 m/s).

Nutrient concentrations in water columns

The concentrations of TP and SRP in the non-dredged treatment groups were observed to increase with increasing wind speed, indicating that wind-induced wave disturbance promotes higher levels of phosphorus in the water column. The TP contents of the GD, SD, and ID groups were 81.6%, 88.8%, and 75.5%, respectively, compared with the TP content of the ND group at a wind speed of 5.2 m/s, while the TP content of GD group was 62.5% lower compared with that of the ND group in the settlement stage (0 m/s; Fig. 2a). A similar trend was observed in the water-column SRP contents (Fig. 2c).

The mean water-column TN contents of the ND group varied between 4.3 and 5.3 g/m^2 under simulated wind speed conditions (Fig. 2b), and no significant differences ($p > 0.05$) between the GD and SD groups were found at the settlement stage. Unlike cases in which the SD and ID groups show reductions in NH_4^+-N content during disturbance and settlement periods, the NH_4^+-N content of the GD group was significantly higher than that of the ND group, especially in the settlement stage (0 m/s) where it was ~ 1.6 times higher (Fig. 2d). The above results indicate that sediment dredging reduces the concentrations of nutrients in the water column under wind-induced wave disturbance conditions, but grab dredging increases the contents of nitrogen and phosphorus in the water column during the settlement stage.

Effect of residual sediment on water-column nutrient concentrations (experiment b)

The concentrations of NH_4^+-N and SRP in the water columns of residual sediment levels between 0 and 10% of the total removed sediment quantity are displayed in Fig. 3. The NH_4^+-N concentrations in the water columns were observed to increase with increasing levels of residual sediment. For example, the NH_4^+-N concentrations in the 3%, 5%, and 10% residual sediment treatment groups were ~ 1.6, 2.5, and 4.2 times higher than that of the control group on day 1, respectively. Moreover, a decreasing trend in the NH_4^+-N content was observed from day 1 to day 7 in each treatment group, and no significant ($p > 0.05$) differences were observed at day 7 between the various groups (Fig. 3a).

The SRP concentrations in the control group varied little over 7 days, with mean values of 0.07–0.098 mg/L. However, the SRP concentration increased by between 30% and 340% in the samples treated with the various residual sediments, and no obvious decrease was observed within the incubation time. For example, the SRP concentrations in the 3%, 5%, and 10% residual sediment treatment groups were still 2.6, 3.1, and 3.5 times that of the control at day 7, respectively (Fig. 3b).

SRP and NH_4^+-N flux after dredging with various dredging methods (experiment c)

Distributions of pore water SRP and NH_4^+-N

The vertical distributions of pore water SRP and NH_4^+-N in the non-dredged and post-dredged sediments associated with the grab-dredging and suction-dredging areas are presented in Fig. 4. The concentrations of NH_4^+-N and SRP in the pore water of the non-dredged sediments in the suction-dredging areas are much higher than those of the post-dredged sediments to a depth of 10 cm (Fig. 4a, b), indicating that polluted surface sediments are successfully removed by suction dredging. However, the opposite trend was observed for the grab-dredging areas (Fig. 4b, d), which means that grab dredging incompletely removes contaminated sediments, and the quantity of residual sediments is high.

SRP and NH_4^+-N fluxes after suction dredging and grab dredging

The SRP- and NH_4^+-N-diffusion fluxes are shown in Fig. 5. A significantly lower amount of NH_4^+-N was observed at the post-dredged sediment-water interface (SWI) of the suction-dredging area; it was 78.1% lower compared with that of the non-dredged sediments. Conversely, the NH_4^+-N fluxes of the post-dredged SWI of the grab-dredging area was 34.3 mg/m^2/day, which is ~ 2.6 times higher than that of the non-dredged SWI (Fig. 5a). The SRP fluxes in the post-dredged SWI of the suction-dredging and grab-dredging areas were found to be 1.8 and 2.3 mg/m^2/day, which are 0.5 and 6.4 times those of the non-dredged SWIs, respectively (Fig. 5b).

Discussion

Influence of dredging method on sediment resuspension

Sediment dredging has often been used to restore navigable depths (navigation dredging) and to remedy contaminated sediments (environmental dredging); however, the primary objectives of these two processes are different (National Research Council 2007). The chemical and physical characteristics of the sediment, the hydraulic conditions of the site, and the selection of the dredging equipment need to be evaluated prior to implementing environmental dredging (Shen et al. 2013), as these factors affect resuspension (dispersion of sediments in the water column), release (contaminants from interstitial water or suspended particulate matter), and residuals (sediments remaining after dredging) during and after the dredging process (Choppala et al. 2018). In the present study, dredging with various methods was simulated to assess sediment resuspension and nutrient release following dredging under the background and moderate wind speed (1.7–5.2 m/s) conditions of Lake Taihu (Qin et al. 2004). The results showed better performance of inhibition sediment resuspension and nutrient release by ideal dredging compared with the other two dredging treatments, since no residual sediments existed. However, grab dredging and suction dredging are frequently used as environmental remediation measures in Lake Taihu for the purpose of reducing internal nutrient loading (Fan et al. 2004), despite the inconsistent dredging results observed in field experiments. Moreover, it is difficult to ensure the removal of all contaminated sediments with no residual sediments during dredging projects. Thus, we also considered the difference between suction dredging and grab dredging.

Sediment dredging significantly decreases the TSS contents of water columns compared with non-dredging during wind speeds of 1.7–5.2 m/s, which is consistent with the results of previous studies (Yu et al. 2012; Ding et al. 2018). Moreover, ideal dredging exhibits a better capacity to inhibit the resuspension of particulate matter compared with the other two treatments (Fig. 1). The bulk densities and water contents of sediments are important for sediment resuspension, since they determine their critical shear stresses (Håkanson, 2005). The increase in bulk density and the decrease in water content caused by dredging were demonstrated to be beneficial for inhibiting sediment resuspension in both simulated tests and field experiments (Zhong et al. 2008) and provides an explanation for the lower levels of TSS in the dredged sediments (Fig. 1). Moreover, the residuals consist mostly of surficial soft sediment, which decreased in order of GD, SD, and ID treatments, resulting in a gradually increasing bulk density and lower resuspension sediments. Furthermore, the TSS contents of the non-dredged and dredged groups decreased by 43.1% and 18.5–27.9%, respectively, as the wind speed was decreased from 5.2 to 1.7 m/s, and no significant differences were observed between the groups during the settlement stage ($p > 0.05$). These results indicate that the surface layers of non-dredged sediments are more prone to resuspension and sedimentation under the action of wind, since the surface sediment layers are loose.

Suction dredging with a cutterhead is usually smaller that commonly used in grab dredging with conventional calm, because the dredging cut depth tends to be shallower, providing more accuracy and precision (Palermo and Hays 2013). Consequently, the new sediment surface layer formed after suction dredging was plainer and contained fewer residual

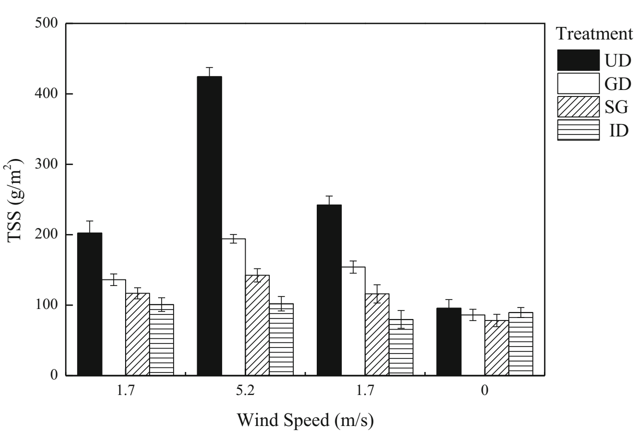

Fig. 1 Total suspended solid (TSS) contents of water column following dredging with different types of equipment during wind-induced disturbance(UD: non-dredged, GD: grab dredging, SD: suction dredging, ID: ideal dredging)

sediments compared with that produced by grab dredging; hence, the smaller particles in the residual sediment are more likely to resuspend at low wind speeds, which is consistent with expectations based on sediment resuspension theory (Li et al., 2017). However, sediments are often transported during dredging, and these sediments make important contributions to residual sediments; however, they are not considered in this study. As a result, the different TSS contents of the water columns after dredging with the various methods may be somewhat underestimated. In addition, although results from smaller dredging equipment used in indoor simulations are often not scalable to larger equipment, they can provide useful information for full-scale dredging operations in the field.

Effect of dredging methods on nutrient release

The resuspension of sediments under wind-induced wave conditions is a typical characteristic of Lake Taihu because of its shallowness (water depth of ~ 2 m) and large area. The nutrient level of a water column often increases during sediment resuspension in the presence of currents or waves (Qin et al. 2006; Søndergaard et al. 2013), which is consistent with the observed increases in the TN and TP levels of the non-dredged groups at a wind speed of 5.2 m/s (Fig. 2). However, we observed opposing results that depended on the dredging method; that is, ideal dredging and suction dredging reduced the SRP and NH_4^+-N contents in the water column, while these levels were higher as a result of grab dredging (Fig. 2). The new surface layer is V-shaped after grab dredging, and deep sediments are exposed in the middle and while residual sediments are retained on both sides, resulting in higher water content and effective release area, which is conducive to the release of nitrogen (N) and phosphorus (P) across the new sediment–water interface; this does not occur in ideal dredging and suction dredging (Liu et al. 2019).

The levels of residual sediments during suction dredging and grab dredging were ~ 5–9% and 5–20%, respectively (Palermo and Hays 2013). Fewer residual sediments lead to lower suspended matter under windy conditions (Fig. 1), which is a reason for the lower levels of dissolved nutrients in the water from suction dredging under windy conditions (Zhu et al. 2007). Moreover, the new sediment surface layer after dredging may form a thin oxide layer owing to oxygen enrichment resulting from wind disturbance, which controls nutrient exchange across the sediment-water interface (Fan et al. 2004; Qin et al. 2006). However, sedimentation and mineralization of large amounts of residual sediment at the new surface sediment may alter the redox environment, which is important for releasing metal-bound nutrients (Giles et al. 2016) and is consistent with the higher concentrations of SRP and NH_4^+-N in the overlying and interstitial water found in this study (Figs. 3 and 4).

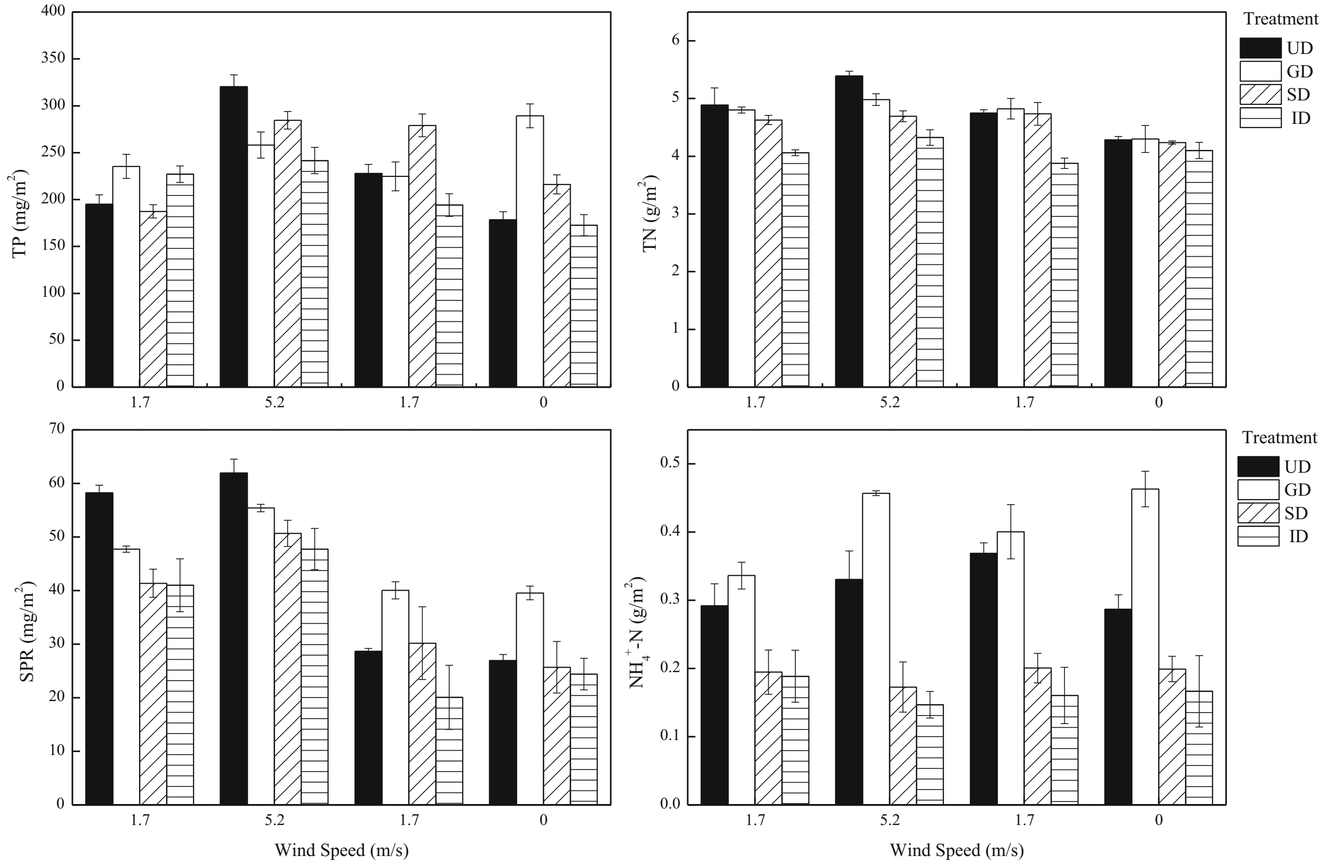

Fig. 2 Nutrient concentrations in water column after dredging with different types of equipment during wind-induced disturbance(UD: non-dredged, GD: grab dredging, SD: suction dredging, ID: ideal dredging)

The NH_4^+-N and SRP flux results also show that their release rates were inhibited and promoted by suction dredging and grab dredging, respectively (Fig. 5). However, quantitatively assessing the release of dissolved nutrients from sediments in field experiments is difficult since many factors, such as chemical and physical characteristics, hydrodynamic disturbances, and temperature, affect the data (Sun et al. 2006). In this study, sediment cores from suction and grab dredging areas were used to evaluate the release of nutrients in the short term; hence, the porosities of the sediments and the concentrations of the nutrients in the pore water were the primary factors affecting the fluxes across the sediment-water interface (Zhong et al., 2018). Thus, higher concentrations of NH_4^+-N and SRP in the pore water of the post-dredged sediments compared with those of the non-dredged sediments in the grab dredging area are the reason for the higher release rate according to Fick's first law (Fan et al. 2004), while the opposite trend was observed in the suction-dredging area (Figs. 4 and 5).

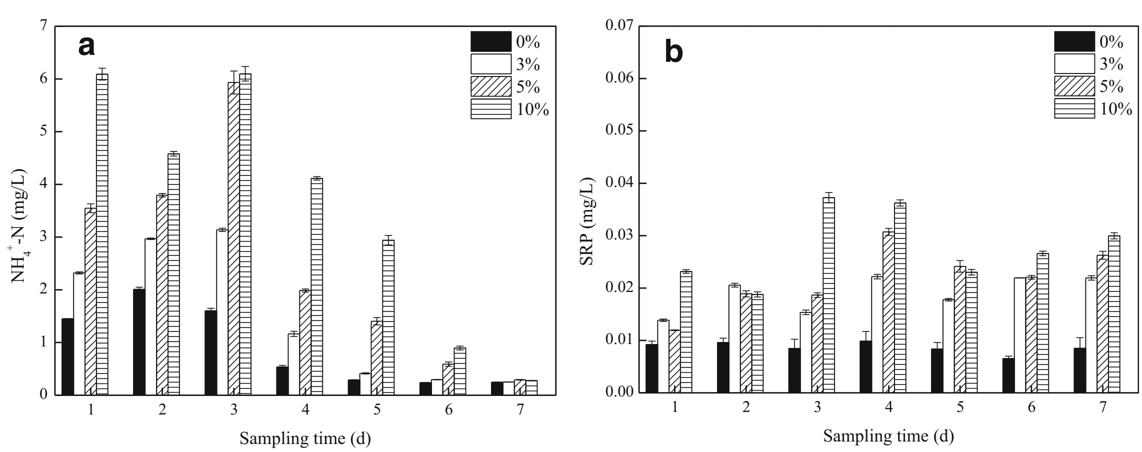

Fig. 3 Effects of residual sediments on **a** NH_4^+-N and **b** soluble reactive phosphorus (SRP) concentrations in the water column

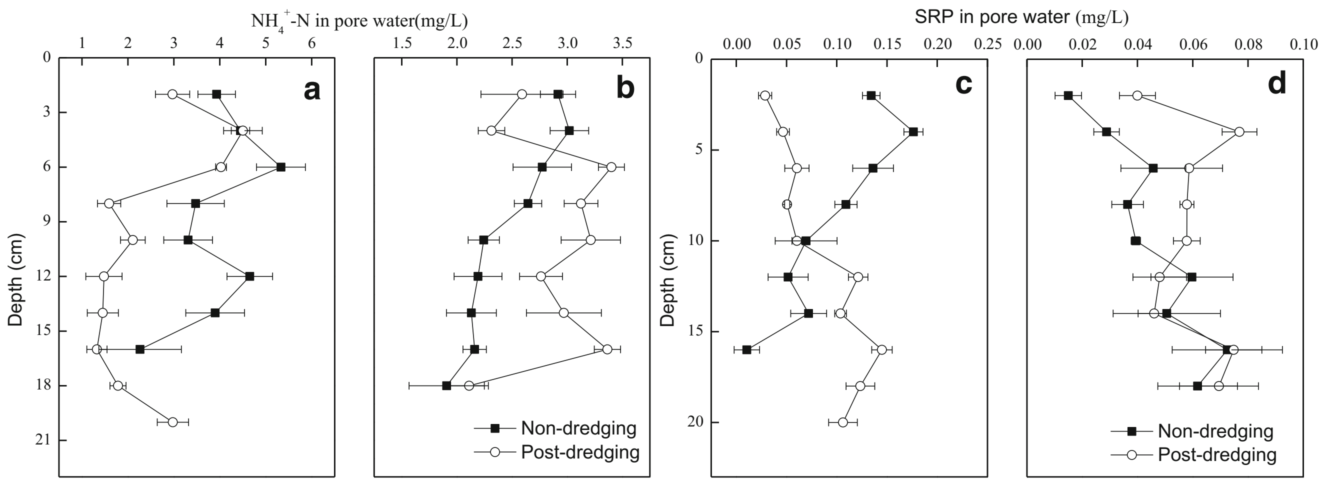

Fig. 4 Soluble reactive phosphorus (SRP) and NH_4^+-N concentrations in pore water associated with suction dredging (**a**, **c**) and grab dredging (**b**, **d**)

The deposition of externally suspended particulate matter influences the effectiveness of dredging, as has been demonstrated both in field and incubation experiments (Chen et al. 2018; Zhu et al. 2011). Grab dredging and suction dredging were respectively carried out in the northern and western regions of Lake Taihu, where a southeasterly wind prevails during the summer, leading to the accumulation of large amounts of phytoplankton in Meiliang Bay (Fan et al. 1998). The sedimentation and decomposition of algal cells increase the nutrient load of the surface sediment (Wang et al. 2016), which also provides a reason for the observed increase in the nutrient levels in the pore water and the high release rate from the sediments of the grab-dredging area (Figs. 4 and 5); however, this was not evaluated in this study.

Implications for dredging projects

Better performance of inhibition sediment resuspension and nutrient release is found for suction dredging compared with grab dredging under both disturbance and static conditions, and improvements in water quality through sediment dredging decreased with increasing of residual sediments in this study. Therefore, measures should be taken to reduce residual sediments during and post-sediment dredging; for example, the characteristics of the sediments (bulk density, particle size, and mineralogy) and the site conditions (e.g., water depth and waves) need to be completely analyzed before selecting the dredging method. Furthermore, engineering methods such silt curtains could be used to decrease suspended sediments during dredging.

However, here, we simply assessed the effects of residual sediments on nutrient release under static conditions; the resuspension of residual sediments during sediment dredging or under wave conditions may be more complicated and have a profound influence on the ecosystem (Li et al. 2011). In addition, the combined effects of residual sediments and hydrodynamic disturbance on nutrient release will be addressed by field experiments in future work.

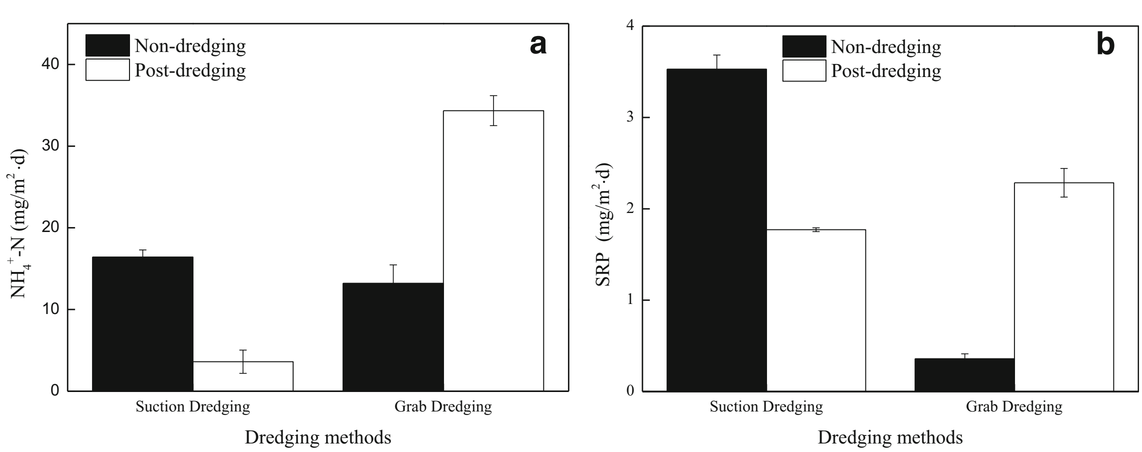

Fig. 5 **a** NH_4^+-N and **b** soluble reactive phosphorus (SRP) fluxes after suction dredging and grab dredging

Conclusions

The resuspension of sediments is effectively suppressed by sediment dredging, while grab dredging promotes the release of SRP and NH_4^+-N under windy conditions. The concentrations of SRP and NH_4^+-N in the pore water of post-dredged sediments were significantly higher than those of non-dredged sediments, which accelerate the rates of SRP and NH_4^+-N release from the post-dredged sediments, while the opposite trend was observed for samples from the suction-dredging area. The addition of residual sediments increases the NH_4^+-N and SRP concentrations in the water column, which increases with increasing levels of residual sediment, indicating that additional methods need to be taken into consideration when managing residual sediments during both dredging and post-dredging.

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