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Estimation of internal nutrient release in large shallow Lake Taihu, China

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Abstract Based on field investigation of wave, sediment suspension and the changes in nutrient concentration of the water column in Lake Taihu, China, we proposed two release models to quantify nutrient release under static and dynamic conditions, respectively. Under static conditions, nutrient release from sediments to the overlying water mainly depends on chemical diffusion induced by concentration gradient, in which the nutrient release is controlled by the temperature, dissolved oxygen concentration in the sediment-water interface, oxidation-reduction potential and the concentration difference between porewater and overlying water. Under dynamic condition (or disturbed condition), both dissolved and particulate nutrients in sediments are released into the water column because of wind-induced sediment suspension. The amount of nutrient release under dynamic conditions is larger than that under the static condition. The release of dissolved nutrients, however, does not increase because the wind induced turbulence made oxidation of metallic elements such as Fe (ferric iron), Mn which are capable of precipitating soluble reactive phosphate (SRP). Under dynamic conditions, therefore, the release of total phosphorus (TP) increases dramatically but the release of SRP is close to those under static conditions. In sediments of Lake Taihu, high Fe content leads to a high ratio of Fe to P contents in sediments (Fe:P ratio). Under dynamic conditions, therefore, nutrient release is controlled by the intensity of disturbance, sediment consolidation and nutrient content in sediments. As for dissolved nutrients, especially SRP, the release is also controlled by the intensity of dynamic re-oxidation, Fe content in sediments and nutrient concentration gradient between porewater and overlying water. Based on these two release modes, the release flux in Lake Taihu has been estimated. In the static condition (*i.e.* laboratory experimental condition), total release of NH_4^+-N for whole lake is ca. 10,000 ton/a, and PO_4^{3-}-P is ca. 900 ton/a. In the dynamic condition, nutrient release following sediment suspension was estimated according to three different intensities of wind forcing which were defined as “calm” (wind speed is less than 2 m/s), “gentle” (wind speed is greater than 2 m/s and less than 6 m/s) and “gust” (wind speed is greater than 6 m/s). The release rate in the condition of “calm” was estimated in terms of the nutrient release in the laboratory experimental static condition; whereas the release rate in conditions of “gentle” and “gust” was estimated in terms of measurement during sediment resuspension conducted in flume experiments. With the observation of wind velocity and frequency in 2001, each type of wind forcing took the frequency of 12%, 82% and 6% for “calm”, “gentle” and “gust”, respectively. The yearly release of nitrogen was 81,000 ton and phosphorus was 21,000 ton, which is about 2—6 folds of annual external loading, respectively.

Keywords: shallow lake, eutrophication, internal loading, sediment, nutrient, dynamic turbulence.

Nutrient release from sediments as the internal loading of deep lakes has been well documented[1—3], but rarely in shallow lakes, which raised arguments about the dredging for controlling the internal loading in shallow lakes in China[4]. Oxidation-reduction potential of sediment-water interface was believed to be the main factor controlling nutrient release. Anaerobic environment is favorable for the mineralization and degradation of nutrients in sediments. Whereas under the aerobic environment, the release of dissolved nutrient from sediments would decrease due to adsorption and precipitation by Fe, Mn oxides in the sediment-water interface[2]. These observations are obtained under the circumstance that the water-sediment interface is not disturbed. In the middle and lower reaches of the Yangtze River, most lakes are shallow and threatened with eutrophication. One of the distinct characters of shallow lakes is that the sediments are frequently resuspended by wind-wave disturbance, which destroys water-sediment interface non-periodically. Therefore, oxidized and reduced ambient switch frequently. Lake Taihu is a large shallow lake, with an area of 2338 km^2, a mean depth of less than 2 m and the maximum depth of less than 3 m. There are *Microcystis* algal blooms resulting from the eutrophication during summertime. At present, Lake Taihu restoration is mainly focused on reducing external loading of nutrients. However, it is not clear what the role of the internal nutrient release is in this large shallow lake. Here we propose two modes of sediment release existing in large shallow lakes. Practical estimation method of sediment release is also suggested based on the field investigations and flume experiments for sediment resuspension.

1 Materials and methods

1.1 Site description

Lake Taihu is located in the Yangtze River Delta with a surface area of 2338 km^2, a mean depth of 1.9 m and a maximum depth of 2.6 m[5]. The capacity of Lake Taihu is 4.4 billion m^3, 70% of which is supplied by the Tiaoxi River in the southwest and the Nanxi River in the west[6]. About 60%—70% of its outflow goes into the Taipu River through the eastern Lake Taihu, which connects the East China Sea via the Huangpu River[6]. Therefore, the retention time of the lake water in the southern part of Lake Taihu is much shorter than that in the northern part, which might have been one of the causes for poor water quality in the northern Lake Taihu. The water supply of the Lake Taihu comes mainly from mountainous areas from the southwest, whereas the pollutants come mainly from Changzhou City to the northwest of the lake drainage and Wuxi City to the north area. The pollutants are mainly distributed in the sediments of Meiliang Bay, Zhushan Bay and Wuli Bay from the north.

Water quality of Lake Taihu has been deteriorating since the 1950s. In 1960, total inorganic nitrogen (TIN) in the lake was only 0.05 mg L^{-1}, orthophosphate (PO_4^{3-}-P) was 0.02 mg L^{-1} and chemical oxygen demand (COD_{Mn}) was 1.90 mg L^{-1} [7]. By the year 1981, TIN had increased to 0.894 mg L^{-1}, 19 times as much as that in 1960, and COD_{Mn} was 2.83 mg L^{-1}, a 49% increase compared with that in 1960. In 1988 TIN and TN concentrations were 1.12 and 1.84 mg L^{-1}, respectively[8]. However, by the year 1998, it was mounted to 1.58 mg L^{-1} and 2.34 mg L^{-1}1). In 1988 the total phosphorus (TP) and COD_{Mn} were 0.032 mg L^{-1} and 3.30 mg L^{-1}, respectively[6], and by 1998 were 0.085 mg L^{-1} and 5.03 mg L^{-1}1), *i.e.* 2.7 and 1.5 times, respectively. Corresponding to the increases in the external nutrient loading, Lake Taihu has experienced severe algal blooms dominated by a *Microcystis* algal[9]. In the 1960s, the *Microcystis* algal bloom was only found in Wuli Bay, but now it has extended in all

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1) Taihu Laboratory for Lake Ecosystem Research, Annals of Taihu Laboratory for Lake Ecosystem Research, Chinese Academy of Sciences, 1998.

the northern Lake Taihu[5].

1.2 Field investigation

Field investigations on Lake Taihu were conducted in Feb. 1998, July 1998, June 2001, Sept. 2001 and May 2003. The two investigations in 1998 were conducted at the sites inside Meiliang Bay (Sampling No.1) and at the mouth of the bay (Sampling No.4) (Fig. 1). These investigations were aimed to study the vertical profiles of nutrient and total suspended solids (TSS) concentration under different wind conditions. Both sampling sites were at pelagic areas with different sediment accumulations. Soft sediment depth is much higher in No. 1 than No. 4. Wind speed, wind direction, water temperature, transparency and lake current were measured *in situ*. Samples from different water depths were taken to analyze TSS concentration, total organic matter (TOM) content and different forms of N and P. Three different wind intensities were observed on Feb. 26 (2 m s^{-1}), Feb. 24 (5 m s^{-1}) and March 11 (6.5 m s^{-1}), respectively, which were used to represent light, medium and strong wind conditions. The water samples were collected from three layers, *i.e.* 0.9*h*, 0.5*h* and 0.1*h* (*h* stands for the water depth). There was no significant difference on wind speed, all between 2 m s^{-1} and 4 m s^{-1}, during the investigations conducted on July 23, 25 and 30, 1998. The water samples were collected from 5 layers, *i.e.* 0.1*h*, 0.25*h*, 0.5*h*, 0.75*h* and 0.9*h*.

Fig. 1. Location of field sampling sites in Taihu Lake.

In June 2001, 4 sediment cores with a length of 26 cm were collected from No. 2 at the center of Meiliang Bay, No.5 at Dapukou in northwestern lake, No.6 at Xiaomeikou in southwestern lake and No.7 at East Lake Taihu (Fig. 1). Each core was sliced by every 2 cm and the oxidation-reduction potential (Eh), porosity, specific gravity, size, moisture content, organic matter content, total nitrogen, total phosphorus, were measured. Porewater from each core was obtained by centrifugation and its DTN and DTP concentrations were measured.

From 8 to 11 in September 2001, an observation platform was built at site No. 1 in Meiliang Bay, where capacitive wave recorder and a SonTek Doppler current meter was deployed to obtain time-series measurements of wave and current. *In situ* water temperature, transparency, wind speed and water depth were also measured. Meanwhile, water samples from 7 different layers, *i.e.* 0, 1.0, 1.5, 2.0, 2.25 2.50 and 2.7 m (the water depth was 2.75 m) were taken three times a day (at 13:00, 17:00, 21:00 on Sep 8; 9:00, 13:00, 17:00 during Sept. 9—11) to monitor the changes in TSS and nutrient concentrations.

In May 2003, water samples from 0.2 m, 0.9 m, 1.4 m and 1.9 m (the water depth was 1.95 m) were taken at No. 3 in the south of Meiliang Bay close to the east shore when the gust was experienced on May 6 and breeze on May 10. TSS, loss on ignition (LOI), TP, dissolved total phosphorus (DTP) and SRP were analyzed. The site was ~100 m away from the shore, and the sediment was approximately 20 cm thick. Field observations noted there has been gentle wind speed and rain for three days till the afternoon of May 6. The wind speed began to rise from the evening of May 6, and was stronger on May 7 with speeds above 8 m s^{-1} from 9:00 to 17:00, and 12 m s^{-1} at 13:00. The prevailing west wind and longer wind fetch brought heavy dynamic disturbance within the lake. On May 8 wind speed decreased to 4—6 m s^{-1}. Since then the wind speed dropped below 3 m s^{-1} till May 10 when the east wind prevailed with the waves subsided in the observed area.

1.3 Experiments of nutrient release in the laboratory

To evaluate the release rate and amount of nutrients from sediments to overlying water under static and different temperature conditions, sediment cores incubation was carried out in laboratory. The intact sediment cores were collected in different zones of Lake Taihu with a height of over 20 cm. In the laboratory, the overlying water in the cores was carefully moved by siphon then filtered to remove algae and suspended particulate in the water. The filtered overlying water was carefully dropped onto the sediment cores with 30 cm height without disturbance. All the sediment cores were vertically put into the circulated water bath machine (Colora WK100, ±0.1℃) under specified temperature and incubated without light. 50 mL water samples were taken out from the columns at 20 cm below the water surface by a syringe in every 0, 3, 6, 12, 24, 36, 48, 72h, respectively. After collection, the preserved filtered water was recharged into the columns to the original volume. Releasing rate calculation refers to the equation listed below:

$$R = \left[V(C_n - C_o) + \sum_{j=1}^{n} V_{j-1}(C_{j-1} - C_a) \right] \Big/ S \cdot t,$$

in which, R is release rate (mg m^{-2} d^{-1}); V is volume of overlying water in the columns (l) ; C_n, C_o and C_{j-1} is nutrient concentration in the overlying water at time of n, o(origin) and $j-1$ (mg L^{-1}), respectively; C_a is nutrient concentration in the water added to the overlying water (mg L^{-1}); V_{j-1} is the sample volume at time of $j-1$ (l); S is the surface area of sediment cores (m^2); t is release time (d). All the release rates calculated were apparent release rates. Three different water temperature (*WT*) scenarios, 5℃ (*WT*<10℃), 15℃ (10℃ < *WT* < 20℃), 25℃ (20℃<*WT*), represent winter, spring/autumn, and summer conditions. According to the measured daily water temperature from Taihu Laboratory for Lake Ecosystem Research, the number of days for each specified temperature scenario can be counted and multiplied by the release rate, and finally summarized to obtain the yearly release amount. In terms of the observations, the number of days for water temperature of 5℃, 15℃ and 25℃ is roughly 75 days, 120 days and 170 days, respectively.

1.4 Analytical methods

The methodologies for sample collection and analysis were detailed in Huang *et al.* (1999)[10] and Jin & Tu (1992)[11]. TSS and Chl-a were measured by gravimetric analysis and ethanol extraction colorimetry after being filtered onto Whatman GF/C filters. Electro-conductivity (EC) and pH were measured by the electrode method. Dissolved oxygen (DO) and COD_{Mn} were by titration. TN and TP concentrations in surface water and porewater were measured by potassium persulfate oxidation and Mo-Sb antispectrophotometry. PO_4^{3-}-P and NH_4^+-N were analyzed by molybdate spectro-photometric method and Nessler's reagent colorimetric method. The measurements of DTN and DTP were the same as TN and TP's after the water was filtered through 0.45 μm GF/C filters. SRP was analyzed by Mo-Sb antispectrophotometry of filtered water samples. Moisture content and porocity were measured by air-drying the sediment sample in oven at 105℃ for 8 h. Oxidation-reduction potential (Eh) and the size of sediment particles were measured according to the electrode method and laser particle size analyzer, respectively. TN and TP in sediments were measured by the potassium persulphate oxidation method and the organic matter content in sediments was measured by loss on ignition (LOI, which denotes the rate of organic matter in the total solids).

2 Results

2.1 Vertical profiles of nutrient concentration in the sediment and overlying water

Nutrients in sediments would release mainly due to the existing concentration gradient between sediment porewater and overlying water. Fig. 2 presents vertical profiles of the mean nutrient concentrations in the water column and in sediments porewater in Meiliang Bay, on 8—11, Sept. 2001 (three times measurement a day). Nutrient concentrations in the sediment porewater were considerably higher than those in overlying water. Concentration of DTN was 10 times higher in porewater than that in overlying water, and DTP was 7—8 times higher. In sediments, concentrations of DTN fluctuated and generally increased with depth, while concentrations of DTP varied greatly and showed no apparent trend with depth. It should be noticed that the increase and decrease of nitrogen and phosphorus with depth were nearly synchronous, which indicated that the sediments were disturbed by

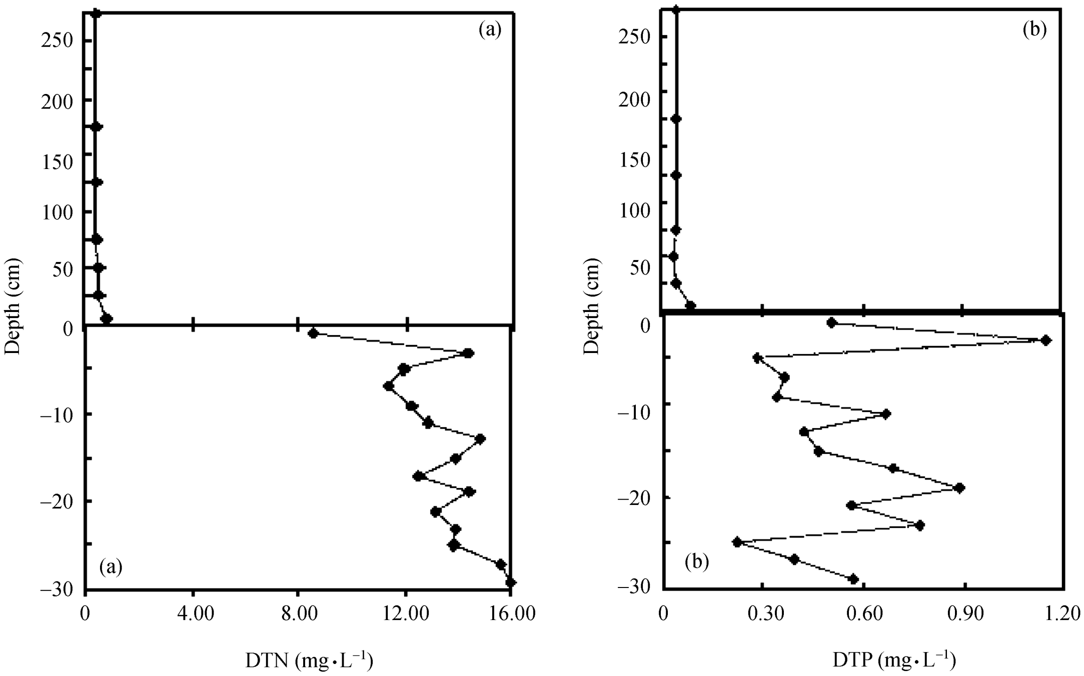

Fig. 2. Vertical distribution of concentrations of DTN and DTP in water and porewater. Investigated at site 2 from 8 to 11, Sept. 2001 (3 times every day and total 12 times).

dynamic function periodically and/or discontinuously.

Water quality parameter profiles in overlying water at sites No. 1 and No. 4 in Meiliang Bay on July 23, 25 and 30, 1998 are shown in Fig.3. Dissolved total nitrogen increased with water depth. Total suspended solids (TSS) and organic matter contents were typically higher near the lake bottom, but TN, TP and Chl-a concentrations were greater in upper layer of water column than those in near bottom layer of water column, which shows that the dissolved nutrient concentration will be affected by the nutrient release from the sediments but the TN, TP and Chl-a will be influenced by the phytoplankton and suspended organic detritus. Thus the nutrient conditions same as the light condition is severely spatially uneven in shallow lakes.

2.2 Relationship between nutrient concentration in overlying water and wind speed

The weighted mean values of several water quality variables from 7 different depths in Sept. 2001 were used to establish a possible correlation with wind speed (Fig. 4). Since TSS concentration was much higher near the water-sediment interface and affected by sampling, the data from the lowest layer of water column were discarded when the average concentration of SS in water column was calculated. This will not affect the qualitative conclusion of the release of nutrient under dynamic disturbances.

The concentrations of TSS, total organic matter (TOM), Chl-a, TN and TP increased with wind speed, as shown in Fig. 4(a), (e), (f), (g) and (h), respectively, while COD_{Mn}, TDN, TDP decreased with wind speed (Fig. 4(b), (c) and (c)). Obviously, the enhanced dynamic disturbances brought more TSS, Chl-a and TOM to the water column due to re-suspension; as a result, the TN and TP contents in water would be also greatly increased. However, soluble nutrients did not exhibit apparent increase, probably due to adsorption of particles.

Data from site No.3, Meiliang Bay collected on 6—11 May, 2003 revealed different concentrations in TSS, LOI and TP under different wind conditions (Fig. 5). Concentrations of SS and TP were high under high wind speed (~7—8 m s^{-1}) and opposite under low wind speed (less than 3 m s^{-1}), which was the direct result of increased suspension of sediments under strong wind stresses (Fig. 5). However, the ratio of organic matter (LOI) in the total solid was low under high wind speed and high under low wind speed. No

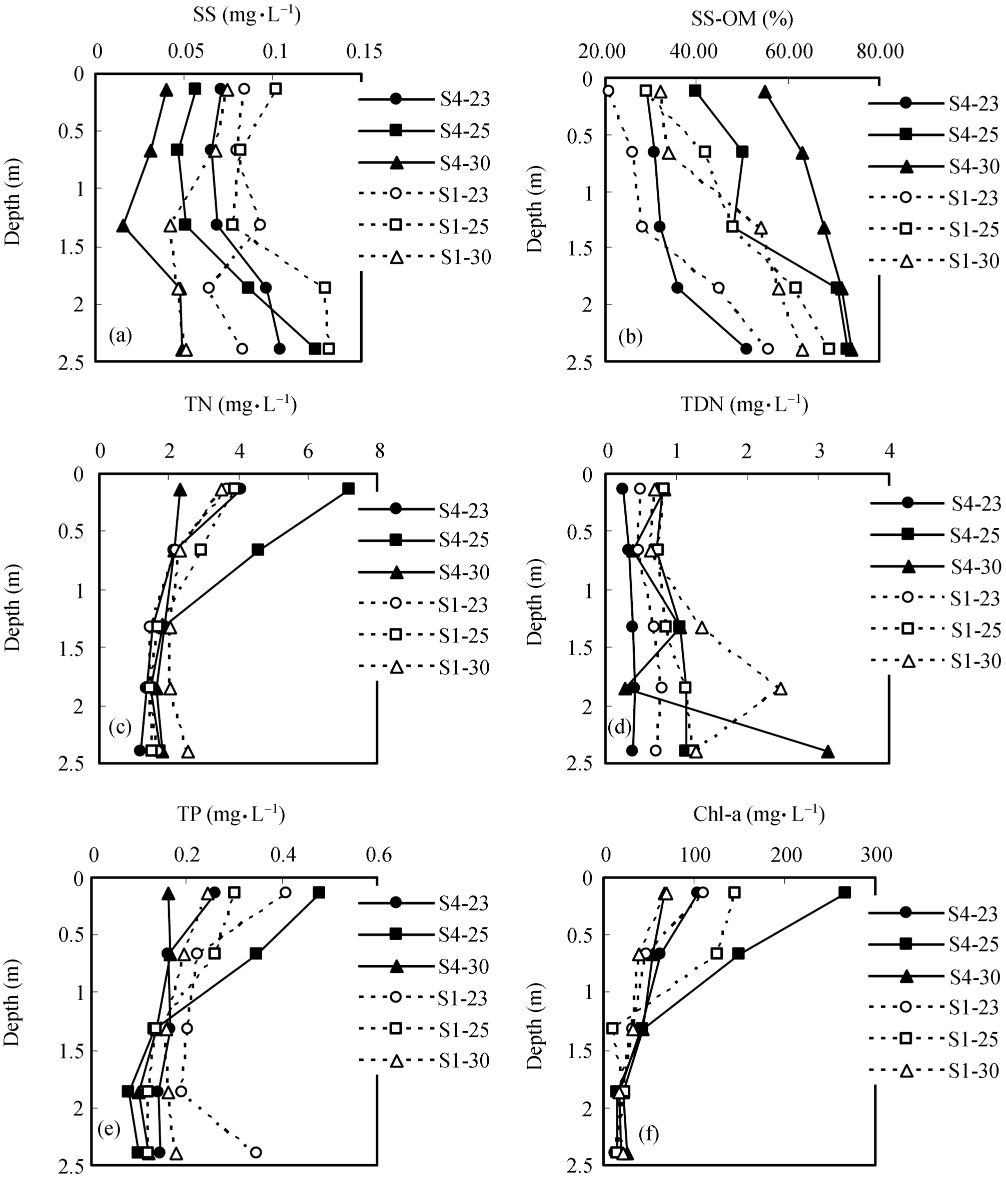

Fig. 3. Main water quality parameters change with water depth in Lake Taihu in July 1998. S1-23, site 1 on July 23, 1998; S1-25, site 1 on july 25, 1998; S1-30, site 1 on july 30 1998; S4-23, site 4 on July 23, 1998; S4-25, site 4 on July 25, 1998; S4-30, site 4 on July 30, 1998.

obvious increase of SRP was noted under different wind stresses, similar to the situations found in Sept. 2001, Meiliang Bay.

2.3 The modes of nutrient release from sediment in large shallow lakes

Normally, there are several nutrient transport mechanisms from sediments to overlaying water, *i.e.* diffusion, wind-induced water turbulence, bioturbation, gas equilibration, attached algae and rooted aquatic plants[3]. In Lake Taihu, the first two kinds of transport are the main types of nutrient release. Nutrient diffusion from sediments to overlying water column exists in the calm condition of lake whereas the nutrient release following the sediment resuspension takes place during the wind-induced water turbulence. In the field, these two kinds of nutrient release will happen alternately. In the calm condition, the water-sediment interface will be weakly oxidized, sometimes in weak reduction. The nutrient release will be transported by the diffusion and the diffusion rate of nutrient will count on the temperature. In the windy period, the

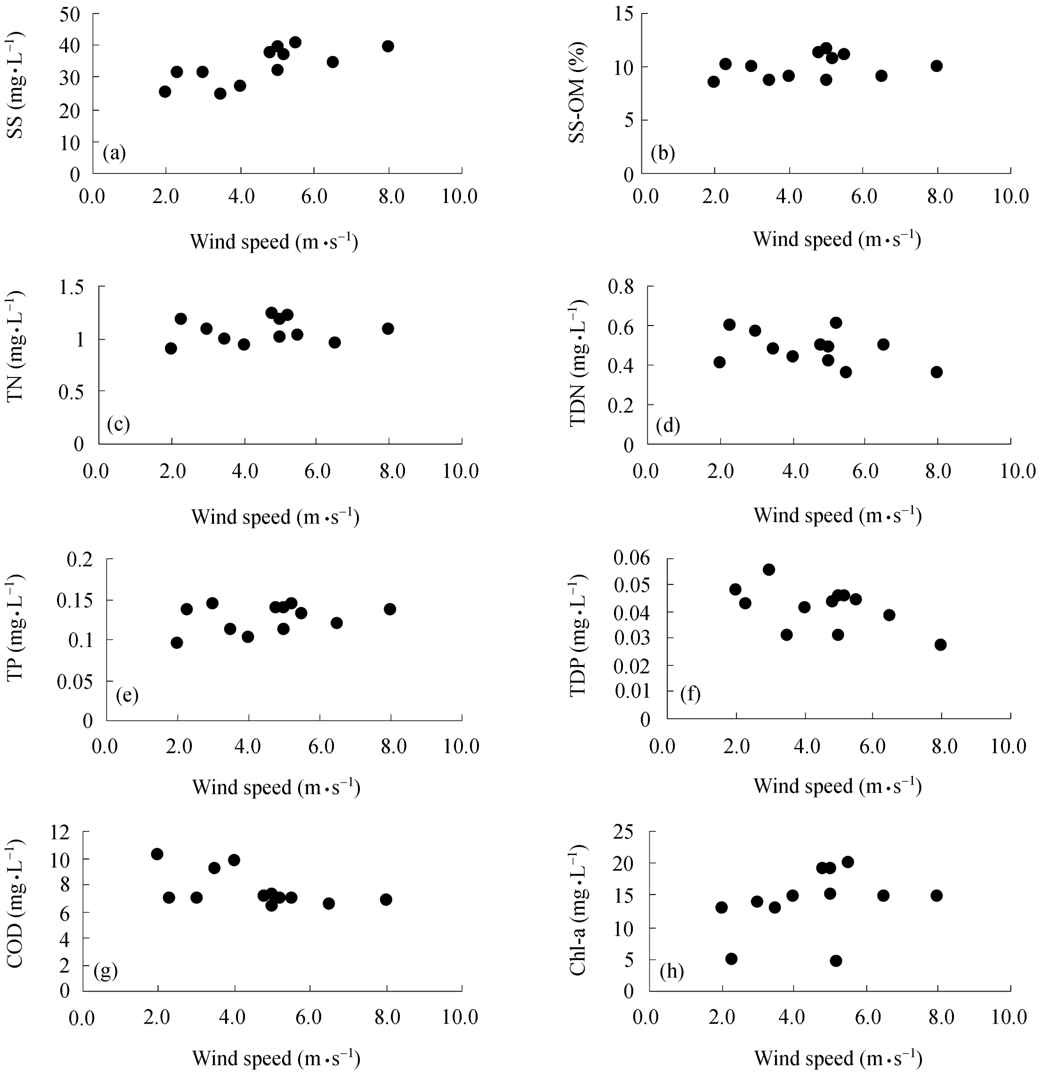

Fig. 4. Column averaged water quality parameters changes with wind speed in Meiliang Bay (site No. 2) in September 2001. (a) Concentration of SS; (b) concentration of SS-OM; (c) concentration of TN; (d) concentration of TDN ; (e) concentration of TP; (f) concentration of TDP; (g) concentration of COD; (h) concentration of Chl-a.

sediment will be re-suspended and bring about massive nutrient, whatever fraction of the nutrients, to the overlaying water. Obviously, the latter mode of nutrient release has higher efficiency than the former.

The nutrient concentrations in porewater increase with sediment depth in shallow lakes[12]. The constant weak oxidized condition across the sediment-water interface favors the decomposition of sedimentary organic matter. At the same time, the dynamic disturbance erodes the surface sediment particles and releases dissolved nutrients to the water column. Some dissolved interstitial nutrients, especially phosphate, may be adsorbed by ferric iron and other oxides. Under calm conditions, the suspended sediment particles and the adsorbed nutrients, may settle to the bottom of the lake, which are subject to another suspension during the next wind disturbance[12]. During the calm period, the nutrient release from sediments is controlled by the diffusion associated with the gradient of nutrients between interstitial water and overlaying water. The heavy wind-wave process not only greatly increases TP and TN concentrations in water column, but also leads to a possible decrease of soluble nutrients in water. This is a totally mixed mode of nutrient

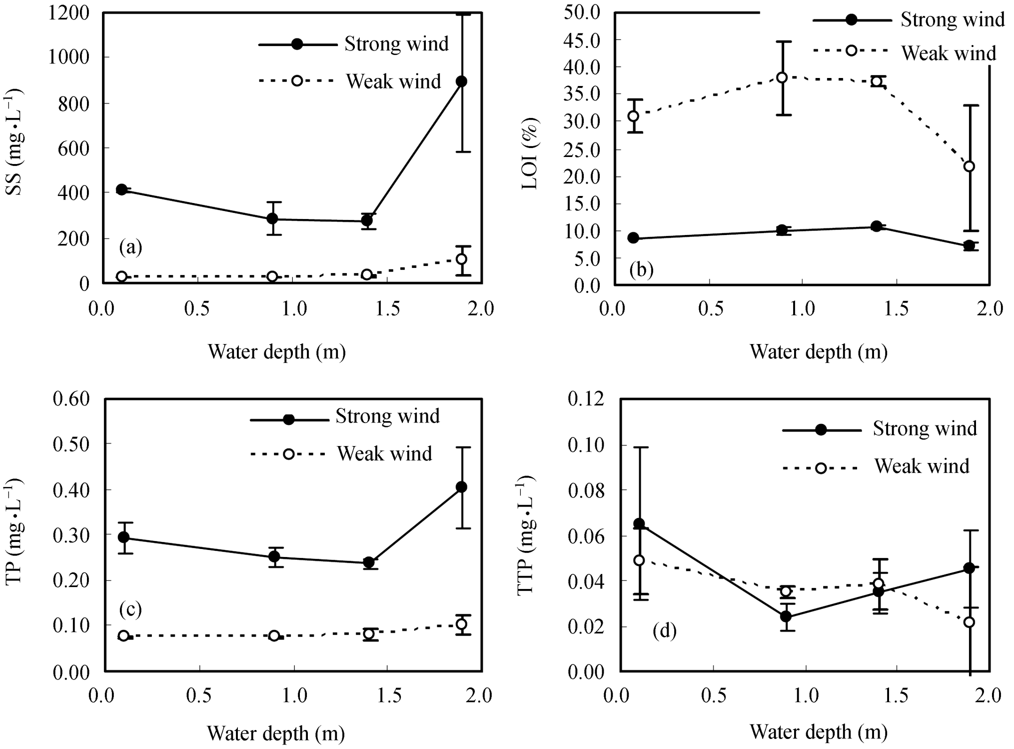

Fig. 5. Concentration of SS, LOI of SS, TP and TDP changes with different wind forcing (strong wind forcing with wind speed greater than 8 m s^{-1}, weak wind forcing with wind speed less than 3 m s^{-1}) at site No.3 in Meiliang Bay, Lake Taihu.

release and different from the purely diffusion mode in deep lakes.

2.4 Nutrient exchange flux between water-sediment interface in static conditions

Tables 1 and 2 show the exchange rates and yearly amounts of release of NH_4^+-N and PO_4^{3-}-P in static conditions. From Table 1, the release rate of NH_4^+-N increases with the rise of temperature, particularly in the cool conditions. Generally the lower water temperature will make some lake areas be “sink” rather than “source” of nutrients. Compared with ammonia nitrogen, release of PO_4^{3-}-P is rather complicated, sometimes contradictory (Table 2). Release rate does not increase with temperature, indicating that temperature is not the dominated factor influencing the phosphate release. The yearly amount of nutrient release in static conditions is still considerable, and amounts of NH_4^+-N and PO_4^{3-}-P release are roughly 10,000 ton and 900 ton, respectively, taking about 20%—30% and one third of annually external loading of nitrogen and phosphate.

2.5 Estimates of the total nutrient release in Lake Taihu under dynamic conditions

Estimates for soluble nutrient release are rather complicated, because the sediment suspension was usually in company with processes of soluble nutrient release and adsorption, and the adsorption and suspension processes for SS in sediments are related to oxygen and Fe concentrations in water. Here we described an estimate for the releases of DTN, DTP from porewater, and TN and TP from sediments under one distinct dynamic process. It was supposed that, dissolved nutrients released from porewater were not adsorbed by suspended solids and there was no sedimentation. In the wind-wave disturbance process, the dissolved nutrients in sediment porewater were carried out to the overlying water column and were bioavailable without any inactive reaction. Therefore, the internal loading of soluble nutrients means the total dissolved nutrients in porewater in all the eroded sediments. In the same way, the internal loading of TN and TP means the total nitrogen and phosphorus in overall eroded sediments in a distinct wind-wave dynamics process. Based on

Table 1 The rate and amount of NH_4^+-N exchange on the sediment-water interface of Lake Taihu[9]

Lake district	Area of soft sediment (km^2)	Rate of NH_4^+-N (mg·m^{-2}·d^{-1})			Flux (t a^{-1})
		5℃(75 d)	15℃(120 d)	25℃(170 d)	
East Wuli Bay	3.4	78.8±27.6	-113.9±52.4	13.1±7.5	−18.8±10.0
West Wuli Bay	1.1	33.7±11.8	66.2±30.5	187.0±106.6	46.5±24.9
Xiaowanli Bay	19.2	23.1±8.1	17.1±7.9	40.7±23.2	205.7±105.6
Center of Meiliang Bay	21.5	17.3±6.1	131.7±60.6	−11.2±6.4	326.5±142.6
Mashan Bay	21.2	94.9±117.7	−44.8±42.1	−77.2±49.4	−241.3±98.1
Gongshan Bay	74.8	13.2±16.4	−92.0±86.4	63.1±40.4	51.6±170.2
Zhushan Bay	24.9	−19.3±23.9	−15.1±14.2	56.9±36.4	159.6±66.9
West littoral area	247.6	−48.6±17.0	−22.2±10.2	62.4±35.6	1067.0±879.2
Southwest center	214.0	−27.1±33.6	1.0±1.0	39.6±25.3	1030.8±406.8
Southwest littoral	203.6	−3.9±4.8	4.2±4.0	45.6±29.2	1621.7±1033.2
South of Mashan	101.8	−75.3±93.4	79.3±74.5	30.6±19.6	923.3±536.6
Center of Taihu	119.8	−13.6±4.8	0.1±0.1	20.7±11.8	301.8±198.7
Littoral of Xishan	162.2	−18.3±22.7	55.2±51.9	23.5±15.0	1500.7±1149.5
Xukou Bay	118.0	6.4±7.9	−51.3±48.2	19.7±12.6	−274.4±359.6
Eastern Taihu	289.7	28.7±10.0	64.5±29.7	18.0±10.3	3868.9±1809.5
Mean value	—	−16.0±17.6	12.6±6.9	34.1±20.8	—
Sum	1631.8	—	—	—	10569.6±6991.4

Table 2 The rate and amount of PO_4^{3-}-P exchange on the sediment-water interface of Lake Taihu1)

Lake district	Area of soft sediment (km^2)	Rate of PO_4^{3-}-P (mg·m^{-2}·d^{-1})			Flux (t a^{-1})
		5℃(75 d)	15℃(120 d)	25℃(170 d)	
East Wuli Bay	3.4	2.95±1.99	−0.40±0.34	0.50±0.50	0.9±0.7
West Wuli Bay	1.1	5.20±3.51	3.13±2.61	2.11±2.10	1.2 ±1.0
Xiaowanli Bay	19.2	2.87±1.94	−3.25±2.72	−3.72±3.70	−15.5±15.6
Center of Meiliang Bay	21.5	1.20±0.81	−0.13±0.11	−0.57±0.57	-0.5±1.0
Mashan Bay	21.2	2.57±0.84	0.29±0.10	−0.80±0.28	1.9±0.6
Gongshan Bay	74.8	−0.08±0.03	4.02±1.35	0.63±0.22	43.6±14.8
Zhushan Bay	24.9	−2.08±0.68	2.42±0.82	2.54±0.88	14.1±4.9
West littoral area	247.6	3.93±2.65	1.60±1.34	0.60±0.60	145.9±114.2
Southwest center	214.0	1.33±0.43	−2.83±0.95	−0.66±0.23	−75.2±25.8
Southwest littoral	203.6	2.19±0.71	5.67±1.91	1.37±0.47	219.4±74.0
South of Mashan	101.8	−3.88±1.26	2.49±0.84	0.29±0.10	5.7±2.3
Center of Taihu	119.8	1.44±0.97	−1.76±1.47	0.78±0.78	3.7±3.5
Littoral of Xishan	162.2	2.65±0.87	3.13±1.05	1.44±0.50	133.1±44.9
Xukou Bay	118.0	3.37±1.1	0.22±0.08	1.49±0.52	63.0±21.2
Eastern Taihu	289.7	0.24±0.16	3.59±3.00	4.41±4.39	358.1±334.0
Mean value	—	1.52±0.78	1.78±0.96	1.32±1.05	—
Sum	1631.8	—	—	—	899.4±573.6

the wave flume experiments, the strong wave in Lake Taihu may erode the sediment of top 10 cm depth. The detailed results of the experiments were presented in literature[12]. Therefore, another hypothesis is that the surface 10 cm sediments could be suspended in a strong enough hydrodynamic process.

Estimates for nutrient release from porewater were obtained based on the calculations of sediment porosity, TN, TP concentrations in porewater (Table 3). Physicochemical characteristics (*i.e.* gross weight, TOM, porewater contents, porosity) of 4 sediment cores in June 2001, *i.e.* revealed that the surface 5—10 cm sediment had been actively involved in the exchange of sediment and the overlying water[12]. As a result, estimates of nutrient release from sediments in one heavy dynamic process were calculated assuming

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1) Fan Chengxin, Zhang Lu, Bao Xianming *et al.*, Migration mechanism of biogenic elements and their quantification on the sediment-water interface of Lake Taihu. II. Chemical thermodynamic mechanism of phosphorus release and its source-sink transition, *Journal of Lake Sciences*, 2006, in press.

that suspension occurred in the top 10 cm sediment. Spatial distribution of surface sediments was not even, and detailed distribution of the depth of the loose sediment in Lake Taihu was presented in Luo *et al.* (2004)[13]. The Lake Taihu was divided into three districts: the Meiliang Bay, East Lake Taihu, and the rest part of the lake (Main Lake Taihu). The vertical distribution of the physicochemical characteristics of the sediments was calculated according to the four sediment cores. As a result, the total release of nutrients from the top 10 cm sediments could be calculated: ~29618 kg DTN and ~1514 kg DTP in East Lake Taihu; ~23059 kg DTN and ~1236kg DTP in Meiliang Bay; ~477668 kg DTN and ~20606 kg DTP in the main Lake Taihu, which were equivalent to an increase of TN by 0.12 mg/L and TP by 0.005 mg/L in the whole Lake Taihu when the top 10 cm sediments were eroded into overlying water columns. Compared with the mean concentrations of TP (2—4 mg/L) and TN (0.01—0.1mg/L) in water column in Lake Taihu, each strong sediment suspension would result an increase of TN and TP by 3%—6% and 5%—50%, respectively.

Table 3 Estimates of total release of TN, TP from pore waters in top 10 cm sediments in 3 sub-lake districts of Lake Taihu

	Main Lake Taihu	East Lake Taihu	Meiliang Bay
Porosity (%)	40.2	45.2	45.3
TN contents (mg/L)	8.37	4.89	8.21
TP contents (mg/L)	0.36	0.25	0.44
Areas included (km^2)	1431	134	62
N release from pore-water (kg)	477668	29618	23059
P release from pore-water (kg)	20606	1514	1236

However, the actual release of nutrients from sediments would be lower than estimates, as there are aquatic plants in East Lake Taihu which could lower the suspension and release of sediments. Moreover, the adsorption and flocculation by particles may also decrease the concentration of dissolved nutrients with the high SS concentration in overlying water column. Sometimes some soluble nutrients especially SRP decreased under dynamic suspension conditions.

The total nutrients released from sediment, whether the soluble nutrients or particulates, could be estimated by assuming that the top 10 cm sediments were eroded into overlying water column and not considering the sedimentation of the suspended solids. The sediment cores in June, 2001 were chosen for analysis of TN and TP in sediments. Assuming that the whole 10 cm surface sediments were suspended under one heavy dynamic process, the total release from sediments for the whole Lake Taihu could be up to 1.85×10^5 ton TN and 4.11×10^4 ton TP, *i.e.* 1.63×10^5 ton TN and 3.73×10^4 ton TP for the main Lake Taihu; 1.42×10^4 ton TN and 2.55×10^3 ton TP for East Lake Taihu; and 5.92×10^3 ton TN and 1.21×10^3 ton TP for the Meiliang Bay, respectively (Table 4).

Table 4 Estimates on the N, P release under dynamic suspension of surficial 10 cm sediments in 3 sub-lake district of Lake Taihu

	Main Lake Taihu	East Lake Taihu	Meiliang Bay
Gross weight averaged (t/m^3)	1.52	1.33	1.34
Water content (%)	0.43	0.59	0.57
Mean N contents (kg/t)	1.31	1.95	1.64
Mean P contents (kg/t)	0.30	0.35	0.34
Sediment area included (km^2)	1431	134	62
Total N release (t)	165200	14158	5916
Total P release (t)	37314	2550	1214

2.6 Estimate of annual nutrient release in this large shallow lake

From the above calculation of nutrient release, in the calm condition (laboratory experiment), annually NH_4^+-N and PO_4^{3-}-P is about 10570 ton and 899 ton, respectively. In the dynamic condition (wind-wave imposed on the lake), the sediment re-suspension will cause the dissolved interstitial nutrient release of nitrogen 530 ton and phosphorus 23 tons, and the TN and TP release *ca.* 185,275 ton and 41,078 ton, respectively.

Nutrient release estimates in above two release modes provide the opportunity to calculate the yearly nutrient release. According to the observations of wind speed in Taihu Laboratory for Lake Ecosystem Research, this area is experiencing the monsoon climate, *i.e.* prevailing north-west wind in winter and south-east wind in summer. In addition, the observation of wave height against the wind speed shows that effective wave height is just 3.5 cm when the wind speed is less than or equal to 2 m s^{-1}[14], which is defined as the “calm” condition because in this condition, there is only rippling in the lake; when wind speed greater than 2 m s^{-1} and less than 6 m s^{-1}, the effective wave height is 15 cm or 1/10 frequent wave height is 60—70 cm, which is defined as "gentle" as this kind wind forcing intensity will make the overlying water well oxygen-rich but would not make sediment re-suspension dramatically; when the wind speed is greater than 6 m s^{-1}, the sediment will be re-suspended significantly, which is defined as "gust". By the wind speed investigation in 2001, about 45 days were "calm", taking 12% of year round days, and 298 days were "gentle", taking 82%, and 22 days were "gust", taking about 6%. Because the instantaneous gust (less than 1 h gust proceed) is very frequent in the lake around areas, the actual frequency of "gust" was probably underestimated.

In terms of the percentage of "calm" weather and the release rate obtained in laboratory, total release of nitrogen (NH_4^+-N) and phosphate (PO_4^{3-}-P) is 1272 ton and 108 ton respectively. For the "gentle" weather, there is no experiment to determine the release rate. Here we employ the results from flume experiments[15]. In the condition of "gentle" wind forcing, the sediment will not be resuspended dramatically, but the water will be well aerated, the shear stress between the water-sediment is about 0.019 N m^{-2}. In the "gust" condition, the sediment will be eroded and suspended significantly. The shear stress, meanwhile, is about 0.217 N m^{-2}. Correspondingly, the release rate of TN is 1.92×10^{-3}mg m^{-2} s^{-1}, and TP is 5.69×10^{-4} mg m^{-2} s^{-1} during "gentle" condition, whereas the release rate of TN is 1.16×10^{-2} mg m^{-2} s^{-1} and TP is 2.14×10^{-3} mg m^{-2} s^{-1}. According to the number of days of "gentle" and "gust" wind conditions occur in Lake Taihu, the total release for TN is 55,430 ton and TP is 16,390 ton for "gentle" condition, and for "gust" condition, TN is 24,750 ton and TP is 4,565 ton. Thus the annual release will be obtained by summing above calculation and the yearly release of TN is 8.1×10^4 ton and TP is 2.1×10^4 ton. In terms of investigations of external loading in Lake Taihu ranged from 39,000 to 41,000 ton for nitrogen and 2,900 to 3,800 ton for phosphorus[5,6]. Nutrient release from sediment will account for 2—6 folds of external loading, in which the release by turbulence will be greatly higher than diffusion. For the TN and TP release following the sediment resuspension, even one "gust" imposing on the lake and making sediment resuspension will result in massive nutrient released. Total TN and TP release from sediment resuspension will increase the TN and TP concentration of overlying water column. But only a small percentage of nutrition will contribute to the eutrophication, most nutrient fraction will not be utilized by the phytoplankton[16]. Moreover, the nutrient release will take place near the water-sediment interface. Because of the flocculation, absorption by suspended particles and ferric iron, considerably dissolved nutrition will precipitate and be buried in the sediments. In the control of lake eutrophication, such a tremendous internal nutrient source should not be neglected, even though most of the suspended nutrients exhibited little impact on the lake eutrophication.

3 Discussion

The nutrient (TN and TP) concentrations in the overlying water will greatly increase under wind-stressed disturbances. Experiments in laboratory have found that the suspension-and-diffusion-induced nutrient increase in overlying water would be up to dozen of times against those under diffusion[17]. In Lake Arresø, Denmark, a lake with a surface area of 41 km^2 and a mean depth of 2.9 m, wind-induced suspension could increase the water column nutrient concentrations up to 20—30 times greater than usual under laboratory simulations[18]. Statistics indicated that SS and TP concentrations highly correlated with wind speed[18,19]. Similar phenomena were also noted during simulations in laboratory using samples from Lakes Taihu[20], Gehu[21] and Xuanwu[22]. Investigation in Meiliang Bay of Lake Taihu in 1998 revealed that SS content would double in the conditions of 6 m s^{-1} wind speed, and increase with depth, in accordance with sand contents increment. The upper 5—10 cm surface sediments were not only actively involved in the nutrient exchange across the sediment-water interface, but also provided a basis for the nutrient transportation to the overlying water under dynamic disturbance and suspension; beneath 5—10 cm, the nutrient could be carried to the upper water through gradient difference-induced diffusion[12]. Similar finding has been published in Lake Apopka, USA[17].

Nutrient exchange across sediment and the overlying water interface is not only controlled by dynamic disturbances, but also by oxidation and reduction potential (Eh) at the sediment-water interface. This is especially true for soluble nutrients like SRP[2,23]. The oxidized condition favors the formation of Fe or Mn oxides in the surface of sediments, which can enhance the adsorption ability for soluble nutrients and inhibit the nutrient release to the overlying water. Reduced condition enhances the release of dissolved nutrients to the upper water[24,25]. For this reason, variations in dissolved oxygen in the sediment-water column interface in a given site are good indicators for the nutrient release and velocity. Deep lakes have a stable sediment-water interface, since the wind-stressed suspension was so common in shallow lakes. On the other hand, the constant dynamic disturbance in shallow Lake Taihu frequently transports more oxygen to the sediment-water interface. Field observations revealed small spatial variations in DO concentration in Lake Taihu, ranging from 9.0 to 9.5 mg L^{-1}[6,26]. As a result, the Eh potentials across the sediment-water interface differed slightly, *i.e.* from −100 to −200 mV, indicating a weak reduced environment[12]. The static release from sediments in shallow lakes was likely lower than that in deep lakes, which typically possess a more reduced sediment-water interface.

In shallow lakes like Lake Taihu, accurate estimates for internal sources, especially for SRP, require further understanding the metallic elements' behavior in water and the sediments. Dynamic disturbances could release the nutrients from the sediments through suspension, which leads to the increases in the concentrations of SS, TN and TP in overlying water. At the same time, the release of soluble nutrients contents, especially SRP, will decrease due to re-oxygenation in water. The Fe contents in sediments could have a great impact on the internal nutrient release[27]. Investigations from over 100 lake sediments in Denmark found that total Fe and TP in sediments were positively correlated, while the TP in overlying water were negatively correlated with the ratio of content of Fe and P (Fe:P ratio) in sediments. The higher the Fe:P ratio in sediments, the lower the TP concentration in the overlying water[27]. A Fe:P ratio of 15 in sediments could be criteria for defining evident P release from the sediment[25]. In Lake Taihu, the Fe:P ratio was between 20 and 40[16], indicating that under intensive dynamic disturbance, there is a trend to have higher TP and less SRP in the lake water. In that case, most released nutrients following the resuspension could not affect the ecosystem and eutrophication. But the resuspension is so frequent and the calculated annual nutrient release is so high in this lake, the accumulative effects of nutrient release will exert profound influence on the lake ecosystem, which should be addressed in the following work.

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