

Impacts of hydrodynamic disturbance on sediment resuspension, phosphorus and phosphatase release, and cyanobacterial growth in Lake Tai

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Abstract The objective of this study was to link hydrodynamic disturbance with sediment resuspension, phosphorus release, and algal growth in Lake Tai, a typical shallow lake located in the south of the Yangtze River Delta in China. With this regard, a sediment–water–algae laboratory experiment was conducted and extrapolated to the real situation in terms of field observations. The results show that the algal growth rate synchronically increased with dissolved total phosphorus (DTP) release rate. The DTP decreased with increase of bottom flow velocity, indicating that the phosphorus release rate was lower than its transfer rate into algal biomass. While all levels of hydrodynamic disturbances could increase sediment resuspension and phosphorus release, a low to moderate disturbance was beneficial, but a strong disturbance was harmful for algal growth. Also, a low to moderate disturbance caused the dissolved alkaline phosphatase activity

(DAPA) to increase with time, which provided the enzyme for hydrolyzing a variety of organic phosphorus compounds from bed sediment into algae-needed nutritional DTP. The experiment proved to be an efficient means to understanding eutrophication mechanisms of large shallow lakes such as Lake Tai.

Keywords DAPA · DTP · Eutrophication · Experiment · *M. aeruginosa* · Shallow lake

Introduction

Lake eutrophication is a worldwide environmental problem that threatens ecosystem health. It not only creates imbalances among different biological processes, but also decreases ecosystem biodiversity (Zhai et al. 2010). Shallow lakes are relatively easily shifted to a new trophic state because: (1) their shallow depths are accompanied by high concentrations of sediment; (2) they lack stable long-term thermal stratification (Padisák and Reynolds 2003; Read et al. 2011); (3) they incur frequent mixing of the entire water column and resuspension of bed sediments (Vicente et al. 2012); and (4) there is substantial internal loading of nutrients from the lake sediments to the water column (Søndergaard et al. 2013). In lakes that have such features, water quality conditions are likely to have a complex relationship with hydrodynamic process, nutrient (e.g., phosphorus) release, and algal growth at the sediment–water interface.

The hydrodynamic process, an important physical phenomenon, is a key factor that affects nutrient transport and transformation, especially at the sediment–water interface (You et al. 2007), because lake bed sediments are usually rich in phosphorus, mainly in the form of phosphate (Yuan

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et al. 2014). Investigations on large and shallow lakes, such as Lake Balaton in Hungary (Luettich et al. 1990), Lake Tuakitoto in New Zealand (Ogilvie and Mitchell 1998), Lake Okeechobee in the USA (Jin and Ji 2004), and Lake Tai in China (Wu et al. 2013), indicated that wind-induced disturbance was critical to resuspension of bed sediments and horizontal distribution of the bloom-forming *Microcystis* (Wu et al. 2010). On the other hand, some other studies (e.g., Chuai et al. 2011; Hu et al. 2011) have revealed that flow currents can propel resuspension of bed sediments and thus release of phosphorus, because current-induced turbulence can reduce the thickness of diffusion boundary layer and thus enhance mass transport (i.e., the molecular diffusion flux) of phosphorus across the sediment–water interface (Fan et al. 2010). For a given lake, although waves and currents are two different momentums (i.e., hydrodynamic disturbances), both are transformed into shear stress on the lake bed to affect sediment resuspension. Thus, shear stress can be used as the surrogate of the overall hydrodynamic disturbance and there is no need to differentiate waves from currents. Hereafter, sheer stress and hydrodynamic disturbance are interchangeably used with the same meaning.

Two types of methods, including field observation and laboratory experiment, have been used to study the effects of hydrodynamic disturbance on sediment resuspension. For instance, Horppila and Nurminen (2005) and Kelderman et al. (2012) observed sediment resuspension and nutrient exchange resulting from various windy conditions, while Laima et al. (1998) used a flow chamber and Hu et al. (2011) used a flume to simulate sediment resuspension resulting from various flow regimes. However, there exists some research space in linking hydrodynamic disturbance with sediment resuspension, nutrient release, and algal growth because of the difficulty in duplicating field observations in an identical environment (e.g., water temperature and light) and fermenting algae in flow chamber and flume.

Phosphorus, which is usually introduced into lakes by runoff and wastewater discharge and can be accumulated in bed sediments (Chen et al. 2011; Duong et al. 2014), is recognized as the most limiting nutrient for algal production of most lakes. Phosphatase is an enzyme that can hydrolyze a variety of organic phosphorus compounds into orthophosphate and alcohol. Although the soluble inorganic phosphate concentration in lake water is generally low, planktons can produce phosphatase to hydrolyze organic phosphorus into inorganic phosphate (Reichardt 1971). This enzyme plays an important role in sustaining the supply of inorganic phosphate needed by algae (Zhang et al. 2007; Zhou et al. 2008) and thus often used as an indicator of the phosphorus nutritional status of phytoplankton communities (Labry et al. 2005).

The objective of this study was to link hydrodynamic disturbance with sediment resuspension, phosphorus release, and algal growth. A sediment–water–algae laboratory experiment was conducted to assay phosphorus nutrient and phosphatase release in relation to cyanobacterial growth as influenced by hydrodynamic disturbance. The water samples from Lake Tai were analyzed for chlorophyll-a (Chl-a), total phosphorus (TP), dissolved total phosphorus (DTP), total alkaline phosphatase activity (TAPA), and dissolved alkaline phosphatase activity (DAPA). In addition, field observations and experiment results were integrated to examine the effects of hydrodynamic disturbance on phosphorus release and algal growth. The field observations consist of flow velocity (u_z) (surrogate of hydrodynamic disturbance), chlorophyll-a (Chl-a), and levels of nutrient species of TP and DTP in the water of Lake Tai.

Materials and methods

Study area

Lake Tai, also called Lake Taihu, Tai Lake, or Taihu Lake in literature, is a typical shallow lake located in the south of the Yangtze River Delta in China (Paerl et al. 2011; Wilhelm et al. 2011) (Fig. 1). The lake has an average water depth of 1.9 m and a surface area of 2,338 km² (Paerl et al. 2011). Lake Tai, an important regional freshwater resource (Qin et al. 2010), is infamous for its widespread algal bloom, which has seriously degraded the water quality (Huang et al. 2014a). Across the lake area, the algal bloom is most serious in the large, semi-enclosed Zhushan Bay and Meiliang Bay (Xie et al. 2003).

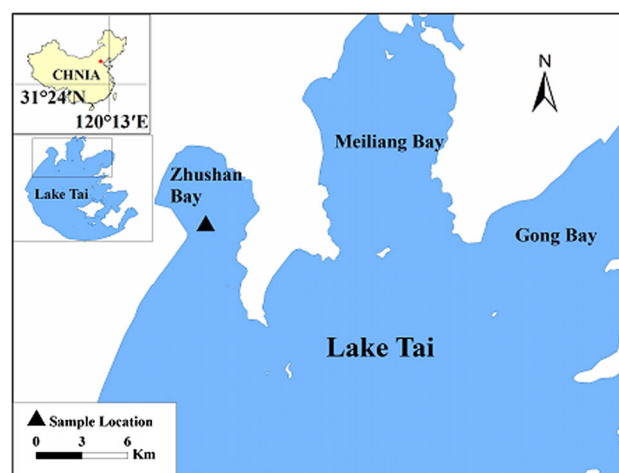


Fig. 1 Map showing the location of Lake Tai and the sampling point

Experiment

In this study, an experiment including sediment, deionized water, and algae (illustrated in Fig. 2) was used to simulate the effects of various disturbances on algal growth. The experiment focused specifically on the shear stress caused by the action of a stirring rod on sediment resuspension, thus enabling us to generate realistic dynamic simulations of the shear stress produced by water currents in the laboratory. The apparatus consisted of a motor stirrer mounted above a transparent borosilicate glass cylinder with a diameter of 15 cm and a height of 25 cm (an effective volumetric capacity of 4L). The device incorporated a motor stirrer that could be operated at various rotational speeds to mimic different hydrodynamic conditions.

Common estimates of the active sediment depth vary between a thin surface layer (the top 0 cm) to the top 10 cm in shallow lakes (Reddy et al. 1996; Meis et al. 2013), so the sediment samples used in this study were taken from the top 10 cm of the lake bed in the Zhushan Bay of Lake Tai (shown as the solid triangle in Fig. 1). On the day the samples were collected, in June 2012, the sampling region had a water depth of 1.9 m. The samples were collected using a Petersen grab sampler purchased from the Wuhan Hengling Technology Company, Wuhan, China. All samples were stored in a refrigerator at 4 °C until use. To avoid the effect of bacteria across all experimental trials, the sediment samples were sterilized in the sealed 121 °C steam pan for 1 h to eliminate any microorganisms before use (Jiang et al. 2008).

Microcystis aeruginosa (*M. aeruginosa*) was selected as the indicating alga in this study. *M. aeruginosa*, obtained from the Chinese Research Academy of Environmental Sciences (CRAES) Innovation Base of Lake Eco-environment, were raised in M11 medium (Jin et al. 2009). *M. aeruginosa* that had reached the exponential growth phase were then

inoculated into the cylinders at a density of 8×10^5 cells mL^{-1} for the experimental runs (Wang et al. 2011).

The sediment specimen depth in the cylinders was restricted to a height of 4 cm. The cylinders were prepared as follows: once the sterilized sediment had been placed in the bottom of the cylinder, 3 L deionized water (sterilized at 121 °C for 0.5 h) was slowly added using a siphon (to avoid sediment resuspension) to a height of 16 cm and a blade stirrer suspended above the cylinder. Based on the results obtained from several preliminary runs and values provided in the literature (e.g., Sun et al. 2007), the stirring rod was inserted into the water column at a level 5 cm above the surface of the sediment (Fig. 2). Finally, the cylinder was sealed by a sterilized film and left undisturbed for 2 days to reach equilibrium (Sun et al. 2007).

To mimic possible natural disturbances affecting Lake Tai, a series of experiments were run with the blade stirrer operated at different rotational speeds (0, 100, 200, 300 and 400 rad min^{-1}) to represent a range of typical situations. For each given rotational speed, three identical experimental setups were operated synchronically and 100 mL water samples were extracted from each of the triplicate cylinders every 2 days. The experiment did not end until algae growth reached a steady period. The water samples collected were analyzed for Chl-a, TP, DTP, TAPA, and DAPA. Chl-a was extracted with acetone (90 %) and determined using a spectrophotometer-based method (US EPA 1997). TP and DTP were analyzed following the standard methods described in Chen et al. (2003a, b). TAPA (unfiltered) and DAPA (<0.2 μm) were assayed by an ultraviolet–visible spectrophotometer as the release of p-nitrophenol from model substrate p-nitrophenyl phosphate (pNPP) according to Gao et al. (2006) and Chen et al. (2011). The enzyme kinetic module (SigmaPlot 8.0, SPSS, Inc) was used to estimate the kinetic constant maximum reaction velocity (V_{max}). All the experiments were cultivated in an illumination incubator Safe PGX under conditions of 25 ± 1 °C, 2,000 lux and light/dark (L/D) 12/12 h cycles (Wu et al., 2012). The incubator was purchased from Ningbo Haishu Apparatus Company of China.

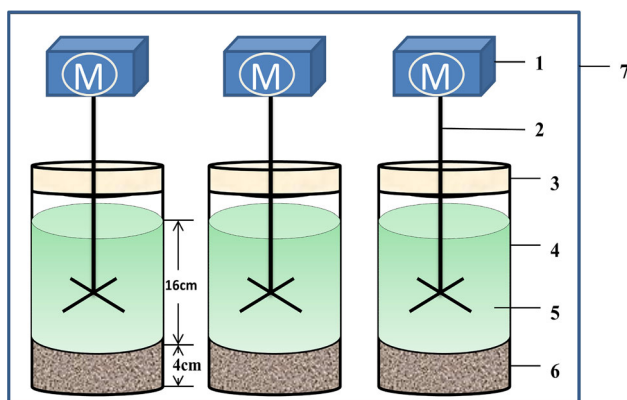


Fig. 2 Illustration of the experimental apparatus: 1 motor stirrer; 2 stirring rod; 3 sterilized sealing film; 4 transparent reactive cylinder; 5 overlying water; 6 sediment; and 7 phytotron

Field data

The field observations including data on flow velocity, Chl-a, TP, and DTP were synchronously measured in Meiliang Bay of Lake Tai by the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGL CAS) for 2008, 2009, 2010, and 2011 following the guidelines provided by the Chinese Ministry of Environmental Protection (Fig. 1). The flow velocity (u_z) is near the sediment bed and produces shear stress easily for the field condition, hence, causing a dynamic effect for the experiment similar to that of Lake Tai (i.e., the water flow velocity 50 cm

above the lake bed). Across the lake area, Zhushan Bay and Meiliang Bay are semi-enclosed with the most algal bloom (Xie et al. 2003). TP and DTP concentrations of overlying water are 0.188 and 0.04 mg L⁻¹ in Zhushan Bay and 0.156 and 0.04 mg L⁻¹ in Meiliang Bay; TP concentrations of the sediment are 0.75 g P kg⁻¹ dry solids in Zhushan Bay and 0.49 g P kg⁻¹ dry solids in Meiliang Bay (Wang et al. 2011). Zhushan Bay is geographically adjacent to, hydraulically connected with and having similar water quality and sediment as, Meiliang Bay. These field data for Meiliang Bay were reasonably presumed to be true for Zhushan Bay as well. The data collected were checked for quality by experts at NIGLCAS.

Selection of rotational speeds based on field data

Bed sediments of shallow lakes can influence the physiochemical environment of the water column through resuspension. As stated above, the process of sediment resuspension in a shallow lake can be initiated by the shear stress induced by both winds and flow currents. When the wind energy is transmitted from the lake surface to the bottom of the lake, the energy dissipates and decreases with increasing depth. This transmission process can be described by fluid particle trajectories induced by wave motion in the vertical direction (Jin and Ji 2004). The wave-induced hydrodynamic disturbance is added up with the current-induced hydrodynamic disturbance to create the shear stress for sediment resuspension. While the former disturbance can become larger on few windy days, the two disturbances are comparable in magnitude for most days (Qin et al. 2004). A statistical analysis of the filed data indicated that in Lake Tai, the occurrence of wind speed less than 4 m s⁻¹ was over 50 % and the mean wind speed was 3.5 m s⁻¹. Therefore, this study used rotating water currents in the laboratory to create shear stresses to surrogate the in situ overall hydrodynamic disturbances induced both by wind waves and water currents in Lake Tai. The in situ shear stresses (Fig. 3; Table 1) were computed using the observed values of flow velocity (u_z) at 50 cm above the bed sediment surface, assuming that u_z is the overall result of wave and current momentums.

The in situ shear stress was computed as (Sheng and Lick 1979; Hawley 2000):

$$\tau = \rho f \left(\frac{u}{100} \right)^2, \quad (1)$$

where τ is the shear stress on the bed sediment surface (N m⁻²), ρ is the water density (=1,000 kg m⁻³), $f = 1/R_e$ is a dimensionless skin friction coefficient (here taken to be $f = 0.02$ based on Laenen and LeTourneau (1996) and considering that Lake Tai has a shallower mean water depth and thus a larger mean bottom flow velocity), R_e is

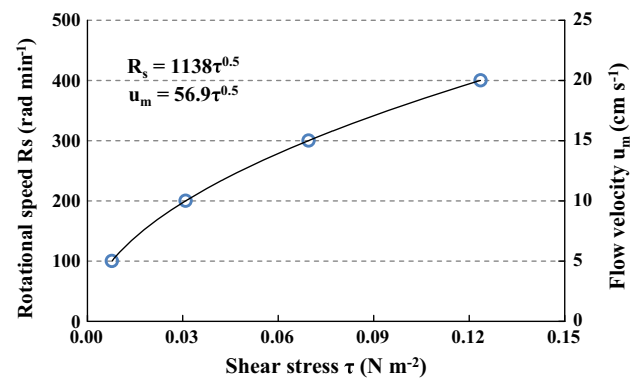


Fig. 3 Plot showing the rotational speeds (R_s) used in the laboratory experiment and the responding bottom flow velocities (u_m) of real Lake Tai versus the resulting bottom shear stresses (τ) of real Lake Tai

Table 1 The computed shear stresses at the bed surface of Lake Tai

Laboratory experiment		Real Lake Tai		
R_s (rad min ⁻¹)	u_m (cm s ⁻¹)	u_z (cm s ⁻¹)	u (cm s ⁻¹)	τ (N m ⁻²)
100	5	15.81	1.96	0.008
200	10	31.62	3.93	0.031
300	15	47.43	5.89	0.069
400	20	63.25	7.86	0.124

The computation was done using Eqs. (1)–(6); the variables are defined in these equations

the Reynolds number, and u is the bottom boundary velocity (i.e., the velocity in the vicinity of the bed sediment surface) (cm s⁻¹).

u was computed as:

$$u = \frac{k u_z}{\ln(z/z_0)}, \quad (2)$$

where $k = 0.4$ is the von Kármán's constant, u_z is the flow velocity at a height z above the bed sediment surface (herein, $z = 50$ cm based on our field measurement) (cm s⁻¹), and z_0 is the surface roughness (herein, it is assumed $z_0 = 2$ cm based on Wüest and Lorke 2003).

Based on the Froude number similitude principle (Finemore and Franzini 2002), a set of rotational speeds (R_s) (Fig. 3; Table 1) was selected such that the Froude number (Fr_m) in the laboratory experiment would be equal to that (Fr_p) in the field condition:

$$Fr_m = Fr_p. \quad (3)$$

For the laboratory experiment:

$$Fr_m = \frac{u_m}{\sqrt{g h_m}}, \quad (4)$$

where u_m is the tangential speed in the laboratory experiment, h_m is the height above the sediment surface in the

laboratory experiment (herein, $h_m = 5$ cm), and g is the gravitational acceleration ($m\ s^{-2}$). For the field condition:

$$Fr_p = \frac{u_z}{\sqrt{gh_z}}, \tag{5}$$

where $h_z = z = 50$ cm.

Based on the generic relation between tangential and angular speed, the laboratory experimental rotational speed was computed as:

$$u_m = \frac{R_s}{60} r, \tag{6}$$

where R_s is the rotational speed ($rad\ min^{-1}$), and r is the radius of the stirring rod (herein, $r = 3.0$ cm).

The field-observed bottom flow velocity varied from 0.3 to 37 $cm\ s^{-1}$. As stated above, the occurrence of the bottom flow velocities less than 5 $cm\ s^{-1}$ was over 70 %. The rotational speeds were selected to mimic the prevailing bottom flow velocities of 0–20 $cm\ s^{-1}$ in Lake Tai. As a result, the blade stirrer was operated at rotational speeds (in $rad\ min^{-1}$) of 0 (CK), 100 (C1), 200 (C2), 300 (C3), and 400 (C4) for the laboratory experiment (Table 1).

Statistical analysis methods

For each experimental run, the measured values in all trials for a given parameter were pooled to formulate a single dataset, which in turn was used to compute the mean and standard deviation for that parameter. The datasets for all experimental runs for each parameter were then used to conduct a multiple comparison t test (Neter et al. 1996) in SPSS® 16.0. The average values, along with the maximum and minimum deviations, were plotted against measurement day in OriginLab® Origin 8.5 to visually examine whether and how the results of the runs were different. Laboratory experiment and field observation data were plotted using a box graph to examine the effects of hydrodynamic disturbance.

Results

Laboratory experiment

The Chl-a concentrations for a rotational speed of $\leq 300\ rad\ min^{-1}$ were significantly higher than those for the control condition (CK) (p value < 0.05), whereas the Chl-a concentrations for the rotational speed of $400\ rad\ min^{-1}$ were significantly lower than those for CK (p value < 0.001) (Fig. 4; Table 2). Averaged across the 21 measurement days, there was a similar trend of Chl-a concentrations for rotational speeds of 100, 200, and 300 $rad\ min^{-1}$. Chl-a concentration increased over time

when the rotational speed was $\leq 300\ rad\ min^{-1}$ (Fig. 4), including the static condition, but it decreased over time when the rotational speed was raised to $400\ rad\ min^{-1}$. Depending on the rotational speed, Chl-a concentration initially increased slowly and then either increased rapidly or decreased gradually. The peak of Chl-a concentration ($2,985\ \mu g\ L^{-1}$) appeared on day 21 for a rotational speed of $300\ rad\ min^{-1}$.

Microcystis aeruginosa might have adapted to the sediment–water interface environment by day 3, because for rotational speeds of $\leq 300\ rad\ min^{-1}$, these started growing rapidly from day 5 and then steadily grew as a logarithmic function of time (Fig. 4). On day 5, the maximum Chl-a concentration was $292\ \mu g\ L^{-1}$ and the water was visibly pale green. The *M. aeruginosa* growth reached its plateau on day 15, when the maximum Chl-a concentration was $1,963\ \mu g\ L^{-1}$ and the water was visibly dark green.

Although TP concentrations for a given rotational speed varied more or less, they were consistently higher than those for the control condition (p value < 0.05) (Fig. 5a; Table 2). Averaged across the 21 measurement days, the TP concentrations increased over time for both the disturbing and static conditions. There was a similar trend for the TP concentrations at rotational speeds of 200, 300, and 400 $rad\ min^{-1}$. The DTP concentrations for all rotational speeds were obviously higher than those for the control condition (Fig. 5b). Averaged across the 21 measurement days, the DTP concentrations increased over time regardless of rotational speeds, indicating that phosphorus was released from the sediments. The DTP concentrations at rotational speeds of 200 and 300 $rad\ min^{-1}$ were higher than those for the other rotational speeds.

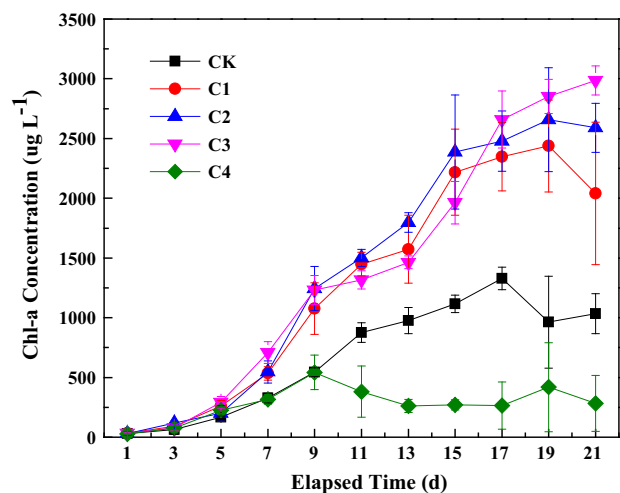


Fig. 4 Plot showing the laboratory experiment means (solid lines) and ranges (vertical bars) of chlorophyll-a (Chl-a) concentrations for rotational speeds (in $rad\ min^{-1}$) of 0 (CK), 100 (C1), 200 (C2), 300 (C3), and 400 (C4) versus time

Table 2 The mean \pm standard deviation of chlorophyll-a and phosphorus nutrients in the laboratory experiment

	Rotational speed of motor stirrer (rad min^{-1})				
	0	100	200	300	400
Chlorophyll-a (Chl-a) ($\mu\text{g L}^{-1}$)	675.36 ± 95.22	$1,278.59 \pm 215.61^{**}$	$1,413.70 \pm 172.26^{**}$	$1,416.98 \pm 100.18^{**}$	$278.82 \pm 122.85^{***}$
Total phosphorus (TP) (mg L^{-1})	1.45 ± 0.26	$2.11 \pm 0.19^*$	$2.52 \pm 0.26^{**}$	$2.64 \pm 0.38^{**}$	$2.55 \pm 0.88^{**}$
Dissolved total phosphorus (DTP) (mg L^{-1})	0.38 ± 0.17	0.55 ± 0.16	$0.66 \pm 0.12^{**}$	$0.85 \pm 0.27^{***}$	$0.60 \pm 0.17^*$
Total alkaline phosphatase activity (TAPA) ($\mu\text{mol L}^{-1} \text{min}^{-1}$)	0.026 ± 0.006	0.032 ± 0.01	0.038 ± 0.006	$0.04 \pm 0.006^{**}$	$0.05 \pm 0.013^{***}$
Dissolved alkaline phosphatase activity (DAPA) ($\mu\text{mol L}^{-1} \text{min}^{-1}$)	0.007 ± 0.001	$0.013 \pm 0.003^*$	$0.016 \pm 0.002^{**}$	$0.006 \pm 0.001^*$	0.006 ± 0.001

Significantly different from that for rotational speed of zero at a significance level of $\alpha = 0.05$ (*), 0.01 (**), and 0.001 (***)

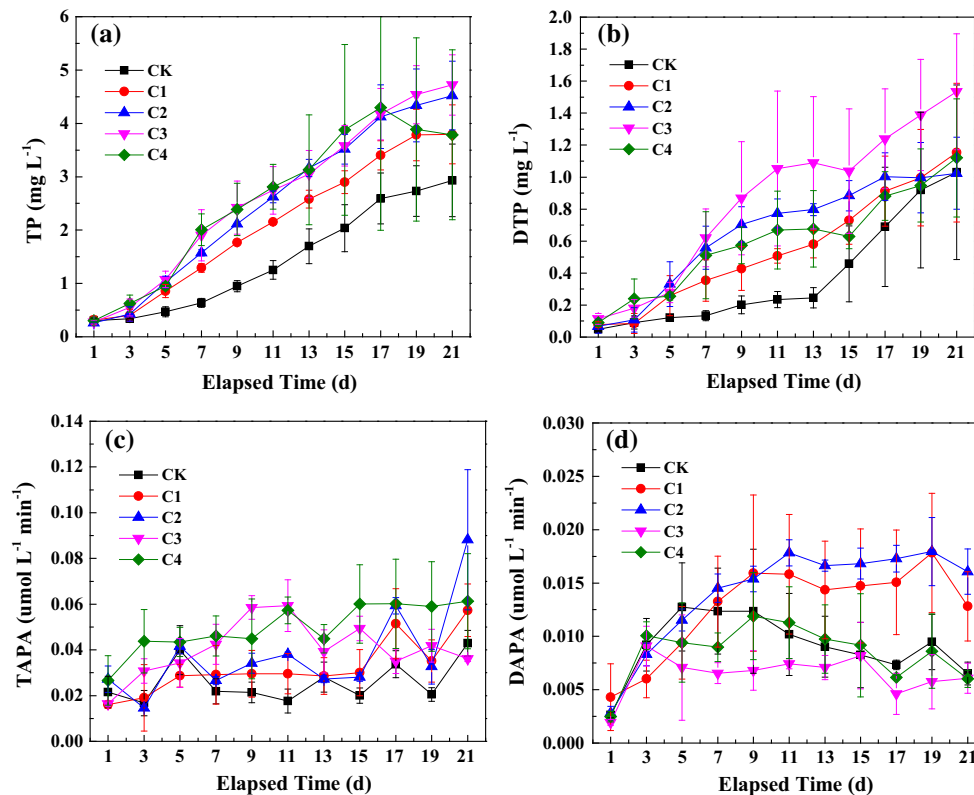


Fig. 5 Plots showing the laboratory experiment means (solid lines) and ranges (vertical bars) of: **a** total phosphorus (TP), **b** dissolved total phosphorus (DTP), **c** total alkaline phosphatase activity (TAPA),

and **d** dissolved alkaline phosphatase activity (DAPA) for rotational speeds (in rad min^{-1}) of 0 (CK), 100 (C1), 200 (C2), 300 (C3), and 400 (C4), versus time

The TAPA for rotational speeds of 300 and 400 rad min^{-1} were significantly higher than those for the control condition (p value <0.01) (Fig. 5c; Table 2). Averaged across the 21 measurement days, the TAPA increased slightly with time. Similarly, the DAPA was also a function of rotational speed and time (Fig. 5d). The DAPA values for rotational speeds 100 and 200 rad min^{-1} were

significantly higher than those for the other rotational speeds and the control condition (p value <0.05), while the DAPA values for rotational speeds 300 rad min^{-1} were noticeably lower than those for the control condition (Table 2). Averaged across the 21 measurement days, the DAPA increased with time for rotational speeds of 100 and 200 rad min^{-1} , whereas the DAPA decreased with time for

rotational speeds of 300 and 400 rad min⁻¹ and the control condition.

The Chl-a, TP, DTP, and TAPA all varied as a quadratic function of bottom flow velocity (Fig. 6). Based on the data from day 5 to day 15 when *M. aeruginosa* growth was at the logarithmic phase (Fig. 4), the Chl-a growing rate had a similar trend with the DTP release rate (Fig. 6a, c): the rates at velocities of $u_m = 5, 10, \text{ and } 15 \text{ cm s}^{-1}$ (equivalent rotational speeds of $R_s = 100, 200, \text{ and } 300 \text{ rad min}^{-1}$, respectively) were higher than those at the velocity of $u_m = 20 \text{ cm s}^{-1}$ (equivalent rotational speed of $R_s = 400 \text{ rad min}^{-1}$). Both rates decreased at the rotational speed of 400 rad min⁻¹. The TP release rate became stagnant when velocity $\geq 20 \text{ cm s}^{-1}$ (Fig. 6b). In contrast, the maximum reaction velocity of TAPA monotonically increased with flow velocity (Fig. 6d).

Field observation versus laboratory experiment

The field-observed bottom flow velocity varied from 0.3 to 37 cm s⁻¹ (Fig. 7), while the observed mean concentrations of Chl-a, TP, and DTP were 20.4 ug L⁻¹, 0.15, and 0.04 mg L⁻¹, respectively. More than 70 % of the velocities were between 0 and 5 cm s⁻¹, when relatively high Chl-a, TP, and DTP concentrations occurred (Fig. 7). When velocities were $>5 \text{ cm s}^{-1}$, the concentrations tended to decrease with increase of velocity and were consistently lower than the responding averages. Based on the Froude number similitude principle, the rotational speeds of $R_s = 100, 200, 300, \text{ and } 400 \text{ rad min}^{-1}$ responded to the in situ bottom flow velocities of $u = 1.96, 3.93, 5.89, \text{ and } 7.86 \text{ cm s}^{-1}$, respectively (Fig. 3). As expected, the shear stress consistently increases with rotational speed or bottom flow velocity (Table 1) with $\tau = 0.008\text{--}0.124 \text{ N m}^{-2}$.

For the laboratory experiment, the Chl-a concentrations when $R_s \leq 300 \text{ rad min}^{-1}$ were significantly higher than those when $R_s = 400 \text{ rad min}^{-1}$ ($p \text{ value} = 0.001$) (Fig. 8). Correspondingly, for the field observation, the Chl-a concentrations when $u \leq 5 \text{ cm s}^{-1}$ were significantly higher than those when $u > 5 \text{ cm s}^{-1}$. Such an agreement indicated that the laboratory experiment could be used to examine sediment–water–algae interactions in Lake Tai. As with the laboratory experiment, the field observation also revealed a positive relation between Chl-a and hydrodynamic stress when $u < 5 \text{ cm s}^{-1}$, suggesting that a moderate hydrodynamic disturbance was good for *M. aeruginosa* growth. However, the negative relation when $u \geq 5 \text{ cm s}^{-1}$ indicated that a strong hydrodynamic disturbance would be bad for *M. aeruginosa* growth. Also, the field observation revealed that the DTP decreased with increase of bottom flow velocity, indicating that the phosphorus release rate was lower than its transfer rate into algal biomass.

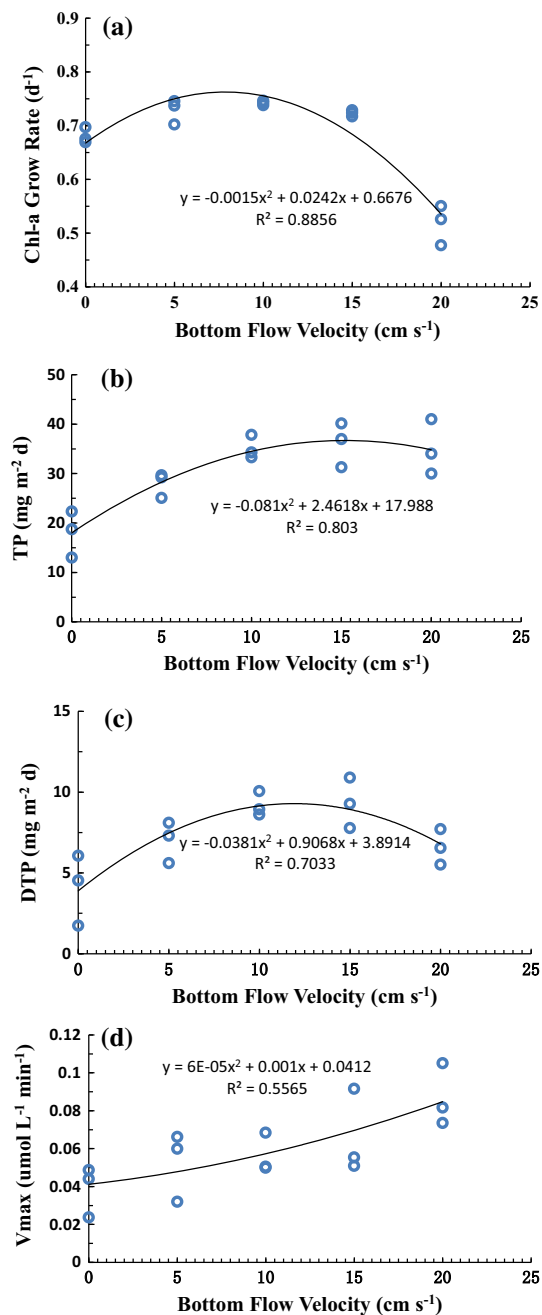


Fig. 6 Plots showing the laboratory experiment: **a** chlorophyll-a (Chl-a) growth rate (Ono and Cuello 2007), **b** total phosphorous (TP) release rate (Ding et al. 2007), **c** dissolved total phosphorus (DTP) release rate (Ding et al. 2007), and **d** TAPA maximum reaction velocity (V_{max}) (Gao et al. 2006) versus the bottom flow velocity that is the responding tangential speed of a laboratory experiment rotational speed

Discussion

Phosphorus release rate can be influenced by changes of hydrodynamic disturbance, biogeochemical process, and environment (Yuan et al. 2014). The TP concentrations for

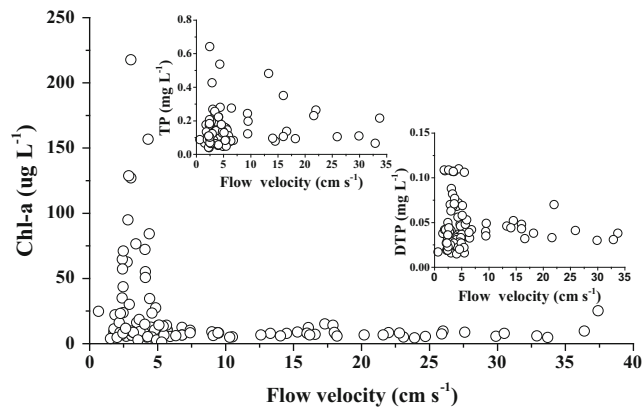


Fig. 7 Plots showing the field-observed chlorophyll-a (Chl-a), total phosphorous (TP), and dissolved total phosphorus (DTP) versus the field-observed bottom flow velocity

rotational speed of 400 rad min^{-1} had a similar trend with those for rotational speeds of 200 and 300 rad min^{-1} , whereas the DTP concentrations for rotational speed of 400 rad min^{-1} were obviously lower than those for rotational speeds of 200 and 300 rad min^{-1} . The moderate hydrodynamic disturbances at rotational speeds of 200 and 300 rad min^{-1} were good for algal growth, but the strong hydrodynamic disturbance at rotational speed of 400 rad min^{-1} was harmful. In contrast, the TAPA did not increase much with time regardless of rotational speeds, while the DAPA rapidly increased with time for rotational speeds of 100 and 200 rad min^{-1} but decreased with time for rotational speeds of 300 and 400 rad min^{-1} . One possible reason is that strong disturbance caused more sediment to be resuspended and then mixed with water.

Another possible reason is that the high phosphate concentration prevented APA from being released from sediments for rotational speed of 300 rad min^{-1} .

The Chl-a concentrations in the laboratory experiment were higher than in field observations. One possible explanation was that the laboratory experiments were conducted under conditions that were more favorable for algal growth because hydrodynamic disturbance was the sole varying factor, whereas in the real lake algal growth was more likely to be affected by dynamic factors such as flow regime as well as temperature and light conditions (Huang et al. 2014b) that could not be adequately realized in the laboratory setting. Also, in the real lake, algae could be consumed by other aquatic species (Zhang et al. 2012). Another possible explanation is that the very different spatial scales of the experimental apparatus and the real lake need to be considered when interpreting the results. For example, the mean water depth of Lake Tai is about 1.8 m, but the water depth in the laboratory simulator was only 16 cm. Similarly, the average field Chl-a concentration was 25 ug L^{-1} , while the average experiment Chl-a concentration was $1,200 \text{ ug L}^{-1}$. The ratio of these concentrations ($1,200 \div 25 = 48$) is of a similar magnitude to the reciprocal of the ratio of the water depths ($190 \div 16 = 12$), which indicates that the experimental results may indeed reflect the real lake situations after scaling and consumption effects are taken into account.

The average *M.aeruginosa* growth rate for $\tau \leq 0.069 \text{ N m}^{-2}$ was higher than that for $\tau > 0.069 \text{ N m}^{-2}$. This inflection shear stress is consistent with the threshold stress reported by Qin et al. (2004) and Luo and Qin

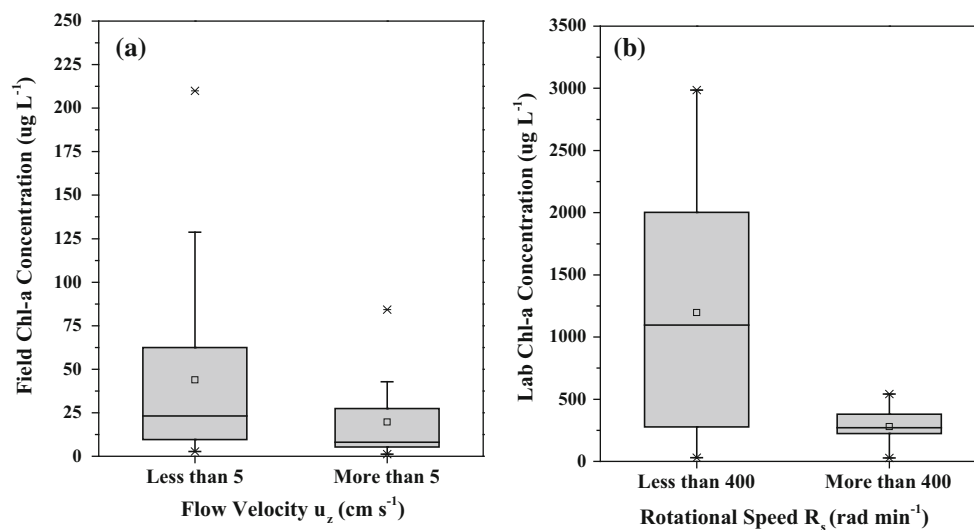


Fig. 8 Box plots of chlorophyll-a (Chl-a) concentrations from: **a** the field observations of real Lake Tai and **b** the laboratory experiment of bed sediment samples of Lake Tai. For each box plot, the two groups

are subdivided in terms of the hydrodynamic disturbance that is either good or bad for algal growth

(2003). This experiment–field integrated study clearly elucidated that low- to medium-level disturbances can be beneficial for algae growth, while higher-level disturbances are harmful. This is consistent with the findings of Yan et al. (2007) and Ndong et al. (2014). The critical shear stress was approximately 0.069 N m^{-2} , which is comparable with the range ($0\text{--}0.4 \text{ N m}^{-2}$) reported by others (e.g., Laenen and LeTourneau 1996; Xu 1998; Hawley 2000; Luo and Qin 2003). This value reflects the combined effect of wave- and current-induced momentums. Smaller values (e.g., Wu et al. 2013) have been reported when only one of these two momentums was considered. The shear stress created by water currents can be one or two magnitudes lower than that created by wind waves. Qin et al. (2004) found that the shear stresses created by wind waves and water currents were $0.0\text{--}0.4$ and $0.0\text{--}0.01 \text{ N m}^{-2}$, respectively.

Conclusions

The experiment–field integrated study examined interactions of sediment resuspension, phosphorus release, and algal growth as influenced by hydrodynamic disturbance. The results showed that the algal growth rate increased synchronically with the dissolved total phosphorus (DTP) release rate. A low to moderate hydrodynamic disturbance was judged to promote the release of phosphorus from bed sediment in Lake Tai and be beneficial for algal growth. Under such a disturbance, the dissolved alkaline phosphatase activity (DAPA) increased with time to make sure that the algae-needed nutritional phosphorus was continuously released from the bed sediment. However, a strong hydrodynamic disturbance could be harmful for algal growth.

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