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Characteristics of sediment resuspension in Lake Taihu, China: A wave flume study

Yanqing Ding[a,b], Limin Sun[a,c], Boqiang Qin[b,*], Tingfeng Wu[b], Xia Shen[d], Yongping Wang[d]

[a] School of Resource and Geosciences, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[b] Taihu Laboratory for Lake Ecosystem Research, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[c] School of Environment, Beijing Normal University, State Key Joint Laboratory of Environmental Simulation and Pollution Control, Beijing 100875, China
[d] Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing 210029, China

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ABSTRACT

Lake Taihu is a typical shallow lake which frequently happens sediment resuspension induced by wind-induced waves. The experiments are carried on to simulate the wave disturbance processes in wave flume by setting a series of wave periods (1.2 s, 1.5 s, 1.8 s) and wave heights (2 cm, 10 cm). It aims to analyze the characteristics of sediment resuspension and the mechanisms of nutrients release and to evaluate the effects of sediment dredging on sediment resuspension and nutrients release in Lake Taihu. The results show that wave shear stress during 2 cm and 10 cm wave height processes ranges 0.018–0.023 N/m^2 and 0.221–0.307 N/m^2, respectively. Wave shear stress has no significant differences between wave periods. Wave height has much more effects on sediment resuspension. Wave height of 2 cm could induce total suspended solids (TSS) reaching up to 5.21 g/m^2 and resuspension flux of sediment (M) up to 1.74 g/m^2. TSS sharply increases to 30.33–52.41 g/m^2 and M reached up to 48.94 g/m^2 when wave height reaches to 10 cm. The disturbance depth under different sediment bulk weights ranges from 0.089 to 0.161 mm. Variation of suspended solids in 3 layers (1 cm, 5 cm, 20 cm above sediment interface) has no significant differences. Organic matter, TN and TP have positive relationship with SS. Organic matter is only accounted for 5.7%–7.3% of SS. The experiments under different sediment bulk densities (1.34 g/cm^3, 1.47 g/cm^3 and 1.59 g/cm^3) find that TSS and M fall by 44.2% and 39.8% with sediment bulk density increasing, respectively. Total TN, DTN, TP and DTP decrease by 24.3%–33.6%. It indicates that sediment dredging could effectively reduce SS concentration and nutrient levels in water column. The researches provide a theoretical basis for sediment dredging to control the shore zone of Lake Taihu for lake management.

1. Introduction

Shallow lakes are characterized by episodic resuspension of sediments. Resuspension occurs when the bottom shear stress exceeds the critical shear stress, which depends on water content and sediment grain size (Håkanson and Jansson, 1983). Several hydrodynamic processes can trigger resuspension including wind-induced waves (Hamilton and Mitchell, 1997; Wu et al., 2013a,b), current and turbulence fluctuations (You et al., 2007; Luo et al., 2006), although wind-induced waves are commonly the primary driving force in shallow lakes (Håkanson, 2005). Sheng and Lick (1979) found that wave-generated shear stress contributed to more than 70% of sediment resuspension happened in shallow lakes.

Frequent wind-induced resuspension generally occurs over temporal scales from minutes to hours (Villard et al., 1999; Liu and Huang, 2009) and may affect the function of lacustrine ecosystems. The dynamic processes at water-sediment interface are critical for transporting solid particles and nutrients (Wang et al., 2014; Wu et al., 2013b). Internal nutrient release occurs when sediments are re-suspended by wind-driven currents and waves acting on the water-sediment interface. Excessive nutrients loading, especially nitrogen (N) and phosphorus (P), has led to the appearance of eutrophication and massive harmful algal blooms (Smith, 1983; Abell et al., 2010; Xu et al., 2010; Zhang et al., 2014).

Lake Taihu is a typical shallow lake with a surface area of 2338 km^2 and a mean depth of 1.9 m, which commonly happens wind-induced sediment resuspension due to the lake's high dynamic ratio (Håkanson, 1982). Approximately 1100 km^2 of lakebed are covered by sediment, which accounts for about 47.5% of the lake area (Luo et al., 2004). Due to the Southeast monsoon, sediments are primarily

* Corresponding author.
E-mail address: qinbq@niglas.ac.cn (B. Qin).

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deposited in the western and northern portions of Lake Taihu with thickness greater than 4 m (Luo et al., 2004). Lakebed sediments are commonly rich in N and P, especially top surface sediments. Nitrogen content in the surface sediment is 0.05% - 0.2%, while total phosphorus is 0.01% - 0.05% (Fan et al., 2000). The hydrology and nutrient input result in a trophic gradient characterized by hypertrophic conditions in the northern part of Lake Taihu and mesotrophic conditions in the southeastern part of Lake Taihu (Chen et al., 2003). Satellite imaging shows that algal blooms are prominent in large parts of the northwestern and central lake after typhoon events (Zhu et al., 2014).

In 2007, Lake Taihu experienced a toxic algae bloom that made headlines around the world (Qin et al., 2010). Over the subsequent decade, considerable attention has been paid to eutrophication control in Lake Taihu. Nutrient release induced by sediment suspension is an important nutrient source in shallow eutrophic lakes (Wu et al. 2013a; Wang et al., 2015). Current field monitoring of wind-induced sediment resuspension mainly focuses on water quality (Fan et al., 2003; Zhu et al., 2007; Wu et al., 2009). It is difficult to understand the relationship between wave action and nutrients release due to complex hydrodynamics. Numerical models are applied to reproduce water currents and waves to study the effects of hydrodynamics on sediment resuspension and water quality (Hu et al., 2006). Numerous experimental methods have been applied to analyzing the hydrodynamic effects of waves on sediment suspension, including Y-shape apparatus (You et al., 2007), annular current flume experiments (Widdows et al., 2002) and wave flume experiments (Sun et al., 2006). Wave flume experiment is ideal for defining wave stress by regulating wave height and period.

In this study, we design wave flume experiments to explore the characteristics of sediment resuspension and the mechanism of sediment nutrient release in Lake Taihu. The aims of these serial experiments are to (1) analyze the hydrodynamic conditions under different wave periods and wave heights in the wave flume; (2) analyze the variations of suspended solids (SS) and nutrients in different hydrodynamic conditions; (3) establish the relationships among wave characteristics, resuspension and nutrients release; (4) evaluate the effect of sediment dredging from the perspective of sediment bulk density.

2. Materials and methods

2.1. Study area

Lake Taihu is the third largest freshwater lake in the lower Yangtze River Delta in China between 30°56′–31°33′N and 119°53′–120°36′E. Water temperature ranges from 4.8 to 29.2 °C with an average annual water temperature of 17.3 °C (Zhao et al., 2011). Wind speed varies between 0 and 10 m/s with an average wind speed of 4.3 m/s (southeaster) in spring and summer and 0.9 m/s (northwester) in the autumn and winter (Qian, 2012). Water quality has seriously degraded over the last several decades due to severe eutrophication (Huang et al., 2014). Outbreaks of cyanobacteria blooms are commonly correlated with sustained winds, which confirms that wind-induced wave disturbance is an essential driving force for internal nutrient release induced by sediment resuspension in Lake Taihu (Kristensen et al., 1992; Ding et al., 2012). Algal blooms are most intense in Zhushan and Meiliang Bays (Xie et al., 2003) (Fig. 1).

Meiliang Bay is a semi-enclosed bay in the northern part of Lake Taihu with an area of 130 km^2 and a mean depth of 1.8 m. Fifty percent of the Meiliang Bay lakebed is covered by sediment rich in organic matter (Fan et al., 2000). Since 1998, Meiliang Bay has experienced severe algal blooms in summer and autumn (Chen et al., 2003; Guo, 2007). The Liangxi and Zhiwu rivers bring municipal contaminants from Wuxi city and Changzhou city into Meiliang Bay, which contributes to increasing eutrophication.

2.2. Experiment

Sediments collected from Meiliang Bay mainly consist of silty sand with an average particle size of 13 μm. The top 15-cm sediments rich in organic matter were collected by the environmental cutter suction dredger and then transferred to the laboratory at the Hydraulic Academy in Nanjing, Chinese Ministry of Water Resources. The top 15 cm sediments are the active sediment layer in Taihu Lake (Qin et al., 2004; Hu et al., 2006). Then, sediments were stirred well and paved on the middle of wave flume, with sediment length 7 m and thickness 7–10 cm (Fig. 2). After sediment in the flume naturally settled for one month, water was slowly poured into the wave flume until the water depth reached at 40 cm depth. Then, the system was kept still for several days. The wave flume (length: 25 m, width: 0.5 m, height: 0.8 m) is equipped with wave-maker at the inlet and wave alleviator at the opposite end. Wave height and wave period were collected by capacitive wave instrument (MTS, USA) which are installed at both ends of the sediment section. The whole system is automatically controlled via a computer.

The wave intensity is controlled by setting six groups of hydrodynamic conditions for different wave periods (1.2 s, 1.5 s and 1.8 s) and wave heights (2cm, 10 cm) to simulate wave disturbances commonly occurring in Lake Taihu. The bulk density of top - 2 cm sediments in wave flume is measured before each group test (1.34 g/cm^3, 1.47 g/cm^3, 1.59 g/cm^3, respectively). Water samples are collected at 3 water column layers (1 cm, 5 cm and 20 cm above the water-sediment interface, respectively, Fig. 1). Three parallel water samples are taken for each layer. After background sampling, the wave-maker is switched on to produce regular sinusoidal waves 2 cm height (WH2) for 60 min and then 10 cm height (WH10) for 120 min. Water samples are collected at 30 and 60 min during the WH2 wave period and at, 70, 90, 120, and150 min during the WH10 wave period.

2.3. Sample analysis

Water samples were divided into two subsamples, with one set of subsamples immediately filtered for suspended solids and the other set analyzed for nutrients. To determine SS, the remaining particulate matter on the filters after 100–250 ml sampling water was dried at 105 °C for 4 h until its weight kept constant. Organic matter (OM) was measured using a 4 - h ignition of the dried particulate matter on a membrane at 550 °C. The loss on ignition (LOI) is the ratio of OM to SS. Total Nitrogen (TN), total Phosphorus (TP), dissolved total phosphorus (DTP) and dissolved total nitrogen (DTN) were determined by spectrophotometry after digestion with alkaline potassium persulfate (Jin and Tu, 1990). The detection limit is 0.01 mg/L for TN and DTN and 0.01 mg/L for TP and DTP.

2.4. Data processing

Preliminary treatment of the experimental data was performed in MATLAB 7.0. One-way analysis of variance (ANOVA) was carried out using SPSS 19.0 software to test for significant differences between the various hydrodynamic conditions. A significance level of $p < 0.05$ is used for all tests.

2.4.1. Wave shear stress

Grant and Madsen (1979) first proposed the basic theory of bottom shear stress at the water-sediment interface. In shallow lakes, the shear stress caused by wave at the water-sediment interface can be calculated by the following equation:

$$\tau_w^b = 0.5\rho f_w u_m^2 \quad (1)$$

where τ_w^b is the wave shear stress, N/m^2; ρ is the water density, kg/m^3; f_w is the wave friction coefficient; u_m is the maximum wave orbital

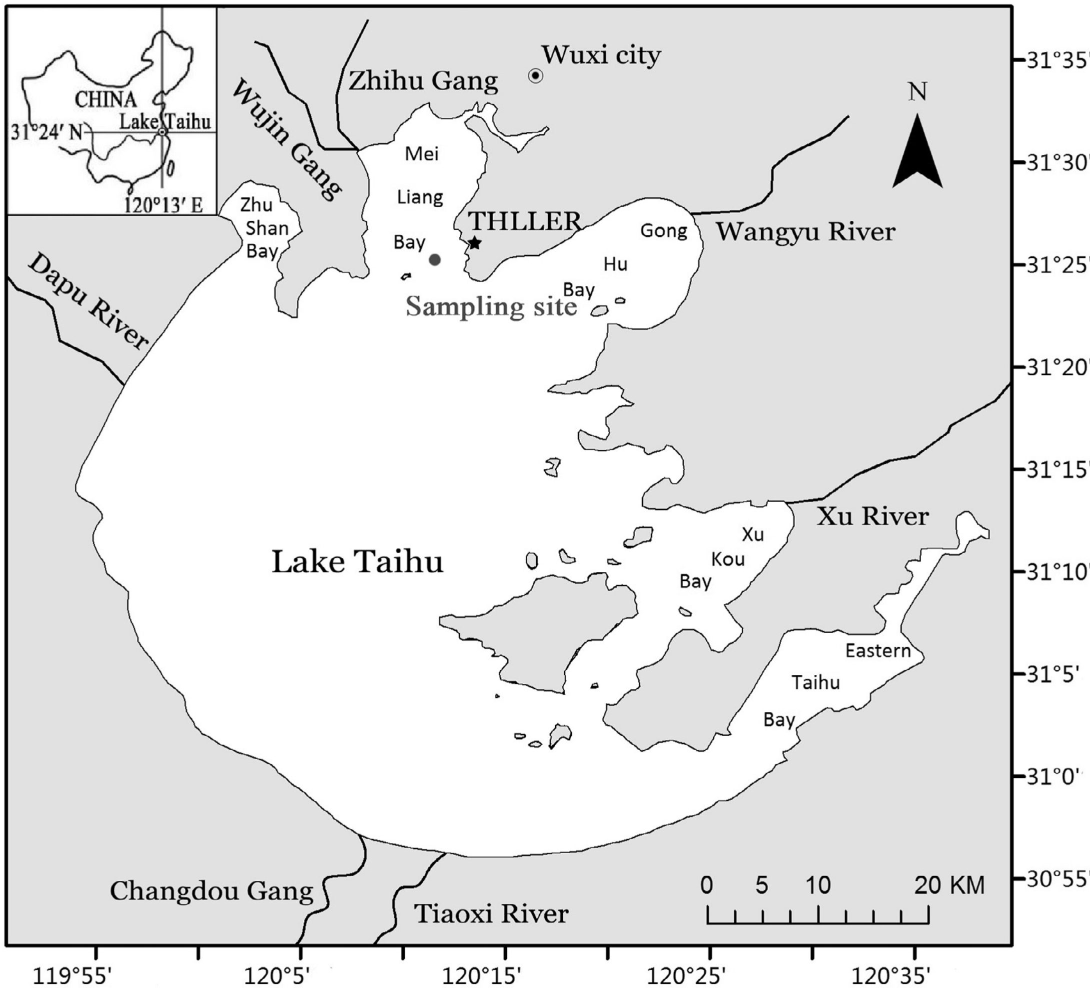

Fig. 1. Location of Lake Taihu and the sampling site. Sediment collected site (circle with a point); TLLER (Taihu Laboratory for Lake Ecosystem Research) (pentagon).

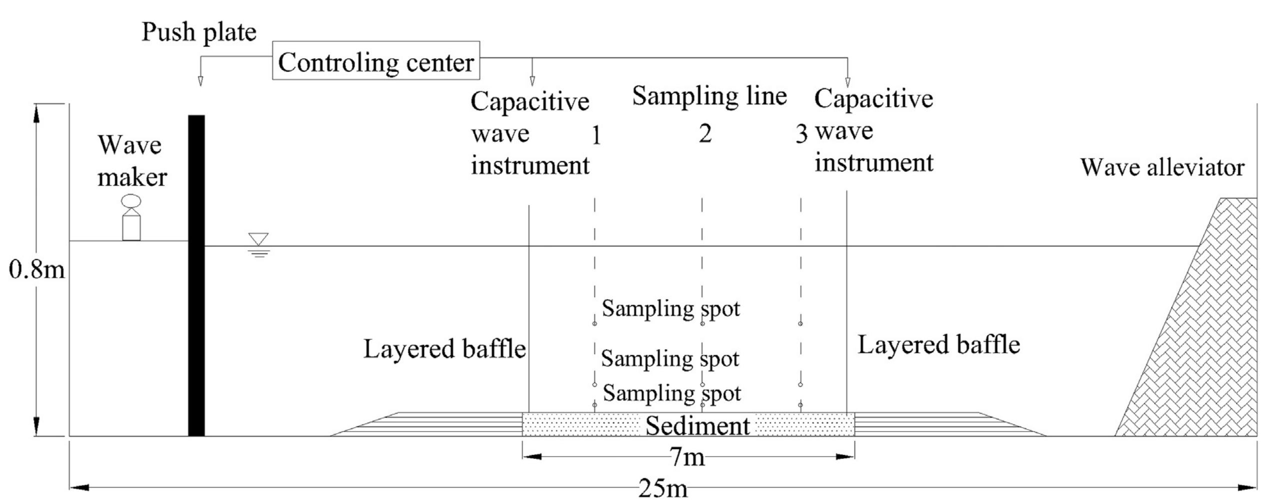

Fig. 2. Sketch map of the wave flume, sampling site in three layers (1cm above sediment, 5 cm above sediment, 20 cm above sediment).

velocity near the bed, m/s.

The f_w is calculated as follows (Jiang et al., 2000):

$$f_w = \exp[5.2(A_\delta/K_S)^{-0.19} - 6.0] \quad (2)$$

where A_δ is the wave-particle amplitude (m), which is determined by linear wave theory. $A_\delta = H_s/[2sinh(2\pi h/L_s)]$ (Where H_s is effective wave height (m); L_s is wave length (m); K_s is physical roughness of the lake bottom. This study uses 0.2 mm as the lake bottom roughness based on previous studies (Hawley, 2000; Luo, 2004; Nielsen et al., 2001; Qin et al., 2004); when $A_\delta/K_\delta \le 1.59$, $f_w = 0.3$.

u_m is calculated as follows:

$$u_m = \pi H_s/(T_s sinh(2\pi h/L_s)) \quad (3)$$

where T_s is wave period, s and L_s is effective wave length, which can be expressed as follows:

$$L_s = gT_s^2 \tanh(2\pi h/L_s)/2\pi \quad (4)$$

Since the total shear stress is primarily caused by wind-induced waves in Lake Taihu (Li et al., 2017), the shear stress is approximated as the wave shear stress.

2.4.2. Resuspension flux

Samples were collected at 1, 5 and 20 cm above the water–sediment interface, so the corresponding layer thicknesses were 3 cm (bottom layer), 7 cm (middle layer) and 30 cm (upper layer), respectively.

Total amount of suspended solids in the water column per unit area is the Total of Suspended Solids (TSS, g/m^2), which is calculated as follows:

$$TSS = \sum_{i=1}^{n} SS_i \Delta z_i / 100 \quad (5)$$

where SS_i is suspended solids concentration in the i-th layer, mg/L; Δzi is the thickness of the i-th water layer, cm; n is total vertical layers.

$$M_i = TSS_i - TSS_{i-1} \quad (6)$$

The resuspension flux, M_i is the resuspension flux at i-th sampling time.

The sediment disturbance depth can be calculated using the following equation (Gouleau et al., 2000; Gao and Jia, 2004):

$$H = M/(\gamma_{wet}(1-W)) \quad (7)$$

where H is the Mean disturbance depth, mm; M is the total amount of resuspended solids, g/m^2; γ_{wet} is the wet bulk density of sediments, g/cm^3; W is the moisture content of sediments, %.

In order to analyze the variations of nutrient content, we introduce the total amount of water column material per unit area (T, g/m^2). The specific calculation method is similar to TSS.

3. Results

3.1. Hydrodynamic characteristics

The dynamic process has WH2 wave process and WH10 wave process. During WH2 wave processes, the maximum wave orbital velocity near the lakebed ranges from 0.031 m/s to 0.041 m/s (Table 1). Bottom wave shear stress ranges from 0.018 to 0.023 N/m^2 (Table 1). When wave height reaches up to 10 cm, the maximum wave orbital velocity varies from 0.154 m/s to 0.256 m/s and wave shear stress is from 0.221 N/m^2 to 0.307 N/m^2. The wave shear stresses during WH2 wave processes are remarkably small. The wave shear stress during WH10 wave processes is significantly larger than that under 2 cm wave height ($p < 0.01$). The relationship between the wave period and bottom shear stress shows the positive correlation ($p < 0.01$), which indicates that shear stress magnitude increases with wave period increasing. While, wave shear stresses have no significant difference between 1.2 s, 1.5 s and 1.8 s.

Table 1
Wave characteristics and shear stress associated with production of 2 cm (WH2) and 10 cm (WH10) wave height processes.

Wave period (s)	Wave height (cm)	Maximum wave orbital velocity near the bed (m/s)	Wave length (m)	Shear stress/(N/m^2)
1.2	2	0.031	1.935	0.018
1.2	10	0.154	1.935	0.221
1.5	2	0.038	2.614	0.022
1.5	10	0.188	2.614	0.280
1.8	2	0.041	3.267	0.023
1.8	10	0.206	3.267	0.307

Table 2
Resuspension flux with sediments density of 1.59 g/cm^3 under varying wave conditions.

Wave height H (cm)	T = 1.2 s		T = 1.5 s		T = 1.8 s	
	TSS (g/m^2)	M (g/m^2)	TSS (g/m^2)	M (g/m^2)	TSS (g/m^2)	M (g/m^2)
0	3.85		0.94		3.47	
2	4.56	0.71	1.32	0.38	5.21	1.74
10	30.33	26.48	48.84	47.90	52.41	48.94

3.2. Sediment resuspension and hydrodynamic conditions

Wave shear stress acting on the sediment-water interface exceeds the critical stress to induce sediment resuspension and to increase TSS concentration. According to the hydraulic judging criteria, the critical stress for sediment resuspension means that the surface particles began to gradually float upward. During the WH2 wave processes, sediment particulates just floats near the sediment-water interface and only the smaller sediment particles are suspended into the water column. TSS varies from 1.32 to 5.21 g/m^2 and resuspension flux is 0.38–1.74 g/m^2 under different wave periods during the WH2 wave period (Table 2). TSS and resuspension flux (M) under different wave periods have no significant increase based on the initial values. Wave shear stresses under 10 cm wave height are much larger than the critical stress. During WH10 wave processes, sediment particulates are largely suspended into water column. TSS increases sharply to 30.33 g/m^2 - 52.41 g/m^2, which is almost 50 times of the initial value. Resuspension flux reached up to 48.94 g/m^2. TSS and resuspension flux (M) under different wave periods has no significant difference ($p < 0.01$).

Sediment disturbance depth depends on wave shear and sediment bulk weight. During 1.5 s wave period processes, the calculated disturbance depth under different bulk weigh sediments ranges from 0.089 mm to 0.161 mm (Table 3). The disturbance depth is proportional to TSS in the water column ($p < 0.01$) and inversely proportional to the wet bulk density of the sediment ($p < 0.01$). In other words, the disturbance depth increases with the suspended solids increasing and decreased with sediment bulk density.

3.3. Variations of SS and nutrients during suspension processes

Before beginning to make waves, the background water samples in three layers (above sediment 1 cm, 5 cm, 20 cm) are collected. From bottom to top the layers, SS concentration in water column is 3.4 mg/L, 3.4 mg/L and 2.0 mg/L (Fig. 3), respectively. The initial TSS is 0.94 g/m^2 (Fig. 4).After 60 min of WH2 wave processes, there is no significant increase of SS concentration in the overlying water. The SS of the bottom and middle layers rises slightly to 7.8 mg/L and 8.1 mg/L, respectively and the upper layer is unexpectedly reduced to 1.75 mg/L. At WH2 stage, the bottom shear stress is only 0.022 N/m^2, which is less than the critical shear stress. So, sediment particles remain near to the water–sediment interface and oscillate with the wave action.

Subsequently, as the wave height increases to 10 cm, SS in each layer increases rapidly and transparency of the overlying water is reduced. SS concentration at 1 cm, 5 cm and 20 cm above the water-

Table 3
Disturbance depth under sediment with different bulk densities during 1.5 s wave period.

γ_{wet} (g/cm^3)	M (g/m^2)	Water content W (%)	Depth H (mm)
1.34	72.38	66.4	0.161
1.47	58.59	66.4	0.119
1.59	47.90	66.4	0.089

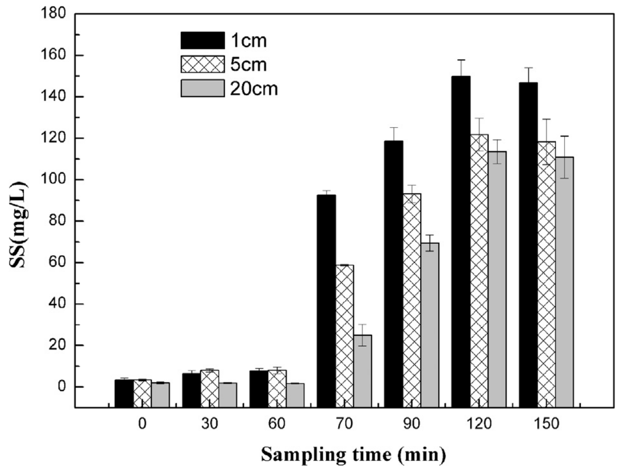

Fig. 3. Variation of suspended solids (SS) concentration in 1 cm, 5 cm, and 20 cm above the sediment during wave processes.

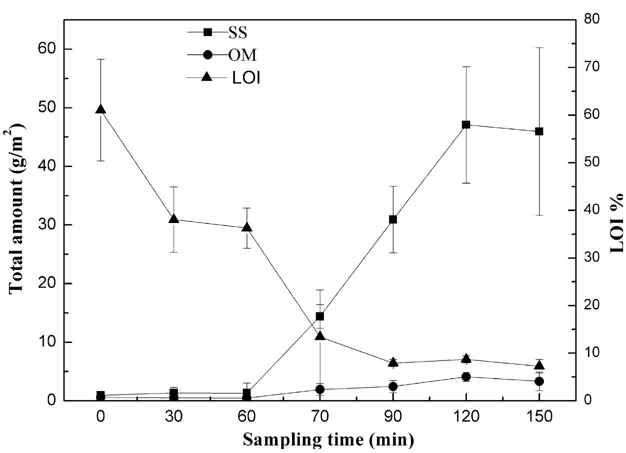

Fig. 4. Variations of total suspended solids (SS), organic matter (OM) and loss on ignition (LOI) in water column during wave processes.

sediment interface increases to 27 times, 17 times and 12 times of the initial value, respectively. TSS increases rapidly to 15 times of background levels (Fig. 4). SS concentration gradually increases and reaches to the peak after 120 min. By now, SS concentration in the bottom, middle and upper layers is 160.9 mg/L, 127.8 mg/L and 116.9 mg/L, respectively. TSS also increases to 48.8 g/m^2, which is higher than 50 times of initial value. SS concentration of the bottom layer was significantly higher than that of the upper ($p < 0.01$) and middle ($p < 0.01$) layers and variation trends of SS concentration in three layers keep consistent.

TSS has the positive correlation with OM, TN and TP (Table 4, $p < 0.01$), which further indicates that the variation trends of OM, TN and TP are consistent with SS in the overlying water throughout the trial. After WH2 wave process, the total amount of OM has a slight

Table 4
Correlation coefficients of total amount of SS, OM, N and P.

	SS	OM	TN	DTN	TP	DTP
SS	1					
OM	0.996*	1				
TN	0.949*	0.933*	1			
DTN	−0.503	−0.473	−0.634	1		
TP	0.982*	0.976*	0.971*	−0.554	1	
DTP	−0.383	−0.363	−0.532	0.401	−0.401	1

Notes: (*$p < 0.01$)

increase, while LOI decreased from 62% to 38% (Fig. 4). While the total amount of TN and TP experience a slight increase (Fig. 5). After 60 min of WH10 wave process, total amount of OM increases from 0.58 g/m^2 to 3.46 g/m^2 and LOI decreases from 38% to 8%, which indicates that the majority of re-suspended solids are inorganic substances. The background values of TN and TP is 0.704 g/m^2 and 0.015 g/m^2, respectively. WH2 wave process has little effect on TN and TP concentration in water column. After WH10 wave process begin, TN and TP rapidly increase in the initial 5–10 min. TN and TP steadily increases 1.16 to 1.86 times in the later 120 min. DTN and DTP r show no obvious variation throughout the experiment. Specifically, DTN and DTP significantly decrease after 30 min of WH10 wave, which may be due to the increase of particles concentration which could adsorb the soluble nutrients.

3.4. Sediment resuspension under different sediment bulk densities

Sediment dredging remove the surface high organic and floppy sediment and induces to increase the sediment bulk density. Before the wave processes, the bulk densities of the top 2 cm sediments is measured 1.34 g/cm^3, 1.47 g/cm^3, 1.59 g/cm^3, respectively. After wave processes, TSS and resuspension flux in water column under three sediment bulk densities is shown in Table 5. Results show that TSS and resuspension flux of suspended solids (M) under three different wave periods are significant different ($p < 0.01$). TSS and M increased with wave period increasing. At the same wave period, TSS and M has an extremely significant decreasing with the sediment bulk density gradually increasing ($p < 0.001$, Table 5, Fig. 6a). After twice sediment dredging, TSS and M in the overlying water have fallen by about 44.2% and 39.8%, respectively. Similarly, OM ($p < 0.01$, Fig. 6b), TN ($p < 0.01$, Fig. 6c), DTN ($p < 0.01$, Fig. 6d), TP ($p < 0.05$, Fig. 6e) and DTP ($p < 0.05$, Fig. 6f) are significantly reduced with increasing bulk density. After dredging twice, final values for total TN, DTN, TP and DTP decreased by 24.3% - 33.6%.

4. Discussion

4.1. Dynamic analysis and sediment resuspension

In shallow lake ecosystem, wind-induced waves are the primary force driving sediment resuspension (Qin et al., 2006; Stone, 2011). Sediment resuspension is commonly estimated as a function of the shear stress on the lakebed above a critical value (Wang et al., 2014). The critical shear stress inducing sediment suspension range from 0.01 to 0.1 N/m^2 (Fan et al., 2004; James et al., 1997; Sheng and Lick, 1979). In the series of wave flume experiments, the wave shear stress during the WH2 processes wave period is between 0.018 N/m^2 and 0.023 N/m^2. This value is equivalent with the critical value of 0.019 N/m^2 calculated by Luo et al. (2006) and 0.02 N/m^2 by Li et al. (2017). The wave shear stress during the WH2 processes is significantly smaller than the critical value (0.037 N/m^2) which derives from the medium size sediment with 0.017 mm grain size and 1.3 g/cm^3 sediment bulk density by Qin et al. (2004). According to researches on the suspended solids and wave shear stress, WH2 and WH10 wave processes are equivalent to the field wind speed of 3.0 m/s and 8.0 m/s in Lake Taihu based on shear stress in the field (Qin et al., 2004; Luo et al., 2006; Sun et al., 2006), respectively.

The critical wave stress inducing sediment resuspension depends on sediment size, viscosity, water content, shape, density, and other chemical properties. Therefore, it is complicated to quantitatively describe the relationship between the critical stress and sediment properties (Luo et al., 2006). Thus sediments properties vary widely due to significant temporal and spatial variation in Lake Taihu. The critical stress will change according to these variations.

Previous studies (Qiao et al., 2011; Li et al., 2017) indicate there is a relationship between wave-induced shear stress and SS. According to

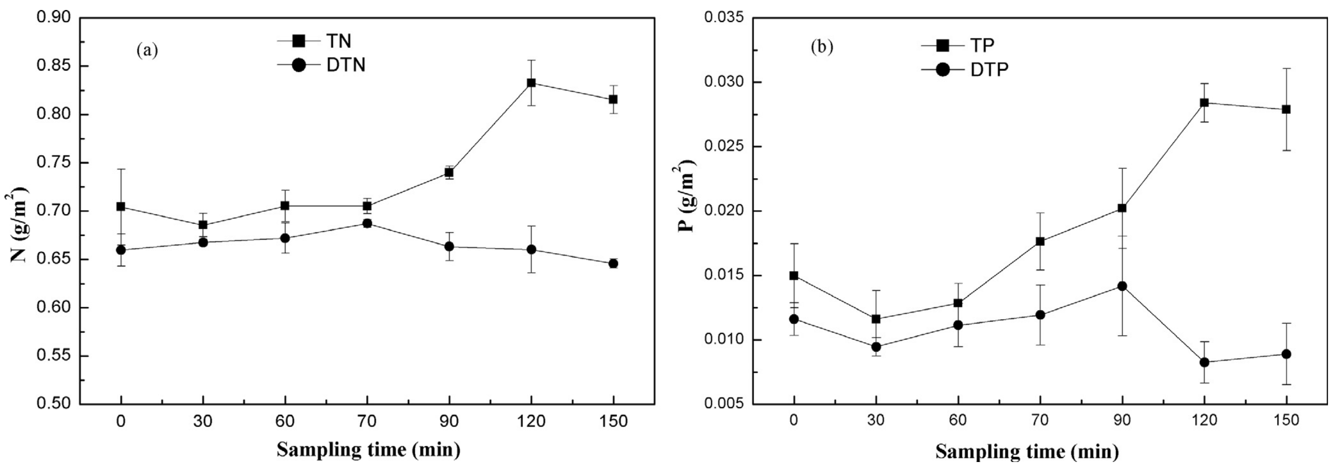

Fig. 5. Variation of N (a) and P (b) in water column during wave processes, total nitrogen (TN) and dissolved total nitrogen (DTN), total phosphorus (TP) and dissolved total phosphorus (DTP).

Table 5
TSS and resuspension flux during different wave period processes with the variable sediment bulk densities.

γ_{wet} (g/cm³)	TSS (g/m²)			M (g/m²)		
	T = 1.2 s	T = 1.5 s	T = 1.8 s	T = 1.2 s	T = 1.5 s	T = 1.8 s
1.34	54.31	73.5	82.98	43.97	72.38	66.61
1.47	44.21	59.18	65.96	38.87	58.59	62.32
1.59	30.33	48.84	52.41	26.48	47.90	48.94

the researches about the quantitative relationship between SS and wind speed (V) ($SS = \alpha V^{\beta} + SS_0$) (Qiao et al., 2011), we analyze the relationship between bottom shear stress and total SS, OM, TN, TP, respectively (Fig. 7). Bottom shear stress adequately correlates with total SS ($R^2 = 0.990$, $p < 0.01$), OM ($R^2 = 0.956$, $p < 0.01$), TN ($R^2 = 0.967$, $p < 0.05$) and TP ($R^2 = 0.986$, $p < 0.05$). The SS of each layer is different in various suspended conditions. Furthermore, SS and bottom shear stress show similar correlations in 3 different water layers. That shows that the best fit formula for SS and wave shear stress is $SS = \alpha V^{\beta} + SSC_0$, with $R^2 = 0.990$. Li et al. (2017) divided the sediment suspension process into four stages using three shear stress thresholds. During WH2 wave process (~3.0 m/s wind speed), only a small amount solids were floated above the lake bed. However, a large number of sediments solids are rapidly suspended after WH10 wave action (~8.0 m/s wind speed), which is consistent with sediment resuspension theory (Li et al., 2017). Vertically, results show that after 10 min WH10 wave disturbance, SS in the bottom, middle, and upper layers increased by 27 times, 17 times and 12 times, respectively. However, after 60 min WH2 wave disturbance, SS in the bottom layer increases by only 4.4 mg/L and SS in the upper layer dramatically decreases from 2.0 mg/L to 1.75 mg/L. That means that the resuspension of sediments is accompanied by concurrent sedimentation of the suspended matter. This phenomenon is particularly evident in the WH2 wave process. Following WH10 wave process, SS in all layer increases significantly in the initial 30 min and then gradually stabilizes. Qin et al. (2004) and Ding et al. (2011) found that mass exchange near the water–sediment interface occurs primarily within the top 5–10 cm of sediment. During this process, SS in the bottom layer (1cm above the water-sediment interface) is significantly higher than that of the upper (20 cm above the water-sediment interface) and middle layer (5cm above the water-sediment interface) ($p < 0.01$), and the variation trend of SS in these three layers were consistent.

4.2. Effects of sediment resuspension on nutrients release

The dynamic processes of near-bed sediments are critical for transporting solid particles and nutrients (Wang et al., 2014; Wu et al., 2013a). Internal nutrient release occurs when sediments are re-suspended into water column by currents or waves. Wave disturbance rapidly increases SS in the overlying water, with OM accounting for only 5.7% - 7.3%. The stronger the wave disturbance is, the larger the proportion of inorganic particles in the suspended matter, which is consistent with field observations (Ding et al., 2012; Li et al., 2017). OM, TN and TP have positive relationship with SS. The increase in OM, TN and TP concentrations in the overlying water are caused by wave-induced sediment suspension, which is consistent with other field studies in shallow lakes (Søndergaard et al., 2013; Qin et al., 2006; Ding et al., 2012).

In large shallow lakes, the release of dissolved nutrients from sediment commonly occurs in conjunction with molecular diffusion, adsorption and desorption, and is affected by changes in redox conditions and hydrodynamic disturbances. Therefore, it is difficult to quantitatively identify the effects of hydrodynamic disturbance on the internal release of dissolved nutrients based on field observations (Qin et al., 2004; Sun et al., 2006). During WH2 wave process, DTN and DTP in the bottom layer slightly increases with sediment resuspension. After 30 min WH10 wave disturbance, DTN and DTP concentrations in the overlying water rapidly decreased (Fig. 5). One possible explanation is that soluble substances are easily adsorbed by particulate matter and subaqueous sediments (Sun et al., 2006; Zhang et al., 2013). Under wave disturbance, sediments resuspension can largely increase SS concentration in the overlying water and decrease of median SS particle size. Therefore, sediment resuspension induced by wavedistinctly increase fine particles to further increases nutrients adsorption. Another possible explanation is that the dissolved oxygen (DO) concentration increases in the overlying water and the interstitial water of sediments due to the disturbance of oxygen enrichment (Ding et al., 2011). It forms a thin oxide layer is formed on the surface of the sediments to increase the adsorption capacity of the sediments for metal elements such as iron (Fe) and manganese (Mn) (Zhu et al., 2005).

The critical shear stress in Lake Taihu ranges 0.01–0.1 N/m² (Qin et al., 2004; Luo et al., 2006). It's roughly equivalent to 5–6 m/s wind speed in the field. Nutrients release induced by hydrodynamics happens every day in Lake Taihu (Qin et al., 2006). Resuspension flux of nutrients also is very high. It is evaluated that the medium wave disturbance intensity (5–6 m/s wind speed) could induce 166 mg/(m²·d) of TN and 49 mg/(m²·d) of TP release (Luo et al., 2006). Although most of TN and TP are particle nitrogen and particle phosphorus which could not be directly taken in by algae and bacteria, 58% of the total

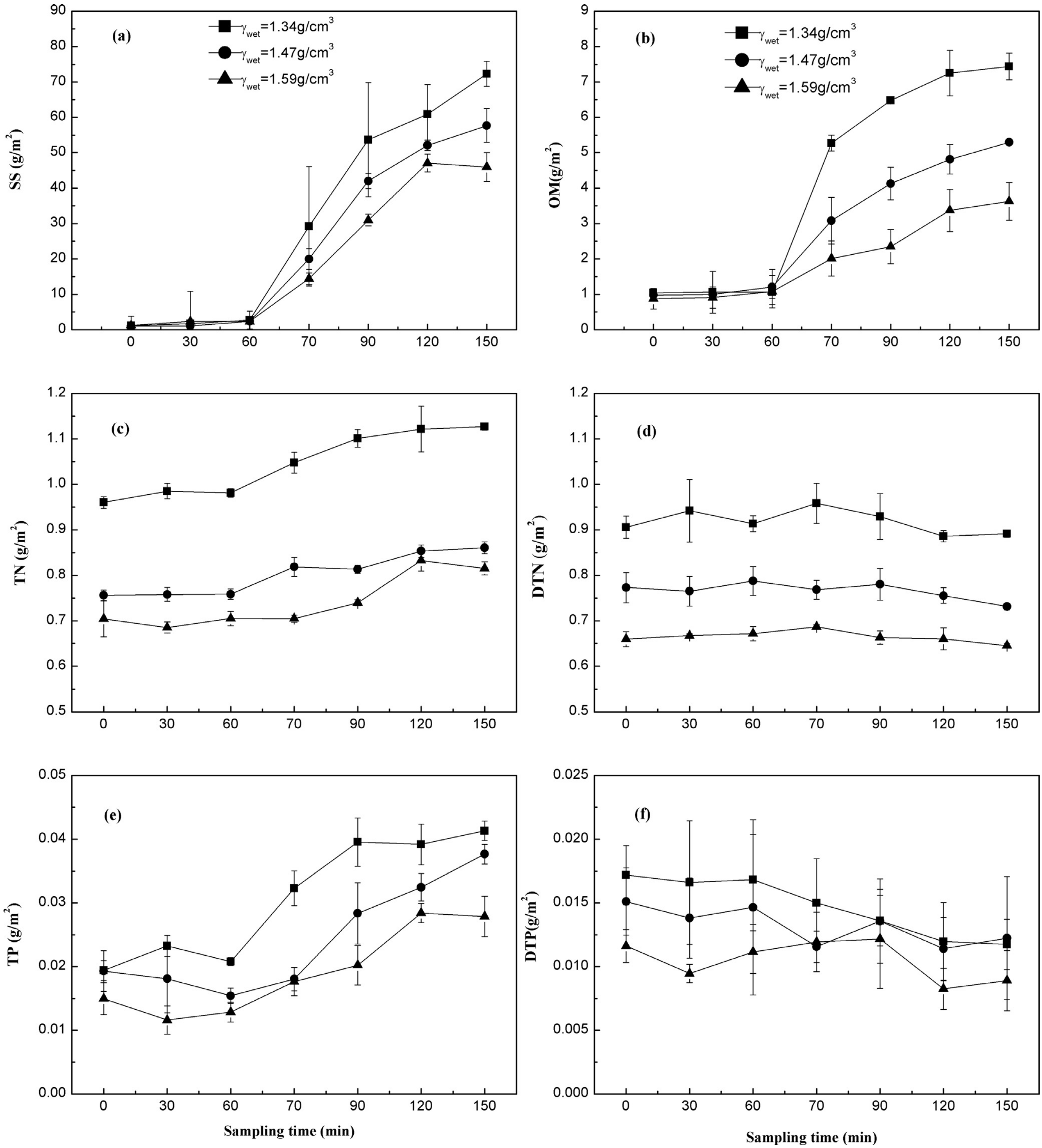

Fig. 6. Variation of suspended solids and nutrients with different sediment bulk densities during wave processes, suspended solids (SS, a), organic matter (OM, b), total nitrogen (TN, c), dissolved total nitrogen (DTN, d), total phosphorus (TP, e) and dissolved total phosphorus (DTP, f).

phosphorus could be hydrolyzed into inorganic phosphate in Lake Taihu (Gao et al. 2006). Therefore, sediment resuspension could compensate for nutrients deficiency of algae growth (Ding et al. 2016, 2017) and also lead to the algae bloom (Paerl 2008; Wu et al., 2013a). Ding et al. observe the effect of typhoon morakot on Lake Taihu and found that the biomass of algae rapidly increased after typhoon passed away (2012). Lake Taihu is affected by monsoon and is blowed from south and southeast wind. Satellite imaging also showed that algal blooms developed in most parts of the northwestern and central lake after both typhoon events (Zhu et al., 2014). Wherefore, algae blooms easily happen in these regions due to their location, which are at divergence area of wind and have the long wind length. Strong sediment resuspensions frequently happen to promot nutrients cycling.

Sediment dredging to control eutrophication in Lake Taihu has been controversial. Experimental results reflect that bulk density and TSS show a highly negative correlation ($p < 0.01$), which is consistent with the results of the indoor simulation test (Zhong et al., 2009a,b). Similarly, after sediment is dredged twice, the sediment bulk density increase and TN, DTN, TP and DTP significantly decrease by 24.3% - 33.6% ($p < 0.01$). Therefore, it indicates that nutrients in sediments

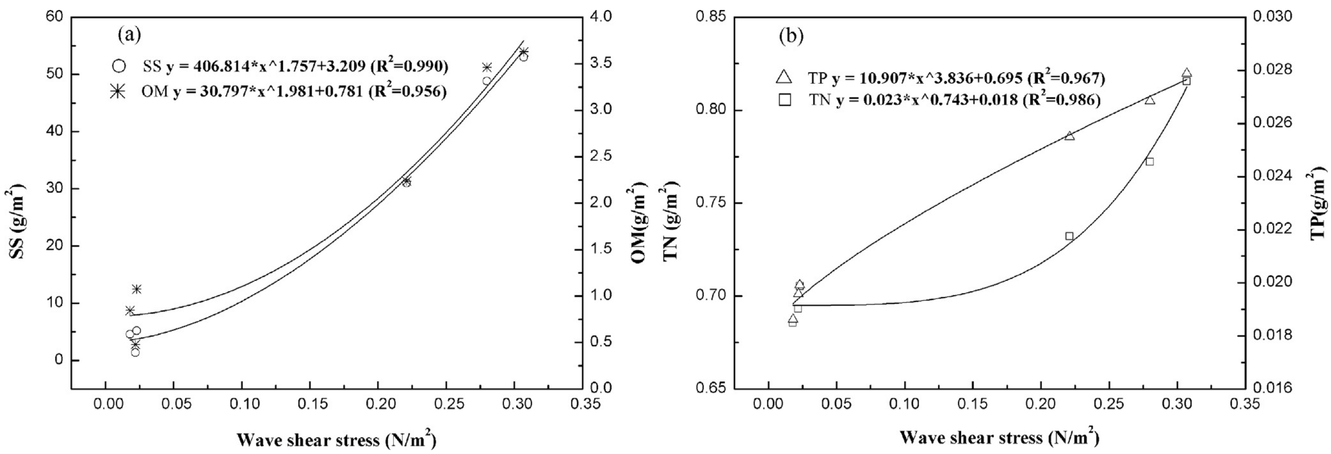

Fig. 7. Relationships between the wave shear stress and suspended solids (SS) (a), organic matter (OM) (a), total nitrogen (TN) (b) and total phosphorus (TP) (b).

after dredging have a lower release potential. While, it is hard to carry on sediment dredge in open water area. It is better to carry on sediment dredge on shore zone, especially on the wind divergence area. It is suggested that sediment dredging may be a useful measure for controlling eutrophication of shore zone in Lake Taihu.

5. Conclusion

Sediment resuspension is the typical characteristic of shallow lakes. Wave flume experiments could help to understand the characteristics of sediment resuspension in Lake Taihu. Bottom wave shear stresses have more close relationship with wave height than wave period and had the positive correlation with wave height. Under the 10 cm wave height, wave shear stresses reached up to 0.307 N/m^2, which made the TSS concentration rapidly increase to 82.98 g/m^2 and resuspension flux of sediment reach up to 72.38 g/m^2. The calculation showed the sediment disturbance depth reached up to 0.161 mm. Then, sediment resuspension induced sediment nutrients releasing into water column, especially particle N and P. Therefore, hydrodynamics accelerated the nutrients cycling. Furthermore, the experiments under different sediment bulk densities found sediment dredging could effectively reduce SS concentration and nutrient levels. Our research results provides a theoretical basis of sediment dredging to control eutrophication of shore zone of Lake Taihu for lake management.

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