Critical velocity in phosphorus exchange processes across the sediment-water interface

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Abstract

Sediments are ultimate sinks of nutrients in lakes that record the pollution history evolutionary processes, and anthropogenic activities of a lake. However, sediments are considered as inner sources of environmental factor changes such as the variation in hydrodynamic conditions because of the nutrients they release. How does this process happen? This study investigates a typical nutrient phosphorus (P) exchange among sediment, suspended particle matter (SPM), and water. Compared with numerical and experimental studies, this study confirms that the critical velocity that occurs at a lower flow rate state exists in the range of 7 to 15 cm/sec. Critical velocity below the critical flow rate promotes the migration of particulate phosphorus (PP) to the SPM. On the other hand, critical velocity above the critical flow rate promotes the release of PP in water.

Key words: abrupt expansion flow; critical velocity; lake eutrophication; phosphorus exchange

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Introduction

Shallow lakes, such as the Taihu Lake (China), are strongly influenced by sediment resuspension, which has long been recognized as an important internal physical process that affects various ecological aspects of lakes. Nutrient pollution is the main cause of lake eutrophication (Jiménez-Cárceles and Álvarez-Rogel, 2008; Jin et al., 2008; Kaiserli et al., 2002). High nutrient levels cause the rapid growth of algae that become blooms, which endanger public health and aquatic ecosystems (Kisand and Nõges, 2003; Wang et al., 2009; Pettersson, 2001; Qin et al., 2004). Phosphorus (P) is the primary nutrient that limits algae growth in lakes. P exchange processes across the sediment-water interface are particularly important in shallow lakes (Reddy et al., 1996). Studies on the behaviors of sorption and desorption of P have recently increased because the transport of sediment associated with P in shallow lakes often constitute a high percentage (23%–61%) of the total annual P flux (Wan et al., 2010). The potentially available P induced by sediment resuspension exceeds 20 times that of external loading during the

open-water season (Rydin, 2000). Consequently, accurate quantification of the P exchange across the sediment-water interface during sediment resuspension is essential for estimating the benthic P flux and understanding P circulation.

P exchange across the sediment-water interface through adsorption-desorption and coprecipitation-dissolution processes plays a critical role in governing dissolved phosphate concentrations in overlying waters (Saavedra and Delgado, 2005; Selig, 2003; Bale et al., 2006). Such exchange processes are largely controlled by the chemical composition and physical properties of particles (Fu et al., 2009). Hydrodynamic-induced turbulence in shallow lakes appears to have a significant influence on the exchange between sediment and water and it can increase the suspension of sediment particles and even promote the outward movement of P dissolved in pore water (Bowes et al., 2008; Li et al., 2010). The P release from the sediment to the lake water occurs either as the mobilization of P from suspended sediment particles or after mobilization into the dissolved P-pool in sediment pore water and the subsequent upward transport of the dissolved species into the water (Sun et al., 2009). Thus, sediments with

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different hydrodynamics may have different P adsorption-desorption characteristics.

Quantification of P release from sediment is usually presented with batch experiments or intact sediment simulation. Several related environmental factors are also widely researched in simulated experiments of sediment P release (Takeda and Fukushima, 2004; Kamiya et al. 2001). Sediment resuspension flow with abrupt expansion has received limited attention, even though it is common in nature, such as in estuaries. Sediment P release in estuaries is more active because of changes in hydrodynamic conditions. Some experiments have been conducted to simulate natural water stirring by using plungers, stirrers, or oscillating grids (Peng et al., 2007). Consequently, the rates of P entrainment were likely overestimated and restricted. The current study considers the processes with different hydraulic conditions caused by changes in P form. The irregularity of the flow may weaken or even reverse the flow rate of the stimulative effect to P release.

Based on the characteristics of P fractionated and inherent flow, this study suggests the construction of the optimal scheme for water nutrient changes from the single factor of prominent hydrodynamic condition. The simulated dynamic evolution of nutrients represented by P was solely investigated on P fractions in suspended particle matter (SPM). The different regions with varying hydraulic characteristics under high-nutrient conditions were selected, and P fractions were analyzed in the overlying water and SPM. Critical velocity was revealed using the space-scale research method in the P exchange processes across the sediment-water interface.

1 Materials and methods

1.1 Sampling and pretreatment

The Dapu Estuary formed an abrupt expansion flow because of water diversion from the Dapu River to the Taihu Lake, resulting in a higher P exchange process. Sample sites were situated in the west basin of the Taihu Lake in East China, which is a heavily polluted area (Wan et al., 2011). Sediment samples were collected from the top 0.05 m layer of the sediment by using a cylindrical sample device with an inner diameter of 0.06 m and pipe length of 0.5 m. The samples were transported to the laboratory in air-sealed boxes. To rule out the effects of biological activity on P release, sterilization was conducted under air-dried, homogenized conditions. Subsequently, the samples were passed through a 150 μm sieve.

Water samples were collected 0.5 m below the surface. Sediment samples were analyzed for total phosphorus (TP) using the standards, measurements, and testing protocol. Water content and water loss on ignition measurements were based on weight loss after drying and combusting the sediments at 105°C and 550°C, respectively. The total organic carbon in the sediments was determined after

treating the sample with $\text{K}_2\text{Cr}_2\text{O}_7/\text{H}_2\text{SO}_4$. The particle size was analyzed using a laser particle analyzer (Mastersizer 2000, Malvern, British). All samples were analyzed in triplicate, and data were expressed in average.

1.2 Annular flume system

Annular flumes convert the length of straight flumes into a time criterion that satisfies lead time and long distance during sediment particle flocculation and sedimentation. In additionally, annular flumes do not disrupt the flocculation state because of the recovery tank. The laboratory flume system is composed of two independent annular flumes, both of which have 0.3 m and 0.56 m inner and outer diameters, respectively. Thus, a 0.13-m wide annular channel and a 0.21 m wide abrupt expansion area were created. Each channel had a continuous bed with a total area of 0.3 m^2 , working depth of 0.25 m, and maximum volume of 70 L. Water flow was induced by rotating an annular driver cylinder using two or four paddles. The annular flumes were programmed to generate free-stream currents with velocities in the range of 0.05 to 0.5 m/sec in 0.05 m/sec stepwise increments controlled by the gearbox. Current velocities in the flumes, including the upward and downward velocities, were measured using a 3D Sontek Acoustic Doppler Velocimeter (Sontek, USA).

1.3 Hydrodynamic model and experimental methods

A 3D Large Eddy Simulation (LES) model was used to simulate the abrupt expansion flow in the annual flumes. Such method was previously applied to the study flows of simple fluids and the complex mixtures in straight flumes. The LES equation can be expressed as follows (Markatos, 1986):

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial (\bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j)}{\partial x_j} \quad (1)$$

where, x_j is spatial coordinate, $\bar{u}_i$ is time-average velocity in x_i , $\bar{u}_j$ is time-average velocity in x_j , ρ is fluid density, p is instantaneous pressure and ν is kinematical viscosity coefficient.

The isotropic filter that filters out the small-scale fluctuation is assumed to be partially balanced. The form of eddy viscosity subgrid Reynolds stress model can be expressed as follows (Murakami and Mochida, 1995):

$$\bar{\tau}_{ij} = 2\nu_t \bar{S}_{ij} - \bar{\tau}_{kk} \delta_{ij} = 2(C_s \Delta)^2 \bar{S}_{ij} (2\bar{S}_{ij} \bar{S}_{ij})^{1/2} - \frac{1}{3} \bar{\tau}_{kk} \delta_{ij} \quad (2)$$

where, ν_t is the eddy viscosity coefficient, δ_{ij} is the Kronecker symbol, $C_s > 0$ is the Smagorinsky constant, τ_{ij} is subgrid Reynolds stress, τ_{kk} is impact factor of small eddy to large eddy and Δ is the filter scale. The stress rate tensor (S_{ij}) is given by:

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3)$$

In this study, the abrupt expansion flow in the annular flume is predicted using LES, and local refinement is used for the non-uniform tetrahedral grid subdivision method.

Five sample sites (divided by hydraulics: main inflow zone #1, main flow zone #2, main outflow zone #4, reflux decreasing zone #3, reflux increasing zone #5) for the P fraction of SPM were compared to investigate the effects of the hydraulic conditions on P release. Sediments were paved at a depth of 0.05 m. Water samples were filled in an annular flume on a 0.22-m scale. Velocity characteristics were measured in the flume system.

In the experiments, the device was activated and the average flow velocities measured using the Acoustic Doppler velocimetry were 0.07, 0.15, and 0.3 m/sec. Then, flow rate stability was achieved after 30 min, which was determined based on the method provided by Wan et al. (2011). In addition, samples were collected in the upper, middle, and bottom zones of the water body under the three operating conditions. Then, 300 mL of the samples were divided into two equal parts, one portion was used to determine SPM concentration by using the gravimetric method (GB11901-89) and the other portion was used to analyze the P fraction in SPM and water after centrifugation.

2 Results and discussion

2.1 Turbulent characteristics in abrupt expansion flow

Abrupt expansion flow research has a significant impact on the flume scale on flow. The presence of a large vortex motion is a distinguishing feature. The vortex affected by the flume has its own laws in the reflux zone, as shown in **Fig. 1**. The vortex was generated in the reflux zone and the main flow migrated to the outside in low flow rate condition, as shown in **Fig. 1a**. The length scale of the reflux zone to the inside was greater than that to the outside. The scale and shape of the vortex changed with increasing flow rate, as shown in **Fig. 1b** and **c**. The length scale of the reflux zone to the outside became smaller, and the vortex shapes were round and oval that filled the inside of the flume. Vortex formation is not very active because of the low flow rate which induced shorter vortex lifetime.

The sediment movement and flow turbulence intensity (N) are closely related, and thus, the investigation of flow reflux is significant for future studies on sediment-water nutrient transport mechanisms. The maximum value of N appeared in **Fig. 2c** and the minimum value appeared in **Fig. 2a**. In general, N increased with water depth, and the maximum value appeared in water interface under lower flow rate conditions. Longitudinal, transverse, and vertical

Fig. 1 (a) Main stream migrated to the outside, formation of small vortex at $V = 0.07$ m/sec, (b) formation of moderate vortex that occurred in the reflux zone at $V = 0.15$ m/sec, (c) main stream migrated obviously to the outside, formation of big vortex followed by round and oval vortex shapes that filled the inside of the flume at $V = 0.3$ m/sec.

Fig. 2 Statistical average value of the measured turbulence intensity (N) distribution across the vertical. $\frac{u'}{u_*}$, $\frac{v'}{u_*}$, and $\frac{w'}{u_*}$ are the longitudinal, transverse, and vertical turbulence intensities, respectively. Turbulence intensity increased in all directions with increasing disturbance. Horizontal and vertical turbulence intensities are more evident in the 3D flow characteristics. (a) $V = 0.07$ m/sec, (b) $V = 0.15$ m/sec, (c) $V = 0.3$ m/sec.

turbulence intensities were varied as follows: $\frac{u'}{u_s} > \frac{v'}{u_s} > \frac{w'}{u_s}$, which fitted the classical turbulence law. Disturbance increase caused a significant increment in $\frac{v'}{u_s}$ and $\frac{w'}{u_s}$, causing the flow turbulence to show more 3D features. This finding can be attributed to the change in flow structure, which gradually self-resumes in the abrupt expansion flow. N can enhance sediment transport capacity, and thus, the N of the transverse and vertical directions cannot be ignored.

2.2 Different spatial exchanges of dissolved total phosphorous under different flow rate conditions

The initial concentration of dissolved total phosphorous (DTP) was 120 $\mu\text{g/L}$. **Figure 3** shows that the maximum release flux of DTP by using SPM in the initial stage appeared at the main outflow zone (#4), and the maximum release flux of DTP by the overlying water appeared at the reflux decreasing zone (#3). The concentrations of DTP gradually increased in the main inflow zone #1 and the main flow zone (#2). The DTP increased by 31.6, 26.7, 48.5, 41.1, 23.9, and 8.2 $\mu\text{g/L}$, respectively. The

Fig. 3 Average concentration of dissolved total phosphorous (DTP) in the top, middle, and bottom varied with flow rate. The flow irregularity may weaken or even reverse the velocity of the stimulative effect on DTP release.

maximum increment appeared at the main inflow zone (#1), indicating that P desorption in SPM was continuously converted into DTP in these two zones. P desorption in overlying water occurred in the reflux decreasing zone (#3) under lower flow rate conditions, and the desorption amplitude was 23.1 $\mu\text{g/L}$. P desorption was converted into P adsorption in the overlying water when the flow rate increased. The adsorption amplitude were 121.6 and 33.5 $\mu\text{g/L}$, respectively. A similar situation occurred in the main outflow zone (#4) and reflux increase zone (#5) under lower and moderate flow rates. DTP concentration of DTP gradually increased with the increased flow rate, and P desorption in SPM was significant. When the flow rate reached 7 and 15 cm/sec, the DTP increased by 112.2 and 72.4 $\mu\text{g/L}$, respectively in the main outflow zone (#4), and 86.2 and 49.9 $\mu\text{g/L}$, respectively in the reflux increase zone (#5). However, P adsorption was converted into P desorption in the overlying water of the main outflow zone (#4) and reflux increase zone (#5) when the flow rate reached 30 cm/sec. The DTP decreased by 29.4 and 27.3 $\mu\text{g/L}$, respectively. These results suggest that the P release was significantly affected by the flow rate in the classic flow or similar to the classic flow conditions. If the flow conditions become complex, the flow rate may not be a decisive factor and the flow irregularity may weaken or even reverse the velocity of stimulative effect to DTP release.

2.3 Different spatial exchanges of TP and particulate phosphorous under different flow rate conditions

Figure 4a shows that TP had an initial concentration of 331.2 $\mu\text{g/L}$. Compared with the initial concentration, the TP concentration significantly decreased under the low flow rate conditions. The maximum release flux of TP by the overlying water appeared at the reflux decreasing zone (#3). The TP decreased by 231, 180, and 166 $\mu\text{g/L}$ in the reflux decreasing zone (#3), the main flow zone (#2), and main inflow zone (#1), respectively. TP concentrations exhibited an overall increasing trend with increasing flow

Fig. 4 Average concentration of total phosphorous (TP) and particulate phosphorous (PP) in the top, middle, and bottom varied with flow rate. A critical flow rate was observed.

rate. At a flow rate of 0.15 m/sec, the increment of TP is 26.7, 19.8, 118.6, 325.9, and 381.9 $\mu\text{g/L}$ in different zones. The order was #4 > #5 > #3 > #1 > #2. When the flow rate reached 0.3 m/sec, the increment of TP is 482.3, 210.4, 468.7, and 47.1 $\mu\text{g/L}$ in #1, #2, #3, and #5 respectively TP concentration in main outflow zone (#4) decreased to 38.3 $\mu\text{g/L}$.

As can be seen in **Fig. 4b**, the particulate phosphorous (PP) concentration was 211.1 $\mu\text{g/L}$. The change in PP was similar to that in TP. Compared with the initial concentration, the PP concentration significantly decreased under low flow rate conditions. The maximum release flux of PP by the overlying water appeared at the main inflow zone (#1). The fluxes of PP decreased by 151, 145.5, and 124.8 $\mu\text{g/L}$ in the inflow zone (#1), the main flow zone (#2), and the reflux decreasing zone (#3), respectively. PP concentration exhibited an overall increasing trend with increasing flow rate. At a flow rate of 0.15 m/sec, the fluxes of PP increased by 94.4, 22.1, 40.4, 186.5, and 237.8 $\mu\text{g/L}$ in different zones. The order was #4 > #5 > #1 > #2 > #3. At a flow rate of 0.3 m/sec, the fluxes of PP increased by 279.4, 191.7, 327.6, 12.3, and 74.5 $\mu\text{g/L}$ in different zones. The maximum and minimum flux increases appeared at the reflux decreasing zone (#3) and main inflow zone (#1), respectively.

PP and TP are closely related. The increased TP concentration in the heavily polluted river is mainly caused by the increased PP concentration. A critical velocity at the range of 7 to 15 cm/sec was observed. The migration of PP to SPM is promoted below the critical flow rate, whereas PP release in the water is promoted above the critical flow rate. The change of TP depends on the change in PP because of the flow rate. Previous studies described the variation in TP as the water quality criterion instead of all P form, which only represents a variation in PP. PP is the main participant in the flocculation and sedimentation effects of SPM, indicating that SPM has an exclusive adsorption to PP.

3 Conclusions

This article investigated P exchange across the water-sediment interface under different flow rates. The turbulent characteristics of the abrupt expansion flows were discussed using simulations and experimental methods. As the flow rate increased, the length scale of the reflux zone to the outside became smaller and the vortex shapes were round and oval that filled the inside of the flume. N is closely related to sediment movement. Transverse and vertical turbulence intensities greatly increased with increasing disturbance, and thus, the N of transverse and vertical directions cannot be ignored. Nutrient represented by P under high-nutrient conditions was investigated on P fractions in suspended particle matter and simulated dynamic evolution. The results of this study suggest that

the P release was significantly affected by the flow rate under classic flow or similar to classic flow conditions. The flow rate may not be a decisive factor when flow conditions become complex, and flow irregularity may weaken or even reverse the velocity of the stimulative effect to DTP release. Critical velocity was revealed using the space-scale research method in P exchange processes across the sediment-water interface. A critical velocity was found at the range of 7 to 15 cm/sec. The migration of PP to the SPM is promoted below the critical flow rate, whereas the PP release in water is promoted above the critical flow rate. The change in TP depends on the change in PP under flow rate conditions. This study promotes the understanding of P exchange across the sediment-water interface. In addition, this study also contributes to the development of the baseline and controlling program on lake eutrophication.

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