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Original Research

Measurements of Erosion Rate of Undisturbed Sediment under Different Hydrodynamic Conditions in Lake Taihu, China

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Abstract

Sediment erosion and nutrient release play a significant role on the degradation of water quality and eutrophication in large shallow lakes. Lake Taihu, the third largest freshwater lake in China, is suffering severe eutrophication and internal nutrient release. In this paper, sediment cores were sampled in different lake regions to determine sediment properties (e.g. particle size and bulk density), nutrient concentrations in the sediment, etc. Flume experiments were developed to examine the sediment erosion rate by using the undisturbed sediment cores under different hydrodynamic conditions in Lake Taihu. The results showed that the sediment properties exhibited great spatial heterogeneity. Particle sizes decreased with increasing depth of sediment thickness. Sediment bulk density increased with sediment depth. TN concentration increased with sediment depth, while TP concentration didn't show a similar trend in different sampling sites. Erosion rate is a function of particle size, bulk density, and shear stress. It decreased with increasing sediment depth and decreasing flow velocity. The erosion depth in this study was less than 1cm under the flow velocity of 5 to 30 cm/s, indicating that unidirectional flows have little impact on sediment erosion in Lake Taihu.

Keywords: erosion rate, particle size, bulk density, nutrient concentration

Introduction

Contaminants settle down, accumulate, and are buried at depths of up to several meters in the bottom sediments of lakes. These sediments are easy to erode when wind blows and in-flows scour, thus nutrients are released into the water column and the clarity of water decreases. These processes can also affect aquatic plants, since photosynthesis processes are affected, and thus the dead plants exacerbate water quality, the content of dissolved oxygen lowers, and algae bloom and water quality worsen [1]. Hence, the sediment erosion and nutrient release processes have a significant impact on water quality and eutrophication in eutrophic lakes, even when external nutrient sources are under control [2]. For large shallow lakes, sediment erosion occurs more easily than in deep

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lakes due to the longer wind fetch and the stronger turbulence near the bottom.

Various studies have focused on erosional properties in order to study sediment erosion [3, 4]. These studies claimed that sediment erosion rate varies with depth within the sediment at different sites, and is a function of particle size, bulk density, and shear stress. Jesse et al. [5] mentioned that the erosion rate increases to an initial maximum value and then decreases as particle size increases when bulk density and shear stress were constant. The erosion rate obviously increases with shear stress. The bottom shear stress increases with flow rates and induces the particles to move, either resuspending or sliding. These tests qualitatively determine that erosion rates depend on at least the following parameters: bulk density, particle size distribution, organic content, and sediment porosity. Therefore, those parameters should be determined prior to measuring sediment erosion.

Many devices and methods have been developed to measure sediment erosion both in situ and in the laboratory. The main devices include annular flume, *ex situ* flume or Sea Carousel, shaker, sediment erosion with depth (SED) flume or adjustable shear stress erosion and transport (ASSET) flume, and Ravens flume [4]. These flumes are operated at different flow rates corresponding to different bottom stresses, and the erosion rates are observed as a function of bottom stress. All the various devices have advantages and disadvantages concerning erosion conditions, economy, flow conditions, and sediment depth. The advantage of annular flume is that the "infinite" flow length results in a fully developed boundary layer, leading to the estimation of bed shear stress easily obtained from velocity profiles. But the annular flow with inherent secondary currents could generate a non-uniform shear stress distribution across the channel. For the shaker, the flow driving system may break the suspended flocs in the water column, resulting in the boundary layer not being fully developed in the test section [6]. For the straight open channel flume, the eroded sediment is lost at the outlet section due to the open system. The advantage is that impact of secondary currents is minimized in the straight erosion section.

In this study, a special flume device (similar to the SED flume) was used with the advantage of adjusting flow velocity to gain different shear stresses to produce various erosion effects. This was also selected for its ability to measure sediment erosion rates at different flow rates, and to maintain the originality of the sediment sampled from the field. Moreover, this device is simple, convenient, and produces accurate results. For an ordinary core, the sediment was taken from field work and reconstructed to be poured into the core for several days. In this case, the larger and heavier particles settled down first, then followed the lighter particles, creating a bed of stratified particles. The special core used in this experiment is a well-mixed core in which the slurry could settle for several days which reduced the water content and slowly remixed. The sediment particles in this core are undisturbed and relatively homogeneous, which keeps the original state as in the field.

The objectives of this paper are:

1. Determine the spatial distribution of sediment properties, including particle size, bulk density, and nutrient concentration in Lake Taihu
2. Quantify the shear stress under different flow conditions and the critical shear stress under different sediment depths
3. Calculate the sediment erosion rate under different flow velocities
4. Develop the function between erosion rate and particle size, bulk density, shear stress, and flow velocity

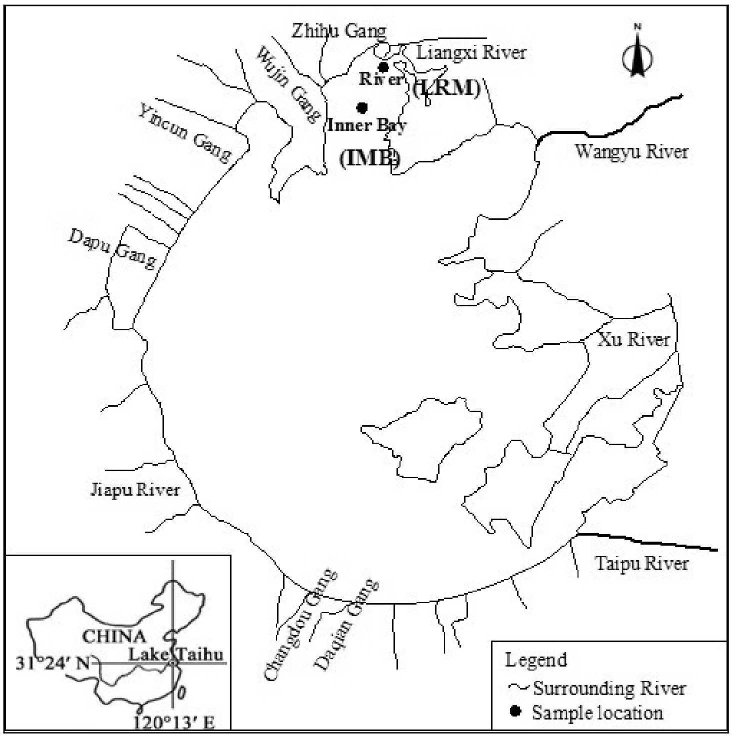

Fig. 1. The two sampling sites (Liangxi River Mouth, LRM and Inner Meiliang Bay, IMB) in Lake Taihu.

At present, no general quantitative theory of sediment erosion properties is available for fine-grained sediments. Experiments are therefore needed to determine these properties.

Study Area

Lake Taihu, a well-known freshwater lake located at the lower reach of the Changjiang delta, is a typical large shallow lake. Its mean water depth is less than two meters (1.89 m) and surface area is 2,338 km^2 [1] (Fig. 1). The volume of Lake Taihu is 44.28×10^8 m^3, and the hydraulic retention time varies from 219 to 365 days [7]. The lacustrine depths within the sediment in most regions of Taihu range from 0.5 to 2.0 m, and the lake is easily affected by wind due to its shallowness. The current velocity ranges from 5 to 30 cm/s when wind is blowing with the speed of 5 to 20 m/s, which mostly produce big waves and lake currents, thus resulting in high sediment resuspension [8].

There are 172 major tributaries connecting to Lake Taihu [7]. The watershed is divided into two regions, named upstream and downstream by Zhihugang River and Gulougang River [9]. Similarly, for the convenience of analysis, Taihu is divided into eight parts: Zhushan Bay, Meiliang Bay, Gonghu Bay, Northwest Zone, Southwest Zone, Central Zone, East Epigeal Zone, and Dongtaihu Bay [10]. The wind field of Lake Taihu varies with seasons. Mostly, the wind direction is southeast, especially in summer. Wind speed is higher in the southern part of the lake compared with the northern part [11].

Methods and Materials

Description of the Flume

A schematic of the flume is shown in Fig. 2. It was essentially a straight flume, which had an open mouth at the bottom through which a circular cross-section coring tube containing undisturbed sediment can be inserted. The main components of the flume are an inlet section for developed unidirectional flow, the test section, the coring tube, a flow exit section, a water storage tank, and a pump to force water through the system. The inlet section, coring tube, test section, and exit section were made of clear acrylic or polycarbonate so that we could clearly observe the sediment-water interactions. The diameter of the circular sampling coring tube was 9 cm.

Water was pumped through the system from a 1 m^3 storage tank to a rectangular duct through a flow converter. This duct was 5 cm in height, 15 cm in width, and 200 cm in length; it connected with the test section, which had an open mouth with diameter of 9 cm to match the circular coring tubes. The flow was regulated by a three-way valve to enable part of the flow to enter the duct while the remainder returned to the tank. Also, there was a small valve in the duct downstream of the test section that was open at high flow rates to keep the pressure at atmospheric conditions. Different current velocity was obtained by controlling the height of the inflow and outflow water tank to gain different altitude heights.

At the start of each test, the coring tube was filled with undisturbed sediments. The coring tube with sediment was inserted into the bottom of the test section. An operator, driven by a variable-speed controller, was connected to a mechanical jack and moved the sediment upward using a piston inside the end of the coring tube. Hence, the sediments can be raised to the bottom level of the test section at any time. The speed of the jack movement can be controlled at a variable rate in measurable increments as small as 0.5 mm.

Water was forced through the test section over the surface of the sediments. The shear produced by this flow caused sediment erosion. When sediment eroded, the core was continually moved upwards slightly by the operator so that the sediment-water interface remained level with the bottom of the test section. Shear stress was known as a function of flow rate from the standard pipe flow theory. The erosion rate was recorded as the upward movement of the sediments in the coring tube over time.

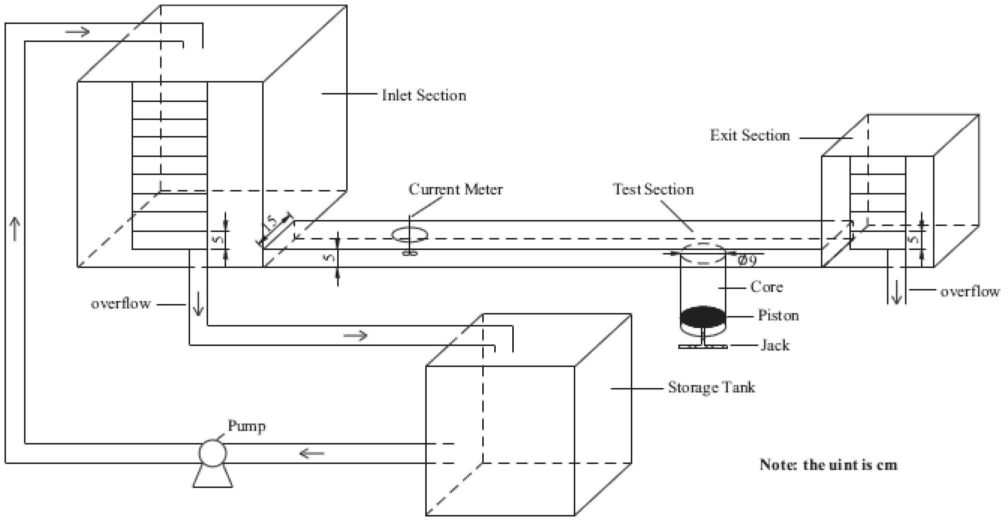

Fig. 2. A high shear stress sediment erosion flume to measure sediment erosion rate.

Sampling Site Selection and Sediment Core Sampling

Two sampling sites were selected as Liangxi River Mouth (LRM) (120º10′31″E, 31º30′30″N) and Inner Meiliang Bay (IMB) (120º12′46″E, 31º32′4.6″N) (Fig. 1). Both sites were located in Meiliang Bay. The two sampling sites represented two kinds of hydrographic environment: lake and river mouth. LRM was near a tributary while IMB was inner bay, which can reflect the difference of environmental effect between river mouth and inner bay. Meiliang Bay (120º10′31″E, 31º30′31″N) is a shallow semi-enclosed large bay covering approximately 130 km^2, situated in the northern part of Lake Taihu. It offers drinking water to the people of Wuxi City and also to the factories. However, the ecosystem of the lake is seriously distributed with a rapid increasing social economy and population. Meiliang Bay has been the most polluted area of Lake Taihu since 1989. Increasing frequency of algae blooms has negatively affected many socio-economic aspects and ecosystem components. Researchers have paid attention to the evolution of Meiliang Bay's physical, chemical, and biological characteristics. Meanwhile, many restoration efforts have been made to improve water quality, such as sediment dredging and water transfer. Hence Meiliang Bay was chosen as the study area to research sediment properties and sediment erosion. Fig. 1 shows the map of sediment sampling locations.

The sediment cores were collected by the use of a columnar sampler from the two sites. Cores were penetrated into the sediment bed by applying pressure to the top of the core sleeve. The penetration depth varied with sediment characteristics (i.e., deep penetration occurs in soft sediment rather than compact sediment). This resulted in the sediment core being obtained relatively undisturbed from its natural surroundings. The coring sleeve was fixed with a plug, which slided up to act later as a piston. Sediment cores varying in length from 10 to 30 cm were obtained by this method.

At each site, two duplicate sampling cores were taken. To determine the TN and TP concentrations at different layers, the surface sediments (upper 0-15 cm) of each core were sliced into 10 layers, at an interval of 1 cm for the upper 5 cm and 2 cm for the lower 10 cm (i.e. five layers×1 cm, and five layers×2 cm). These were first put into plastic bags and then transferred to the laboratory for further analysis.

Measurements of Sediment Bulk Properties and Nutrient Concentration

Particle Size

Average particle sizes and particle size distributions were determined by use of a Malvern Particle Sizer for particle diameters between 0.1 and 1000 μm. A small amount of sediments were mixed with water and disaggregated in a Waring blender. Approximately 1 mL of this solution was then used for analysis by the particle sizer. The distribution of grain sizes and the average grain sizes as a function of depth were obtained.

Bulk Density

In order to determine the bulk density of the sediments at a particular depth, the sediment analysis cores were frozen, sliced into 3 to 4 cm sections, and then weighed (wet weight). They were then dried in the oven at approximately 75ºC for 2 days and weighed again (dry weight). The water content w was then given by:

$$w = \left[\frac{m_w\text{-}m_d}{m_w} \right] \tag{1}$$

...where m_w and m_d were the wet and dry weights, respectively. The bulk density ρ (gm/cm^3) was related to the water content by:

$$\rho = \frac{\rho_s \rho_w}{\rho_w + (\rho_s\text{-}\rho_w)w} \tag{2}$$

...where ρ_s was density of the solid particles and ρ_w was density of water. The total error in bulk density measurements was within ±0.001 gm/cm^3.

Nutrient Concentration

Chemical analysis was conducted in the State Key Laboratory of Hydrology – Water Resources and Hydraulic Engineering of Hohai University, China. The sediment samples were first dried naturally at room temperature, and then ground and screened with a 100-mesh sieve. The TN and TP concentrations of all the samples were determined by the semi-micro Kjeldahl method and the H_2SO_4-$HCLO_4$ digestion method, respectively [1].

Results

Sediment Bulk Properties

Particle Size Distribution

Sediment particle sizes varied from 0.3 to 1000 μm at LRM and IMB (Fig. 3). The largest volumes of particle size diameter were around 20 and 150 μm, respectively. At LRM, the volume friction of particle sizes 20 and 130 μm were 2.8 and 4.0%, respectively. However, at IMB the volume friction of particle sizes 28 and 150 μm were 3.6 and 3.2%, respectively. The volume of small particles was less than that of large particles at LRM. However, the trend was opposite at IMB. The particle volume decreased when particle sizes smaller than 20 μm at LRM. And it decreased when particle sizes larger than 130. The same scenario occurred at IMB. The particle volume was lowest with a size of 70 μm and 80 μm at LRM and IMB, respectively. The particle volume decreased sharply at large sizes and tended to be zero for particle sizes reaching 200 μm. Each sediment particle size distribution was fairly narrow.

Particle size distribution at the vertical direction was different at two sampling sites as well. Particle sizes of surface sediment seemed to be larger than that of deeper sedi-

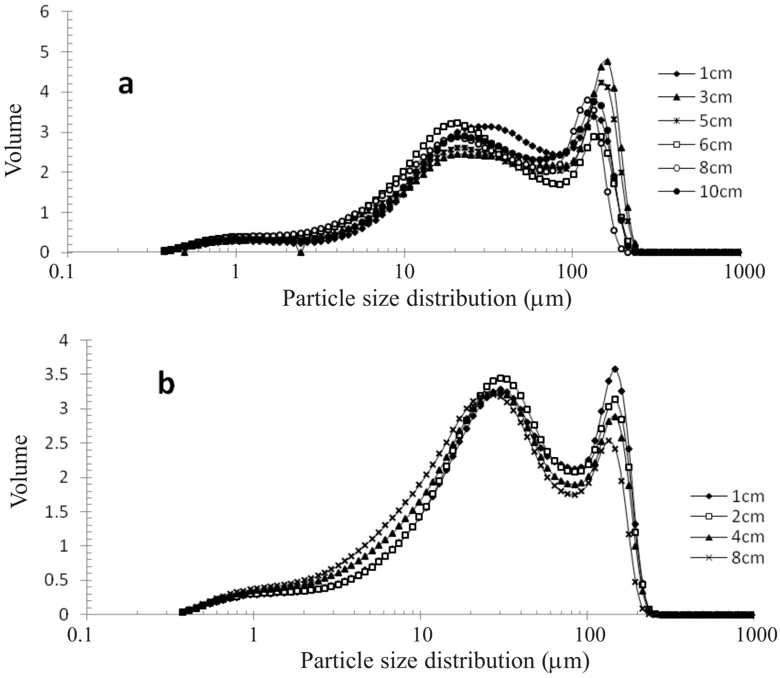

Fig. 3. Particle size distributions with depth in the sediment in a) LRM and b) IMB.

ment (Fig. 3). This decreased slightly when depth within the sediment increased. Particle sizes around 130 μm and 150 μm mainly distributed 1 cm deep in the sediment for the two sites. And particle volume decreased as the depths within the sediment increased. Particle size of 20 μm mainly distributed 6 cm or deeper in the sediment at LRM. At IMB, particle sizes of 28 μm mainly distributed 2 cm or higher in the sediment. The sediment particles got the same volume friction with particle sizes around 15, 40, 130, 160 μm and 16, 40, 140, 160 μm in each depth within the sediment at LRM and IMB, respectively. This meant that sediment particle sizes were uniformly distributed.

Bulk Density

Depth in each size class of sediment greatly determined sediment bulk density. The result for the variation of bulk density with depth for a single core measured by the density profiler is shown in Fig. 4. In different sediment layers, the bulk density of sediment showed quite different properties. The sediment depth can be divided into three layers by the profile of bulk density: the upper layer with sharply increased bulk density (0-10 cm), the middle layer with constant and slightly increased bulk density (10-22 cm), and the lower layer with decreased bulk density (22-36 cm). For the upper layer, bulk density increased with depth in the sediment at both LRM and IMB. The minimal bulk density was 0-4 cm deep in the sediment with the value of 1.16 g/cm^3 and 1.28 g/cm^3 at LRM and IMB, respectively. For the middle layer, the bulk density was almost constant (1.56 g/cm^3) and slightly increased to the maximum value (1.74 g/cm^3) at depth range of 10-18 cm and 20-22 cm in the sediment at both LRM and IMB, respectively. For the lower layer, the bulk density decreased to a constant value (1.60 g/cm^3) and kept constant at depth range of 22-26 cm and 26-36 cm in the sediment at both LRM and IMB, respectively.

The increasing rate of bulk density at LRM was higher than that of IMB in the upper layer of sediment (0-10 cm). However, the increasing and decreasing rates of bulk density at LRM was lower than that of IMB in deep layers of sediment (18-22 cm, 22-26 cm). Generally, bulk density was related to sediment class and topography.

Nutrient Concentration in the Sediment Core

The average TN and TP concentrations in the surface sediments at the two sampling sites were calculated by arithmetic method to average all the measured concentration data as mentioned in Lu's paper [1] (Table 1). In detail, the average TN contents were 0.194% and 0.168% at LRM and IMB, respectively. And the average TP contents were

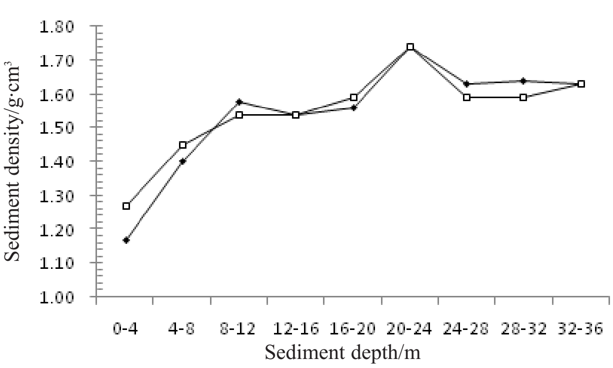

Fig. 4. Variations of bulk density with depth in the sediment in LRM and IMB.

Table 1. Nutrient concentrations of TN and TP in LRM and IMB.

Average nutrient concentrations			
Sites	TN (%)	TP (%)	*TN/TP*
LRM	0.194	0.113	1.72
IMB	0.168	0.153	1.098

0.113% and 0.153% at LRM and IMB, respectively. The TN increased with sediment depth. The range scales of TN concentration were large at the two measuring sites (Fig. 5). The peak TN contents of 0.39% and 0.24% occurred 11 cm and 7 cm deep (the middle and upper layer of the sediment, respectively) in the sediment at LRM and IMB, respectively. The TP contents decreased and increased with depth in the sediment at LRM and IMB, respectively. Maximum TP contents of 0.13% were detected in the surface-layer sediments without remarkable variations in the vertical profile at LRM. However, maximum TP contents of 0.17% occurred at a depth of 6 cm in the sediment at IMB with little fluctuation in the vertical profile. TP was largely located in the upper layer of the sediment. The nutrients in surface sediments were distributed unevenly at the two sites.

Erosion Rate

The erosion rate is recorded as the upward movement of the sediments in the coring tube over time. The relationship between sediment erosion rate, flow velocity, and sediment depth is shown in Fig. 6. The erosion rate of sediment decreased with increasing depth in the sediment and decreasing flow velocity. The value of erosion rate ranged narrowly from 0.0001 to 0.01 mm/s. The erosion depth was within 10 mm. Sediment erosion rates range from 0.00017 to 0.00056 mm/s with erosion depth from 1 to 3 mm under flow velocity of 5 cm/s, whereas it changed from 0.00019 to 0.00075 mm/s with erosion depth ranging from 2 to 4 mm under flow velocity of 15 cm/s. Also, sediment erosion rate increased from 0.00019 to 0.00083 mm/s with erosion depth ranging from 4 to 7 mm under flow velocity of 20 cm/s and changed from 0.00025 to 0.00111 mm/s with erosion depth ranging from 8 to 10 mm under flow velocity of 30 cm/s. The relationship between sediment erosion rate and sediment depth was linear. The linear relationship was described as:

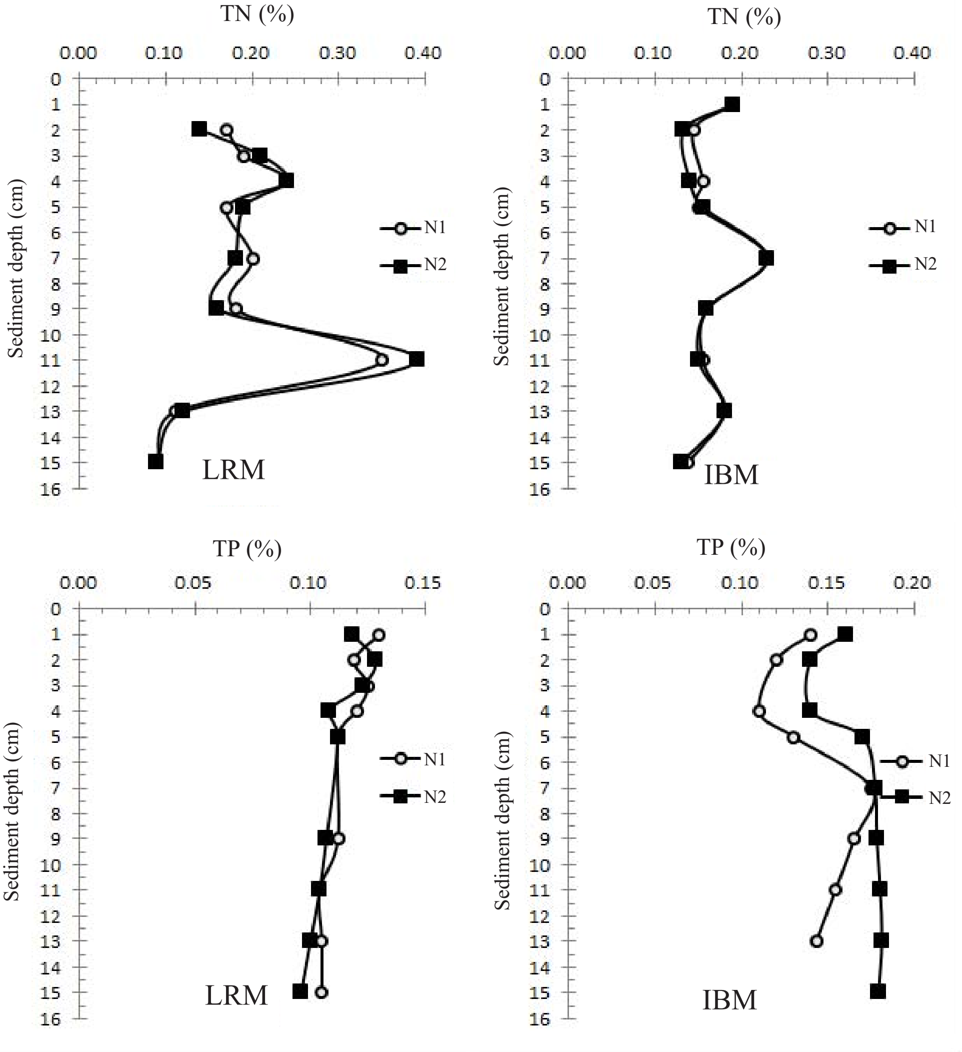

Fig. 5. Vertical distributions of TN and TP with depth in the sediment in LRM and IMB.

$$E = (3.44h - v - 4.845)/12593.8 \qquad R^2 = 0.936 \qquad (3)$$

...where h is depth in the sediment (mm), E is erosion rate (mm/s), and v is flow velocity (cm/s). It confirmed that erosion rate was affected by the external natural condition contrary to the formula mentioned above, which was associated with inner properties of sediment. Hence, the sediment erosion rate can be calculated by measuring flow velocity and depth in the sediment.

Discussion

Effects of Sediment Properties on Sediment Erosion Rate

Erosion rate is mainly influenced by the following factors: particle size distribution, sediment bulk density, organic content, critical shear stress, and many external factors (i.e. flow velocity, wind speed, vegetation). Through experimental operations, erosion rate can be measured as a function of depth in the sediment for its relationship with shear stress and critical shear stress. This paper concentrated on the sediment property and shear stress on sediment erosion, and figured out the corresponding variation of nutrient concentrations.

Particle Size

Particle size is a main component of sediment character and decides sediment erosion rate. The distribution of grain sizes as a function of depth was obtained from the experiment. Large particles mainly existed in the upper layer of sediment compared with small particles (0.02-0.002 mm), while very smalr ones (<0.002 mm) existed deeper in the sediment (Fig. 3). Particle sizes obviously decreased with increasing depth in the sediment. This can be regarded as an indicator to somehow reflect sediment erosion depth. As the flow rate over a sediment bed increased, the movement of the smallest and easiest-to-move particles was first noticeable to an observer. These eroded particles then travelled a relatively short distance until they came to a new location and stop. As the flow rate increased further, more and more particles participated in this process of erosion, transport, and deposition, and then the movement of the particles was sustained. Some particles were suspended in the water body, and some returned to the sediment.

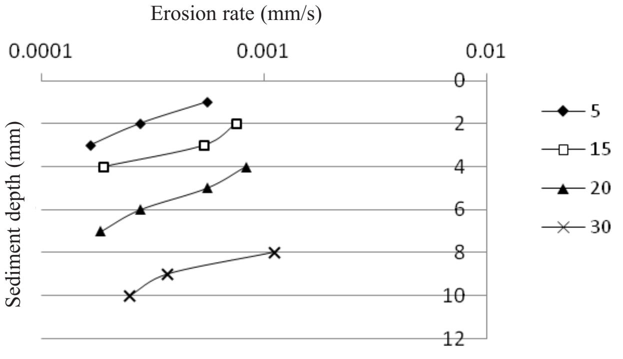

Fig. 6. Variation of sediment erosion rates with depth in the sediment at each flow velocity.

For the large particles, the force of gravity prevented particles from eroding into the water body. The fine grain particles less than 100 μm behaving as a cohesive manner were also seldom disturbed by flow. The particles ranging between fine grain and large were easy to erode. The sediment erosion rate first increased to a maximal value and then decreased as particle size increased. So the small particles (without cohesive manner) above the large particles were suspended in the water body when disturbed by flow, whiles the large particles remained. This made the large particles reveal at the sediment surface. When large particles were scoured into the water body, they redeposited sharply compared with the small particles. The small particles redeposited above and attached to the large particles. This circulation process formed up, inducing small particles to stay in the water body for the long-term and large particles to settle down in the sediment. This explained why the superficial particles in the sediment were large. Hence, the sediment erosion depth was influenced by the main location of large sediment particles.

The particle size distribution was different at the river mouth (LRM) and in lakes (IMB). The volume of large particles was higher than small particles at the river mouth, which was opposite in lakes. Particles at the river mouth were scoured along with the flow, so that fine grain particles were scoured downstream, leaving the large particles. The main particles were silt and clay in lakes, so the small particles were in higher volume friction than large particles.

Bulk Density

Bulk density as a function of depth varied in a vertical direction, and changed with time and particle size. The variation trend of bulk density with depth was illustrated above, increasing with depth. This was to be expected as the pore waters and tiny gas bubbles being forced out of sediment layer due to extrusion by the overlying sediments occurred. After consolidation, sediments with large bulk density were of great compaction thus prevented sediments from eroding. This was similar to the results of Rich's et al. [3]. The variation trend of bulk density with time was not involved in this study, but other studies have dealt with it extensively [3, 5]. Jesse et al. [5] mentioned that bulk density increases with time, and the increasing rate is large initially, and then decreases as time increases with a slow sediment consolidation. Sediments that consist of larger particles initially consolidated relatively rapidly and gained a high bulk density that remained long-term. On the contrary, sediments that consist of finer particles consolidated slowly and the bulk density kept varying for a long period. The range of bulk densities attained during this period of time was greater than that of the larger particles. The sediment bulk density was high when finer particles deposited and consolidated compared with large particles. Sediment bulk density was large in deep layers of sediment (the middle and lower layer) and the tiny sediment particles mainly existed deep in the sediment, which was in agreement with the result of particle size mentioned above. The upper layer sediment was easy to erode into a water body, causing variable bulk density. Surface sediment of the upper layer was in dynamic balance of suspension and deposition affected by flow. The cohesive sediment slightly flocculated and settled down to get increasing bulk density along with sediment depth. Indirectly, it indicated the relationship between bulk density and particle size. Jesse et al. [5] mentioned that the erosion rates are independent of bulk density for particle size equal to or greater than 222 µm. And for the small particles the erosion rate decreases as bulk density increases. The main particle sizes of LRM and IMB were less than 222 µm, resulting in great influence of bulk density on erosion rate. In general, bulk density was related to water content and sediment characters. It was an essential parameter reflecting compaction and suspension potential of sediments. Both sediment content and water content had a decisive effect on sediment erosion rate.

The bulk density distributions were different in lake and at river mouth similar to particle size. Sediment bulk density at the river mouth (LRM) was smaller than in lake (IMB). And the bulk density attained a quick maximum value at the river mouth compared with the lake. Combining the illustration mentioned above, the large particles at the river mouth consolidated rapidly within a short time while the small particles in lakes consolidated slowly and got higher bulk density with a long time. The results were quite in accord with each other.

Relationship between Sediment Erosion and Nutrients Distribution

Sediment pollution degree is mainly determined by the sediment inner properties (i.e. mean particle size and bulk density) and the external conditions (i.e. flow velocity, wind speed, temperature, and vegetation), which are difficult to control. To manage the effects of nutrients on sediment pollution, attention should be paid on sediment characteristics like particle size and bulk density. The sediment pollution degree from low to high corresponds to coarse particles, fine grain particles, and small particles, respectively. The coarse particles with great weight were prevented from suspending by force of gravity, whereas fine grain particles with distinct adhesive ability were easily combined with each other and condensed to larger particles. Hence the small particles between coarse and fine grain particles were easy to suspend. The superficial area of fine grain particles was greater than that of coarse particles with the same weight, thus making the nutrients easily absorbable to the fine grain particles. The nutrients absorbed by the fine grain particles were released into the water body when they suspended. With high sediment pollution degree, water quality can be easily influenced by sediment erosion. This explained why the fine grain particles with highest nutrient concentration possessed a greater threat to water quality when sediment eroded. Bulk density is a sediment property indirectly related to sediment nutrient. The water content and porosity of sediment can be represented by bulk density. Porosity decided nutrient diffusion ability and greatly related to sediment erosion. High porosity led to low sediment content, hence sediment eroded and nutrients diffused easily with great porosity. So, bulk density affected water quality indirectly.

After sediment erosion, types of silt, putrefaction, gravel, microorganisms, and organics were released to the water body. These organics turned to nutrients after degradation, affecting water quality. TN and TP were the main water quality index with great directionality of eutrophication.

Sediment Properties in Different Regions of Lake Taihu

Sediment properties such as particle size, bulk density, nutrients, and erosion rate were quite different in different regions of Lake Taihu. As feedback, the differences of sediment properties come from the water environment such as aquatic organisms, fish, submerged or emergent vegetation, and water pollution. Current also could influence sediment property as it relates to shear stress, which could induce sediment erosion when it was larger than the critical shear stress of the sediment. All these impact the settling of sediment and the inner structure, like particle size distribution and bulk density. A statistic of sediment properties in four regions of Lake Taihu (northwest, southwest, Meiliang Bay, and eastern Taihu) were compared in Qin et al. [8]. The particle size distribution of lake sediment reflected influx of the basins, the lake ecosystems, and sediment erosion potential. It was obvious that particle size distributions of sediment at the four sites of Lake Taihu were nearly the same. There was no significant difference in the median size of sediment particles among the four sites in Lake Taihu. The main particle sizes of the four sites were 4-6 µm and 16-20 µm, and the minimum median particle size was found in Meiliang Bay.

The vertical variation of bulk density with depth in the sediment showed similar trends at the four sites of Lake Taihu. The bulk density increased greatly at the superficial 10 cm of sediment in Meiliang Bay and Eastern Taihu. However, it only increased greatly at the upper 5 cm in Northwest and Southwest of the lake. Bulk density of Eastern Taihu Bay with the deepest transition zone changed greatly with sediment depth followed by Meiliang Bay. For nutrient distribution, the nutrient concentration (TN and TP) slightly fluctuated within 10 cm at the vertical height of sediment and greatly changed when sediment depth reached 10 cm. The range scale of nutrient concentration in eastern Taihu was minimal. The TN concentration was the smallest and largest in Eastern Taihu and Northwest Lake, respectively. However, the vertical distribution of TP was slightly different from that of TN. TP concentration was the minimum in eastern Taihu but TP concentration was maximum in Meiliang Bay for the superficial 10 cm, and in Southwest Lake beyond 10 cm depth. This explained how the sediment properties have similar trends at the vertical depth and in different contents in each region of Lake Taihu. In different areas of Lake Taihu the erosion rate of sediment, measured by the Nanjing Institute of Geography and Limnology, was different as well. The peak erosion rate occurred in the central lake area, then followed Meiliang Bay, Wuli Bay, and Gonghu. And the lowest erosion rate occurred at eastern Taihu Bay. The extent of lake area and large wind speed caused high shear stress in the central lake area. There existed many hydrophytes in eastern Taihu Bay, which can restrain sediment erosion, and the bay was mostly free from wind. Erosion rate can be different in each season for the variation of wind speeds and directions, flow velocities, and aquatic living differences.

For the sediment erosion rates in Lake Taihu, much research had been done and the results were quite different. Luo et al. [12] mentioned that the erosion depth of the sediments can reach 30 cm when the wind speed was 20 m/s. He concluded this by calculating shear stresses under different wind speeds. Hu et al. [13] claimed the magnitude of erosion depths was in millimeters. Hu summarized this by doing experiments with a sampling device that can accurate layering at vertical direction. The erosion depth gained from this study was less than 10 mm, which was in agreement with Hu et al. [13]. This diversity may result from their different ways of calculation and analysis, different experimental devices, or sediment properties from different measuring sites. Also, it illustrated that undirectional flows had little impact on sediment erosion.

Comparison with Other Natural Sediments

Many previous works on sediment showed that sediment properties are quite different at different sampling sites including lakes, rivers, estuaries, and the sea. The difference may result from experimental apparatus and methods, the disturbed and undisturbed sediment, and different sampling environments. The sampling sediment used in this experiment was undisturbed, maintaining the original sediment structure just like in the field, which was important when analyzing the vertical distribution of sediment properties. Hence, this kind of difference greatly impacts the result. The limitation of this study was that it was a laboratory experiment, even though the sediment was undisturbed-sampled from field work but the water column was not the same as in the field environment. We couldn't copy the water circumstance around the sampling sediment.

For the sampling environment, different physical and chemical environments make the composition of sediment different from each other. Also, the sedimentary environment properties greatly impact sediment properties at different sampling sites. In this study, IMB was a symbol of the shallow lake while LRM reflected river mouth. The difference of sediment properties like particle sizes and bulk densities in IMB and LRM analyzed above showed the difference for lakes and river mouth. For rivers, the particle sizes ranged from 0.5 to 600 μm, and the bulk densities ranged from 1.41 to 1.51 g/cm^3 (e.g. Detroit River [3]). Obviously, the range scales of sediment properties in rivers were much smaller than in lakes and river mouth.

The nutrient concentration and distribution of sediment were determined by many factors, including material source, settling rate, mineralization, sedimentary redox condition, and sedimentary sizes. Hence, different sampling sites reflected different nutrient concentrations and distributions to a certain degree. TN and TP concentration at sea are larger than in lakes [14]. However, TN concentration in rivers is smaller than that in lakes [15]. For nutrient distribution, the TN and TP concentrations decrease with sediment depth sharply in sea, and the decreasing trend is quite obvious compared with the trend of lakes [16]. Actually, sediment properties of different sampling sites in the same lake can be quite different. Hence, the comparison of sedimentary environment was not quite absolute. When sediment eroded into a water body, the nutrients absorbed on the sediment particles and the nutrients existed in the pore water release into water body to influence water quality. Hence sediment erosion rate was a significant sediment property when concerning water quality.

Conclusions

Sediment properties, nutrients, and erosion rates were measured as a function of sediment depth. The vertical variation trend of each parameter was different at different regions of Lake Taihu. Large particles mainly existed in the upper layer of sediment, which corresponded to small bulk density. When sediment depth increased, particle size decreased and bulk density increased. The variation of nutrients was disordered. TN mainly existed in the deep layer of sediment while TP mainly existed in the up layer of sediment. The sediment erosion rate increased with flow velocity and decreased with depth in the sediment. The sediment erosion depth was measured to be within 10 mm, and undirectional flows had little impact on sediment erosion. The properties of sediment greatly impacted the sediment erosion rate. Fine-grain particles behaved in a cohesive manner and coarse particles with a large force of gravity hardly suspended compared with particles falling between fine grain and coarse particles. Large bulk density with great sediment consolidation prevented sediment from eroding.

The distribution of sediment properties in each region of Lake Taihu, in different water bodies like lakes, rivers, estuaries, and sea was quite different. For different water environments, the morphological characteristics and water ecology were quite different. The results from this study will be of great importance to practical issues such as ecological restoration and environmental protection of Lake Taihu and other similar lakes and water systems.

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