

RESEARCH ARTICLE

The Influence of Macrophytes on Sediment Resuspension and the Effect of Associated Nutrients in a Shallow and Large Lake (Lake Taihu, China)

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Abstract

A yearlong campaign to examine sediment resuspension was conducted in large, shallow and eutrophic Lake Taihu, China, to investigate the influence of vegetation on sediment resuspension and its nutrient effects. The study was conducted at 6 sites located in both phytoplankton-dominated zone and macrophyte-dominated zone of the lake, lasting for a total of 13 months, with collections made at two-week intervals. Sediment resuspension in Taihu, with a two-week high average rate of 1771 g·m⁻²·d⁻¹ and a yearly average rate of 377 g·m⁻²·d⁻¹, is much stronger than in many other lakes worldwide, as Taihu is quite shallow and contains a long fetch. The occurrence of macrophytes, however, provided quite strong abatement of sediment resuspension, which may reduce the sediment resuspension rate up to 29-fold. The contribution of nitrogen and phosphorus to the water column from sediment resuspension was estimated as 0.34 mg·L⁻¹ and 0.051 mg·L⁻¹ in the phytoplankton-dominated zone. Sediment resuspension also largely reduced transparency and then stimulated phytoplankton growth. Therefore, sediment resuspension may be one of the most important factors delaying the recovery of eutrophic Lake Taihu, and the influence of sediment resuspension on water quality must also be taken into account by the lake managers when they determine the restoration target.

Introduction

In shallow lakes, sediment resuspension is a very common phenomenon and has an important influence on the ecosystem. Particles resuspended from the bottom sediment may increase turbidity and deteriorate the underwater light field [1–3]. The resuspension process influences nutrient flux at the sediment-water interface and in the water column [4–6], and then affects primary production by macrophytes and phytoplankton [7,8]. Suspending nutrients from the

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sediment increase phytoplankton biomass, delaying the recovery of eutrophic lake ecosystems [9,10], and thus considerable attention is paid to sediment resuspension in the management of water quality.

Previous studies have shown that the intensity of sediment resuspension is influenced by many factors, including lake shape, water depth, sediment quality, wind-induced wave action and macrophyte coverage [11,12]. Shallow and large lakes are especially prone to sediment resuspension due to wind-induced wave action [12–15], and seasonal variation in wind-wave processes may substantially influence the yearly sediment resuspension rate. Wind-induced wave was considered the more important factor influencing sediment resuspension than currents, especially under strong wind forcing, which could easily result in sediment resuspension [15–18]. The existence of aquatic macrophytes is also a key factor influencing sediment resuspension in shallow lakes [19], because of the effect of vegetation on hydrodynamics as macrophytes substantially moderate the effect of wind waves [20].

Due to the variety of factors affecting resuspension, there is substantial between-lake as well as spatial and temporal within-lake variation in sediment resuspension [11,21,22]. The dynamic ratio (the square root of lake surface area in square kilometers divided by the average depth in meters) has been used in analyzing the relationship between wave disturbance and sediment resuspension [9]. According to studies in 36 Florida lakes [23], lakes with dynamic ratios above 0.8 are prone to sediment resuspension.

Lake Taihu (referred as “Taihu” below for short) is very shallow, with a maximum depth of less than 3 meters and an average depth of 1.9 meters, and has a large surface area of 2338 km² [24]. Taihu thus has a relatively high dynamic ratio (25.4) compared with many other lakes [25]. Earlier studies in Taihu indicated that sediment resuspension in this large and shallow lake played a significant part in chemical and biological processes [26].

Eutrophication has been a big problem in Taihu for several decades [24] to the point where harmful algal blooms caused a drinking water crisis in 2007, which affected two million people [27,28]. This serious event has raised considerable concern resulting in efforts to control phytoplankton blooms, but the complicated environmental processes driving these blooms, including sediment resuspension, have made the effort difficult [28,29].

Taihu has two distinctly different ecotypes, which are phytoplankton- and macrophyte-dominated areas. These two ecotypes in Taihu have significantly different turbidity levels and underwater light fields [30], which indicate differences also in sediment resuspension. However, previous studies on sediment resuspension in Taihu have been conducted mostly in the phytoplankton-dominated zone, but seldom in the macrophyte-dominated zone, or only with short-term observations [26,31,32], and thus may not represent a comprehensive situation of sediment resuspension processes, nor predict the ecological effects of these processes.

As sediment resuspension is an important factor regulating internal nutrient loading, the development and coverage of macrophytes may be important in the overall nutrient flux of shallow water bodies [33]. Quantitative methods to evaluate resuspension processes in Taihu are still lacking and no comprehensive studies on the influence of macrophytes on sediment resuspension have been conducted which cover all seasons. As noted above earlier observations concerning sediment resuspension mechanisms and subsequent control methods in other lakes may not be suitable for Taihu [34–36], because of different dynamic ratios or driving factors for resuspension in different lakes, or even in different parts of the lake [37].

Therefore, to understand the linkage between the sediment-water interaction and resuspension-originated nutrient loading that causes massive phytoplankton blooms and deteriorate water quality, a comprehensive spatial and temporal study on continuous sediment resuspension processes is of interest. In this study, 6 sites were chosen that were spatially distributed in the two different ecotypes, phytoplankton- and macrophyte-dominated, and with different

distances from the lakeshore in Taihu. The study duration was more than one year so as to cover all seasons, including a typhoon period with high winds. This study aimed to quantify the influence of vegetation on sediment resuspension and to quantify resuspension-borne phosphorus and nitrogen loading.

Material and Methods

Ethics statement

No specific permits were required for the described field studies. The location studied is not privately-owned or protected in any way, and the field studies did not involve endangered or protected species.

Observation sites

Sediment resuspension measurements were conducted at 6 sites ranging from lakeshore to open water in both the phytoplankton-dominated and macrophyte-dominated zones ([Fig 1](#)). Site 1 was located near the field station of Taihu Laboratory for Lake Ecosystem Research (TLLER) in Meiliang Bay, 250 m from the lakeshore. Site 3 was located in the central part of the lake, while site 2 was located between sites 1 and 3. Sites 1, 2 and 3 represent a transect from the lake shore to open water in the phytoplankton-dominated zone. Meiliang Bay is one of the most polluted regions in Taihu, with the earliest phytoplankton bloom occurring here in 1980s [[39](#)].

Sites 4, 5 and 6 were all located in Gonghu Bay, representing areas with full macrophyte coverage, semi-macrophyte coverage and no macrophyte coverage, respectively. Site 4 was located 800 m from the eastern lakeshore and nearly 1500 m from the southern lakeshore, with 100% macrophyte coverage (*Potamogeton maackianus*, *Potamogeton malaianus*, *Nymphoides peltatum*, *Trapa incisa*, *Ceratophyllum demersum*, *Myriophyllum spicatum* and *Hydrilla verticillata*). Site 5 was located 1000 m from the eastern lakeshore and 1400 m from the southern lakeshore, with 60% (visual estimation) macrophyte coverage, with similar species composition as site 4. At sites 4 and 5, macrophytes sprout in late March, grow to the water surface in May, and wither from October until December. Site 6 was located in the central part of the bay bottom, where phytoplankton blooms have extended in recent decades causing a gradual disappearance of macrophytes [[40](#)]. Therefore, site 6 in this study was sorted with the sites from phytoplankton-dominated zone, to show the differences between macrophyte covered area (sites 4 and 5) and no macrophyte covered area (site 6) at the same bay ([Table 1](#)).

Sediment resuspension observation

Sediment resuspension was measured using triplicate plexi-glass traps (30 cm long and 5 cm internal diameter) at each site. The upper “mouth” of the traps was fixed at 0.5 m above the sediment, with weights at the bottom to keep them vertical.

Mixtures of water and sediment in traps were collected every 14 to 16 days (depending on weather) from 5 August 2012 to 2 September 2013, resulting in a total of 27 sampling points. All the contents within the traps, including sediment, water, and organic detritus, were collected and taken back to the laboratory to determine suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) concentrations (see details below). Additionally, sediment from the traps was also collected to measure particle size distribution.

On the first sampling date (5 Aug 2012) surface sediment was collected by a grab sampler to determine TN, TP, total organic carbon (TOC) content, water content and particle size distribution.

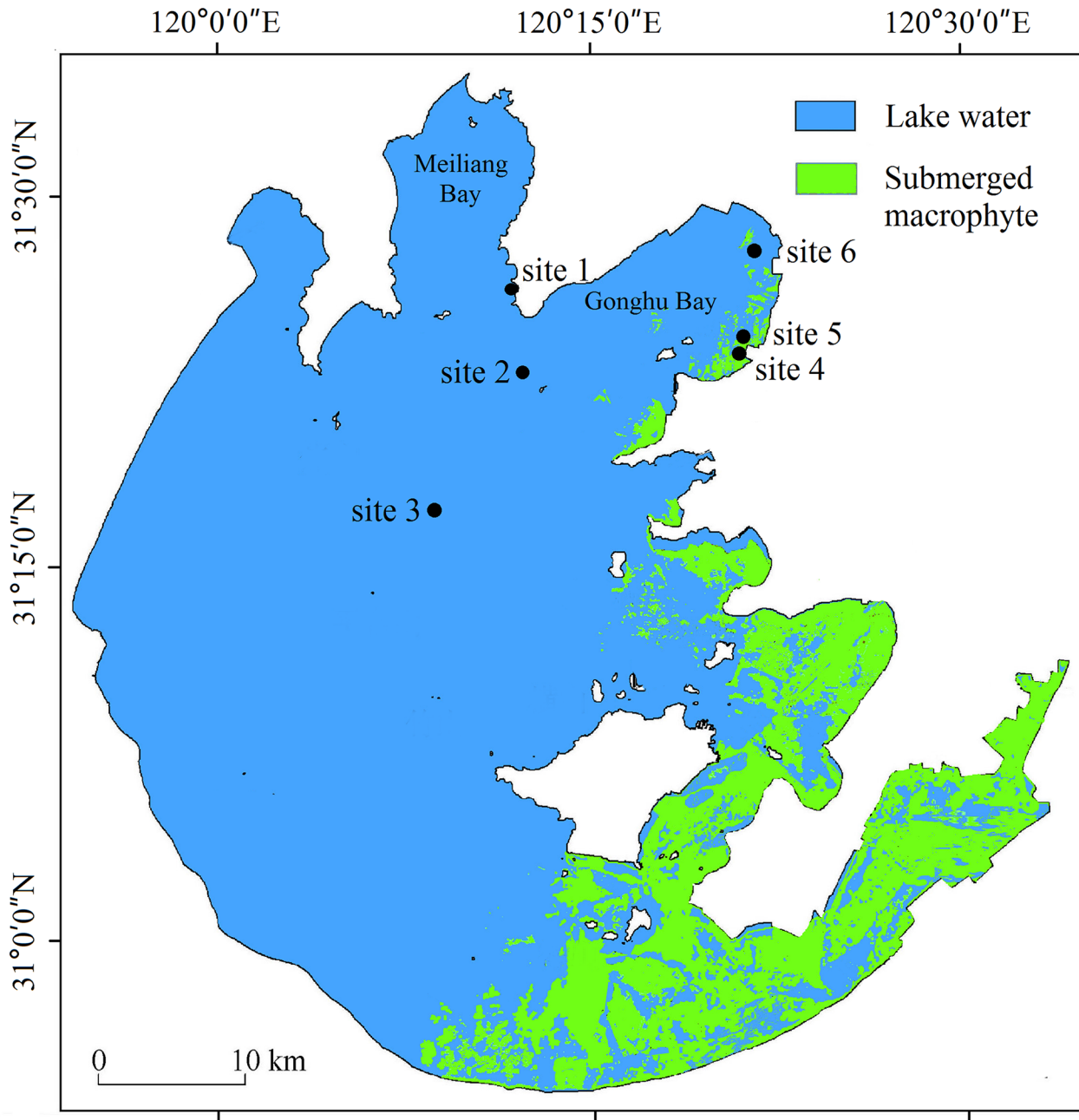


Fig 1. Map of Taihu and 6 observation sites for the trap experiment. Distribution of submerged macrophytes was provided by Dong [38].

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Simultaneously with trap collection, water samples at the surface of the water column were collected to determine SS, TN, TP, dissolved total nitrogen (DTN), dissolved total phosphorus (DTP) and planktonic chlorophyll *a* (Chl-*a*) concentrations. Water temperature was measured *in situ* at the surface of the water column with a Yellow Springs Instruments (YSI) 6600 V2 multi-sensor sonde (YSI Inc., USA).

High-frequency wind speed and direction data (10 min interval) at site 1 were acquired from sensors associated with Global Lake Ecosystem Observation Network (GLEON). Unfortunately, data from 1 Apr 2013 to 12 May 2013 were lost. High-frequency wind speed and

Table 1. Ecotype, water depth and lake water quality at each site during the high productive and the low productive seasons.

Sites		1	2	3	4	5	6
Ecotype		PD ^a	PD	PD	MD ^b	MD	PD
WD ^c (m)	HG ^d	1.6±0.2	2.0±0.5	2.4±0.3	1.4±0.3	1.4±0.3	1.5±0.3
	LG ^e	1.4±0.2	1.6±1.0	2.3±0.6	1.3±0.3	1.3±0.2	1.5±0.3
Chl-a ^f (µg·L ⁻¹)	HG	34±34	32±31	21±22	5±4	6±8	15±11
	LG	8±3	9±2	8±3	5±2	6±2	9±5
SS ^g (mg·L ⁻¹)	HG	59±45	67±31	69±28	3±2	8±6	46±21
	LG	36±23	78±66	111±105	14±12	17±11	35±16
LOI ^h (%)	HG	30±12	30±17	27±15	85±15	50±19	25±10
	LG	29±12	20±8	16±5	44±17	32±10	27±8
TP ⁱ (mg·L ⁻¹)	HG	0.132±0.075	0.126±0.080	0.112±0.060	0.025±0.012	0.028±0.011	0.103±0.034
	LG	0.064±0.013	0.092±0.019	0.116±0.032	0.036±0.019	0.035±0.014	0.098±0.029
TN ^j (mg·L ⁻¹)	HG	1.83±0.77	2.03±0.85	1.99±0.73	0.66±0.16	0.80±0.32	1.87±0.83
	LG	2.77±0.69	3.52±1.09	3.36±0.69	2.04±0.94	1.96±0.66	2.85±0.46

^a “PD” indicates phytoplankton dominated;

^b “MD” indicates macrophyte dominated;

^c “WD” indicates water depth;

^d “HG” indicates high productive season;

^e “LG” indicates low productive season;

^f “Chl-a” indicates chlorophyll a concentration;

^g “SS” indicates suspended solids concentration;

^h “LOI” indicates loss on ignition;

ⁱ “TP” indicates total phosphorus concentration;

^j “TN” indicates total nitrogen concentration.

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direction data (15 min interval) near sites 4 and 5 were recorded from November 2012 onwards by a Hobo automatic recording weather station (Onset Computer Corporation, USA). Wind speed and direction at sites 2, 3 and 6 was not recorded.

Laboratory analysis

SS concentrations and organic carbon content in water samples were measured by weighing the GF/F glass membrane after collection of a known volume (v_w) of water samples. New membranes were pre-combusted at 550°C for 4 hours then weighed (recorded as weight₁, w_1). After filtration the membrane was first dried at 105°C for 4 hours then weighed and recorded as weight₂ (w_2). The filter was subsequently combusted at 550°C for 4 hours, weighted and recorded as weight₃ (w_3). Suspended solids were determined from $SS = (w_2 - w_1) / v_w$, while the organic carbon content was determined depending on loss on ignition (LOI) [41], and $LOI = (w_2 - w_3) / (w_2 - w_1)$.

DTP concentration in filtered water (through GF/F glass membrane) and TP concentration in unfiltered water were determined by spectrophotometry at a wavelength of 700 nm following the molybdenum blue method, after digestion with alkaline potassium persulfate ($K_2S_2O_8 + NaOH$) [42]. DTN concentration in filtered water and TN concentration in unfiltered water were measured by spectrophotometry at 210 nm after digestion [42].

Approximately 10 g (wet weight) sediment was air-dried under room temperature for one week, and weighed before and after air-drying to calculate the water content. The particle size of sediment was determined with laser particle size analyzer (Malvern Instrument, UK) after

acidized in dilute hydrochloric acid and hydrogen peroxide. Air-dried sediments were ground into powder until they could pass a 150- μm mesh. Approximately 20 mg powder was weighed and put into 25 mL deionized water to determine TN and TP concentrations with the same method as used for the water samples [43]. The powder was also used to determine TOC content using the potassium dichromate method according to the national standard method in China (GB 7857-87) [44].

Chl-*a* concentrations were determined by spectrophotometry at wavelengths of 665 nm and 750 nm, following extraction with hot 90% ethanol [45].

Data analysis

Resuspended sediment was estimated by the proposal of Gasith [46], using equations as follows:

$$R' = S' - T'$$

$$R' \times f_R = S' \times f_S - T' \times f_T$$

$$R' = S' \times \frac{f_S - f_T}{f_R - f_T}$$

Here, R' = resuspended sediment (mg, dry weight); S' = entrapped settling flux (mg, dry weight); T' = suspended tripton (mg, dry weight); f_R = organic fraction of surface sediment (%); f_S = organic fraction of entrapped material (%); f_T = organic fraction of suspended tripton (%).

In this study, f_T was much higher than f_R , so the proposal of Gasith was reliably used. Sediment resuspension rate (R) and gross sedimentation rate (S) were calculated using resuspended sediment (g) and entrapped settling flux (g) divided by base area of traps (m^2) and the observation days (d).

TN and TP resuspension rates were calculated using formula as follows:

$$TN_R = (TN_T - DTN_{lw}) \times V_T \times \frac{R/S}{A_t \times D}$$

$$TP_R = (TP_T - DTP_{lw}) \times V_T \times \frac{R/S}{A_t \times D}$$

Here, TN_R = TN resuspension rate ($\text{g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$); TN_T = TN concentration in traps ($\text{mg} \cdot \text{L}^{-1}$); DTN_{lw} = DTN concentration in the water column ($\text{mg} \cdot \text{L}^{-1}$); TP_R = TP resuspension rate ($\text{g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$); TP_T = TP concentration in traps ($\text{mg} \cdot \text{L}^{-1}$); DTP_{lw} = DTP concentration in the water column ($\text{mg} \cdot \text{L}^{-1}$); V_T = water volume in traps (L); R/S = the ratio of sediment resuspension rate to gross sedimentation rate (%); A_t = base area of traps (m^2); D = the observation days (d).

The influence of TN and TP resuspension rates from the sediment on TN and TP concentrations in the water column was estimated in both the phytoplankton- and macrophyte-dominated zones. The increased nutrient concentrations in the water column was calculated using nutrient resuspension rates multiplied by the lake areas in each zone, and then divided by the water volumes in each zone. The averaged area of the macrophyte-dominated zone in Taihu from 2007 to 2010 was approximately 341 km^2 (nearly 15% of the whole lake area) [47], and the rest of the lake area 1997 km^2 , was considered as the phytoplankton-dominated zone. The averaged water volumes in phytoplankton- and macrophyte-dominated zones were approximately 5.4 and 0.9 billion m^3 [48].

High frequency wind speed (10 or 15 min interval) was averaged into daily wind speed. According to earlier studies, Luo et al. [49] found the minimum wind speed for sediment resuspension in Taihu to be 5–6 $\text{m}\cdot\text{s}^{-1}$, and Zhang et al. [50] also indicated that critical wind speed of sediment resuspension in Taihu is between 5 and 6.5 $\text{m}\cdot\text{s}^{-1}$. Therefore, in this study 6 $\text{m}\cdot\text{s}^{-1}$ was set as the critical wind speed for sediment resuspension. For every period of wind with current wind speed higher than 6 $\text{m}\cdot\text{s}^{-1}$ and lasting more than 1 hour, an average wind speed ($\text{m}\cdot\text{s}^{-1}$) was calculated and multiplied with the duration (s). “Effective wind” for each observed period was calculated as the summation of those products (km), and used to represent strong wind causing sediment resuspension. Some high frequency data at site 1 during Apr and May 2013 was lost so effective wind at site 1 was calculated only for 24 observation periods. While for sites 4 and 5, high frequency wind speed data was recorded from November 2012 onwards, thus effective wind was calculated for 20 periods. There is no effective wind data at sites 2, 3 and 6, and therefore correlations between effective wind and resuspended sediment were only conducted at sites 1, 4 and 5.

Average values and standard errors for Chl-*a*, SS, TN and TP concentrations in the water column, sediment and nutrient resuspension rates were calculated with Microsoft Excel 2010. The correlation analyses (between SS concentration and LOI, between TN or TP and Chl-*a* concentrations, and between effective wind and resuspended sediment) were performed by Pearson Correlation with SPSS (Statistical Program for Social Sciences) 13.0 software. The differences comparison analyses (between indicators in zones with macrophyte coverage and void of macrophyte, and between indicators in different seasons) were analyzed by Wilcoxon signed rank test of non-parametric test with SPSS 13.0 software, and significance levels reported as not significant ($p \geq 0.05$), significant ($0.01 \leq p < 0.05$) or highly significant ($p < 0.01$).

Results

Lake water quality

The averaged water depths during the observation year were 1.5, 2.0, and 2.4 m at sites 1, 2, and 3, and 1.4, 1.4, and 1.5 at sites 4, 5, and 6, respectively (Table 1). Chl-*a* concentrations showed highly significant difference ($Z = -6.078$, $p < 0.01$) between the phytoplankton-dominated zone (sites 1, 2, 3, and 6) and macrophyte-dominated zone (sites 4 and 5) (Fig 2). The sampling periods from 5 Aug 2012 to 3 Dec 2012 and from 5 May 2013 to 1 Sep 2013, were determined as “high productive season”, when Chl-*a* concentrations were significantly higher than the other period ($Z = -4.298$, $p < 0.01$, Table 1) in the phytoplankton-dominated zone, with water temperature $24 \pm 7^\circ\text{C}$. The other sampling period from 4 Dec 2012 to 4 May 2013 was determined as the “low productive season”, with water temperature $9 \pm 5^\circ\text{C}$. The percentage of organic matter (LOI) in SS concentration had highly significant negative correlations with SS concentrations ($R^2 = 0.272$, $p < 0.01$, Table 1). TP concentration correlated significantly with Chl-*a* ($p < 0.01$ at all the 6 sites), while TN concentration did not show correlation with Chl-*a* ($p > 0.05$ at all the 6 sites), having the highest value in April and the lowest in August (Table 1).

Sediment properties

With full macrophyte coverage, sediment at site 4 showed the highest water content and TOC content, and sediment at site 2 had the lowest water and TOC content (Table 2). Water and TOC content at other 4 sites were similar, around 50% and 1%, respectively. Sediment at site 4 also showed the highest TN content, almost twice as high as at other sites (Table 2). TP content in the sediment at each site varied, with the highest value at site 6 and lowest at site 5 (Table 2).

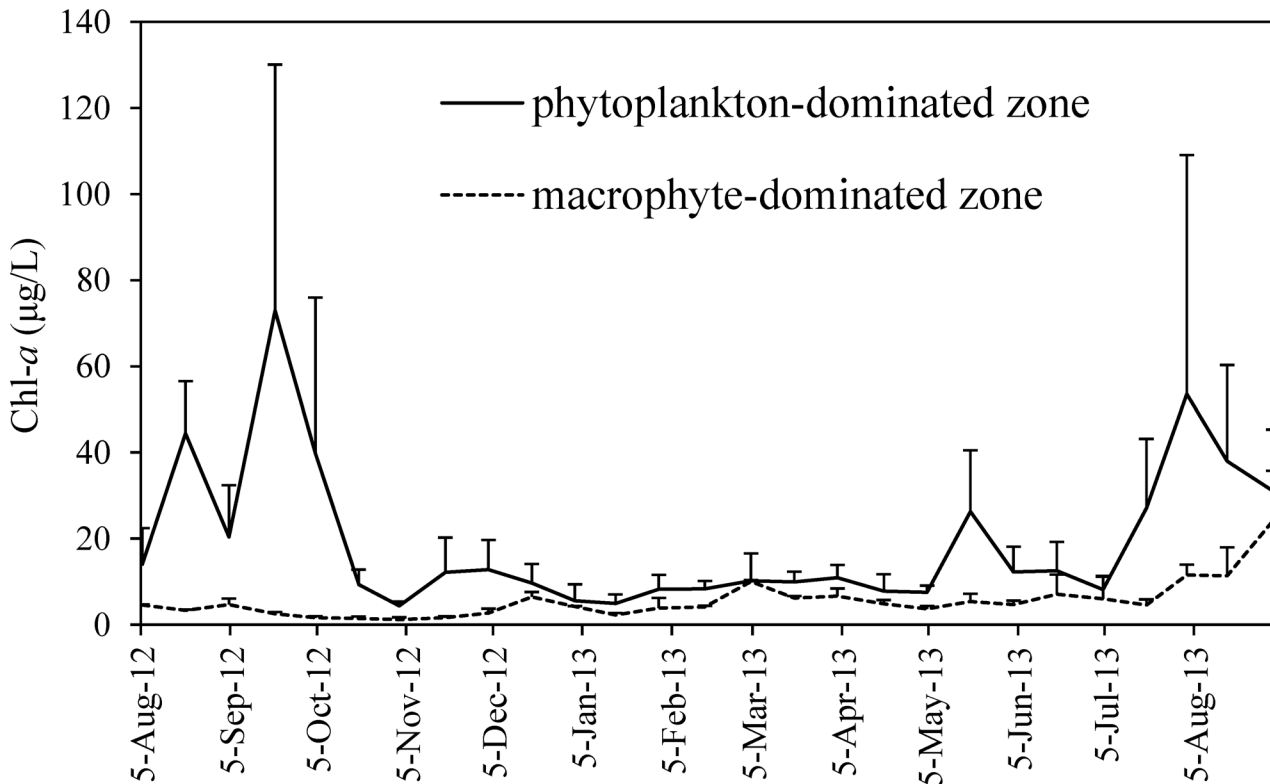


Fig 2. Chlorophyll a concentrations at each site in the water column of phytoplankton- and macrophyte-dominated zone during the observation period.

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Sediment resuspension rate

The relationship of annual average sediment resuspension rate at each site was: site 3 > site 2 > site 1 > site 6 > site 5 > site 4 (Fig 3). Sediment resuspension rate in the phytoplankton-dominated zone was much higher than in the macrophyte-dominated zone and showed a clear increase from the lakeshore sites to the offshore sites. The annual average sediment resuspension rates at sites 1, 2, 3, and 6 were $363 \pm 370 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $486 \pm 355 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $607 \pm 352 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, and $300 \pm 330 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, respectively, while only $7 \pm 11 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and $24 \pm 33 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ at sites 4 and 5. Sediment resuspension rate at sites void of macrophytes (sites 1, 2, 3 and 6) showed highly significant difference ($Z = -6.275, p < 0.01$) with the rates in macrophyte covered area (sites 4 and 5).

Table 2. Sediment properties at each site during the observation.

Sites	Water content (%)	Total nitrogen ($\text{mg} \cdot \text{kg}^{-1}$)	Total phosphorus ($\text{mg} \cdot \text{kg}^{-1}$)	Total organic carbon (%)
1	53 ± 1	2526 ± 338	504 ± 75	1.19 ± 0.04
2	30 ± 0	1992 ± 168	534 ± 28	0.35 ± 0.08
3	54 ± 0	2031 ± 101	372 ± 1	0.98 ± 0.07
4	77 ± 0	4496 ± 136	385 ± 7	4.48 ± 0.06
5	51 ± 0	1900 ± 123	312 ± 2	1.07 ± 0.09
6	47 ± 0	2149 ± 176	660 ± 50	0.97 ± 0.01

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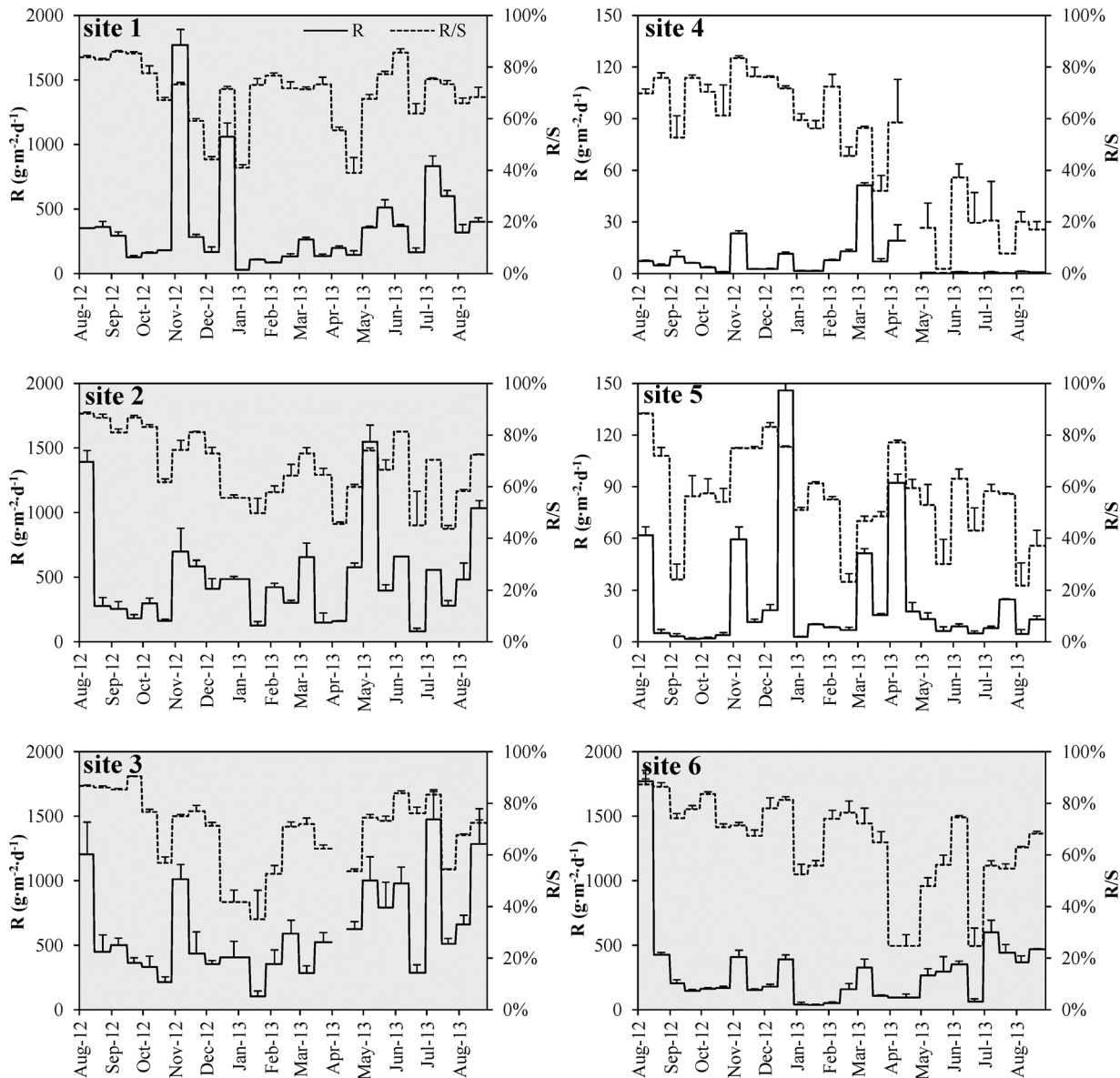


Fig 3. Sediment resuspension rate (R) and the ratio of resuspension to gross sedimentation (R/S) at each site during the observation period. Figures of sites 1, 2, 3 and 6 with gray shading have the same value for y-axis, and figures of sites 4 and 5 have smaller value for y-axis.

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Sediment resuspension rate showed highly significant seasonal variation ($Z = -2.879$, $p < 0.01$) between the high productive and low productive season in the phytoplankton-dominated zone. The average sediment resuspension rates at sites 1, 2, 3, and 6 were higher during the high productive season ($447 \pm 395 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $555 \pm 418 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $722 \pm 383 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, and $396 \pm 382 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, respectively) than during the low productive season ($231 \pm 281 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $377 \pm 178 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $409 \pm 152 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and $148 \pm 115 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, respectively). In the macrophyte-dominated zone, average sediment resuspension rates at sites 4 and 5 during the high productive season ($4 \pm 6 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $15 \pm 18 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) were much lower than during the low productive season ($13 \pm 15 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $38 \pm 45 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), but not showing significant variation ($Z = -1.763$, $p > 0.05$).

Similar to the sediment resuspension rates, the R/S ratio was also higher in the phytoplankton-dominated zone (Fig 3). The ratio of organic matter in trapped sediment (O/S) showed a negative relationship with sediment resuspension rate. The annual average O/S ratios were $9\% \pm 3\%$ at phytoplankton-dominated zone, and $41\% \pm 22\%$ and $19\% \pm 10\%$ at sites 4 and 5. The O/S ratio at site 4 which was fully covered with macrophytes was much higher than all the other sites.

The annual average particle size of trapped sediment at each site was similar. The median particle sizes of trapped sediment were $8.4 \pm 1.6 \mu\text{m}$ and $8.0 \pm 2.5 \mu\text{m}$ in the phytoplankton-dominated and macrophyte-dominated zone, respectively.

Nutrients resuspension rate

The relationship of annual average TN and TP resuspension rate at each site was: site 3 > site 1 > site 2 > site 6 > site 5 > site 4 (Fig 4). Both TN and TP resuspension rates showed highly significant correlations with sediment resuspension rates (Fig 5, $p < 0.01$ at all the 6 sites).

The average TN resuspension rates in the phytoplankton-dominated zone were $1.04 \pm 0.66 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, $0.96 \pm 0.48 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, $1.05 \pm 0.47 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, and $0.68 \pm 0.37 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at sites 1, 2, 3 and 6, respectively, while considerably lower $0.08 \pm 0.07 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $0.11 \pm 0.09 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at sites 4 and 5, increasing significantly from the area of highest macrophyte coverage to the area void of vegetation ($Z = -5.646$, $p < 0.01$).

The average TP resuspension rate showed the same trend with TN resuspension rate (Fig 4). In the phytoplankton-dominated zone, the TP resuspension rates were $0.146 \pm 0.087 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, $0.140 \pm 0.068 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, $0.164 \pm 0.074 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $0.118 \pm 0.070 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at sites 1, 2, 3 and 6, respectively, while only $0.008 \pm 0.008 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $0.010 \pm 0.008 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at sites 4 and 5, being lowest at the sites of highest macrophyte coverage (site 4). The TP resuspension rates at sites 1, 2, 3, and 6 were significantly higher than at sites 4 and 5 ($Z = -6.087$, $p < 0.01$).

Wind speed and direction

Annual average wind speed at site 1 was $3.1 \text{ m}\cdot\text{s}^{-1}$, and the dominant wind direction was from the east. Monthly averaged wind speed ranged from $2.5 \text{ m}\cdot\text{s}^{-1}$ (October 2012) to $3.8 \text{ m}\cdot\text{s}^{-1}$ (August 2012). The dominant wind direction was from the southeast in summer and from the north in winter. Taihu was influenced by Typhoon Haikui in Aug 2012, and the highest wind speed on 8 Aug 2012 was $19.1 \text{ m}\cdot\text{s}^{-1}$. At sites 4 and 5, the annual averaged wind speed was $2.7 \text{ m}\cdot\text{s}^{-1}$, and the dominant wind direction was from the southeast.

Effective wind had highly significant correlation with resuspended sediment at phytoplankton-dominated site 1 (Fig 6, $R^2 = 0.712$, $p < 0.01$) and at macrophyte semi-covered site 5 (Fig 6, $R^2 = 0.807$, $p < 0.01$), but not at macrophyte fully-covered site 4 (Fig 6, $R^2 = 0.084$, $p > 0.05$).

Discussion

The influence of lake morphology on wind-induced resuspension

In both phytoplankton- and macrophyte-dominated zones, sediment resuspension correlated significantly with effective wind, indicating that wind speed is one of the most important factors causing sediment resuspension in large and shallow lakes [51,52], especially long-lasting sustained strong wind [16]. The annual average sediment resuspension rate at the most offshore site (site 3) was nearly 2 times higher than at the lakeshore site (site 1), which was mostly due to the different wind fetch. Site 3 obviously has the longest distance summation to shoreline, and site 1 has the shortest (Table 3). Therefore, located in the central part of the large lake,

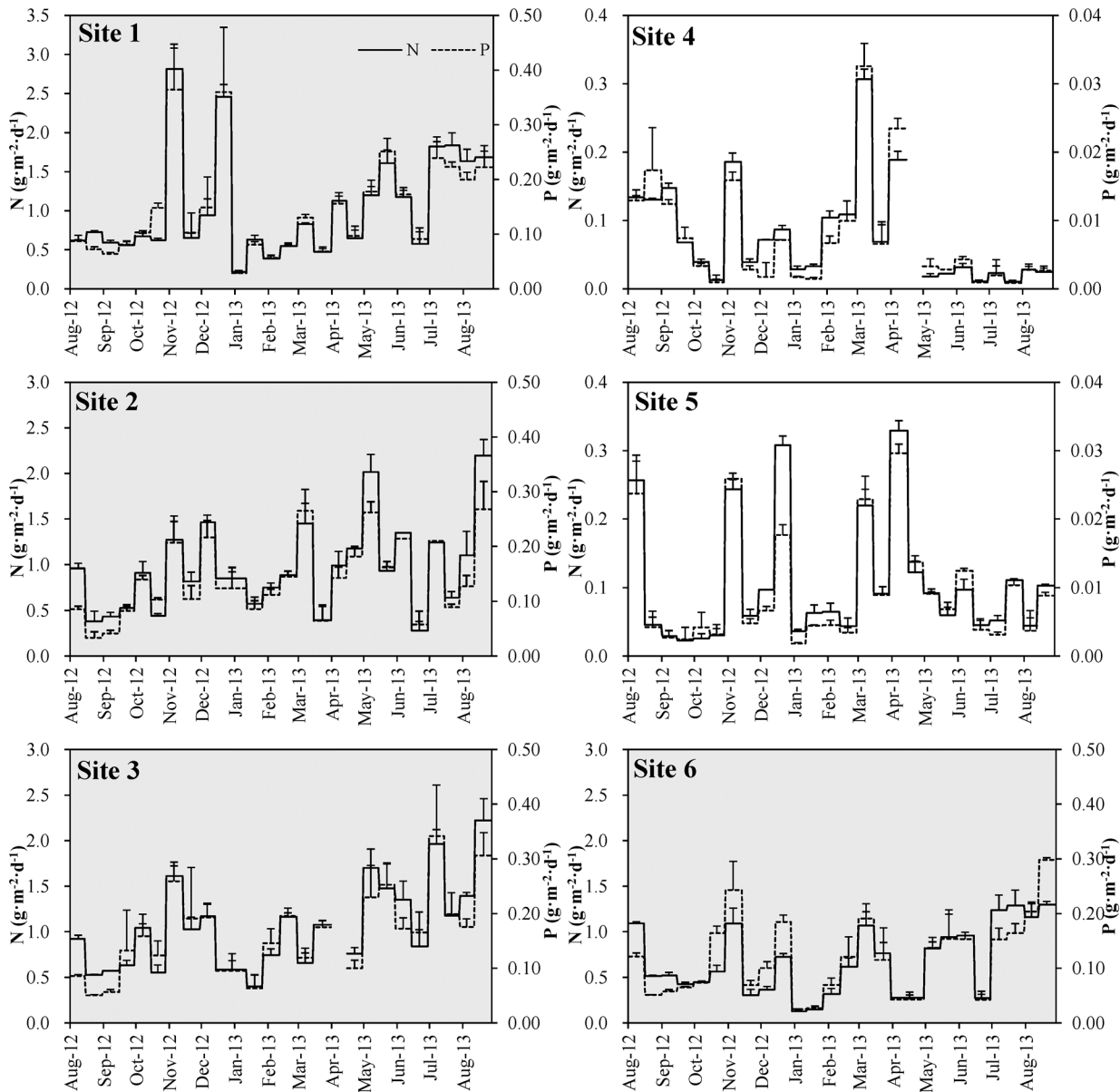


Fig 4. Nitrogen (N) and phosphorus (P) resuspension rate at each site during the observation period. Figures of sites 1, 2, 3 and 6 with gray shading have the same value for y-axis, and figures of sites 4 and 5 have smaller value for y-axis.

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site 3 experienced more wind from each direction than the sites in the bay, and thus also the sediment resuspension rate was higher.

However, under similar wind conditions, sediment resuspension varies strongly depending on lake morphology. Sediment resuspension is prone to occur in lakes with low water depth and large open areas for wind fetch [11,12]. Taihu is very shallow and has quite large surface area, resulting in higher dynamic ratio and sediment resuspension rate. Lakes with smaller dynamic ratios have been shown to have lower sediment resuspension rates (Fig 7), such as shallow but small Lake Wingra, Lake Hiidenvesi and Lake Lammijärvi [8,11,21], or large but deep Lake Peipsi, Saginaw Bay and Lake Okeechobee [8,52,53], or even a larger lake such as Lake Ontario [11]. Lake Markermeer also has a smaller dynamic ratio than Taihu, but a higher

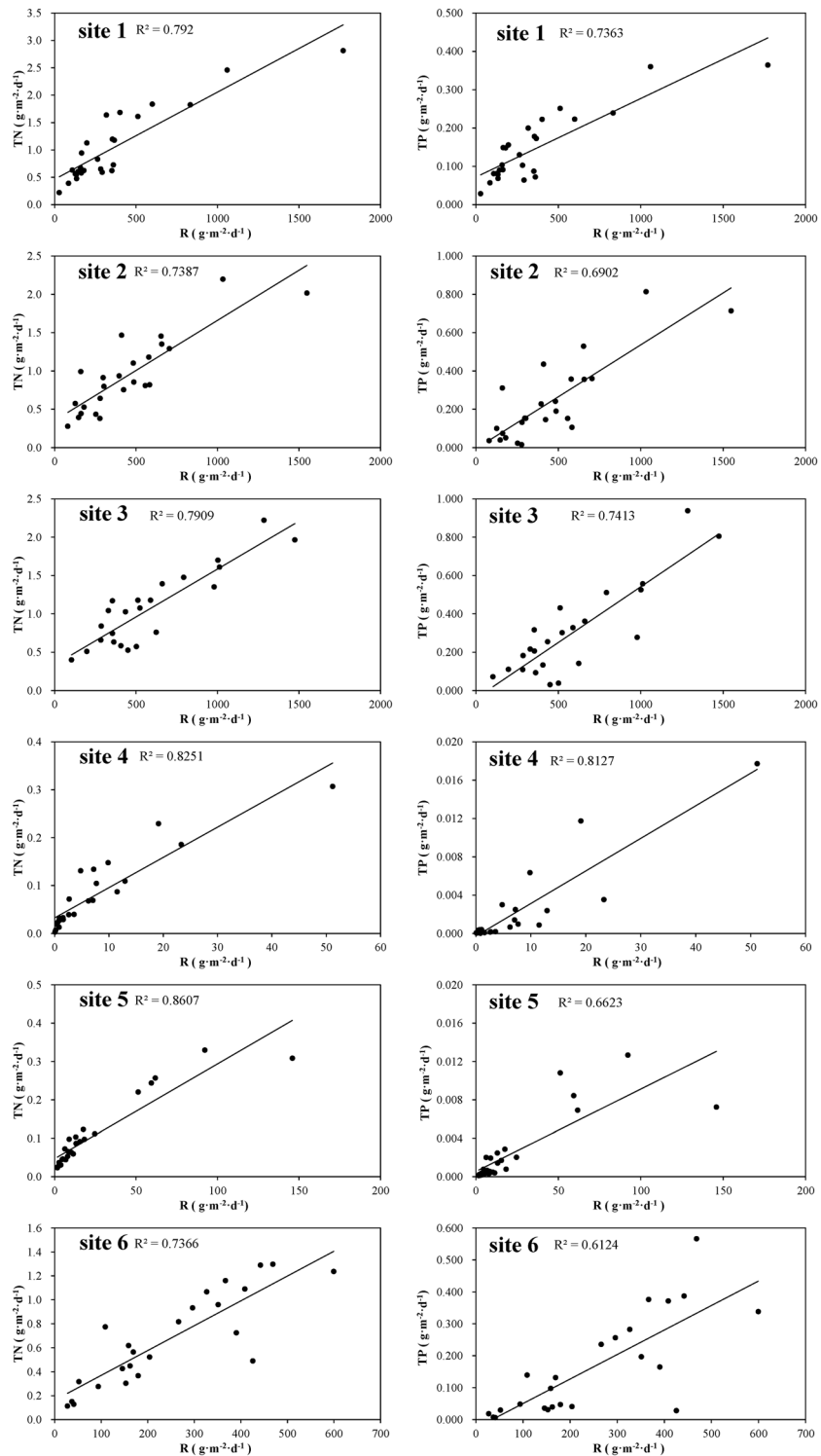


Fig 5. Correlation between sediment resuspension rate and total nitrogen (TN) or total phosphorus (TP) resuspension rate at each site during the observation period.

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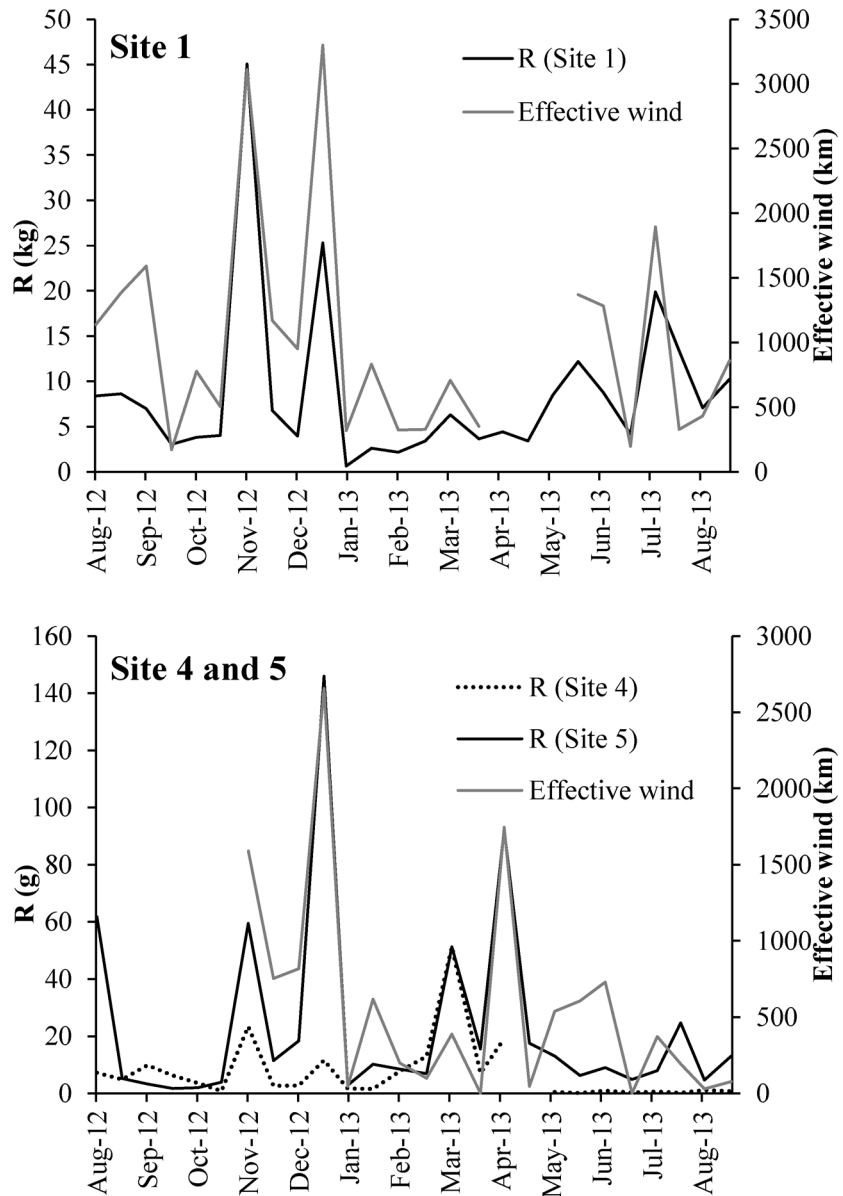


Fig 6. Effective wind and resuspended sediment at sites 1, 4 and 5 during the observation period.

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Table 3. The distances from each site to the shorelines in four directions (km).

Sites	East	South	West	North	Summation
1	0	1	8	0	9
2	11	48	13	5	77
3	22	36	22	29	109
4	1	1	24	8	34
5	1	1	24	9	35
6	2	6	8	3	19

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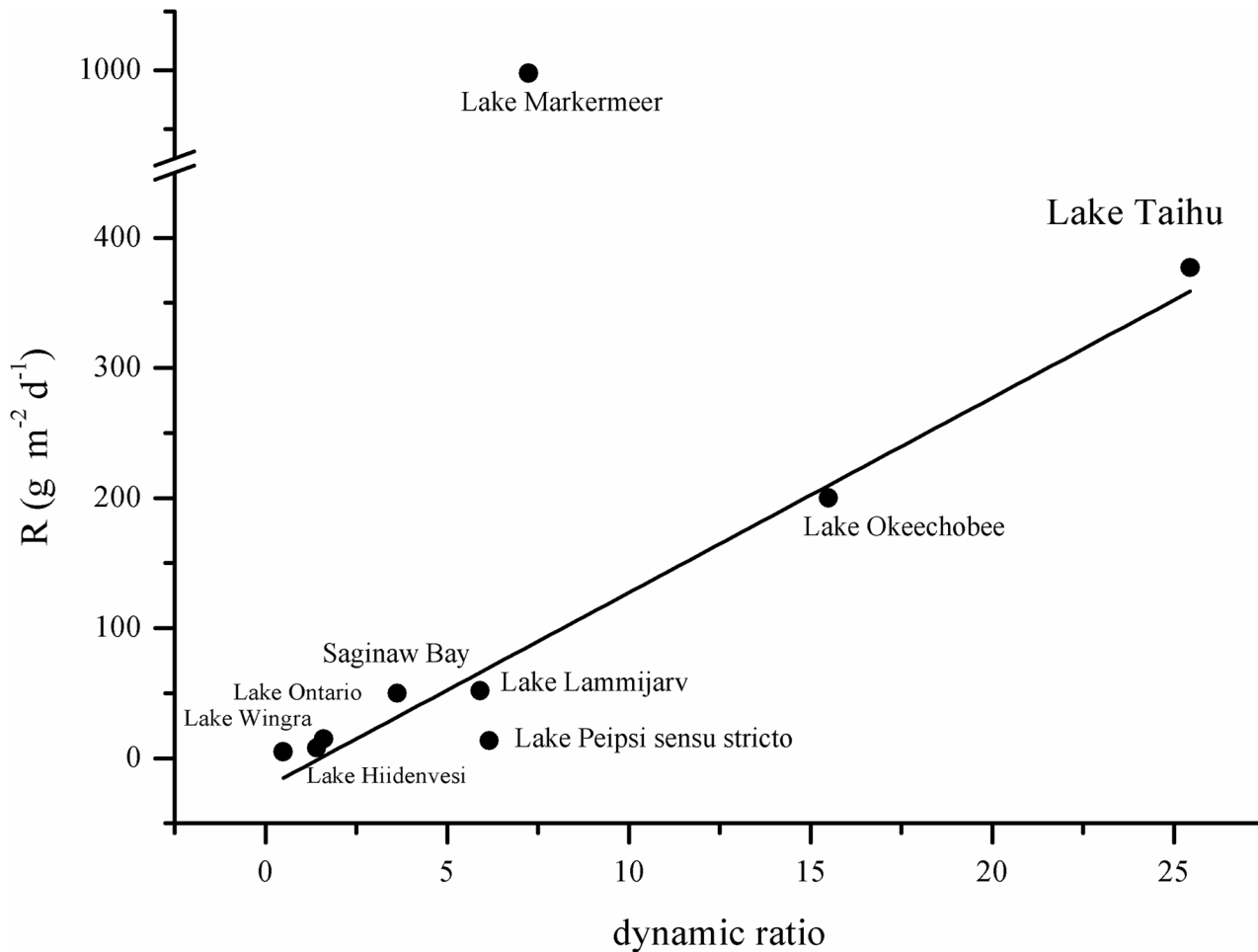


Fig 7. Dynamic ratio and sediment resuspension rate (R) in different lakes. Peak suspended solid concentrations during resuspension were used for Saginaw Bay and Lake Okeechobee instead of sediment resuspension rate (R) data in this figure, as there was no detailed sediment resuspension rate data in the references [52,53]. The trend line showing the relationship between R and dynamic ratio was calculated excluding Lake Markermeer.

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estimated annual sediment resuspension rate (Fig 7). This is mostly due to stronger near-bottom currents ($> 10 \text{ cm}\cdot\text{s}^{-1}$) [22], while currents at site 1 in Taihu ranged from 0.2 to $3.3 \text{ cm}\cdot\text{s}^{-1}$, averaging $1.5 \text{ cm}\cdot\text{s}^{-1}$ [16].

The influence of ecotype on sediment resuspension

Macrophytes showed a stronger influence on the variation of sediment resuspension in different regions than wind fetch in Taihu. The summation of distances from both macrophyte-dominated sites 4 and 5 to the shoreline in four directions is 34 and 35 km, which is nearly 2-fold longer than at site 6 and nearly 4-fold longer than at site 1 (Table 3), but the annual average sediment resuspension rates at sites 4 and 5 were 29-fold lower than corresponding rates at sites void of macrophyte (sites 1, 2, 3, and 6). Therefore, the presence of macrophytes showed a substantial effect on reducing sediment resuspension in Taihu, as proved in other studies in shallow waters [21], for vegetation reduces the wind-induced waves [20,54]. The annual average sediment resuspension rate at macrophyte fully covered site 4 was thus lowest of all sites, showing no correlation to wind speed.

Sediment resuspension also showed variation between the high productive and the low productive seasons in the macrophyte-dominated zone. The ratio of sediment resuspension rates at macrophyte-dominated sites 4 and 5 during the high productive season to that during the low productive season was only 0.31 and 0.39 (Fig 8). Lower wind speed was an important factor for a lower sediment resuspension rate during the high productive season, but the averaged wind speeds at sites 4 and 5 during the high productive and the low productive seasons were $2.6 \text{ m}\cdot\text{s}^{-1}$ and $3.0 \text{ m}\cdot\text{s}^{-1}$, respectively, not showing considerable differences. The ratio of effective wind at sites 4 and 5 during the high productive season to that during the low productive season was 0.82 (Fig 8), indicating that, besides wind speed, the growth and degradation of macrophytes during different seasons was also a very important factor reducing sediment resuspension. During the high productive season, the suspended matter was less, mostly consisted of leaf blades, having larger average median particle size ($9.3 \mu\text{m}$). However, during the low productive season, containing more inorganic matter, the concentration of suspended solids was higher, with smaller average median particle size ($7.5 \mu\text{m}$).

In the phytoplankton-dominated zone, the existence of blooms also caused the sediment resuspension rate to vary during the high productive and the low productive seasons. The ratio of sediment resuspension rate at phytoplankton-dominated site 1 during the high productive season to that during the low productive season was 1.94, but the averaged wind speeds during the high productive season and the low productive season were $3.1 \text{ m}\cdot\text{s}^{-1}$ and $3.0 \text{ m}\cdot\text{s}^{-1}$, respectively, not showing any difference (Fig 8). The ratio of effective wind at site 1 during the high productive season to that during the low productive season was only 1.06, which additionally supported the effect of phytoplankton blooms on sediment resuspension.

The presence of blooms may influence sediment resuspension for several reasons. The accumulation and sedimentation of phytoplankton blooms increase the amount of particulate matter in the water column and sediment surface, which may easily disaggregate and be resuspended [55]. Phytoplankton blooms may capture small particles when sinking or resuspending, as phytoplankton excrete slime [56,57]. Phytoplankton blooms in the water column and on the sediment surface may also increase the organic matter content, aggregate inorganic matter and be easily resuspended.

The annual average sediment resuspension rate in the phytoplankton-dominated zone estimated in this study, based on a one-year observation, was lower than the results estimated by Huang and Liu [32] from June to September. It is mainly because sediment in that study site had a higher organic matter content (5.93–10.53%), and also because that study was conducted only in the high productive season, which may overestimate the annual average value, due to the significant seasonal variation of sediment resuspension rate.

Nutrient supply to the water column by sediment resuspension

Sediment resuspension is an important source for internal nutrient loading in shallow lakes [4,19,26], and our data confirm this is also the case in Taihu: Indeed the nutrient resuspension rate in Taihu was higher compared to other lakes. Phosphorus resuspension rates were estimated as 0.060 to $0.070 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in Lake Arresø [4], and $0.039 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in Lake Hiidenvesi [21], which were much lower than the TP resuspension rate in Taihu's phytoplankton-dominated zone ($0.142 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), although higher than in the macrophyte covered zone ($0.009 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$).

TN and TP concentrations in the water column may be increased by $0.34 \text{ mg}\cdot\text{L}^{-1}$ and $0.051 \text{ mg}\cdot\text{L}^{-1}$ on average caused by sediment resuspension in areas void of macrophytes, while they may only be increased by $0.03 \text{ mg}\cdot\text{L}^{-1}$ and $0.003 \text{ mg}\cdot\text{L}^{-1}$ in macrophyte covered areas, respectively. In addition, the increased nutrient concentration in the water column calculated in the macrophyte-dominated zone might be overestimated, as the large and extensive macrophyte

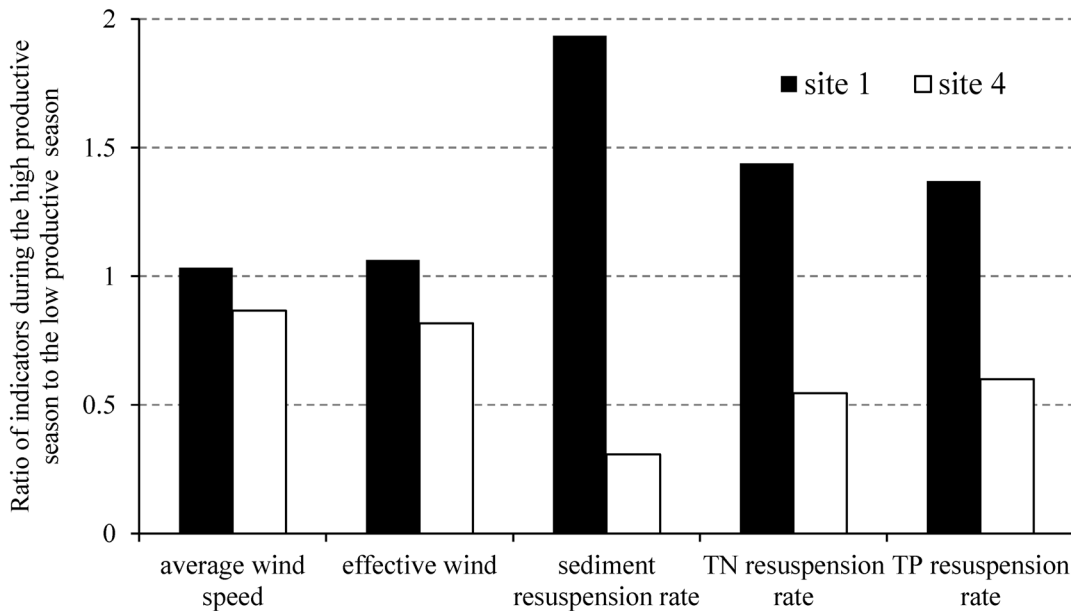


Fig 8. Ratios of average wind speed, effective wind, sediment resuspension rate, total nitrogen (TN) and total phosphorus (TP) resuspension rate during the high productive season to the low productive season at sites 1 and 4.

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coverage in the southeastern lake should have stronger effect in reducing resuspension rate than the small pieces of macrophyte coverage at sites 4 and 5. Thirty percent of the TP content in surface sediment is in algal-available forms [48]. The average equilibrium concentrations of nitrogen and phosphorus at the sediment-water interface in Taihu were 1.10 mg/L and 0.11 mg/L, respectively, and the concentrations were much higher in areas with frequent bloom occurrence [58]. Therefore, nutrients stored in the sediment in Taihu still have great potential to be released into the water column, as an important source for phytoplankton growth.

TN and TP resuspension rates at site 1 was higher than site 2, mostly due to the higher TOC content in the sediment at site 1. The reason for higher TOC content at the lakeshore site 1 was the more efficient source for organic matter, such as submerged plants or reed. Therefore, sediment properties, especially the organic matter content, had an important influence on nutrient resuspension.

The amount of organic matter in suspended sediment was even more important than total sediment resuspension for nutrient resuspension. The annual average TN and TP resuspension rate in the areas void of macrophytes (sites 1, 2, 3 and 6) was 10-fold and 16-fold the resuspension rate in the macrophyte covered areas (sites 4 and 5), respectively. The differences in the nutrient resuspension rates between non-macrophyte and macrophyte-covered areas were not as clear as differences between sediment resuspension rates (29-fold), but similar to the differences in the resuspension rates of organic matter (14-fold).

Similar to the sediment resuspension rate, nutrient resuspension rate also varied between the high productive and the low productive season. At macrophyte fully-covered site 4, the ratios of TN and TP resuspension rates during the high productive season to the low productive season were 0.55 and 0.60 (Fig 8), higher than the ratio of sediment resuspension rate (0.31) but lower than the ratio of effective wind (0.82). At phytoplankton-dominated site 1, the ratios of TN and TP resuspension rates during the high productive season to the low productive season were 1.44 and 1.37 (Fig 8), lower than the ratio of sediment resuspension rate (1.94) but higher than the ratio of effective wind (1.06).

Sediment resuspension promotes phytoplankton growth

Sediment resuspension may add on average $161 \text{ mg}\cdot\text{L}^{-1}$ of suspended solids in the water column in open water areas, while only $6 \text{ mg}\cdot\text{L}^{-1}$ of suspended solids in macrophyte-covered areas. The resuspended sediment may settle down when wind speed decreases and water flow slows down, but the increment of SS concentration during strong wind periods may significantly influence the transparency in the water column. According to the relationship between secchi depth and SS concentration [59] and the regression relationship between the photosynthetically available radiation (PAR) euphotic depth and SS concentration in Taihu [60], when SS concentration is $161 \text{ mg}\cdot\text{L}^{-1}$, the corresponding secchi depth is only 14 cm and PAR euphotic depth is 39 cm. In the macrophyte-covered zone, the calculated secchi depth is over 1 meter and PAR euphotic depth is over 2 meters, even deeper than the water depth at sites 4 and 5, which indicated that macrophytes greatly influenced transparency and the underwater light field.

However, once macrophytes disappear, the lower transparency in the water column caused by sediment resuspension would limit the recolonization of macrophytes. In Taihu, summer blooms are dominated by the buoyant cyanobacteria *Microcystis* spp., which prefers to accumulate at the water surface [39], thus the occurrence of blooms are not affected by reduced light penetration. Due to low transparency, most of the offshore parts of Taihu have no history of macrophyte colonization, not even when eutrophication was not as severe. The restoration of macrophytes could only be considered in certain regions like the lakeshore, and sediment resuspension should be reduced during restoration to ensure colonization using wave barriers or enclosures [32].

Sediment resuspension also brings considerable amounts of nutrients into the water column. TP concentration in Taihu during the 1990s has reported to be above $0.080 \text{ mg}\cdot\text{L}^{-1}$ [24], and during this study TP concentration in the water column was $0.079 \text{ mg}\cdot\text{L}^{-1}$ in average for all 6 sites and $0.106 \text{ mg}\cdot\text{L}^{-1}$ in average for 3 sites in the phytoplankton-dominated zone. The amount of phosphorus resuspended from the sediment in the zone void of macrophytes was comparable with the TP concentration in the water column, and indicates a trophic state index of 61 (in a scale of 0–100) according to Carlson [61]. The trophic state index calculated for TP concentration showed a continuous high trophic level in Taihu, and would not decrease as long as resuspended sediment showed such significant influence. This influence of sediment resuspension on phosphorus concentration in the water column should be considered in lake management and restoration target determination.

At present, sediment resuspension in the macrophyte-dominated zone is low and does not affect water quality. However, the TN and TP contents in the sediment at macrophyte fully covered area (site 4) are much higher than other sites, and the distance summation from site 4 to shorelines are also longer than at sites 6 and 1. Once phytoplankton blooms become dominant, site 4 may face very strong sediment resuspension without the inhibiting effect of macrophytes, similar to site 6, where the shift from macrophyte-dominated zone to non-macrophyte zone has occurred.

Conclusion

Sediment resuspension in Taihu, especially in the phytoplankton-dominated zone, is much stronger than in many other lakes worldwide. Lake morphology is the key factor for the high sediment resuspension rate in Taihu, as it is very shallow and large to ensure long wind fetch. However, sediment resuspension in different areas of the lake varied a lot due to the ecotype. Under similar wind speed, the growth of macrophytes may reduce sediment resuspension rate by 29-fold according to the annual observation.

Sediment resuspension brought numerous nutrients into the water column and correspondingly reduced transparency. The low transparency prevented the growth or recovery of macrophytes, but benefited the blooming of *Microcystis* spp. in Taihu. The strong and fast cycling of nutrients at the sediment-water interface caused by sediment resuspension kept the phosphorus concentrations in the lake water at a high trophic level in Taihu and stimulated phytoplankton growth.

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Author Contributions

Conceived and designed the experiments: MZ GZ LN BQ AV. Performed the experiments: MZ GZ TW JD. Analyzed the data: MZ GZ LN. Contributed reagents/materials/analysis tools: MZ GZ LN. Wrote the paper: MZ GZ LN YZ.

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