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Dynamics of sediment resuspension and the conceptual schema of nutrient release in the large shallow Lake Taihu, China

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Abstract **On the basis of investigations *in situ*, it was found that mass exchange on the water-sediment interface occurred chiefly on the superficial sediment within 5—10 cm. The spatial physicochemical character of sediment was distributed uniformly. The observation of lake currents and waves indicated that the dynamic sources, which act on the interface of water and sediment, came mainly from waves under strong wind forcing, while the critical shear stresses due to the waves and currents were of the same magnitude under weak wind forcing. The critical shear stress that leads to extensive sediment resuspension was about 0.03—0.04N/m^2, equivalent to a wind speed *in situ* up to 4 m/s. If a dynamic intensity exceeded the critical shear stress, such as a wind velocity up to 6.5 m/s, massive sediment re-suspension would be observed in the lake. Furthermore, field investigations revealed that the nutrient concentration of pore water within the sediment was far greater than that of overlaying water, which provides objective conditions for the nutrient release from sediment. According to nutrient analyses in the pore water from the superficial 5—10 cm sediments, a severe dynamic process in the Taihu Lake would bring out a peak nutrient release, i.e. a 0.12 mg/L increase of TN, and 0.005 mg/L increase of TP in the lake. In the end, a general scheme of nutrient release from sediment in large shallow lakes was put forward: when the wind-driven forcing imposes on the lake, it will make the sediment resuspension. At the same time, the nutrition from the pore water will follow the sediment resuspension release to overlaying water. Because of oxidation of solid particulates when it resuspends from sediment, the disturbance of hydrodynamics will enhance the suspension particulates absorbing nutrition. After the withdrawal of wind forcing, the suspended mass would deposit and bring part of the released nutrients back into sediment. The degraded organic particulate would be separated to the pore water within the sediment under the condition of deposition, and wait for the next wind forcing.**

Keywords: Taihu Lake, dynamics, nutrient release, nutrient concentration, sediment.

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Shallow lakes are common along the coastlines in Eastern China and in the middle and lower reaches of the Yangtze River[1]. Nowadays most of these lakes are confronted with the threat of eutrophication[2]. Worldwide experiences of research as well as practices on eutrophication of shallow lakes showed that after controlling external nutrition, the internal loadings due to release from the sediment must be considered and ecological remediation should be carried out at the same time[3—16]. More and more evidences showed that the sediment of shallow lakes was a key source of lake nutrients[3,9,11,12,17—20]. So far most researches have been mainly emphasized on the chemical states and nutrient content in the sediment[20—28], as well as on the laboratory simulations concerning the sediment release of nutrient under different conditions[12, 29—38]. The results of these studies indicated that the lake sediment might be a source for release, or a sink for absorption under specific conditions. The studies also showed that the release of nutrient from the sediment under disturbance was far greater than that under static condition[6,12,39]. Because the simulated conditions of these experiments are different from the field, let alone to estimate the practical sediment release as well as the internal loadings within a lake. As a result, the problem of release in shallow lakes has been ambiguous for a long time, which puts the measures of reducing nutritious loadings such as dredging under dispute[40].

Release of sediment is correlated with its resuspension process. Sediment resuspension dynamic and measurements were firstly developed and applied in the coast engineering[41—43]. The studies on the shallow lake and bay found that sediment resuspension was mainly caused by waves[44]. Researches of the Great Lakes, North America showed that the concentration and particle diameter of resuspended matter was related with shear force across the sediment-water interface[45]. In the 1990s, numerical experiments to analyze the influence of hydrodynamic force on the sediment resuspension in lakes were applied, and hydrodynamic-based simulation models on sediment deposition/erosion and resuspension processes present[46—49]. Generally, most studies were carried out on the coastal engineering instead of on lakes, let alone on the environmental and ecological impacts of lake sediment resuspension. However, the impacts of sediment resuspension of lakes are great and vital to the aquatic ecology and environment, especially in shallow lakes because it could affect the nutrient release, water transparency and even the primary production. In Taihu Lake, the outbreak of blue-green algae bloom often follow the strong course of wave and wind, which indicates that the sediment resuspension resulting from dynamic force may be related with ecosystem through affecting nutrition loadings or light climate of waters. This paper tries to illuminate the relation between dynamic and sediment resuspension in a typical shallow lake—— Taihu Lake. Furthermore, the nutrient releases due to sediment resuspension were estimated and the conceptual scheme of nutrient exchange across the water-sediment interface in large shallow lakes was illustrated.

2 Field experiments, observation and analytical methods

Taihu Lake is located in the Yangtze River Delta with an area of 2338 km^2 and a catchment of 36895 km^2. Mean water depth is 1.9 m and maximum depth is no mre than 3 m. This study was carried out through a series of field and laboratory experiments. In order to collect the physicochemical character of sediment, columnar samples were collected in the five lake sites in June 2001, i.e. No. 5 is located in Meiliang Bay (E31°29′00″, N120°10′03″, denoted Meiliang Bay); No. 1 is located in Northwestern Lake (E31°18′25″, N119°56′37″, denoted Northwest); No. 3 is located in Southwestern Lake (E31°05′05″, N120°06′04″ denoted Southwest); No. 4 is located in Eastern Taihu Lake (E31°01′18″, N120°27′14″, denoted Eastern Taihu); and No. 2 is located the center of Taihu Lake (E31°13′58″, N120°13′03″) (Fig. 1). Columnar samples were collected directly by gravity sampler except at No. 2 due to rigid loess sediment. After sampling, each sample was taken back to the laboratory and segmented by 1—2 cm intervals. Sediments exceeding 26 cm depth were discarded, as they could not be engaged in the nutrient exchange at the sediment-water interface.

In order to get the flux of nutrient and particulates at the sediment-water interface, regularly observations of hydrologic parameters, water sampling for water quality analysis and columnar sediment sampling were conducted during Sep. 8 to 11. The water sampling was preceded three times every day (at 13:00, 17:00, 21:00 on 8 Sep., at 09:00, 13:00, 17:00 on 9—11 Sep.) from seven layers, i.e. surface water, 1.0 m, 1.5 m, 2.0 m, 2.25 m, 2.5 m and 2.7 m (The maximum depth was 2.75 m). Meanwhile, some hydrologic parameters such as water temperature, transparency, wind velocity and depth were monitored. Before ending 4-day field observations, the columnar samples of sediment were taken, and segmented every 1~2 cm for further analysis. Each 1.0 L water sample was withdrawn by manual pump directly into plastic bottles of 1.0 L, and then taken back to the laboratory for analysis. Measurements such as pH, conductivity, dissolved oxygen (DO), chlorophyll-a, chemical oxygen demand (COD) and suspended substance (SS) were initialized as soon as possible adopting standard methods, i.e. electrode for pH and conductivity; gravity methods for SS and organic substance. Moreover, TN and TP in the waters, pore water as well as in the sediment were determined by $K_2(SO_4)_2$-oxygenation method. Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were analyzed same as TN and TP. Some physicochemical factors of sediment, such as moisture content, bulk density, Eh and particle size, were also measured individually by the method of dry-oven, ring-cutting, electrode, laser particle size analyzer. Organic substance in the sediment was determined by burning loss.

Fig. 1. Distribution of field investigation sites, Lake Taihu, China.

For the sake of understanding and comparing the shear stress imposed on the sediment-water interface due to lake currents and waves, a wave meter and a Doppler flow meter were deployed at No. 2 (Fig. 1) during 23—28, July, 2002. The Doppler could simultaneously record lake flows at 6 vertical layers of every 20 cm interval, i.e. 1st layer at −60 cm, 6th layer at –160 cm. The wave height, length and frequency were collected at every 0.1 s, and statistically processed every 20 minutes of records.

Sediments up to 1—2 m^3 taken from No. 5 during early 2001 in Meiliang Bay were laid at the bottom of flume in the laboratory for wave-induced sediment resuspension experiment under conditions of three water depths (30, 40, 50 cm). There were 36 groups in total. The bulk densities of experimented sediment were 1.289, 1.290, 1.338 g/cm^3 individually with an average bulk density of 1.30 g/cm^3, which was consistent with that of the actual layer of the bottom of Taihu Lake *in situ*. That the sediment resuspension under the actions of wave was recognized until most sediment began to move at the flume bottom and the phenomena of sediment transportation were observed. Through experiments, the critical factors of wave (wave height, period and wave length) corresponding with sediment resuspension were obtained and the critical shear stress was determined.

3 The physicochemical character and spatial distribution of sediment in Taihu Lake

The spatial composition of particle size of sediments was nearly the same at four sites of Taihu Lake (Fig. 2).

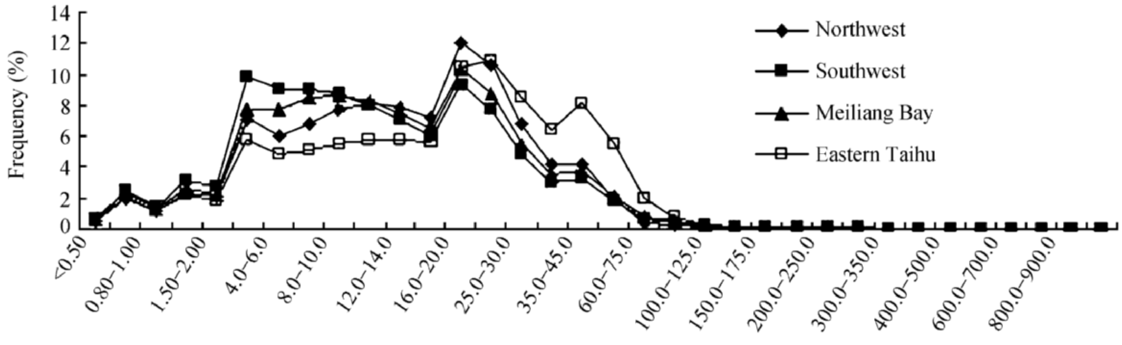

Fig. 2. Distribution of particle sizes (μm) of sediment at four sites in Taihu Lake

Most of them were 2.0—20.0 μm, and 16—20 μm was dominant. All these showed that the spatial distribution of particle sizes was highly uniform through the elutriation, removal and movement, which was consistent with previous investigations[50]. Fig. 3 showed that the medium particle sizes of four sites changed a little with depth except for East Taihu Lake, the latter of them exhibited an obvious increase with depth. Moreover, the particle sizes of East Taihu Lake were bigger than that of other sites, which was obviously related to the fact that the East Taihu Lake was a main channel for flood discharge[50].

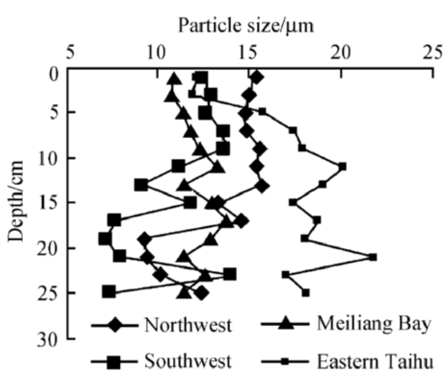

Fig. 3. Changes of medium diameter of sediment vs depth at four sites in Taihu Lake.

From the changes of moisture content with depth at four sites, it showed that the moisture content exhibited active variations at the superficial 10 cm sediment in Meiliang Bay and East Taihu Lake and at the superficial 5 cm sediment in Southwest of lake and Northwest of lake, i.e. the content decreased from 60%—70% to ~40% (Fig. 4). Beneath the active layer, the content was 40% and kept stable. The changes of bulk density and the content of organic substance of sediment showed similar variations at four sites with that of moisture content (Figs. 5 and 6). At the superficial 10 cm sediment in Meiliang Bay and East Taihu Lake and at the superficial 5 cm sediment in Southwest Lake and Northwest Lake, the bulk density increased rapidly with depth, while the content of organic substance decreased; beneath the active layer, they were observed constant or little increase (Figs. 5 and 6). All these changes in the East Taihu sediment were the most obvious, which was related with the fact that there were abundant organic substances in the sediment and changed greatly with depth.

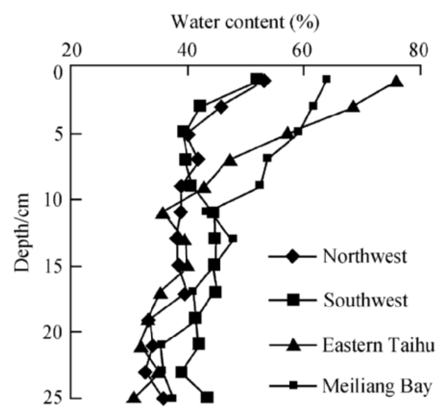

Fig. 4. Changes of moisture content of sediment with the depth at four sites in Taihu Lake.

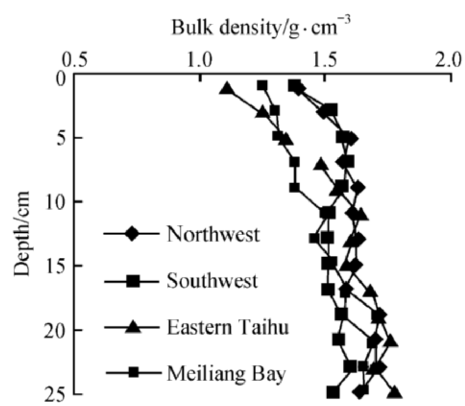

Fig. 5. Changes of bulk density of sediment with the depth at four sites in Taihu Lake.

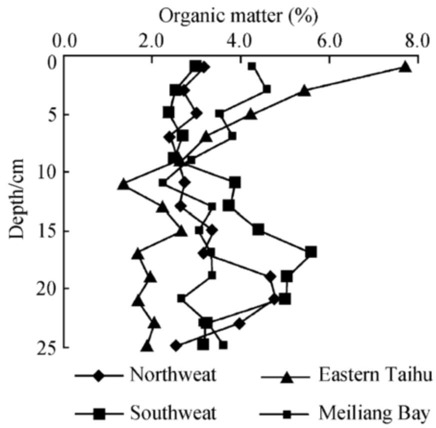

Fig. 6. Changes of content of organic matters of sediment with the depth at four sites in Taihu Lake.

Overall, the superficial 5—10 cm sediment was actively engaged in continuous exchange with superjacent water, resulting in corresponding drastic index changes at the layer that were different from those beneath the layer. In Meiliang Bay and East Taihu Lake, the active layer was 10 cm, while in Southwestern Lake and Northwestern lake, it could merely be 5 cm. The difference was probably that productions were great in Meiliang Bay and East Taihu Lake, the contents of organic substance were higher, which made the sediment have the characters of higher moisture content and lower bulk density when compared with that of the same depth of open waters in Taihu Lake. Overall, there was not obvious difference in physicochemical character of sediment in Taihu Lake in horizontal space, which offered great facility for estimating the rate of nutrient release.

4 The dynamic analysis of sediment suspension in Taihu Lake

The main dynamic force of sediment suspension in Taihu Lake comes from the action of lake currents and waves. In order to define their contributions, we used formulas for calculation as well as on the field investigations of lake current and wave.

The shear stress due to wave's disturbance at the sediment-water interface would be calculated as[44]

$$T_{\mathrm{w}}^{b} = \rho f_{\mathrm{w}} u_{\mathrm{m}}^{2} \cos(2\pi t / T_{\mathrm{s}}) \cos(2\pi t / T_{\mathrm{s}}), \tag{1}$$

among which ρ is the density of water. We adopted the following formula to calculate $\boldsymbol{u}_{\mathrm{m}}$, which is the greatest horizontal velocity of bottom coming from wave's disturbance[51]:

$$\boldsymbol{u}_{\mathrm{m}} = \pi H_{\mathrm{s}} / (T_{\mathrm{s}} \sinh(2\pi d / L_{\mathrm{s}})), \tag{2}$$

where L_{s} is the significant wave length at the depth of h, and can be calculated as

$$L_{\mathrm{s}} = g T_{\mathrm{S}}^{2} \tanh(2\pi d / L_{\mathrm{s}}) / 2\pi \tag{3}$$

whereas T_{s} and H_{s} are the period and height of significant wave respectively, and π is circumference ratio, f_{w} is the coefficient of wave friction, in relation with degree of roughness of lake bottom and Reynolds number, and can be calculated as[52]

$$f_{\mathrm{w}} = \exp[-6 + 5.2(A_{\delta} / K_{\mathrm{s}})]^{-0.19}, \tag{4}$$

where $A_{\delta}=H_{\mathrm{s}}/[2 \sinh(2\pi h/L_{\mathrm{s}})]$, and K_{s} is the physical degree of roughness of lake bottom (=0.2 mm[53]).

The following formula was used to calculate the shear stress coming from lake current[44,54]:

$$T_{c}^{b} = \rho u_{b}^{*} u_{b}^{*}, \tag{5}$$

where ρ is the density of lake water, and u_{b}^{*} can be calculated by the following:

$$u_{b}^{*} = \frac{k_{u_z}}{\ln \dfrac{z}{Z_0}}. \tag{6}$$

In formula (5), k is a constant of Karman (0.4), u_z represents the physical degree of roughness of lake bottom, which is usually insensitive, and could be taken as a constant (=0.2 mm)[54]. The shear stress at the sediment-water interface can be obtained after analyzing the instrumental data of wave meter and Doppler in July 2002 at the center of Taihu Lake (Fig. 7).

The wave was closely related with wind velocity, a SE wind forcing of 1—6 m/s could bring out a significant wave with a height of 10—30 cm and a length of 3—8 m. Simultaneous measurements revealed that the bottom current ranged 1—20 cm/s, which was poorly related with wind field variations. Additionally, the corresponding shear stresses due to waves and currents were 0.001—0.4 N/m^2 and 0.001—0.01 N/m^2, separately. The shear stress due to waves used to be higher than that of currents under stronger winds. Sometimes shear stress due to currents might exceed that of waves when the wind forcing was weaker, as the monitoring *in situ* of 17:30, 23th, and 14:00, 24th, July 2002 indicated. Generally speaking, concerning the shear stresses at the water-sediment interface, both the waves and currents functioned under weaker winds, while the waves would dominate under stronger winds.

5 The analysis of critical shear stress of sediment resuspension in Taihu Lake

We need to determine the critical shear stress of sediment resuspension when we define the contribution of the action of dynamic force. So we used the instrument of wave-generator to precede this experiment in the water flume at the laboratory. The sediment samples used for experiment came from No. 5, Meiliang Bay. The thickness of sediment was about 10 cm and the bulk density of sediment was 1.3 g/cm^3 on the average, which were consistent with that of the actual active layer on the lake bottom on spot. The standard of sediment movement at the action of wave was universal movement. Table 3 shows

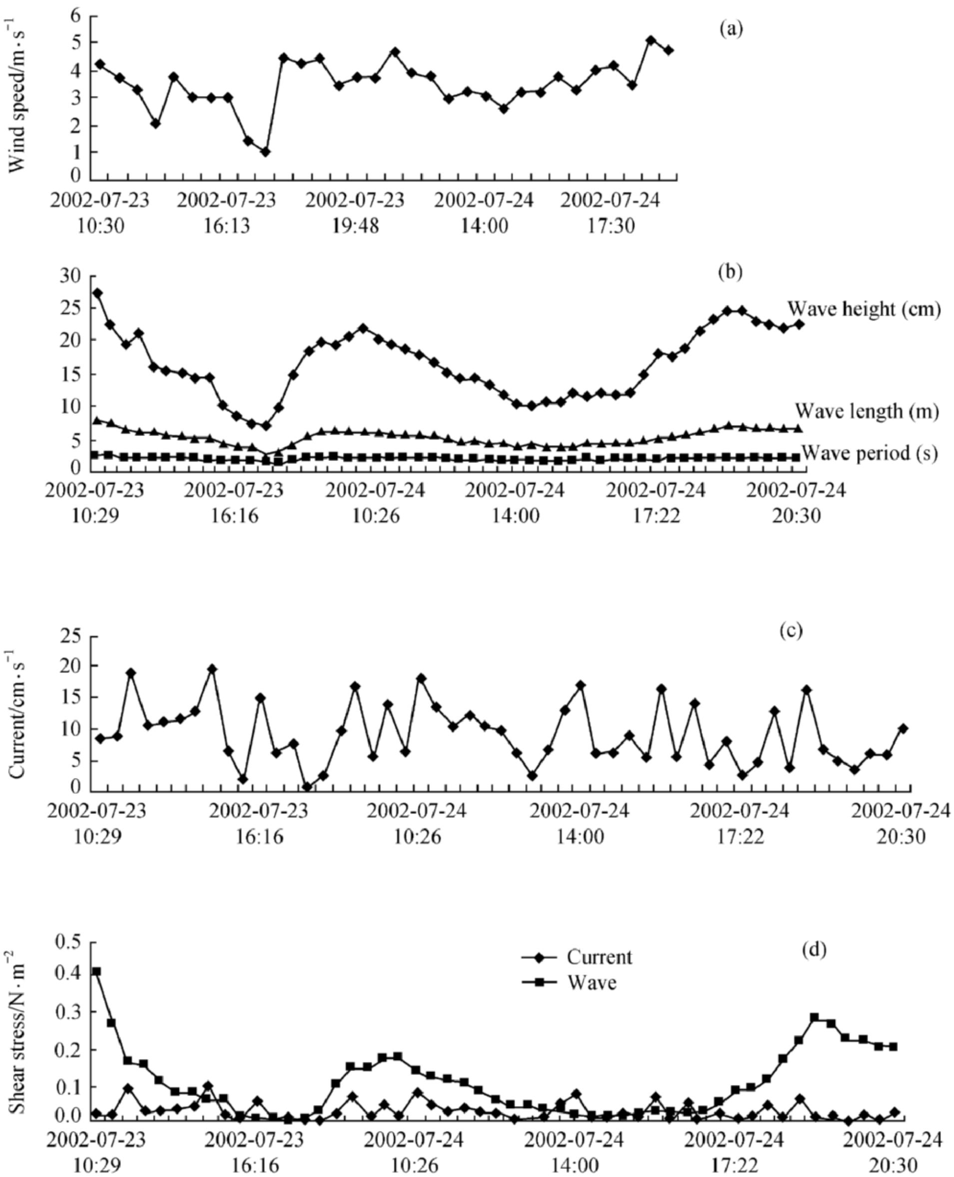

Fig. 7. Shear stress variations at the water-sediment interface due to waves and currents at the center of Taihu Lake, on 23—24 July, 2002. (a) Simultaneous wind velocity(m/s) with short recording time than waves and currents; (b) significant wave height (cm), length (m) and frequency (s); (c) bottom current velocity monitored (cm/s); (d) calculated shear stresses (N/m^2) due to waves and currents according to observed data.

the results of critical wave height when the sediment started to move.

Under laboratory conditions, the critical wave height (H_0) when the sediment started to move and the maximum velocity ($U_{\max(-h)0}$) of bottom current can be calculated by semi-empirical formula [55]:

$$H_0 = 0.12\left(\frac{L}{D}\right)^{1/3} \times \sqrt{\frac{Lsh2kh}{\pi g}\left[\frac{\rho_s-\rho}{\rho}gD + 0.02\left(\frac{D}{D_0}\right)^{1/2}\frac{2.56}{D}\right]}, \quad (7)$$

$$U_{\max(-h)_0} = 0.12\left(\frac{L}{D}\right)^{1/3} \times \left[\frac{\rho_s-\rho}{\rho}gD + 0.02\left(\frac{D}{D_0}\right)^{1/2}\frac{2.56}{D}\right], \quad (8)$$

where L is wave length; D, D_0 is particle size and characteristic particle size separately, H_0 is the critical wave height; ρ, ρ_s is the density of water and sediment each; and h is the water depth. By using these formulas, the critical wave height of sediment suspension in Taihu Lake can be calculated. The calculated results were consistent with those of experiments (Table 1).

Table 1 Comparison on the calculated and experimental results of critical start-up of sediment under the action of waves in Taihu Lake

Medium diameter D/cm	Water height H/cm	Period T/s	Height of start-up wave H_0/cm	
			experimental	calculated
0.0017	30	1.2	9.3	9.79
0.0017	30	1.49	8.7	9.51
0.0017	40	1.1	13.5	14.62
0.0017	40	1.5	12	12.32
0.0017	50	1.1	19	20.83
0.0017	50	1.24	15.6	17.07

Furthermore, we can deduce the bottom shear stress of start-up sediment at the action of waves on the base of formulas (7) and (8). Based on our several times of observations in Taihu Lake, the average wave height was 5—40 cm and the average period was 1.0—2.5 s; as a result, the critical shear stress of sediment resuspension in Taihu Lake can be calculated under different water depths. Part of results can be seen in Table 2.

Table 2 The critical shear stress of sediment resuspension in Taihu Lake

Water depth/m	Period T/s	Critical wave height/cm	Critical shear stress/N • m^{-3}
0.5	1.2	17.95	0.036
1.5	2.4	30.48	0.036
2	2.4	42.56	0.032
2.5	2.4	58.91	0.04
3	2.4	81.8	0.053

From Table 2, the critical shear stress was noted to be ~0.037 N/m^2 on average for superficial sediments with a medium diameter of 0.017 mm and a bulk density of 1.3 g/cm^3. Compared with the data monitored in September 2001(Fig. 7), the noted critical shear stress was about to an intensity under a wind velocity of 4 m/s, which indicated that the shear stress at the water-sediment interface originated mainly from dynamic waves. Relevant researches around the world showed that critical shear stresses for sediment suspension should be 0.01—0.1 N/m^2[44,45,49,56], for example, it was favored to be 0.032 N/m^2 for sediment resuspension in Lake Okeechobee, Florida, U.S.[57]. The results of critical shear stresses of Taihu Lake from experiment are comparable with other lakes.

If the wind forcing would be much greater than the threshold of critical shear stress, sediments would resuspend dramatically. Three kind intensities of wind forcings and the corresponding solid particulates concentration during Feb. 23, 25 and March 11, 1998, in Meiliang Bay were observed, and the results showed that the sediments would be resuspended on a large scale if the wind speed was no less than 6.5 m/s (Fig. 8)[58].

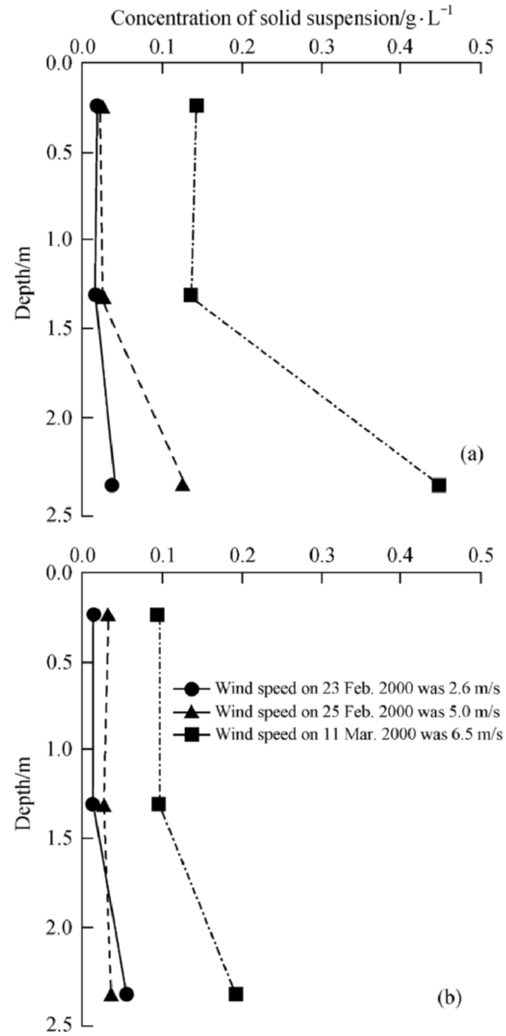

Fig. 8. Concentrations of suspended solids under 3 courses of wave action at two sites (East: upper; West: lower) of Meiliang Bay, 1998.

6 The nutrition release of sediment

Sediment can resuspend at the action of dynamic forcing. The most direct influence of resuspension was that pore water in the sediment would be released after sediment resuspension. Because the concentration of nutrition in pore water was usually much higher than that in overlaying water, noted nutrition release would occur with sediment resuspension. In September 2001, 4 days and 3 times per day and 7 layers each time provided an averaged profile of concentrations of total dissolved nitrogen (DTN) and total dissolved phosphorus (DTP) changing with depth. Similarly, the nutrition in pore water in sediment provided a profile of concentration of TN and TP. The result showed that nutrients in pore water was much higher than that of overlaying water (Fig. 9(a), (b)), which objectively provided a prerequisite for nutrient release from pore water to overlaying waters.

Because sediment suspension may lead to the nutri-

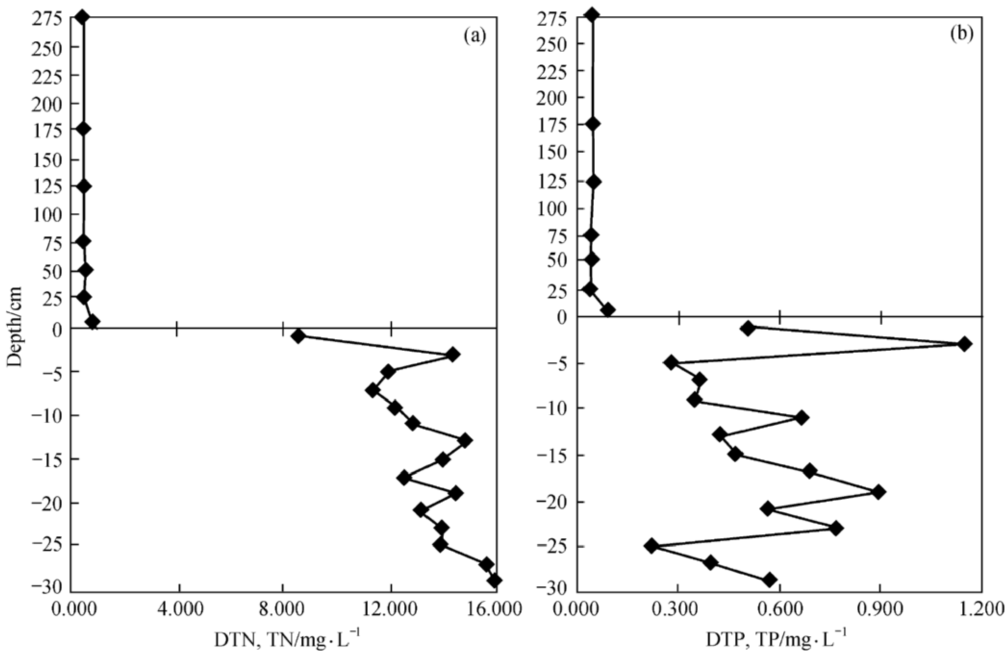

Fig. 9. Vertical cross sections of averaged profile of DTN and DTP in overlaying water and TN,TP profile in pore water of sediment at site 5 in Meiliang Bay from 8 to 11, Sep. 2001 (3 times every day and total 12 times). The abscissa was set as the water-sediment interface. The cross section of DTN and DTP in the overlaying water were above the abscissa, while the cross section of TN,TP in pore water was under the abscissa. It should be noted that samples of water and sediment were not collected at the same time, and the indexes of waters were DTN, DTP and of pore water were TN,TP respectively.

ent release from pore water, the porosity of sediment and the concentration of nutrition in pore water will directly affect the flux of nutrient release. Fig. 10 shows the changes of sediment porosity as the depth changing at four sites in Taihu Lake in June 2001. Except for East Taihu Lake, the porosities of 4 sub-lakes decreased with the sediment depth increasing under the superficial 10 cm. When the depth exceeded 10 cm, the porosity was stable and decreased slowly. Fig. 11 shows the concentration of nutrition in pore water change with depth. It can be seen that the change of concentration of nutrition in pore water was indistinctive under the bottom 10—15 cm, but under this realm, the change was very obvious with the general trend increasing with depth. The condition of East Taihu Lake was special and the changes of TN, TP in pore water were not obvious from the lake bottom to the layer 25 cm below water-sediment interface.

By using these data, we can calculate the nutrient release due to one dynamic process. The sediment in Taihu Lake was distributed unevenly in space, most of them were situated from northwest to southwest along west coast in Meiliang Bay then expanded to East Taihu Lake, while there was little sediment in the middle and northeastern Taihu Lake[59]. Assuming all the top 10 cm sediment exhibiting resuspension, the porosity and the concentration of TN, TP in pore water in four sub-lakes, i.e.

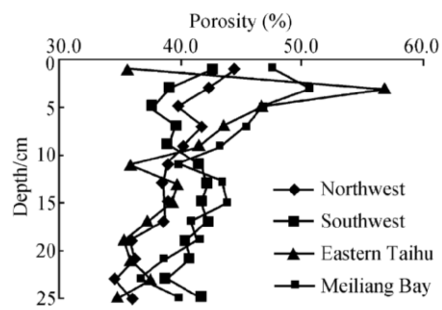

Fig. 10. Degree of porosity of columnar samples as the depth increasing in June 2001 at four sites of Taihu Lake.

Northwest, Southwest, East Taihu and Meiliang Bay can be calculated (Table 5). It was estimated that the sediment area of East Taihu Lake occupied 134 km^2; Meiliang Bay, 62 km^2; and the open Taihu Lake area, 1431 km^2[59]. Assuming the pore space of sediment was filled with water and the porosity of sediment and the concentration of nutrition was distributed evenly in space, the nutrient release due to one severe dynamic process in Taihu Lake can be calculated as follows: there would be an increase of ~29618 kg N and 1514 kg P in East Taihu Lake; in Meiliang Bay, it was ~23059 kg N and 1236 kg P; and in open Taihu Lake area it would be 477668 kg N and 20606 kg P, corresponding to an increase of TN and TP of 0.12 mg/L and 0.005 mg/L individually in the whole Taihu Lake. At present, the concentrations of TN and TP are up to 2—4 mg/L and 0.01—0.1 mg/L separately in Taihu Lake, such an increase due to one severe dynamic process would be estimated to increase the concentrations of TN and TP of lake water by 3%—6% and 5%—50% respectively. Because of the presence of aquatic plants in East Taihu Lake, the sediment resuspension and nutrient release would both be inhibited and the majority of release would be hindered. While in other sub-lakes, the absorbability and flocculation of particle substances would play a key role in restraining sediment release, and lowering the release flux.

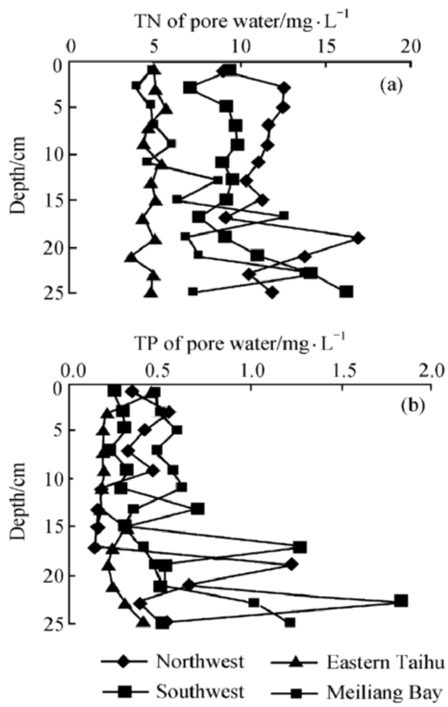

Fig. 11. Variations of TN (upper) and TP (lower) concentrations in pore water of sediment with the depth increasing in June 2001 at four sites of Taihu Lake.

Table 3 The averaged porosity of sediment under the top 10 cm and the concentrations of TN, TP in pore water at four sites of Taihu Lake in June 2001

	Northwest of Lake	Southwest of Lake	East Taihu	Meiliang Bay
Porosity (%)	40.2	40.1	45.2	45.3
TN concentration/mg • L^{-1}	11.64	5.09	4.89	8.21
TP concentration/mg • L^{-1}	0.44	0.28	0.25	0.44

7 The conceptual scheme of nutrient release of sediment in Taihu Lake

In general, only when granular organic substances are degraded into soluble nutrition, can it become internal loadings of lakes. The content of dissolved oxygen (DO) at the water-sediment interface is the main factor that affects the degradation and its outcome. It also determines the supply speed of nutrition from sediments. In shallow lakes like Taihu Lake, the supply of oxygen on the bottom layer is certainly sufficient. The concentration of DO in Taihu Lake is about 7.0—9.0 mg/L. Most active organic substance in shallow lakes, therefore, are easily be oxidized. Because the condition of oxidation at the sediment-water interface was not advantageous for the degradation and release of P and N[12,31], so it is speculated that the degradation and mineralization of organic detritus and granular matter in lake sediment would finally come into being various modalities of N and P which was in favor of biological utilization. The soluble active nutrition in sediments was more than that in overlaying waters. The Eh changing with depth in sediment based on the columnar samples collected from four sites of Taihu Lake in June 2001 showed that the oxidation on the superficial sediment is better than that in deeper layers (Fig. 12). The reduction was intensified with the depth increasing within the top 5—7 cm; beneath this layer, the situation was contrary. About at the depth of 10 cm, the reduction remained stable. Like other indexes, the situation of East Taihu Lake was still different, possibly because the superficial reduction was stronger than other sub-lakes due to higher content of organic matter in sediment, weaker dynamic conditions, and shallower water.

Under certain depths, the porosity of sediment will be seen to decrease rapidly. Since the reduction in sediment strengthened with the depth increasing, it can be concluded that the concentrations of nutrition in pore water and reduction would increase with depth. The concentration of ammonia nitrogen in pore water in columnar samples of sediment was found to increase with the depth in Meiliang Bay and Wuli Lake, especially in the columnar samples near the top 5—10 cm[26]. Such phenomena used to be more commonly observed in the open lake area due to frequent dynamic disturbance rather than that in the bays due to weaker disturbance.

If the sediment was not disturbed, the upward release of nutrition in sediment can proceed only by naturally upward concentration gradient or the perturbation of benthic organisms. This type of release is called static release, which would be weaker in shallow lakes than that in deep lakes under the same conditions, because the supply of DO at the sediment-water interface in shallow lakes is more sufficient than that in deep lakes. The sufficient supply of oxygen was in favor of oxidation of Fe and Mn and enhanced the absorption at the sediment-water interface, and finally retarded the release of nutrition to overlaying water[25,60]. Based on the investigations in Meiliang Bay in early spring of 1998, when the velocity of wind exceeded 6.5 m/s, the concentration of suspended matter in lake would raise dramatically with the depth increasing. The

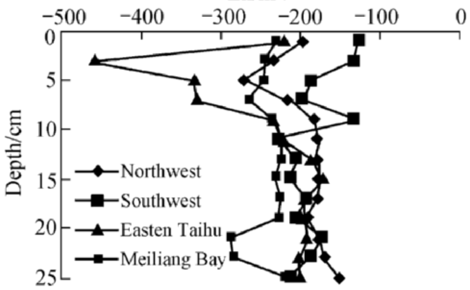

Fig. 12. Eh of columnar samples with the depth increasing in June 2001 at four sites of Taihu Lake.

massive sediment re-suspension would often be seen at the top 5—10 cm, thus the nutrition of pore water in sediment would be released on a large scale. As a result, the dynamic condition not only can reduce the release of nutrition to overlaying water because of re-oxygenation, but also can lead to dramatic increase of release due to massive sediment re-suspension[4]. After the wave and wind procedure, the suspended solids would gradually precipitate and come into being the new sedimentary deposit. Relevant researches have demonstrated that the velocity of degradation of dead plant detritus and organic granular matter in the waters and in the sediment in Taihu Lake would take only several days or weeks[61,62]. Consequently, the organic granular matter of sediment can continuously be degraded and separated out, which provided nutrition of direct biological utilization under dynamic suspension and release. It should be mentioned that there will be absorption and flocculation happening during the course of the deposition of suspended matter and will bring the soluble nutrition in the waters, after absorption, back into the sediment.

Based on the above analysis, we can conclude that the nutrient release in the large shallow lake has its own characteristic. Organic granular matters deposited into the bottom and produced a relatively stable environment of reduction because of the deposition of silts. Through the degradation of organic matter, the nutrition was separated out and came into the pore water. When the wave and wind forcing was imposed on the water, the sediment would re-suspend and the nutrition in pore water would be leaked into the superjacent waters accordingly. Because of the strong oxidation of suspended solids, the release of nutrition would be greatly reduced for perturbation and absorption. With the withdrawal of wave and wind forcing, the suspended solids would precipitate gradually; some of them would bring nutrition and organic matters back into the sediment. This type of nutrient release was totally different from the release in deeper lakes, which used to rely mainly on the nutrient concentration gradients[12,31].

8 Conclusions

(1) The exchanges which the sediment took part in with matters at the sediment-water interface were mainly occurred at the top 5—10 cm in large shallow lakes like Taihu Lake. The active layer would be about 10 cm in Meiliang Bay and East Taihu Lake, while in Northwestern Lake and Southwestern Lake, it might be a mere 5 cm. The reason why there are spatial differences in active layer thickness lied in the fact that the productivity in Meiliang Bay and East Taihu Lake is relatively high, which caused the organic matter abundant, sediment with lighter bulk density easier to resuspend.

(2) The wave courses in Taihu Lake were observed and found well related with wind forcing, while the current not. Under weaker wind-driven waves, the shear stresses due to waves and currents were nearly of the same magnitude; sometimes the currents may overcome. When the winds were stronger, i.e. greater than 4 m/s, the wave would dominate as to shear stress, since the bottom current and the corresponding shear stresses were observed to increase little. At that time, the suspension and sedimentary processes would be mainly affected by wind-driven wave actions instead of currents.

(3) Through experiments and calculations, we can confirm that the critical shear stress of sediment in Taihu Lake is about 0.03—0.04 N/m^2, which is basically no exception as compared with data reported around the world. Such a critical shear stress would be equivalent to an actual wind action of 4 m/s in field where waves dominated. When the wind forcing exceeded such a magnitude, for example 6.5 m/s, massive resuspension of sediment would occur. This conclusion is consistent with investigations *in situ*.

(4) The results of investigations *in situ* showed that the concentration of nutrition in pore water of sediment is far higher than that in overlaying water in Taihu Lake, which provided the condition necessary for the nutrition release from sediment to the superjacent water.

(5) When the velocity of wind was greater than about 6.5 m/s, massive sediment suspension would occur in Taihu Lake. Under this condition, the maximum sediment release of nutrition would be calculated, i.e. 29618 kg N and 1514 kg P in East Taihu Lake; ~23059 kg N and ~1236 kg P in Meiliang Bay; and 477668 kg N and 20606 kg P in open area of Taihu Lake, respectively. Such a maximum sediment release under one severe dynamic wind forcing would correspondingly result in an increase of TN of 0.12 mg/L, and TP of 0.005 mg/L in the whole lake. Nonetheless, the total release actually observed in shallow lakes would be much lower because of the existence of aquatic plants and the interfering of absorption, flocculation and sedimentation of granular matters.

(6) As a large shallow lake, the nutrient release of sediment had its own regularity in Taihu Lake. When the dynamic force was stronger, the sediment would generate suspension from the top several centimeters to tens of centimeter, the dissolved nutrition in sediment would be

released, and such a release under dynamic conditions used to be stronger than that under static conditions. But this kind of nutrient release would be reduced because of re-oxygenation within the water column. Because of absorption and flocculation, parts of nutrition would be carried back to the lake bottom with the precipitation of suspended matters. The organic granular matters will be degraded and separated under the condition of reduction. The sediment would await the next wave and wind forcing for re-suspension and nutrient release. Such a scheme of nutrient release was entirely controlled by dynamic force, and different from that in deeper lakes.

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