Sediment Phosphate Release Flux Under Hydraulic Disturbances in the Shallow Lake of Chaohu, China

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Abstract

Quantifying the effect of hydraulic disturbances on sediment phosphate release is a key issue in the water quality assessment of lakes, especially for the shallow lakes which are susceptible to winds and waves. Here, we sampled the original sediment columns from 12 positions in the eastern, central, and western areas of the Chaohu Lake, a representative shallow lake in China, and observed phosphate release under three levels of hydraulic disturbances in the laboratory. When the disturbance was weak and the surface sediment of bottom mud moved individually (the *Individual Motion Mode*), sediment phosphate release rate was insignificant ($0.24 \text{ mg/m}^2/\text{d}$). When the disturbance was medium and only a small percentage ($<16\%$) of surface sediment started to move (the *Small Motion Mode*), phosphate release rate sharply increased to $4.81 \text{ mg/m}^2/\text{d}$. When the disturbance was further strengthened and most ($\geq 16\%$) of the surface sediment moved (the *General Motion Mode*), phosphate release rate was more than doubled ($10.23 \text{ mg/m}^2/\text{d}$). With the increase of hydraulic disturbance intensity, the variation range of phosphate release also became wider. Spatial distribution showed that the release rate varies the most in the western area, followed by the eastern and the central areas. By extrapolating the experimental results to the real scale, we found the phosphate release fluxes would probably fall within a wide range between 203.43 kg/d to 7311.01 kg/d under different levels of hydrodynamic disturbances with considerably affects phosphate release from shallow lakes. This study also has implications for the pollutant management in other shallow lakes.

1. Introduction

As the main destination of lake nutrients, sediment exchanges phosphorus with the upper water constantly, inducing larger risks to the environment (Carpenter, 2008; Norton et al., 2008; Qin et al., 2019). Previous research revealed that phosphorus release due to sediment resuspension could solely account for 23.7-39.4% to the total phosphorus load, leading to eutrophication of lakes (Deng, 2020). Since the dissolved form of phosphorus is more likely to be emitted into water than the granular form, more attention should be paid to phosphate release. The environmental risk is even larger in shallow lakes, because sediment is more frequently resuspended under hydraulic interference due to poor circulation (Hu et al., 2021), altering the sediment-water interface. However, quantitative assessments of phosphate flux from sediment in response to hydraulic disturbance in shallow lakes are very scarce (Jin et al., 2020), due to poor understanding of the sedimentation and resuspension processes (Reed et al., 2011). In addition, high-frequency sampling required for quantification is difficult to achieve in practice (Yuan et al., 2020). Thus, experiments are necessary to capture the characteristics of phosphate release under different intensities of sediment resuspension stirred by hydraulic disturbance. Although the in-place culture experiment provides actual situation, it is rarely used due to the high cost and technical restrictions (Wu et al., 2020). By culturing column cores, rather than the surface sediment, laboratory experiment can reproduce the phosphate release process under conditions that are very close to the real environment (Teal et al., 2008; Gu et al., 2017). Therefore, phosphate release process can be observed by the properly designed in-door experiments.

Chaohu Lake is a representative shallow lake subject to serious phosphorus pollution (Chen et al., 2015). Under various degrees of hydraulic disturbance, sediment movement in the Chaohu Lake can be very complicated, leading to different situations of phosphate release to the overlying water. According to Chen et al. (2018), sediment initiation is classified into the *Individual Motion Mode*, the *Small Motion Mode*, and the *General Motion Mode*. Characteristics of phosphate release from sediments in different modes should be studied based on laboratory experiments. This paper collected undisturbed sediment column cores from the eastern, western, and central areas of the Chaohu Lake and simulated phosphate release under the three sediment motion modes initiated by different levels of hydraulic disturbances in the laboratory. Thus, the spatial and temporal characteristics of the release fluxes could be analyzed and estimated, providing a reference to the management of phosphorus pollution in other shallow lakes.

2. Methods And Material

2.1 Study area

Chaohu Lake is one of the most famous freshwater lakes located in Hefei City (31.60 °N, 117.87 °E), Anhui Province, China, which has typical characteristics of large shallow lakes. According to statistics, it has an average water level of 8.37 m, a lake basin length of 61.7 km, a width of 12.47 km, a water area of 769.55 km² and an average depth of 2.89 m. The Lake basin also consists an important water system in the middle and lower regions of the Yangtze River Basin.

In order to estimate phosphate release from the sediments of Chaohu Lake, 12 sediment core sampling sites are selected according to the water's distribution feature of the lake area, which are evenly distributed in the Western, Central and Eastern lake regions (Table 1 and Figure 1). Therefore, the experimental results of phosphorus release could represent the situation of the region.

Table 1
Basic Information of the original sediment column cores in the Chaohu Lake

Serial number	Area	Sample number	Latitude(°N)	Longitude(°E)
1	Western	W1	31.7292	117.4065
2		W2	31.7289	117.3795
3		W3	31.7083	117.3868
4		W4	31.6729	117.3700
5	Central	C1	31.6548	117.3955
6		C2	31.6473	117.4524
7		C3	31.6078	117.5196
8		C4	31.5842	117.5466
9	Eastern	E1	31.6188	117.6038
10		E2	31.6644	117.6615
11		E3	31.6798	117.7191
12		E4	31.6661	117.7881

2.2. Design of experiment device

In this study, we prepared sediment column core from 12 sites of the Chaohu Lake in a large-scale column-shaped cylinder (Figure 2). In the light of three starting modes, the sediment moves in the *Individual Motion Mode* when the hydrodynamic force of the overlying water is close to zero; the sediment is in the *Small Motion Mode* when the hydrodynamic disturbance is weak, and the sediment suspends in the *General Motion Mode* when the hydrodynamic force is strong (Guo et al., 2014). Therefore, phosphate release process is simulated in the three sediment starting modes by controlling hydrodynamic disturbance in experiments using a rotary slurry. According to Alonso (1981) and Chun et al (2010), each motion mode has a corresponding occurrence probability. For instance, the moving percentage of the *Individual Motion Mode* does not exceed 2%, while that of the *Small Motion Mode* is less than 16%. When the *General Motion Mode* occurs, the moving percentage of sediment exceeds 16%. Thus, the motion modes can be recognized by observing the occurrence probability of sediment movement. The three motion modes were labeled as “Experiment A”, “Experiment B” and “Experiment C”, respectively. The speed range of the rotary slurry corresponds to each experiment is listed in Table 2. In addition, the indoor water temperature should be kept consistent with that of the outdoor water.

Table 2
Controlling conditions for the sediment phosphate release

Indicators	Experiment A	Experiment B	Experiment C
Start mode	individual movement	small movement	general movement
Speed range of the cyclone (r/min)	0	200-500	500-1200
Probability of movement occurrence (%)	≤2	2–16	≥16

The experimental container is a bottom-closed cylinder with a height of 1.2 m, and an inner diameter of 70 mm. The internal diameter is similar to the diameter of the sediment column sample which is 68 mm, and the wall thickness of the sampling tube is 2.5 mm. The sample is a 20 cm-high cylinder with a diameter of 63 mm, which fits rightly into the experimental container. The hydrodynamic control system consists of speed controller, perturbation propeller and 3D positioning system. Perturbation propeller was linked to a 3D positioning system, which controls the propeller position on the original bottom mud test container. Perturbation propeller was connected to the speed controller, which controls the propeller speed (0–3000 ± 5 r/min). The overlying water was artificially configured according to the water quality index of each sampling site. Different levels of resuspended sediments concentration are represented by different water colors: the blue column indicates a very small concentration, the light column indicates a small concentration, and the gray column indicates a high concentration. Water and sediment samples of in Experiment A were collected at three heights (i.e. 20 cm, 60 cm and 80 cm) to calculate the average value due to the unevenly distributed sediment concentration, while those in Experiment A and C were taken only under 30 cm of the water surface.

2.3. Measurement of phosphate release

We measure the phosphate concentration changes of the overlying water as an index of phosphate release. Since the phosphate exchanging rate was low in Experiment A, the experimental period was set longer (6–7 days, or 144–168 h). During the early stage of the experiment, the substance concentration differed largely, leading to faster molecular diffusion speed. Then, the diffusion rate of the substance gradually decreased over time. Therefore, sampling intervals were lengthened gradually, i.e. 0, 2, 4, 8, 12, 24, 48, 72, 96, 120, 144 h after the experiment was completed. In Experiments B and C, the exchanging rate of phosphate was elevated under stronger hydrostatic disturbance. Therefore, the experimental period was set shorter (3–4 days or 72–96 h). Due to similar reason, the sampling intervals were set unevenly as 0, 0.5, 1, 2, 4, 8, 12, 24, 48 and 72 h after the experiments were completed.

Based on the phosphate concentration monitoring, the cumulative phosphate release rate is calculated using Equation 1 (Luo et al., 2020):

$$R(\text{mg} \cdot \text{m}^{-2} \cdot \text{d}^{-1}) = \frac{\sum (C_{i+1} \cdot V - C_i \cdot V + C_{i+1} \cdot V_s)}{S \cdot T}$$

where C_i and C_{i+1} (mg/L) are the phosphate concentration at the i -th and the $(i+1)$ -th moments, respectively; V is the water volume (4.34 L in this study); V_s is the monitoring sample volume (0.3 L in this study); S (0.00312 m² in this study) is the contacting area of the bottom mud sample and water body in the experiments; T is the time of the experiment.

3. Results

3.1. Changes of phosphate concentration in the overlying water

Hydraulic disturbances caused significant changes in phosphate concentrations released in water bodies in three experimental groups; however, the effects of disturbances were greater at Western area than at Eastern and Central areas in each group (Figure 3). In the view of disturbance intensity, the highest phosphate concentration (0.539 mg/L) released in experiment C with the strongest hydraulic disturbance (500–1200 r/min), followed by those in experiment B (0.526 mg/L, 200–500 r/min) and experiment A (0.502 mg/L, 0 r/min). Regarding to monitoring points, the average variation value of phosphate concentration was always largest at western area (W2), among eastern area (E4) and central area (C1) (Figure 3).

3.2. Changes of the accumulative sediment release rates and the effective rates

According to Equation (1), the release rate of phosphate in the three series of experiments is obtained, and the concrete results are shown in Figure 4.

All cumulative release rates of phosphate went to stable no matter which area the sediment collected from (Figure 4), which is consistent with the release law of sediment phosphate in many other lakes (Precht et al., 2004; You et al., 2007; Chen et al., 2018). The cumulative phosphates release rate fluctuated greatly in the initial stages in three experiments, due to sediments collision and the unsaturated phosphates concentration in the overlying water. As the test proceeded, the phosphates release rate became dynamic stable since the external environment didn't change significantly. Meanwhile, the time required to reach stable cumulative release rate varied, and the stronger the hydraulic disturbance, the longer the stabilization time. In this study, the time to stabilize were 24 hours, 32 hours, and 40 hours in experiment A, B, and C respectively. The stabilized cumulative release rates illustrated in Figure 5 could presented the final and effective release rate of phosphate from sediment. In the view of disturbance intensity, the highest phosphate release rate (25.06 mg/m²/d) in experiment C with the strongest hydraulic disturbance (500–1200 r/min), followed by those in experiment B (14.83 mg/m²/d, 200–500 r/min) and experiment A (1.65 mg/m²/d, 0 r/min). Regarding to monitoring points, the average variation

value of phosphate concentration was always largest at western area (W4), among eastern area (E3) and central area (C3). The effects of disturbances were greater at Western area than at Eastern and Central areas in each group (Figure 5). Thus, the average phosphate release rate in the sediments of the three lake regions shows a law that the values of experiment $A < B < C$, and the fluctuation of phosphate release rate is also $A < B < C$. It can be seen that the release of phosphate in the sediments of the whole Chaohu Lake is mainly affected by the hydrodynamics of the overlying water.

Besides, the five negative effective release rates appeared when the overlying water is stationary, resulting from the relative relationship between phosphate content in sediments and phosphate concentration in water. As the hydrodynamic force increases, the effective release rate increased with the number of negative rates declined. Moreover, the profiles of effective release rate of phosphate at all sampling sites in this study conformed to results in previous study involving hydraulic disturbance (Zhu et al., 2005).

3.3. The total phosphate release flux of the Chaohu Lake

The contribution of released phosphate from sediment to water quality has also been assessed by exploring the phosphate release flux throughout the whole lake region. According to the integral of the cumulative phosphates release rate and lake area (Table 3). It shows that the maximum phosphate release flux from sediments in the *Individual Motion Mode* (or the lake water is almost stationary) approximately reached 203.43 kg/d; the maximum flux is about 3642.68 kg/d under the sediments' *Small Motion Mode* (or the overlying water is weakly disturbed); the maximum flux from sediments in the *General Motion Mode* (or the overlying water is strongly stirred) could probably reach 7311.01 kg/d. Considering that the three modes would appear alternately in the Chaohu Lake during a period, the total sediment release flux of phosphates may vary between 203.43 and 7311.01 kg/d. The release flux is between 3642.68 and 7311.01 kg/d. The interpolated values of precise cumulative phosphate release rates in lake area were calculated and shown in equipotential diagram (Figure 6). It is interesting to find emission centers at two western sites (W2 and W4) and two eastern sites (E3 and E4) in all the three modes, while in the central area, phosphate releasing center shifted from C2 in the *Individual Motion Mode*, to C3 in the *Small Motion Mode*, and to C3 in the *General Motion Mode*. It may be influenced by the rivers that enter the lake. Survey data show that there are several tributaries in both the west and east of Chaohu Lake (Zhang et al., 2020). Among them in the westren of the surrounding Shiwuli River, Tangxi River and Pai river; the water discharged into the lake by Gaozhe River and Shuangqiao River in the eastern. The pollutants they carry flow into the lakes and accumulate in the sediments, which contain excessive levels of pollutants. This would result in concentrated emission in both regions. In addition, studies have shown that the water moves back and forth in the central under the influence of the monsoon (Teng et al., 2021). As a result, the discharge of pollutants in the sediments in the central area is closely related to the hydraulic conditions. This explains the variation of the strongest emission with the increase of hydraulic disturbance.

Table 3
Phosphate release flux from the Chaohu Lake sediment

Serial number	Area	Coverage(km ²)	Experiment A (kg /d)	Experiment B (kg /d)	Experiment C (kg /d)
1	Western	190.79	13.36	1014.05	3015.44
2	Central	293.80	90.34	1179.61	1816.42
3	Eastern	284.96	99.74	1449.02	2479.15
4	All	769.55	203.43	3642.68	7311.01

4. Discussion

4.1. Reliability of the laboratory simulations and extrapolation

In simulating the physical process of pollutant release from sediments in shallow lakes, A hypothetical porous structure of the top layer sediments is usually assumed. Thus, the simulation results generally reflect the release rate in ideal conditions, which also provide a reference to solving the real-world problem. The second controversial problem is determining the thickness of the sampling layer (Corcoran et al., 2015). From the perspective of the influence depth of environmental factors, the thickness should be within 10 cm of the top silt (Liu et al., 2017). In addition, sediment core within 10 cm in shallow lakes is easily to be re-suspended by waves into the water (Qin et al., 2020). Furthermore, the species and biomass of microorganisms and benthic animals are abundant in the top 10 cm layer sediments, resulting in significant benthic disturbances, especially around the depth of 5.75 ± 5.67 cm in global waters (Lgab et al., 2015). In this study, we sampled undisturbed sediment columns of 20 cm from the top sediment, which should be deep enough to simulate the external interference.

In simulating the phosphate release rate under different levels of disturbance, the process that phosphate emission increases with water disturbance increasing and sediment resuspension intensified has been successfully reproduced. This is consistent with the sediment kinematics law that the increase of water disturbance intensity leads to the shifting of sediment threshold mode. The great variation of the release rate also confirmed the fact that shallow lakes are susceptible to flows of tributary bays and to human activities. Therefore, the laboratory simulations of this study are generally reliable.

However, in extrapolating the simulation results to the real-world scale, limitations exist in this study. For one thing, the randomness of wind force of the Chaohu Lake area, which makes the phosphate release process more complex and highly variable, should be further taken into account (Yuan et al., 2020; Yu et al., 2016). In particular, the shift between different Motion Modes of sediments under the effect of winds generally corresponds with great changes in the phosphate release rate, leading to large uncertainty in the

extrapolation. For the other, the effect of temperature should also be studied due to its great impact (Wu et al., 2020; Yu et al., 2020).

4.2. Implication to the pollutant management in other shallow lakes

Sediment resuspension has been demonstrated as the key factor affecting the water quality of shallow lakes (LikaiNiE, 2020). However, sediment resuspension is a complicated and random process in real lakes, which cannot be easily observed. Meanwhile, studies on sediment threshold under different levels of disturbances has also been widely carried out by employing empirical and/or theoretical derivation formulas, yet now the evidence obtained from observation and experiment used to confirm and verify the scientific theories are limited (Tang et al., 2020). Thus, correlating sediment movement and endogenous pollutants release appears meaningful, since sediment environment monitoring guideline for release flux has not been established in China yet, which will result in a poor management of shallow water lakes and further a high ecological risk induced by endogenous released pollutants. In this study, established motion models of phosphate release from sediment with different sediment threshold can standardize the phosphate release process from random sediment resuspension into three standard intensities, and it provides a feasible method of quantifying sediment release and facilitates assessment on endogenous phosphate release in all shallow lakes under uniform standards.

In addition, three sediment starting modes, induced by sediment resuspension, are applicative in most shallow lake sediments. That is to say, the phosphate release model in this study is highly universal without being affected by the natural boundary conditions of shallow lakes.

5. Conclusion

In a typical shallow lake of Chaohu, the phosphate release fluxes from sediment under different hydrodynamic disturbances driven by were studied by setting up a simulation system in the laboratory. Sediment column cores were collected from 12 sites and placed in a properly designed device which integrated a hydraulic control system to simulate different levels of disturbance. The experiment results demonstrate significant difference in the release rates among the three sediment threshold modes, i.e. varying from 0.24 mg/m²/d in the Individual Motion Mode, to 4.81 mg/m²/d in the *Small Motion Mode*, and finally reaching 10.23 mg/m²/d in the *General Motion Mode*. Correspondingly, the total phosphate release fluxes changes from 203.43 kg/d to 7311.01kg/d after a simple extrapolation. For more accurate estimation of the release flux of the lake, the randomness of wind force and the effect of temperature should be taken into account. The method proposed by this study is also applicable to other shallow lakes where sediment resuspension commonly occurs under wind and wave forces.

Declarations

Ethical Approval

The experimental protocol was established, according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of Wuhan University. Written informed consent was obtained from individual or guardian participants.

Consent to Participate

Not applicable.

Consent to Publish

The Author confirms: that the work described has not been published before; that it is not under consideration for publication elsewhere; that its publication has been approved by all co-authors, if any; that its publication has been approved by the responsible authorities at the institution where the work is carried out. The Author agrees to publication in the Journal indicated below and also to publication of the article in English by Springer in Springer's corresponding English-language journal. The copyright to the English-language article is transferred to Springer effective if and when the article is accepted for publication. The author warrants that his/her contribution is original and that he/she has full power to make this grant. The author signs for and accepts responsibility for releasing this material on behalf of any and all co-authors. The copyright transfer covers the exclusive right to reproduce and distribute the article, including reprints, translations, photographic reproductions, microform, electronic form (offline, online) or any other reproductions of similar nature. After submission of the agreement signed by the corresponding author, changes of authorship or in the order of the authors listed will not be accepted by Springer.

Author contribution

This research was done at Wuhan University with strong support from the Chaohu Lake administration in Hefei. We have given guidance and help to the collection of sediments in our experiment. W Luo was responsible for the whole research work, including the experimental work and the analysis of the results. Y Yue designed the main content framework of the manuscript and assisted in the analysis of the experimental results. J Lu assisted in the preparation and operation of the experiment. L Pang mainly assisted in the in-depth analysis of experimental data and the collation of results. S Zhu assisted in some data analysis and the writing of this manuscript.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Availability of data and materials

All data generated or analyzed during this study are included in this manuscript. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Figures

Figure 1

Sampling locations of the original sediment column cores of the Chaohu Lake

Figure 2

Device for simulating measuring sediment phosphate release

Figure 3

Phosphate concentration in the overlying water during the monitoring period

Figure 4

Cumulative release rates of phosphates during the monitoring period

Figure 5

Statistics on the rate of phosphate release in sediments in each lake area

Figure 6

Distribution of the cumulative release rates of phosphate from the Chaohu Lake sediment