

## The regularity of wind-induced sediment resuspension in Meiliang Bay of Lake Taihu

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### ABSTRACT

Contaminants released by wind-induced sediment resuspension could influence the water quality in shallow lakes. This study aims to reveal the quantitative relationship between wind speed ( $v$ ) and sediment resuspension rate ( $r$ ) in Meiliang Bay of Lake Taihu. The study was conducted in three steps. First, the *in situ* wind speed and current velocity were measured over a period of 2 days in Meiliang Bay to establish the relationship between wind and hydrodynamic conditions; second, an indoor experiment was conducted in a cylindrical simulator with sediment from the study area to determine sediment resuspension rates under different hydrodynamic conditions; and third, linkages between sediment resuspension and wind were determined. The average sediment resuspension rate was highly correlated with the wind speed ( $R^2 = 0.99$ ), and was expressed by  $r = 20.72v^{2.034}$  at wind speeds in the range of 0–14 m/s. The critical wind speed for sediment resuspension is about 7 m/s. Under these conditions, the average resuspension rate could reach 1,000 g/(m<sup>2</sup> d), with a total phosphorus release rate of 1.1 g/(m<sup>2</sup> d) and a total nitrogen release rate of 18.1 g/(m<sup>2</sup> d).

**Key words** | cylindrical simulator, sediment resuspension, shear stress, wind

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### INTRODUCTION

Lake eutrophication is a serious environmental problem in China, especially in shallow lakes. Lake Taihu is highly eutrophic, despite many restoration efforts, including the use of macrophytes, sediment dredging, wetland construction, water transfer, and increased nutrient recycling (Xiao *et al.* 2009; Ye *et al.* 2009; Zhai *et al.* 2010). The lake's water quality has not shown any significant improvement, and Meiliang Bay in the northwestern portion of the lake remains especially impaired (Qin 2009; Zhao *et al.* 2013).

Frequent resuspension of sediments is recognized as an important process which impedes the recovery of eutrophic lakes, especially when external nutrient sources are controlled (Ahlgren *et al.* 2011; Christian 2011). Sediment resuspension occurs when bottom shear stress is sufficiently large to disrupt the cohesion of benthic sediment. Wind has a significant effect on the flow velocity in shallow lakes, such as Lake Taihu (Maxam & Webber 2010). Wind-induced currents frequently disturb the water–sediment interface, and often cause significant increases of suspended sediment concentration (SSC) in overlying water. The effect of strong winds on SSC in shallow lakes has been well documented

(e.g., Luettich *et al.* 1990; Bengtsson & Hellström 1992; Arfi *et al.* 1993; Qin *et al.* 2000; Zhu *et al.* 2005). Field observation of sediment resuspension has been achieved under different wind conditions (James *et al.* 2004; Horppila & Nurminen 2005; Hu *et al.* 2006). The Y-shape apparatus, the annular tank, and the particle entrainment simulator were used to produce various degrees of water turbulence in indoor experiments (Cantwell & Burgess 2004; Li *et al.* 2004; Li 2005; Wan *et al.* 2011; Huai *et al.* 2011), but there are still some disadvantages in these methods. Field observation is hard to duplicate under the same environment conditions, and compared to the natural process of sediment resuspension in shallow lakes, the flow velocity created by these simulative devices is more uniform, and the natural characteristics of the sediment may be destroyed. Models have also proved useful for predicting the effect of suspended sediment (Hamilton & Mitchell, 1996; Bailey & Hamilton 1997).

In this study, field observations were made and an improved indoor simulator was used. During the field observation, an acoustic Doppler velocimeter (ADV, SonTek,

USA) was used to measure three-dimensional flow velocity, while a portable aerovane was used to measure wind speed at the same time. In order to understand the relationship between current velocity and sediment resuspension rate in this area, an indoor dynamic simulation experiment was conducted in a self-designed cylindrical simulator (Chinese Invention Patent, application number: 201310236315.1) with sediment taken from the experimental area. The cylindrical simulator was especially designed to simulate the flow structure observed in Lake Taihu. Meanwhile, a sediment sampler (Chinese Invention Patent, application number: 201310184563.6) was designed in this study to preserve the vertical structure of sediment while sampling. The relationship between wind speed, current velocity and sediment resuspension was developed and validated to provide a theoretical basis for understanding the process of sediment resuspension and estimating the amount of sediment contaminants released in Lake Taihu.

## MATERIALS AND METHODS

### Experimental design

Back in the 1970s, Mehta and other researchers studied the relationship between sediment deposition and surface shear stress through laboratory experiments and field trials (Mehta & Partheniades 1975; Partheniades 1977; Sheng & Lick 1979). Lick's (1994) studies in the US Great Lakes also indicated that the concentration and particle size of suspended solids are related to the shear stress of the sediment–water interface. In Lake Taihu, wind is the main driving force. Wind greatly affects the hydrodynamic conditions of the water, and hydrodynamic conditions determine the power of shear stress. Thus we can establish the relationship

between wind and sediment resuspension through the intermediate variable of shear stress.

This study had two major parts: field observations and an indoor experiment. The design was as follows.

- (1) An ADV and a portable aerovane were used to observe the lake flow and wind in the field synchronously, the shear stress was calculated, and then the relationship between the wind and the shear stress was established.
- (2) Sediment resuspension status was simulated under different shear stresses in the laboratory to establish the relationship between the shear stress and sediment resuspension.
- (3) The laboratory results were translated to the field through shear stress to determine the *in situ* relationship between wind and sediment resuspension.

### Field observation

Lake Taihu is a large shallow lake with a surface area of 2,338 km<sup>2</sup> and an average depth of 1.9 m. Table 1 shows the annual average hydrological and meteorological characteristics (Qin *et al.* 2000; Huang & Xu 2009).

For Lake Taihu, the average annual water temperature is 17.3 °C with a range of 4.8–29.2 °C. The vertical temperature drop mainly varies from 0 to 1 °C (Zhao *et al.* 2011). A north-west wind prevails in the winter while a southeast wind prevails in the summer. But in spring and autumn, the wind direction is changeable. Generally, the wind speed varies between 0 and 10 m/s, with an average speed of 4.3 m/s in spring and summer and 0.9 m/s in the autumn and winter. High wind speeds of up to 25 m/s can be measured during typhoons (Qian 2012). Surface water flow is consistent with the wind direction. When the wind speed is low, compensated flow occurs in the bottom water, and the flow direction is opposite to the surface current. Due to the

**Table 1** | Annual average hydrological and meteorological element of Lake Taihu

Lake area (km <sup>2</sup> )	Catchment area (km <sup>2</sup> )	Shoreline length (km)	Average water depth (m)
2,428	36,500	405	1.89
Maximum water depth (m)	Volume (m <sup>3</sup> )	Annual precipitation (mm)	Annual evaporation (mm)
2.8	44 × 10 <sup>8</sup>	1,000–1,300	1,000–1,100
Highest water level (m.a.s.l.)	Lowest water level (m.a.s.l.)	Annual sediment income (kg)	Annual sediment outcome (kg)
5.08	2.02	44 × 10 <sup>7</sup>	10 × 10 <sup>7</sup>
Average temperature (°C)	Highest temperature (°C)	Lowest temperature (°C)	Sunshine hours (h)
15.99	20.2	12.68	1,974.6

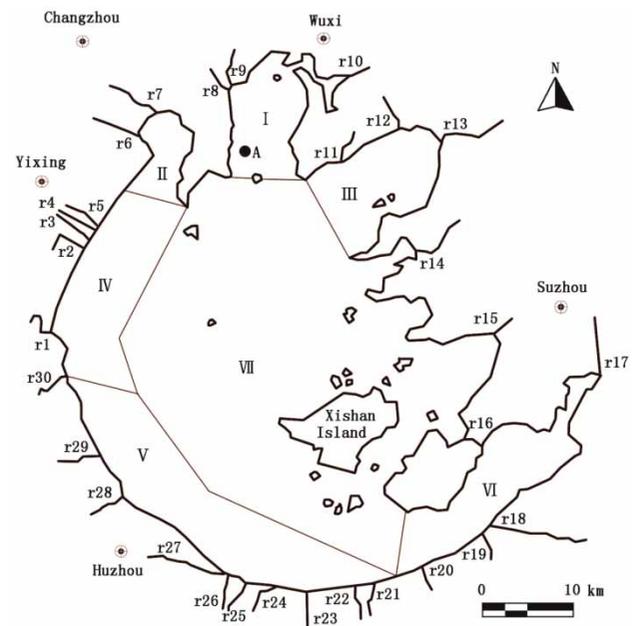
Note: The term 'm.a.s.l.' means 'metres above sea level'.

temporal and spatial variation of wind speed and direction, the flow field is unstable. But if the spatial distribution is more consistent and continues for a certain time, a clear circulation flow field can form with an average flow velocity of about 10 cm/s and a maximum of about 30 cm/s (Qin et al. 2000). The spatial distribution of nitrogen and phosphorus in Lake Taihu is uneven. The total nitrogen (TN) concentration varies from 0.5 to 7 mg/L, and total phosphorus (TP) concentration varies between 0.02 and 0.35 mg/L. The water quality of Meiliang Bay and Zhushan Bay is relatively poor; TN concentration is higher than 4 mg/L while TP concentration is higher than 0.15 mg/L. The water quality of East Taihu Lake is best with TN concentration less than 2.2 mg/L and TP concentration less than 0.08 mg/L. TN concentration trend for different areas of the lake is II > I > III > IV > VII > V > VI (see Figure 1 for lake areas), and TP concentration trend is II > I > IV > III > VII > V > VI (Deng et al. 2008). The sediment is mainly distributed in Zhushan Bay, Meiliang Bay, the west coast area and the center of the lake. Mud covers 47.5% of the lake bottom area. Sediment thickness of Meiliang Bay, Zhushan Bay, the coastal area, the north shore, the lake center, and coasts of Xishan Island are, respectively, 1.2, 0.5, 0.3, 0.4, and 0.15 m. TN content of the sediment ranges from 450 to 5,200 mg/kg but from 800 to 2,300 mg/kg in Meiliang Bay. And TP content ranges from 120 to 1,400 mg/kg but from 200 to 600 mg/kg in Meiliang Bay (Luo et al. 2004; Wang et al. 2012).

In this study, the monitoring site and the *in situ* sediment sampling site are both site A (Figure 1; 31°25'45.14" N, 120°7'44.85" E) in Meiliang Bay, which is severely polluted by industrial wastewater and ship transportation. Three-dimensional flow velocity about 2 cm above the water-sediment interface and wind speed were continuously measured during the field observation from July 8–10 and from October 13–15, 2013. The flow velocity was measured with an ADV and the wind speed and direction were measured with a portable aerovane.

### Sediment resuspension simulate

The main components of the cylindrical simulator (Figure 2) were a pump to force a vertical compensation current, a motor, a bearing turntable, two paddles to force a horizontal circular current, and a container that sediment collected into. The test section was made of clear acrylic or polycarbonate so that the sediment-water interactions could be observed. Sediment thickness was 20 cm with 80–100 cm of overlying water. Both sediment and overlying water were taken from site A and transferred to the laboratory within a few hours.



I. Meiliang Bay II. Zhushan Bay III. Gonghu Bay IV. West coast area  
V. Southern coast area VI. East Lake Taihu VII. Center lake area

Figure 1 | Map of Lake Taihu with the sampling and monitoring site (site A).

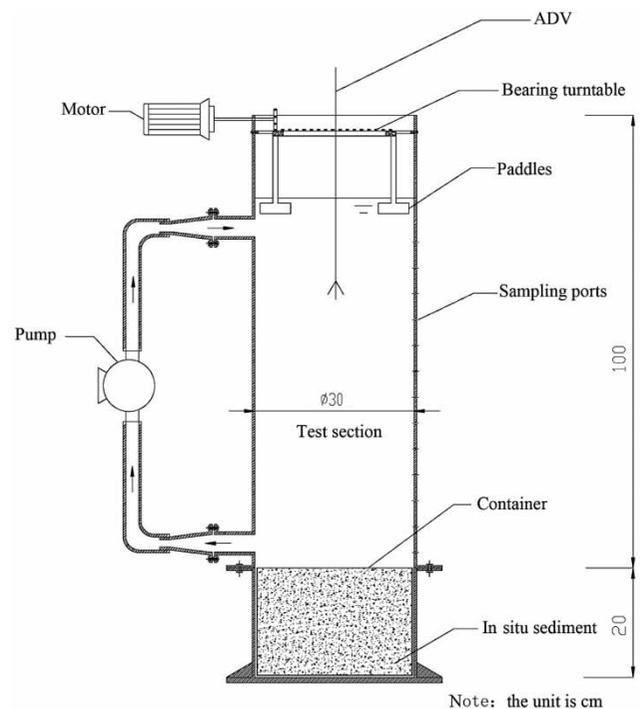


Figure 2 | The schematic diagram of the cylindrical simulator.

During the experiment, the average flow velocity about 2 cm above the water-sediment interface was carefully controlled. The flow velocity was measured with the ADV. Water was sampled through the sampling ports after the

simulator operated at stable conditions for 30 min. About 10 test groups at a range of flow velocities were performed during which TN, TP, and SS concentrations were monitored.

### Measurement of SSC, TN, and TP

The membrane filtration method was used to analyze the SSC in the water samples. First, the water samples were shaken thoroughly and then filtered by glass microfiber filter. Second, the filtered samples were dried at 102–105 °C for 4 h while the blank filters were dried for 2 h before filtration. Third, the samples were weighed with a precision of 0.00001 g after the sediment-laden filters were cooled to room temperature. Finally, SSC were calculated by subtracting the weight of the dry glass microfiber filter before filtration from that after the filtration.

The concentration of TN and TP were measured using an automatic water quality analyzer (AA3, SEAL, Germany). Before measurement, the water samples were filtered using a water-circulation multifunction vacuum pump (SHB-III, Shiding, China).

## RESULTS AND DISCUSSION

### The relationship between wind speed and hydrodynamic situations

The wind speed of Lake Taihu may vary from 0 to 10 m/s, with an average speed of 4.3 m/s in spring and summer and 0.9 m/s in autumn and winter (Qian 2012). During the field observation, the average wind speed varied from 0.2 to 3.2 m/s, while the mean flow velocity varied from 0.69 to 3.53 cm/s. Figure 3 shows the significant power relationship between average wind speed ( $v$ ) and mean flow velocity ( $\bar{u}$ )

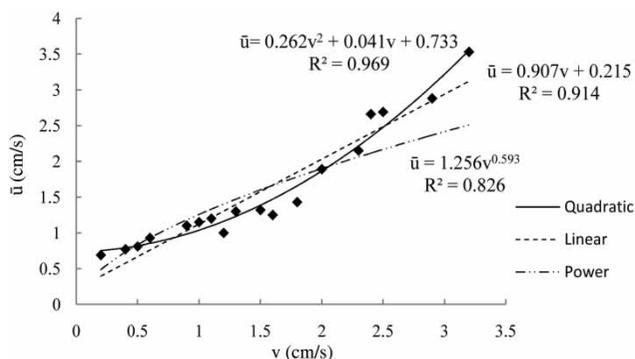


Figure 3 | Relationship between wind speed and mean flow velocity.

with three different formulas. The quadratic formula ( $R^2 = 0.969$ ) was  $\bar{u} = 0.262v^2 + 0.041v + 0.733$ , the liner formula ( $R^2 = 0.914$ ) was  $\bar{u} = 0.907v + 0.215$ , and the power formula ( $R^2 = 0.826$ ) was  $\bar{u} = 1.256v^{0.593}$ . These results indicate a positive correlation between wind speed and flow velocity, and that wind forcing induces hydrodynamic conditions. The power formula ( $\bar{u} = av^b$ ;  $a$  and  $b$  are constants) is often adopted (Hu et al. 2011; Qian et al. 2011). But in this study, the quadratic formula may be more suitable. The quadratic formula and liner formula differ in the zero position from the power formula. These differences may be due to the fact that the water was driven by mechanical power in simulator systems. If the mechanical power stops, the water will stop flowing and therefore there will be a zero velocity. But in Lake Taihu, many factors other than wind cause the water to flow, such as temperature and topography. When the wind speed was smaller than 0.5 m/s, the mean flow velocity was stable. In order to verify the applicability of the experimentally obtained equation, some comparisons are shown in Table 2. The quadratic formula result was closer to reference studies (Qian et al. 2011). In most cases, the wind speed of Lake Taihu varied between 0 and 10 m/s. Within this range, the quadratic formula is more suitable for the field and the power form is more suitable in simulator systems due to different driving conditions.

The concentration and particle size of suspended solids are related to the shear stress of the sediment–water interface (Lick 1994). Shear stress is an important indicator for sediment resuspension flux characterization, and it is closely associated with the flow velocity. It is calculated as follows:

$$\tau = \rho u_*^2; \quad \frac{\bar{u}(z)}{u_*} = \frac{u_* \cdot z}{\mu} \quad (1)$$

where  $\tau$  is the shear stress ( $\text{N/m}^2$ );  $\rho$  is the density of pure water ( $\text{kg/m}^3$ );  $u_*$  is the friction velocity ( $\text{cm/s}$ );  $\bar{u}(z)$  is the velocity at each vertical depth ( $\text{cm/s}$ );  $z$  is the vertical

Table 2 | Comparisons of correspondence between wind speed and mean flow velocity

$v$ (m/s)	$\tau$ ( $10^{-3} \text{ N/m}^2$ )	$\bar{u}$ (cm/s)			
		Ref. (Qian et al. 2011)	Quadratic	Linear	Power
2.4	7.9	2.2	2.3	2.4	2.1
3.0	9.5	3.4	3.2	2.9	2.4
5	21.5	8.2	7.5	4.8	3.3
6.5	34.2	12.9	12.1	6.1	3.8
10	76.4	32.2	27.3	9.3	4.9

coordinate (m); and  $\mu$  is the kinematic viscosity coefficient of pure water (pa s).

Using Equation (1), we calculated the shear stress under different mean flow velocities (Table 2) and then established the relationship between wind speed and shear stress.

### The relationship between hydrodynamic situations and SSC

Due to cohesive forces and flow sweeping, sediment moved initially into groups of tens or hundreds of particles and were then transported into the water column in the form of discrete particles, leaving flaky traces behind on the bed. A remarkable increase of SSC during the experiment process was observed. There was a positive correlation between hydrodynamic forces and the resuspension rate of suspended sediment across the sediment–water interface. Figure 4 shows the relationship between SSC and flow velocity ( $\bar{u}$ ) in the cylindrical simulation experiment. The liner formula ( $R^2 = 0.952$ ) was  $SSC = 10.46\bar{u} - 12.51$ , and the power formula ( $R^2 = 0.982$ ) was  $SSC = 5.09\bar{u}^{1.228}$ . Both formulas had high coefficients of variation, but the linear formula was not suitable when  $\bar{u}$  was less than 1.2 cm/s ( $SSC < 0$ ). According to the experiment, the incipient sediment motion can be generally divided into three states: first, the sediment is about to move (flow velocity ranged from 0 to 1 cm/s); second, only a small quantity of sediment is set in motion (flow velocity ranged from 1 to 4 cm/s); and third, all sediments are in motion (flow velocity ranged from 4 to 14 cm/s). In the first state, the sediments were basically motionless except for a few protrusive particles. The second referred to the state in which only a small quantity of particles could be observed in motion. The third state was one in which all the sediments were set in motion, but not all at the same time, some earlier

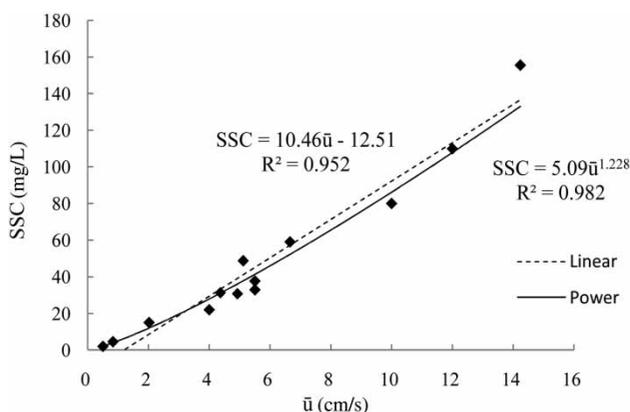


Figure 4 | Relationship between flow velocity and SSC.

and some later, and the motion could be observed in various parts of the bed in certain periods. Based on Equation (1), we were able to calculate the shear stress under different flow velocities (Table 3) and then SSC was calculated under different levels of shear stress.

### The relationship between wind speed and sediment resuspension

Through shear stress, we established links between our field observations and the indoor experiment. We determined the relationship between wind speed and sediment resuspension. Sediment resuspension rate was calculated as follows:

$$r = \left[ \bar{V}(c_n - c_0) + \sum_{j=1}^n V_j(c_{j-1} - c_a) \right] / (A \cdot t) \quad (2)$$

where  $r$  is the sediment resuspension rate ( $\text{mg}/(\text{m}^2 \text{d})$ );  $\bar{V}$  is the volume of water sample in the simulator (L);  $c_n$  is the nutrient concentration in water at the  $n$ th sampling ( $\text{mg}/\text{L}$ );  $c_0$  is the initial nutrient concentration ( $\text{mg}/\text{L}$ );  $V_j$  is the sample volume (L);  $c_{j-1}$  is the nutrient concentration in water at the  $(j-1)$  sampling ( $\text{mg}/\text{L}$ );  $c_a$  is the nutrient concentration after adding original water ( $\text{mg}/\text{L}$ );  $t$  is the release time (d); and  $A$  is the area of the water–sediment interface ( $\text{m}^2$ ).

Sediment resuspension induced by wind is a usual phenomenon which often occurs when the bottom stress is sufficiently large to entrain material from the bed. Some researchers have used the power equation as a mathematical function linking SSC with wind speed in the fieldworks

Table 3 | Shear stress and SSC under different flow velocity in laboratory simulation

$u$ (cm/s)	$\tau$ ( $10^{-3} \text{ N/m}^2$ )	SSC (mg/L)
0.5	4.9	2.2
0.8	7.9	3.9
1.0	9.9	5.1
2.0	20.0	11.9
3.0	29.8	19.6
4.0	40.2	27.9
6.0	60.1	46.0
8.0	82.9	65.4
10.0	102.1	86.0
14.0	148.7	130.1

(Qian et al. 2011; Qiao et al. 2011). Other expressions, such as the exponential function (You et al. 2007; Hu et al. 2011), were determined with previous laboratory simulation. The obtained expression in this work is more similar to field observations in shallow lakes. The average resuspension rate in the overlying water was highly correlated with wind speed ( $R^2 = 0.99$ ), which suggests a good reliability in calculating the average resuspension rate caused by wind. When the flow velocity was in the range of 0–1 cm/s (at wind speeds in the range of 0–3 m/s), sediment resuspension was almost negligible (Figure 5). When the flow velocity increased to 4 cm/s (wind speed: 7 m/s), fine particles were suspended and the water became distinctly turbid. This phenomenon indicated that the shear stress caused by the wind had reached the incipient value. According to previous observations of SSC in Lake Taihu (Qin et al. 2005; Hu et al. 2011), the critical wind speed which caused sediment resuspension was about 5–6.5 m/s. When the wind speed increased from 8 to 14 m/s, much more sediment was suspended. The phenomenon of sediment resuspension in this experiment is similar to that described by Li (2005). Additionally, the average resuspension rates reached 200, 1,000, and 4,400 g/(m<sup>2</sup>d) when the wind speed was about 3, 7, and 14 m/s, respectively. This result is similar to that described by Hu et al. (2011) who found the sediment resuspension rate was in the range of 0–500 g/(m<sup>2</sup>d) in spring (wind speed: 2–6 m/s), 0–1,000 g/(m<sup>2</sup>d) in summer (wind speed: 2–8 m/s), 0–200 g/(m<sup>2</sup>d) in autumn (wind speed: 2–5 m/s), and 0–1,200 g/(m<sup>2</sup>d) in winter (wind speed: 2–6 m/s). Figure 6 shows the relationship between wind speed and resuspension rates for TN and TP. The correlation of TP release rates and wind speed was strong ( $R^2 = 0.934$ ), but the correlation with TN was less so ( $R^2 = 0.831$ ). When the wind speed increased

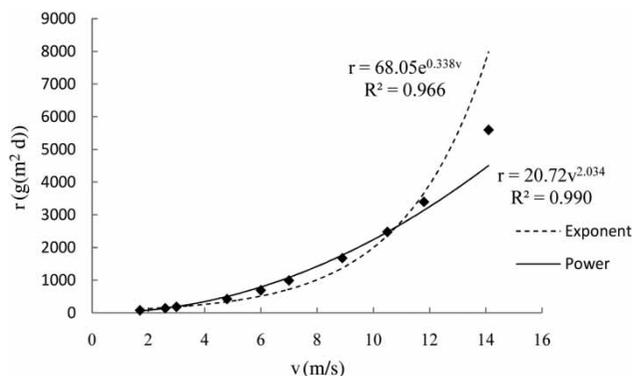


Figure 5 | Relationship between wind speed and sediment resuspension rate.

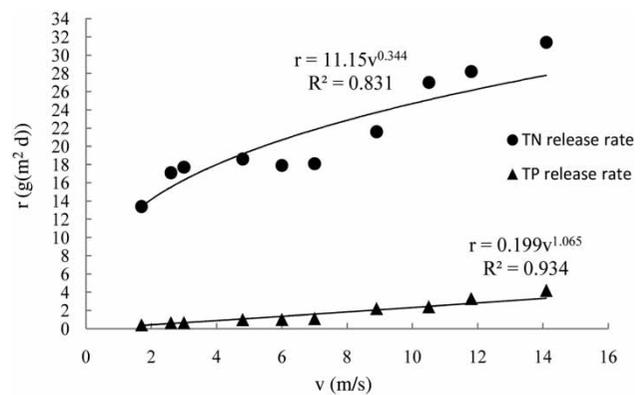


Figure 6 | Relationship between wind speed and TN and TP resuspension rates.

to 7 m/s, the TP release rate increased to 1.1 g/(m<sup>2</sup>d) and TN release rate reached 18.1 g/(m<sup>2</sup>d).

## CONCLUSIONS

Frequent resuspension of sediments is recognized as an important process in large shallow lakes, impeding the recovery of eutrophic lakes. This paper presents field observations and a simulation experiment to study the characteristics of sediment resuspension. Our results reveal a quantitative relationship between wind speed and sediment resuspension. Our findings can be summarized as follows.

- (1) Flow velocity increased with wind speed. A quadratic, linear, and power relationship can be used to express the relationship between wind speed and flow velocity observed in the field. After comparison, a quadratic relationship most closely matches the results in this study. In Lake Taihu, even with no wind there is always a small flow at the bottom of the lake. This explains why this relationship in the field differs from the experimental results.
- (2) The SSC increased with increase of flow velocity. Compared to the linear relationship, the power formula better expressed the relationship between sediment resuspension and flow velocity wind speeds in the range of 0–14 m/s.
- (3) The average resuspension rate in overlying water was strongly correlated with wind speed ( $R^2 = 0.99$ ), which suggests wind speed can be used to accurately calculate average resuspension rates. These two factors can be expressed by  $r = 20.72v^{2.034}$ . The critical wind speed for sediment resuspension is about 7 m/s. Under this condition, the average resuspension rate was 1,000 g/(m<sup>2</sup>d),

the TP release rate was 1.1 g/(m<sup>2</sup> d), and the TN release rate was 18.1 g/(m<sup>2</sup> d). The relationship formula, the critical wind speed and the sediment resuspension rate in this experiment are all similar to reference researches.

Compared to other simulation methods of sediment resuspension, the cylindrical simulator provides more realistic results. The obtained results provided estimated sediment resuspension rates under different wind conditions. Due to the experimental scale and other interfering factors, the accuracy of the parameters derived from the simulator should be improved through further research.

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