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Thin-layer fine-sand capping of polluted sediments decreases nutrients in overlying water of Wuhan Donghu Lake in China

Yang Jiao¹, Lei Xu^{1,2}, Qingman Li^{1*}, Sen Gu^{1,3}

¹ Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, 430072, China

² University of Chinese Academy of Sciences, Beijing, 100039, China

³ Univ. Rennes, CNRS, OSUR, Géosciences - UMR 6118, F-35000 Rennes, France

Corresponding author:

Prof. Dr. Qingman Li

Address: Institute of Hydrobiology, Chinese Academy of Sciences, No. 7 Donghu

South Road, Wuchang District, Wuhan, 430072, PR. China. Tel: 86-27-68780043,

Fax: 86-27-68780123

E-mail: qmli@ihb.ac.cn (Qingman Li)

Abstract

Capping water body sediments with a thin layer of sand is an effective technique to decrease nutrient concentrations in the water column and accelerate ecological restoration of eutrophic water bodies. However, long-term effects of thin-layer sand capping in shallow lakes are reported less often. Using clean fine sand and geotextile mats as capping materials for sediments collected from Wuhan Donghu Lake in China, we designed a 290 d tank experiment with 3 cm of sand capping at four percentages of sediment coverage from 25-100% and a control (no capping). We monitored total nitrogen (TN), total phosphorus (TP), nitrate (NO_3^-), ammonia (NH_4^+) and soluble reactive phosphorus (SRP) in the overlying water every 7 d. Mean TN and NO_3^- concentrations were significantly the lowest ($P<0.05$) at 50% coverage. Further increase in coverage kept them fluctuating. NH_4^+ concentration was significantly lowest ($P<0.05$) at 75% coverage. The relation between coverage and mean TP and SRP concentrations indicated that 75% coverage significantly decreased ($P<0.05$) them, and increasing coverage to 100% decreased them even more. The fluxes of TN and TP estimated between sediments and overlying water showed that the thin fine-sand layer significantly increased the function of sediments as a sink of TN from overlying water and the potential of a sand layer to block release of TP from sediments ($P<0.05$). Our results suggested that if thin-layer sand capping were applied to Wuhan Donghu Lake, more than 50% coverage is required to decrease nutrients in the lake's water.

Keywords: Sediments; Wuhan Donghu Lake; Nutrients; Thin-layer sand capping; Water quality

1. Introduction

Capping water body sediments with a thin layer of sand is an effective technique to decrease nutrient concentrations in the water column and accelerate ecological restoration of eutrophic water bodies. When a water body is subjected to eutrophication, decomposition of organic matter in surface sediments depletes oxygen at the bottom, which accelerates the flux of nutrients from sediments to the water column (Holmboe et al. 2001; Lopez 2004; Lemley et al. 2014). This process can continue for several decades, even after inputs of external nutrients from industrial and domestic wastewater discharge and agricultural runoff have stopped (Søndergaard et al. 2003; Lukkari et al. 2009). In contrast, when surface sediments are in an aerobic state, their increased potential to bind compounds may increase the flux of nutrients from the water column to sediments (Ekeröth et al. 2016; Inoue et al. 2017). To mitigate eutrophication of water bodies, many efforts have attempted to increase the potential of sediments to bind nutrients or to impede fluxes of nutrients from contaminated sediments to the water column (Jacobs and Förstner 1999; Zou et al. 2017; Ehsani and Hayes 2018; Peng et al. 2018). Among these efforts, in situ capping with clean sand to isolate contaminated sediments has been applied widely (Kim and Jung 2010; Pan et al. 2012; Huang et al. 2013).

In situ capping can block release of contaminants from sediments by reducing resuspension of sediment particles, and sorbing or degrading contaminants (Randall et al. 2013; Wang et al. 2014; Samuelsson et al. 2015; Gilmour et al. 2018). This technique has been applied widely to remediate sediments contaminated by different pollutants. Many capping materials have been developed, such as natural minerals, clean soils and activated carbon (Ichihara and Nishio 2013; Patmont et al. 2015; Han et al. 2016), as well as amended attapulgite, to manage the internal load of pollutants in shallow eutrophic lakes.

Clean sand is used as a capping material to remediate contaminated sediments because it is inexpensive, environmentally friendly, and easily obtained. Laboratory experiments and pilot or full-scale field projects have indicated that sand capping can decrease nutrient and trace metal concentrations in overlying water, with the extent of the decrease depending on their species (Han et al. 2016; Kang et al. 2016). To reduce release of toxic organic compounds, clean sand is applied alone or in combination with other materials on the sediments (Huang et al. 2013; Kim et al. 2013; Han et al. 2016).

The thickness of sand capping required to block release of contaminants depends greatly on site-specific characteristics, such as the depth of bioturbation, chemical fate and transport dynamics, capping requirements based on site hydrodynamics and aquatic habitat constraints (Palermo et al. 1998a, 1998b; Bailey and Palermo 2005). However, applying a thick layer of sand can advect pore water from soft contaminated sediments and shift some pollutants directly to the overlying water due to compaction of the sediment matrix by the weight of the sand (Mohan et al. 2000). Applying a thick sand layer is forbidden in shallow eutrophic lakes, since the decrease in depth may reduce storage capacity and alter biological community structure (Boudreau 1998; Lampert et al. 2011). A continuous thick sand layer on sediments also slows restoration of meiofauna communities (Himmelheber et al. 2009; Yin et al. 2010). Results from a short-term laboratory experiment suggest that a layer of fine sand ca. 4 cm thick is sufficient to block release of phosphorus (P) from contaminated sediments (Kim et al. 2007). Therefore, developing thin-layer sand capping approaches is required to supplement or provide alternatives to existing methods.

Like barrier layers placed directly with active amendments, the ability of thin-layer sand capping to block contaminant mobility depends greatly on the stability of the capping layers. A thin sand layer easily mixes with sediments and can no longer

block the release of contaminants because of its low cohesion (McDonough et al. 2007; Lampert et al. 2011). This process is accelerated by bioturbation by benthic organisms (Reible et al. 1996; Timmermann et al. 2011; Sturdivant and Shimizu 2017). Consequently, a thin layer of sand soon loses its ability to block the release of contaminants. Preventing the thin sand layer from mixing completely with contaminated sediments is required to ensure long-term effectiveness. Consequently, capping layers are often applied on top of or between geotextile mats for stabilization (Perelo 2010). Stabilization mats are commercially available and are used with thin organo-clay or activated-carbon capping (Olsta et al. 2006). To date, using geotextile mats and fine sand to cap nutrient-contaminated sediments has been reported less often, especially for shallow eutrophic lakes.

The objective of this study was to investigate long-term effects of thin-layer fine-sand capping of sediments on nutrient concentrations in overlying water, quantify nutrient exchange between sediments and overlying water, and explore the feasibility of using thin-layer sand-capping to control nutrient release from sediments of Wuhan Donghu Lake which is a eutrophic freshwater urban lake. Outdoor sediment tank experiments were performed to monitor changes in total nitrogen (TN), total phosphorus (TP), nitrate (NO_3^-), ammonia (NH_4^+) and soluble reactive phosphorus (SRP) in overlying water over ca. 290 d. We assessed relations between coverage of sediments and nutrient concentrations in overlying water. We also analyzed effects of a thin layer of fine sand and geotextile mats on nutrient exchange between sediments and overlying water.

2. Materials and Methods

2.1. Site description

Sediments for the experiment were collected from Wuhan Donghu Lake ($30^\circ 31' - 30^\circ 36' \text{ N}$, $114^\circ 21' - 114^\circ 28' \text{ E}$), the largest urban lake in China, located in the city of

Wuhan. Wuhan Donghu Lake covers ca. 3,300 ha and is composed of 12 sub lakes of different sizes. The mean water depth is ca 2.0 m (maximum: ca. 6.0 m). Wuhan Donghu Lake is a shallow eutrophic freshwater urban lake. With rapid population growth in recent decades, a large amount of domestic wastewater in the watershed was discharged directly into Wuhan Donghu Lake, resulting in heavy eutrophication in several of its smaller lakes. Several projects have been implemented to restore the ecology of Wuhan Donghu Lake. These projects include eliminating external point-source pollution, improving the lakeshore to reduce non-point-source pollution and reconnecting the lake to the Yangtze River via channels. Nonetheless, when water temperatures increase, release of nutrients from sediments frequently degrades the water quality of Wuhan Donghu Lake, and cyanobacteria can bloom in some of its smaller lakes. Thus, it is necessary to develop suitable approaches for treating the contaminated sediments in Wuhan Donghu Lake.

2.2. Sediment and water sample collection, sand treatment and tank preparation

A Peterson sampler was used to collect ca. 800 kg of contaminated surface sediments (0-10 cm) from Wuhan Donghu Lake (30° 32' 54" N, 114° 21'15" E) in November 2016. The sediments were placed in a large plastic barrel and sent to the experimental station to be mixed until visually homogeneous. At the same time and sites, ca. 10 m³ of lake water was collected. Sand was purchased from a local market, thoroughly washed with lake water to remove mud, air-dried and then passed through sieves to eliminate particles larger than 450 µm in diameter. The density of sand was determined to be ca. 2.40 g·cm⁻³.

Later, using a platform scale, 50.0 (± 0.1) kg of sediment was placed in each of 15 identical rectangular water tanks (ca. 120 cm L × 60 cm W × 100 cm H). The sediment was flattened into a layer ca. 5 cm thick on the bottom of each tank with a plastic plate and, for the 12 tanks with capping treatments, capped with a piece of

geotextile mat that covered 25-100% of the surface (depending on the treatment). The sediment in three tanks was left uncapped, as a control (CK). For the capping-treatment tanks, clean fine sand was then gently added to cover the geotextile mat to a depth of ca. 3 cm (i.e. $7.2 \text{ g}\cdot\text{cm}^{-2}$). For all tanks, ca. 0.65 m^3 of lake water was slowly pumped into each tank by a peristaltic pump (to avoid suspension of sediments) to a depth of 90 cm (Fig. 1). To preventing the sunlight from directly irradiating sediments or capping layers, the outer wall of rectangular tanks was wrapped with black cloth.

Subsamples of the mixed sediments were collected to prepare air-dried and fresh samples. Air-dried samples were dried on a piece of plasticfilm, ground in an agate mortar, passed through a 20 mesh sieve and stored in a glass bottle. Fresh subsamples were sealed in a plastic bottle and kept in the dark at 4°C to measure pH and ferrous iron (Fe^{2+}). At the end of the experiment, samples of the capping layer were also collected and treated using the same procedures as those for fresh sediments.

2.3. Experimental design

Four percentages of sand coverage were established as treatments: 25%, 50%, 75% and 100% (Fig.1). Tanks were kept outdoors for ca. 290 d (Beginning on November 28, 2016). The water column was maintained ca. 90 cm deep throughout the experiment. Each treatment was performed in triplicate. To prevent evaporation from tanks and entry of rainwater into tanks, a transparent plastic plate with a small hole for adding or sampling water was placed on top of each tank. Nutrients in the water column (TN, TP, NO_3^- , NH_4^+ and SRP) were monitored every 7 d by collecting 200 mL from a depth of 50 cm from each tank. At the beginning of experiment, the water quality at the site where sediments were collected was analysed. At the end of the experiment, the capping layers were sampled to analyze TN, TP, organic carbon, Fe^{2+} , Fe^{3+} and particle-size distribution.

Insert Figure 1 here

2.4. Nutrient-exchange calculations

To quantify the effectiveness of fine-sand capping, the nutrient fluxes exchanged at the sediment-water interface were calculated as a function of the percentage of coverage. To estimate the influence of the thin sand layer in intensifying sinks and sources of TN and TP for overlying water, nutrient fluxes (Q_i) at the sediment-water interface were calculated. A flux is the amount of nutrient i exchanged per unit area between overlying water and sediment ($\mu\text{mol}\cdot\text{cm}^{-2}$), obtained from differences in its concentration between the two compartments:

$$Q_i = \Delta C_i \times V/S \quad (1)$$

where Q_i is the flux of nutrient i , ΔC_i is the difference in concentrations in a given period, V is the volume of overlying water and S is the surface area of sediment that is exposed to the water column.

If Q_i is positive, i is released from sediments (serving as a source); if negative, i enters the sediments (serving as a sink). Since a percentage of surface sediments was capped with sand, Eq. 1 can be changed to the following:

$$Q_i = (q_{i,b} + q_{i,c})/S = \Delta C_i \times V/S \quad (2)$$

where $q_{i,b}$ is the amount of i exchangeable through bare sediment and $q_{i,c}$ is the amount exchangeable through the capping layer.

Next, $q_{i,b}$ and $q_{i,c}$ can be expressed using the following equations:

$$q_{i,b} = Q_{i,b} \times S \times (1-d) \quad (3)$$

$$q_{i,c} = Q_{i,c} \times S \times d \quad (4)$$

where $Q_{i,b}$ and $Q_{i,c}$ are unit area fluxes of nutrient i when surface sediment is bare and capped, respectively, and d is the proportion of coverage by sand.

Then, Eq. 2 can be rewritten as:

$$Q_i = Q_{i,b} \times (1-d) + Q_{i,c} \times d \quad (5)$$

$$Q_i = \Delta C_i \times V/S = (Q_{i,c} - Q_{i,b}) \times d + Q_{i,b} \quad (6)$$

Thus, Q_i becomes a linear function of the proportion of coverage (Eq. 6), and the unit area fluxes of nutrient i under two sediment states were obtained statistically from variances of d and ΔC_i from the experiment. Using $Q_{i,b}$ and $Q_{i,c}$, the influence of the thin fine-sand layer in decreasing nutrient exchange to overlying water was quantified.

2.5. Sediment and water analyses

TP from the sediment samples was digested in a tri-acid mixture (HNO_3 , HClO_4 , and H_2SO_4 at a 3:1:1 ratio). P concentrations in the digestate were determined colorimetrically using the molybdenum blue method (Jackson 1973). Kjeldahl N content as sediment TN was determined using digestion in H_2SO_4 followed by colorimetric analysis with the indophenol blue method using a spectrometer (Nelson and Sommers 1980). Total organic carbon in the sediment was analyzed using dry combustion with an automatic nitrogen and carbon analyzer–mass spectrometer. Fe^{3+} and Fe^{2+} were extracted from fresh sediment with 3.0 M HCl and determined using colorimetric analysis (Li et al. 2012). Sediment pH was measured using a potentiometer with a glass electrode as the working electrode. Particle-size distribution of the sediments and capping layers was assessed using an Andreasen pipette (Andreasen 1929).

Water samples were analyzed in the laboratory for TN, TP, NO_3^- , NH_4^+ , SRP, chemical oxygen demand (COD) and pH, except for dissolved oxygen (DO), which was directly analyzed in the field. Nutrients were analyzed according to APHA (1994). The pH was determined using a potentiometer with a working electrode made from glass.

2.6. Statistical analyses

Statistical analyses were performed using SAS 8.2 software (SAS Institute 2001). The series of TN, TP, NO_3^- and SRP of the four treatments were statistically

compared to those of CK using one-way analysis of variance tests (PROC ANOVA, $P<0.05$). Significant differences were considered to be the significant difference with the largest p-value between means. Correlation analysis was performed using the function PROC CORR.

3. Results

3.1. Characteristics of sediments and water quality

Particles larger than 10 μm in diameter dominated the particle-size distribution of sediments in Wuhan Donghu Lake, accounting for 68% of total mass (Table 1). Sediments were classified as silt loam according to the USDA (1999) soil classification system. Sediments of Wuhan Donghu Lake had high concentrations of organic matter, TN and TP: 10.9% and 3.21 and 1.38 $\text{mg}\cdot\text{g}^{-1}$ dry weight (DW), respectively. TN, TP and COD in the water column were 1.82 $\text{mg}\cdot\text{L}^{-1}$, 123.18 $\mu\text{g}\cdot\text{L}^{-1}$ and 4.81 $\text{mg}\cdot\text{L}^{-1}$ respectively, within the range of the Grand IV and V water quality classes of the Chinese Environmental Quality Standards for Surface Water (PRC 2002). DO was low, at 6.5 $\text{mg}\cdot\text{L}^{-1}$.

Insert Table 1 here

3.2. TN, NO_3^- and NH_4^+ dynamics in overlying water

At the beginning of the experiment, mean TN concentration in the overlying water of all treatments (2.18 $\text{mg}\cdot\text{L}^{-1}$) was significantly higher ($P<0.05$) than that in lake water (1.82 $\text{mg}\cdot\text{L}^{-1}$) (Fig. 2D). Also at the beginning, mean TN concentration in the capping treatments (2.24 $\text{mg}\cdot\text{L}^{-1}$) was significantly higher ($P<0.05$) than that in CK (1.92 $\text{mg}\cdot\text{L}^{-1}$) because the thin sand layer compacted the sediments and increased release of their TN.

Dynamics of TN were similar in all treatments, generally oscillating in a decrease-increase-decrease pattern (Fig. 2A). TN first decreased from the beginning

of the experiment to mid-April, slowly increased until early August and then decreased until the end of the experiment. Sand capping decreased TN in overlying water, with the degree depending on the percentage coverage (Fig. 2D). Mean TN concentration in CK was $1.53 \text{ mg}\cdot\text{L}^{-1}$ (range: $0.90\text{-}2.41 \text{ mg}\cdot\text{L}^{-1}$). When 25%, 50%, 75% and 100% of sediments were capped, mean TN concentration was 1.41, 1.21, 1.17 and $1.19 \text{ mg}\cdot\text{L}^{-1}$, respectively (range: $0.82\text{-}1.98$, $0.54\text{-}2.11$, $0.52\text{-}1.75$ and $0.78\text{-}1.53 \text{ mg}\cdot\text{L}^{-1}$, respectively). According to the ANOVA, TN concentrations at 50-100% coverage were significantly lower ($P<0.05$) than that of CK (Fig. 2D). The largest difference in TN in overlying water was $1.57 \text{ mg}\cdot\text{L}^{-1}$ at 50% coverage but decreased to 1.23 and $0.75 \text{ mg}\cdot\text{L}^{-1}$ at 75% and 100% coverage, respectively.

Insert Figure 2 here

Dynamics of NO_3^- concentration in overlying water were similar to those of TN (Fig. 2B). NO_3^- rapidly decreased for the first 70 d, slowly increased to a peak, and then decreased almost to zero by the end of the experiment. Sand capping decreased NO_3^- concentrations in overlying water greatly, with the degree depending on the percentage coverage (Fig. 2D). Mean NO_3^- concentration in CK was $0.30 \text{ mg}\cdot\text{L}^{-1}$ (range: $0.06\text{-}0.61 \text{ mg}\cdot\text{L}^{-1}$). When 25%, 50%, 75% and 100% of sediments were capped, mean NO_3^- concentration was 0.29, 0.22, 0.22 and $0.19 \text{ mg}\cdot\text{L}^{-1}$, respectively (range: $0.09\text{-}0.53$, $0.05\text{-}0.56$, $0.08\text{-}0.33$ and $0.03\text{-}0.31 \text{ mg}\cdot\text{L}^{-1}$, respectively). According to the ANOVA, NO_3^- concentrations at 50-100% coverage were significantly lower ($P<0.05$) than that of CK (Fig. 2D).

Dynamics of NH_4^+ concentration in overlying water differed from those of TN and NO_3^- in that NH_4^+ fluctuated greatly (Fig. 2C). Overall, sand capping generally decreased NH_4^+ in overlying water (Fig. 2D). Mean NH_4^+ concentration in CK was $0.29 \text{ mg}\cdot\text{L}^{-1}$ (range: $0.17\text{-}0.43 \text{ mg}\cdot\text{L}^{-1}$). When 25%, 50%, 75% and 100% of sediments were capped, mean NH_4^+ concentration was 0.22, 0.20, 0.13 and 0.12

mg·L⁻¹, respectively (range: 0.08-0.36, 0.11-0.32, 0.02-0.22 and 0.04-0.23 mg·L⁻¹, respectively). According to the ANOVA, NH₄⁺ concentrations at 25-50% coverage were significantly lower ($P<0.05$) than that of CK, while those at 75-100% were significantly lower ($P<0.05$) still (Fig. 2D).

3.3. TP and SRP dynamics in overlying water

Dynamics of TP concentration in overlying water were similar to those of TN and NO₃⁻ (Fig. 3A). TP decreased from the beginning of the experiment to the middle of January and then increased until early May to late June, depending on the percentage of coverage. The greater the coverage, the shorter was the duration of increase (e.g. ca. 190 d for CK, ca. 90 d for 100% coverage). TP then decreased again, also apparently as a function of coverage (e.g. ca. 80 d for 100% coverage, >100 d for other treatments). Sand capping generally decreased TP in overlying water (Fig. 3C). Mean TP concentration in CK was 119.2 µg·L⁻¹ (range: 42.8-196.0 µg·L⁻¹). When 25%, 50%, 75% and 100% of sediments were capped, mean TP concentration was 77.7, 74.0, 58.8 and 48.3 µg·L⁻¹, respectively (range: 21.7-170.8, 27.0-156.6, 2.3-139.9 and 1.5-127.1 µg·L⁻¹, respectively). According to the ANOVA, TP concentrations at 25-50% coverage were significantly lower ($P<0.05$) than that of CK, while those at 75-100% were significantly lower ($P<0.05$) still (Fig. 3C).

Insert Figure 3 here

Dynamics of SRP concentrations in overlying water were similar to those of TP (Fig. 3B). Minimum and maximum SRP concentrations depended greatly on the percentage of coverage: the greater the coverage, the smaller were the concentrations. Mean SRP concentration in CK was 38.4 µg·L⁻¹ (range: 15.4-63.1 µg·L⁻¹). When 25%, 50%, 75% and 100% of sediments were capped, SRP concentration was 29.7, 28.7, 22.4 and 14.6 µg·L⁻¹, respectively (range: 8.4-53.6, 9.9-53.6, 2.9-44.1 and

2.9–42.7 $\mu\text{g}\cdot\text{L}^{-1}$, respectively). According to the ANOVA, increasing the percentage coverage could significantly decrease ($P<0.05$) SRP concentration (Fig. 3C).

3.4. Nutrient-flux exchange

Three TN and TP balance concentrations (initial, minimum and maximum) observed in the experiment were used to estimate fluxes of nutrient exchange $Q_{i,b}$ and $Q_{i,c}$ when sediment was a sink or source, based on their dynamic curves (Fig. 2A and Fig. 3A). Thin-layer fine-sand capping increased flux of TN to sediments, which significantly enriched sediments serving as a sink ($P<0.05$) (Fig. 4, Table 2). Compared to CK, 100% coverage increased flux of TN to sediments by 92%. In contrast, when sediment served as a source, sand capping did not significantly change ($P>0.05$) TN release. Compared to CK, sand capping did not significantly change ($P>0.05$) flux of TP to sediments. In contrast, when sediment served as a source, sand capping significantly decreased ($P<0.05$) TP release, in which 100% coverage decreased TP flux from bare sediments by 46%.

Insert Table 2 here, Insert Figure 4 here

4. Discussion

Approximately 290 d of monitoring the tanks showed that thin-layer fine-sand capping of sediments can significantly decrease nutrient concentrations in overlying water. The kinds and forms of nutrients differed, as did the coverage required to decrease their concentrations in overlying water. When coverage reached 50%, mean TN and NO_3^- concentrations in overlying water became statistically the lowest. Increasing the coverage further merely kept them from fluctuating. For TP and NH_4^+ concentrations, coverage needed to reach 75% to become statistically the lowest. The relation between coverage and SRP concentrations suggested that increasing coverage from 75% to 100% decreased their concentrations even more. These results indicate that thin-layer sand capping decreases P in overlying water more readily than N, at

least for the sample of sediments from Wuhan Donghu Lake. They also show that sand capping does not change nutrient-exchange dynamics, even when 100% of sediments are capped. Thus, the role of sediments as a sink for and source of nutrients for overlying water does not change when a thin layer of sand is placed on the sediment surface. Therefore, it is necessary to identify the influence of a thin layer of sand on nutrient exchange with overlying water.

When sediments are a source of nutrients for overlying water, even partially capping them with a thin layer of sand can significantly decrease release of TN and TP during release periods compared to those in CK. By physically impeding nutrient release, the sand layer delays it by increasing the diffusion distance between sediments and overlying water (Lampert et al. 2011). The thicker the sand layer and the longer the diffusion distance, the more time is required for nutrients to migrate from surface sediments to overlying water. Our results cannot specify the influence of the thin sand layer in delaying nutrient release; they show only that N and P were released in the same amount of time or less in capping treatments than in CK (Figs. 2 and 3).

Nutrients in overlying water decreased overall due to several factors. First, thin-layer fine-sand capping decreases contact between sediments and overlying water (Lin et al. 2011; Han et al. 2016). When sediments and overlying water exchange nutrients via diffusion, the sediment-water interface is the site of nutrient flux. Since the sand in the capping layer has higher density than surface sediments, it can compress the sediments, decreasing their porosity and thus the surface area of contact between sediments and overlying water. This inference was supported by TN concentrations in overlying water at the beginning of the experiment (Fig. 2D), which were significantly higher in the treatments than in CK. However, when the capping layer is stabilized, the reduction in contact surface area has a preventive effect on the

further release of nutrients in the sediment. Another factor decreasing nutrients in overlying water is the dilution effect of surface sediments (Hyun et al. 2006; Go et al. 2009). Although we used geotextile mats to stabilize the thin sand layer in our tanks, a small part fine sand can pass through the mats and mix with sediments, which directly decreases contact between nutrients bound to sediment particles and interstitial water, slowing the shift of nutrients in sediments to overlying water. Bioturbation by benthic organisms, such as red worms (*Limnodrilus hoffmeister*), chironomid larvae and tubificid oligochaete, can accelerate some capped sediments moved up, and mixed with fine sand (Reible et al. 1996; Timmermann et al. 2011; Sturdivant and Shimizu 2017). Consequently, the sediments are diluted in capping layers, and their contribution to nutrients in overlying water is weakened, compared with bare ones. The inference was also supported by the composition of capping layer at the end of experiments (Table 1), where TN and TP are much lower than the bare sediments. Furthermore, thin-layer fine-sand capping could improve benthic habitats, which may increase nutrient cycling between sediments and overlying water. Due to the dilution effect of fine sand, organic carbon concentration in sediments at the sediment-water interface decreases, which decreases COD and increases DO in overlying water (Hyun et al., 2006; Kim et al., 2007). Although we did not determined DO at the end of experiments, an increased Fe(III)/Fe(II) ratio in capping layers indirectly testifies that thin-layer fine-sand capping improve benthic habitats, which increases nitrogen cycling in overlying water.

Estimates of nutrient-flux exchange confirmed that the thin fine-sand layer influenced TN and TP exchange at the sediment-water interface differently (Fig. 4, Table 2). The thin sand layer intensified sediment's function as a sink for TN, due mainly to transformation of N species. Sand capping of sediments can increase DO in overlying water, as mentioned, which increases decomposition of organic N and

oxidation of NH_4^+ to NO_3^- . Subsequently, NO_3^- can be denitrified to N_2 , which decreases TN in overlying water. For TP in overlying water, the thin sand layer did not intensify sediment's function as a sink for TP. These results are consistent with literature report (Kim and Jung 2010). In contrast, 100% coverage with a thin fine-sand layer decreased TP flux from bare sediments by 46%. This shall be due to the phosphorus migration being affected by its properties (Hickey and Gibbs 2009; Lampert et al. 2011). The phosphorus migration in the solid-liquid phase is inherently slower, compared to other anions, since phosphate carries more negative charges and is easy to interact with the cations on the surface of the solid phase. As mentioned, thin-layer fine-sand capping of sediments can reduce the area of contact between surface sediments and overlying water, which TP release is blocked.

5. Conclusions

Thin-layer fine-sand capping could significantly decrease nutrient concentrations (TN, NO_3^- , NH_4^+ , TP and SRP) in overlying water. The kind and species of nutrients differ, as does the maximum coverage required to decrease their concentrations in overlying water. Mean TN and NO_3^- concentrations in overlying water decreased most at 50% coverage, and increasing coverage merely kept them fluctuating. For TP and NH_4^+ in overlying water, the corresponding coverage necessary was 75%. In contrast, SRP concentrations in overlying water continued to decrease significantly at 75% and 100% coverage. Thin-layer fine sand capping yielded different patterns in the decrease in TN and TP concentrations in overlying water. It intensified the function of sediments as a sink of TN in overlying water and the ability of sediments to block release of TP. Our results suggest that if this technique were applied to improve water quality of Wuhan Donghu Lake, more than 50% coverage is required to decrease nutrients in the lake's water.

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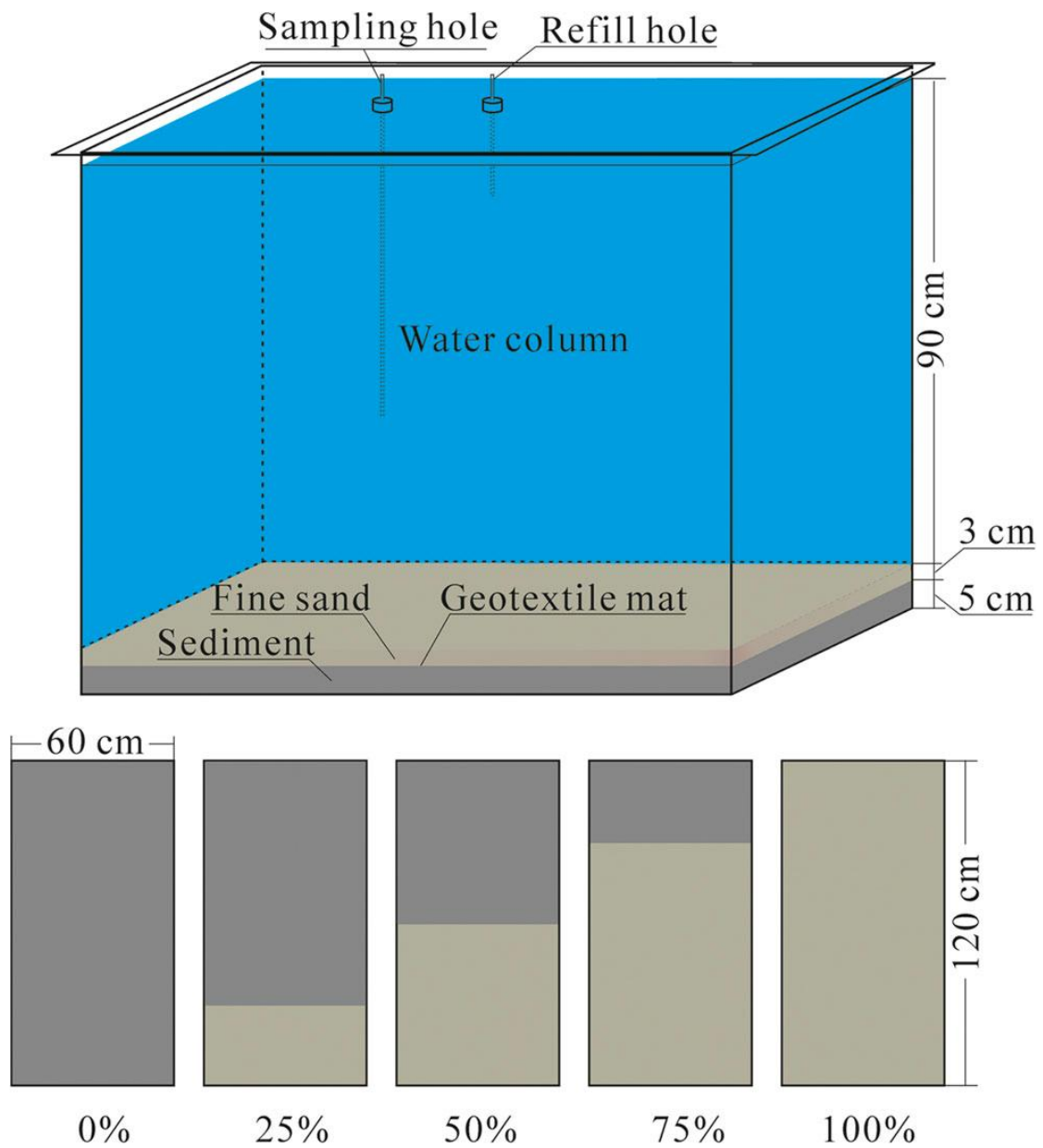


Fig. 1 Diagrams of the tanks used in the experiment (top) from the side and (bottom) from the top, showing the percentage coverage of fine sand used in the control (0%) and four treatments.

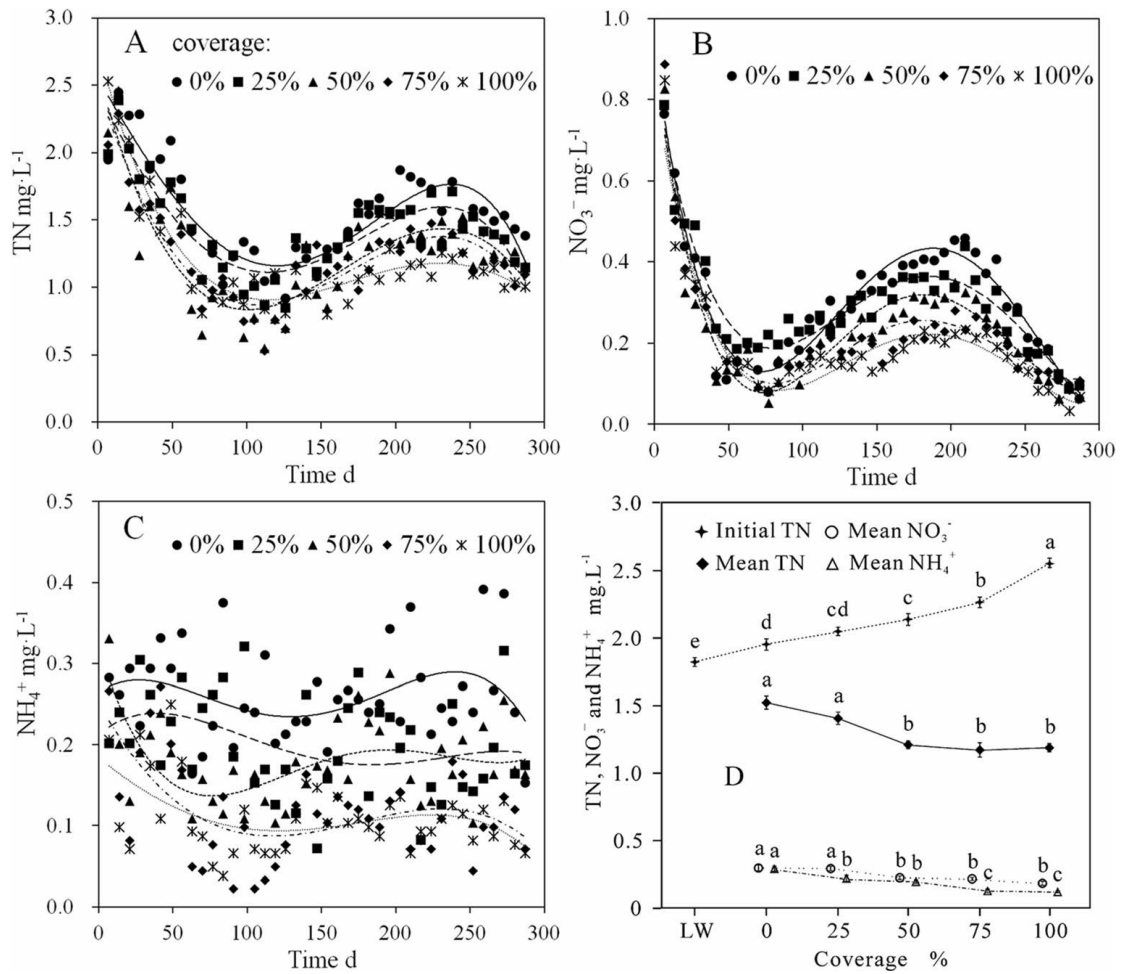


Fig. 2 Dynamics of (A) total nitrogen (TN), (B) NO₃⁻ and (C) NH₄⁺ concentrations in overlying water during the experiment (the first monitoring began on 2 December 2016). D: Means of these N forms in lake water (LW) and as a function of percentage coverage (error bars represent 1 standard deviation; different letters indicate differences significant at P < 0.05).

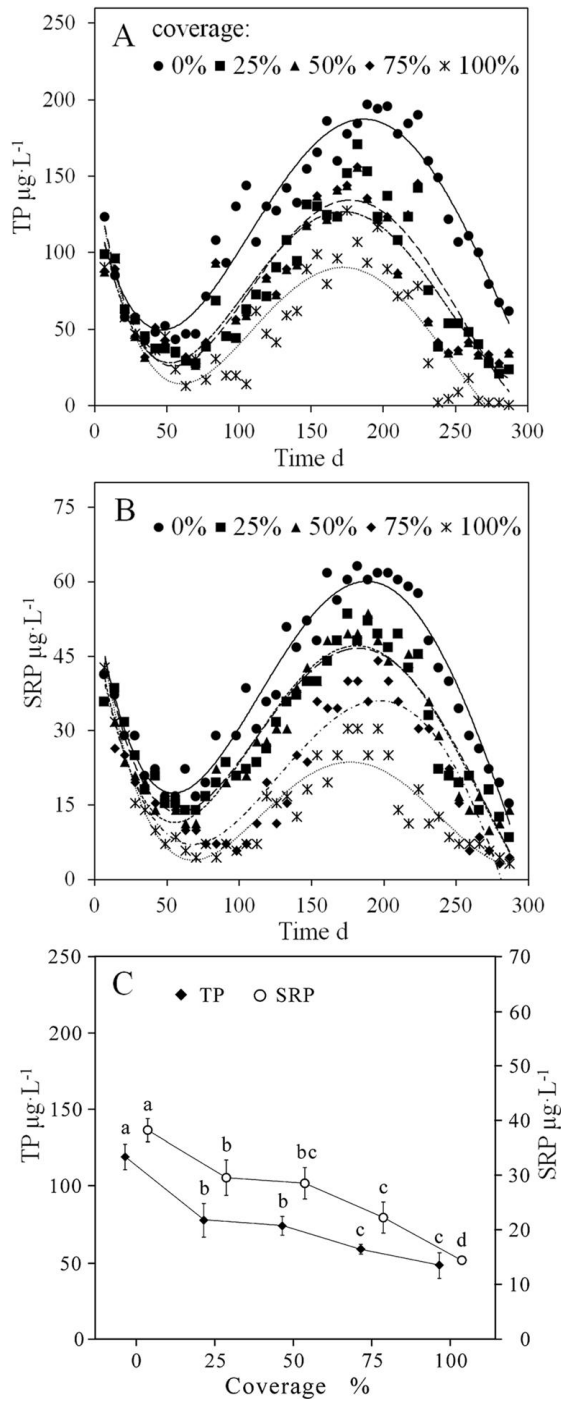


Fig. 3 Dynamics of (A) total phosphorus (TP) and (B) soluble reactive phosphorus (SRP) concentrations in overlying water during the experiment (monitoring began on 2 December 2016 and ended on 29 September 2017). C: Means of TP and SRP as a function of percentage coverage (error bars represent 1 standard deviation; different letters indicate differences significant at $P < 0.05$).

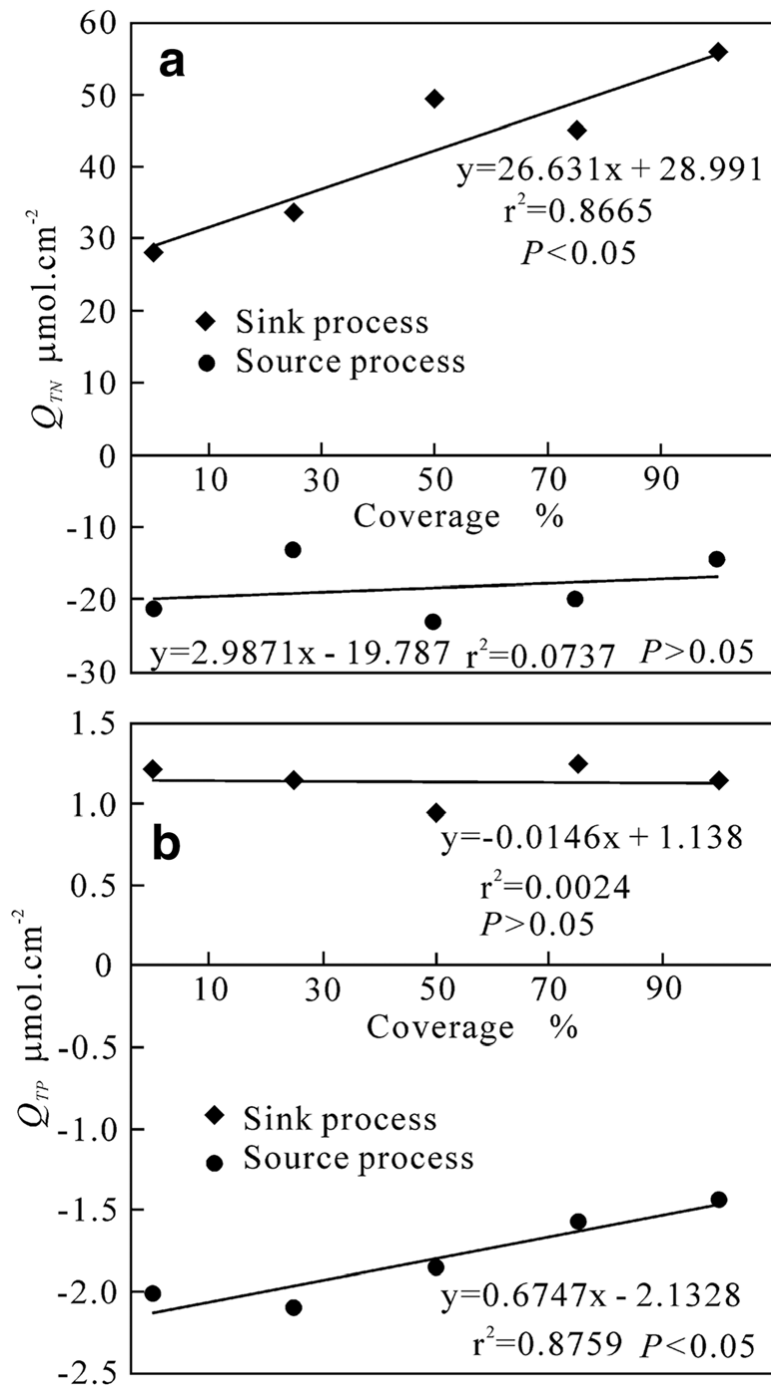


Fig. 4 Relation between percentage coverage of sediments by a thin layer of fine sand and exchange of (A) total nitrogen (TN) and (B) total phosphorus (TP) to (source) or from (sink) the overlying water.

Table 1 Physicochemical characteristics of sediments and water in the beginning, and of capping layers in the end of the experiments. LOI is loss on ignition; TN is total nitrogen; TP is total phosphorus; SRP is soluble reactive phosphorus; COD_{Mn} is chemical oxidation demand obtained by potassium permanganate; DO is dissolved oxygen in the water column; Nutrients in capping layers at the beginning of experiments is neglected due to lower concentration.

Sediments									
pH	LOI	TN	TP	Fe ³⁺ /Fe ²⁺	Particle-size distribution (μm) %				
	%	mg·g ⁻¹ DW	mg·g ⁻¹ DW		<1	1-5	5-10	10-50	>50
7.45 ± 0.10	10.89 ± 0.05	3.21 ± 0.13	1.38 ± 0.02	1.22 ± 0.27	10.80	12.80	8.70	36.90	30.80
Capping layers									
pH	LOI	TN	TP	Fe ³⁺ /Fe ²⁺	Particle-size distribution (μm) %				
	%	mg·g ⁻¹ DW	mg·g ⁻¹ DW		<1	1-5	5-10	10-50	>50
7.25 ± 0.13	0.49 ± 0.15	0.16 ± 0.09	0.08 ± 0.04	1.86 ± 0.34	1.78	0.64	0.45	1.67	95.46
Water column									
pH	COD _{Mn}	TN	NH ₄ ⁺	NO ₃ ⁻	DO	TP	SRP		
	mg·L ⁻¹	mg·L ⁻¹	mg·L ⁻¹	mg·L ⁻¹	mg·L ⁻¹	μg·L ⁻¹	μg·L ⁻¹		
7.78 ± 0.01	4.81 ± 0.24	1.82 ± 0.12	0.28 ± 0.05	0.76 ± 0.05	6.49 ± 0.50	123.18 ± 0.01	41.20 ± 0.01		

Table 2 Apparent fluxes of total nitrogen (TN) and total phosphorus (TP) from sediments

Nutrient ($\mu\text{mol}\cdot\text{cm}^{-2}$)	Sediment as a sink		Sediment as a source	
	$Q_{i,b}$	$Q_{i,c}$	$Q_{i,b}$	$Q_{i,c}$
TN	28.991	55.621	-16.780	-19.787
TP	1.138	1.123	-1.458	-2.133