Research on wind-induced nutrient release in Yangshapao Reservoir, China

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ABSTRACT

Nutrient (total nitrogen (TN) and total phosphorus (TP)) are considered the major indicators to be impacted by wind speed in shallow lakes and reservoirs. As a reservoir situated in Jilin Province, China, Yangshapao Reservoir has been employed for irrigation and urban water use. After 2 years' observation carried out on water quality and wind speed, it was found that the TN, NH_4 and TP are significantly correlated with the bottom shear stress attributed to wind, whereas the dissolved phosphorus (DP) is not. Bottom shear stress is also noticeably associated with dissolved oxygen (DO), thus promoting nutrient release into the water body. In winter, ice can effectively inhibit the wind-induced shear stress, and the TP concentration is evidently lower than in the other seasons. This scenario should be considered in the management of the water quality of the lake and similar lakes.

Key words | dissolved oxygen, shear stress, total nitrogen, total phosphorus, wind-induced

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INTRODUCTION

Excess total phosphorus (TP) is one of the major factors that probably result in eutrophication and algal blooms in rivers, lakes and reservoirs. It has been reported that most of the world's lake and reservoir eutrophication is attributed to phosphorus and total nitrogen (TN) (Khare *et al.* 2019), and most lake and reservoir eutrophication in China is attributed to phosphorus. Some phosphorus pollution in the lake primarily originates from the lake and reservoir sediment that acts as the source or sink of phosphorus in the overlying water. Once the lake or reservoir is disturbed by an external force, the phosphorus in the sediment will begin to desorb and return to the overlying water; subsequently, the sediment will act as the source of phosphorus (Horppila & Nurminen 2005). Given the close correlation between TP concentration and algal biomass, TP can be adopted as an indicator of eutrophication to estimate phytoplankton concentration (Thomann & Mueller 1987). If the TP in the reservoir can reach a higher level under high winds, it will not meet the standards for irrigation and drinking water supply (Zhou *et al.* 2017).

In shallow lakes and reservoirs, hydrodynamics can lead to a variation of nutrient distribution in sediments by inducing internal nutrient release. The release may be affected by water depth, nutrients, water temperature, pH, dissolved oxygen (DO), concentration gradient, redox potential, organisms, as well as hydrodynamics (Orihel *et al.* 2017). Among the mentioned factors, the significance of hydrodynamics is often recognized, especially in shallow lakes (Bormans *et al.* 2016). Compared with that in deep lakes and reservoirs, the sediment in shallow lakes and reservoirs is more susceptible to hydrodynamic disturbances, of which the nutrients can act for the primary productivity of the overlying water (Shen *et al.* 2011; Nürnberg *et al.* 2012). Studies conducted for large and shallow lakes have suggested that wind and waves are critical to sediment resuspension (Mei *et al.* 1997). In recent decades, relevant studies on the

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dynamic characteristics and wind wave effects of suspended sediment have been conducted. The results have suggested that suspended sediment noticeably impacts the release of phosphorus and nitrogen, and that strong wave disturbance can double the phosphorus concentration in the overlying water of lakes (Huang *et al.* 2012). Huang *et al.* (2016) conducted relevant studies using a proposed comprehensive dynamic phosphorus model, and the results revealed that sediment resuspension and phosphorus release noticeably affect phosphorus content in both Taihu Lake and similar shallow lakes.

In the existing studies, some researchers have provided the relationship between phosphorus and nitrogen concentration with variation of wind (Havens *et al.* 2007). Nevertheless, these analyses placed the emphasis on lakes at low latitudes, while studies on the variation of nitrogen and phosphorus concentrations in lakes in cold regions under hydrodynamic conditions have rarely been conducted. In winter, the lake will be frozen, preventing the disturbance of wind speed on lake and reservoir sediment, which will inevitably affect the variation of nutrient concentration in lakes and reservoirs at high latitudes. In this paper, the condition of ice is also taken into account. In the present study, 2 years' field observations of Yangshapao Reservoir situated in Jilin Province, China, were carried out, and the water quality index was measured. The study was conducted on the seasonal variation of nitrogen, DO and phosphorus in the reservoir with the variation of wind in a cold region. This study will help in understanding the transport of phosphorus in Yangshapao Reservoir and in managing the water quality of the reservoir.

METHODS

Study area

The study area is located in Baicheng City, Jilin Province, China. Since it is responsible for irrigation and urban water use, its water quality is critical to production and life. Yangshapao Reservoir has a temperate continental monsoon climate. With a total area of 35–36 km^2, the temperature varies obviously throughout the year, and the annual average precipitation reaches 388.2 mm. The area of Yangshapao Reservoir is primarily covered with clayey soil with an average diameter of the particles of 32.59–40.35 μm. The grain diameter characteristics of the sediment are listed in Table 1. It is acknowledged that the wind directions at Yangshapao Reservoir are primarily NNW and SSW, and the average water depth is nearly 1.5 m.

Table 1 | Grain diameter distribution of the sediment

Grain diameter (*D*, μm)	Percentage (%)
$D < 100$	39.45
$100 < D < 200$	14.37
$D > 200$	46.18

Field observations

The sites for sampling are located as shown in Figure 1, and the samples were taken on May 19th, June 24th, July 22nd, September 5th, October 11th, November 1st, December 8th 2016, as well as March 9th, April 4th and May 9th 2017, respectively. Three samples with a volume of 500 ml were taken at each site, and the water quality indicators were measured by Jilin Provincial Hydrological Bureau. The dissolved phosphorus (DP) and TP in the water were ascertained using the Mo-Sb anti-spectrophotometry method (Hawley & Lesht 1992), the samples for TP determination were digested in advance, and the samples for DP determination were filtered without being digested. TN and NH_4 were determined by ultraviolet spectrophotometry using the alkaline potassium persulfate digestion method and by spectrophotometry using the salicylic acid method, respectively. A multi-parameter probe (Hydrolab DS 5X) was employed to ascertain the DO concentration. The samples were harvested on windy days, and the wind speeds for 2016 and 2017 were collected by the official from Baicheng Meteorological Bureau.

Bed shear stress

It is known that the upper layer of the lake will be covered with ice in winter, which seriously affects the water power of lakes in cold regions. In the meantime, the shear stress was exploited to better describe the relationship between wind speed and disturbance of the lake sediment.

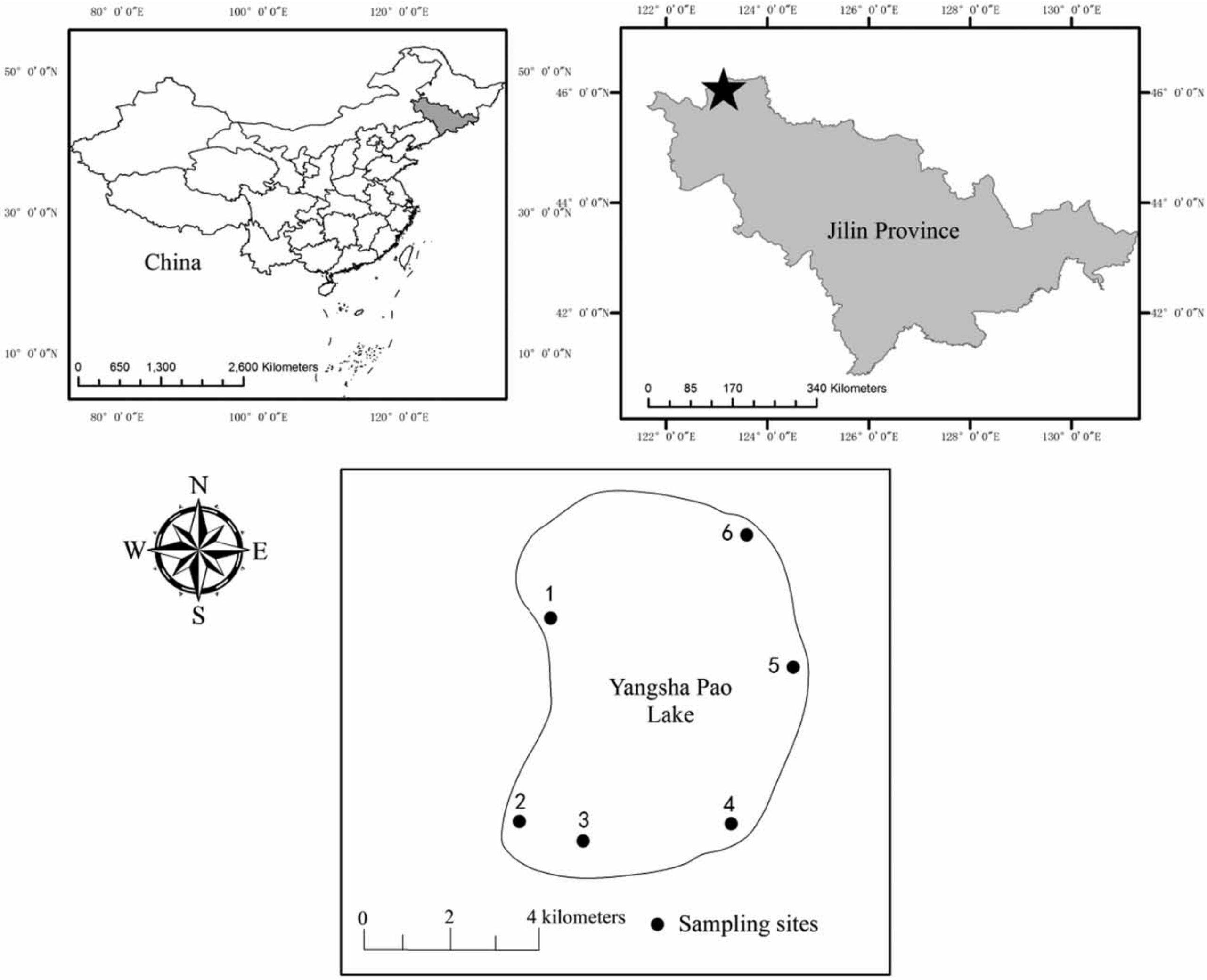

Figure 1 | Map of sampling sites.

Accordingly, wind waves were transformed into shear forces on sediments.

Numerous studies have suggested that the shear stress generated by circulation is on the whole much smaller than that generated by waves in shallow lakes, so it can be ignored (Hamilton & Mitchell 1996). Thus, the wave shear stress can be considered simply as the total bottom shear stress. The bottom shear stress is generated by wind-induced waves, and its calculation can be conducted according to laminar flow theory (Dyer 1986; Teeter *et al.* 2001):

$$\tau_w = \frac{1}{2}\rho f_w U_b^2 \tag{1}$$

where U_b denotes maximum wave orbital velocity; ρ is density of fluid; f_w is friction factor; and f_w can be expressed by:

$$f_w = 2\left(\frac{U_b A_b}{v}\right)^{-0.5} \tag{2}$$

where A_b denotes maximum wave orbital amplitude; and v is kinematic viscosity of water. A_b and U_b are expressed by:

$$A_b = \frac{1}{2\sinh\left(\dfrac{2\pi H}{L}\right)} \tag{3}$$

$$U_b = \frac{\pi h}{T\sinh\left(\dfrac{2\pi H}{L}\right)} \tag{4}$$

By substituting Equations (2)–(4) into Equation (1), the equation can be yielded as:

$$\tau_{\mathrm{w}} = h\left[\rho\frac{\left(v\left(\frac{2\pi}{T}\right)^{3}\right)^{0.5}}{2\sinh\left(\frac{2\pi H}{L}\right)}\right] \tag{5}$$

where h = wave height (m); H = water depth (m); T = wave period (s); and L = wave length (m).

In shallow lakes, the wind-induced wave parameters (e.g., wave height h, wave period T and wave length L) can be estimated by the empirical formulas below (Jin & Ji 2004; Chao *et al.* 2008):

$$\frac{gH}{U_{\mathrm{w}}^2} = 0.283\tanh\left(0.53\left(\frac{gd}{U_{\mathrm{w}}^2}\right)^{3/4}\right)\tanh\left(\frac{0.00565\left(\frac{gF}{U_{\mathrm{w}}^2}\right)}{\tanh\left(0.53\left(\frac{gd}{U_{\mathrm{w}}^2}\right)^{3/8}\right)}\right) \tag{6}$$

$$\frac{gT}{U_{\mathrm{w}}} = 7.54\tanh\left(0.833\left(\frac{gd}{U_{\mathrm{w}}^2}\right)^{3/8}\right)\tanh\left(\frac{0.0379\left(\frac{gF}{U_{\mathrm{w}}^2}\right)^{1/2}}{\tanh\left(0.833\left(\frac{gd}{U_{\mathrm{w}}^2}\right)^{3/8}\right)}\right) \tag{7}$$

$$L = \frac{gT^2}{2\pi}\tanh\frac{2\pi d}{L} \tag{8}$$

where g denotes acceleration of gravity (m/s^2); U_{w} is wind speed (m/s); and F is fetch length of wind (m):

$$F = \frac{\sum x_i\cos\varnothing}{\sum\cos\varnothing} \tag{9}$$

where x_i denotes the distance (m) from the sampling point to the land for every deviation angle; and $\varnothing$ is the deviation angle ($\varnothing$ up to ±45°; intervals of 22.5°) from the wind direction (Kang *et al.* 2019).

RESULTS AND DISCUSSION

The relationship between wind-induced shear stress and nutrient release

It is suggested that strong winds often happen from March to June. The mean wind velocity will exceed 15 m/s occasionally (Figure 2). Wave height will respond to wind speed, and consequently bottom shear stress will also increase with the rise in wave height. Wave height generally remains below a depth of 20 cm, and the maximum values will reach over 30 cm occasionally. The wave height and bottom shear stress are equated to zero from November to March since the reservoir surface is frozen during those days.

Figure 3 obviously shows that the TP concentration is the lowest in December, and it is higher in March to June than in the other months. It was observed that the TP concentration is 0.01 ~ 0.65 mg/L with an average of 0.282 mg/L. Moreover, TP concentration is significantly positively correlated with the bottom shear stress (Table 2). Figure 4 suggests that the DP concentration in December is the lowest. In terms of the DP concentration, it is 0.004–0.65 mg/L with an average of 0.07 mg/L. In addition, no significant correlation is found between DP concentration and the bottom shear stress (Table 2). Furthermore, the concentration of TN is the highest from March to May, and is relatively uniform in the other months (Figure 5). The TN concentration is 1.301–4.553 mg/L with an average of 2.503 mg/L. The TN concentration is not significantly correlated with the bottom shear stress (Table 2). The concentration of NH_4 is the highest in May 2016 and relatively uniform in the other months (Figure 6). The NH_4 concentration is 0.5–2.53 mg/L with an average of 1.142 mg/L. Significant correlation is available between NH_4 concentration and the bottom shear stress (Table 2). The water quality grades are consistent with the Environmental Quality Standards for Surface Water (GB 3838-2002), and the concentrations of TP and TN exceeded the standard of grade V in March to June.

Distinct response of TP and DP dynamics to wind speed

Figure 7(a) shows that TP concentration increases significantly with the rise in shear stress, which is consistent

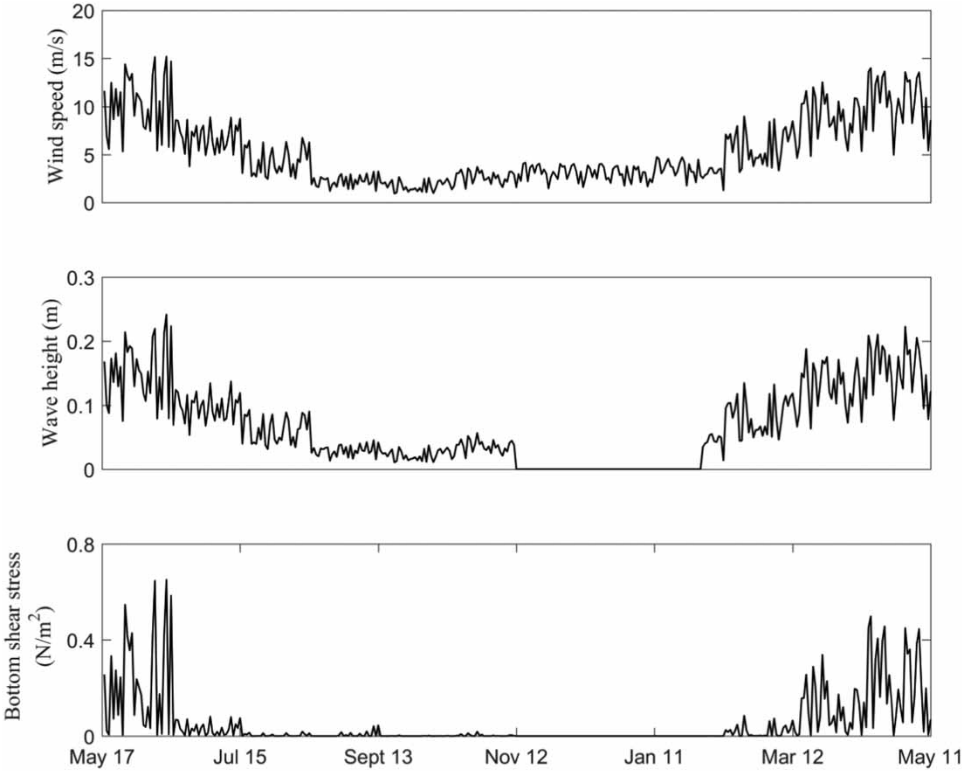

Figure 2 | The average wind velocities (top), wave heights (middle) and bottom shear stress (bottom) in Yangshapao during the study.

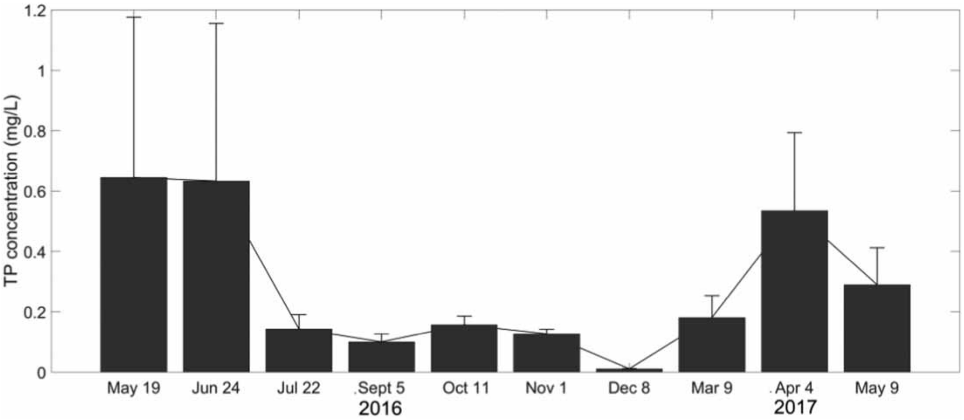

Figure 3 | The TP concentration in Yangshapao during the study.

with the result of the previous study (Chen *et al.* 2015) that TP concentration in the updraft increased by an order of magnitude during a storm event compared with the concentration during background measurements (Cyr *et al.* 2009). With the rise in bed shear stress, a release of DP occurs (Figure 7(b)), while the concentration of DP in the overlying water is not significantly associated with the rise in bed shear stress. Numerous studies have suggested that TP increases after lake sediment resuspension, whereas there has been rare evidence that DP increases (You *et al.* 2007; Withers & Jarvie 2008). Though turbulence enhances the release of DP from sediments (Figure 7(b)), phosphate

Table 2 | The relationship between shear stress, TP, DP, TN, NH_4 and DO

	Shear stress	TP	DP	TN	NH_4	DO
Shear stress	1.000	0.874^a	0.374	0.708^a	0.835^a	0.836^a
TP		1.000	0.549^b	0.477	0.875^a	0.687^b
DP			1.000	0.463	0.441	0.465
TN				1.000	0.526	0.648^a
NH_4					1.000	0.725^a
DO						1.000

[a] Presents $p < 0.05$.
[b] Presents $p < 0.1$.

transported into water can be adsorbed by TSS or assimilated by autotrophic and heterotrophic communities (Marsden 1989). With the rise in shear stress, TP will increase logarithmically, and the determination coefficient of the curve will rise to 0.572; meanwhile, the rule of DP varying with shear stress is not noticeable, and the coefficient of determination is only 0.2383. TP varies obviously with season; it is 0.01 mg/L in December and almost 65 times greater than December in May and June. This characteristic of TP in the reservoir should be fully considered in the process of reservoir management.

The effect of wind speed on DO

The variation of DO concentration is illustrated in Figure 8, suggesting that the DO concentration is highest in May, and lowest in December. It is consistent with the existing study that the potential for winter anoxia of ice-covered

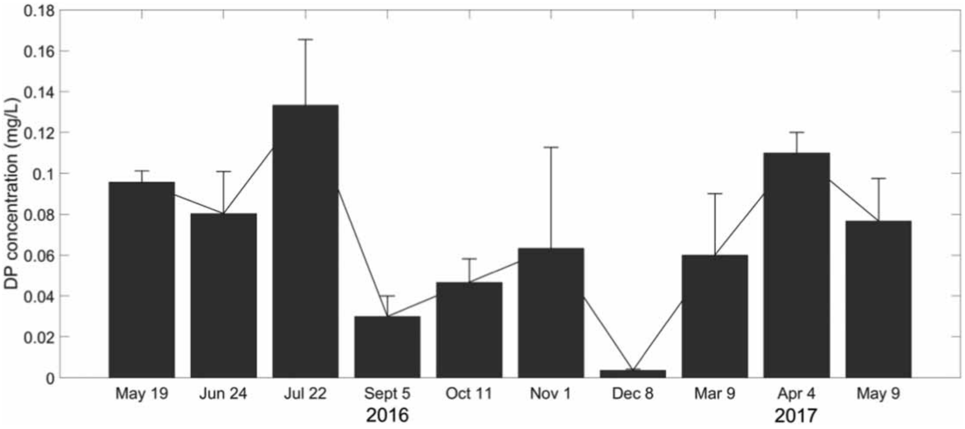

Figure 4 | The DP concentration in Yangshapao during the study.

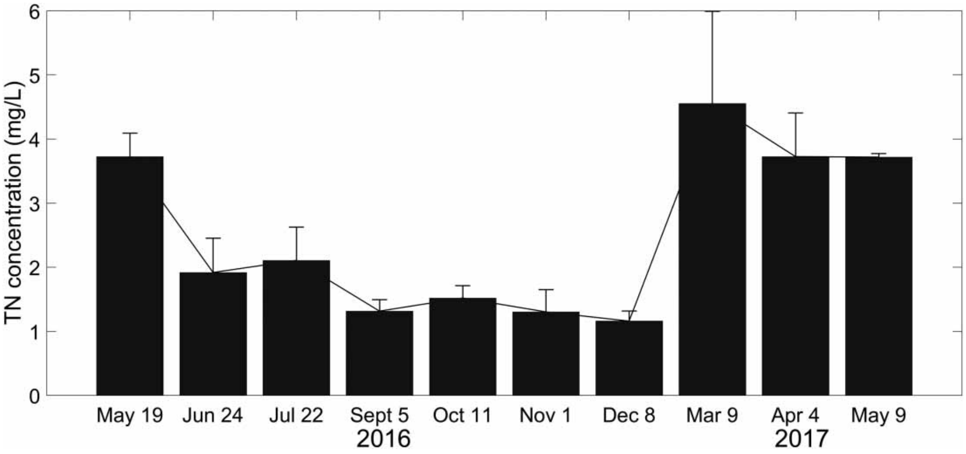

Figure 5 | The TN concentration in Yangshapao during the study.

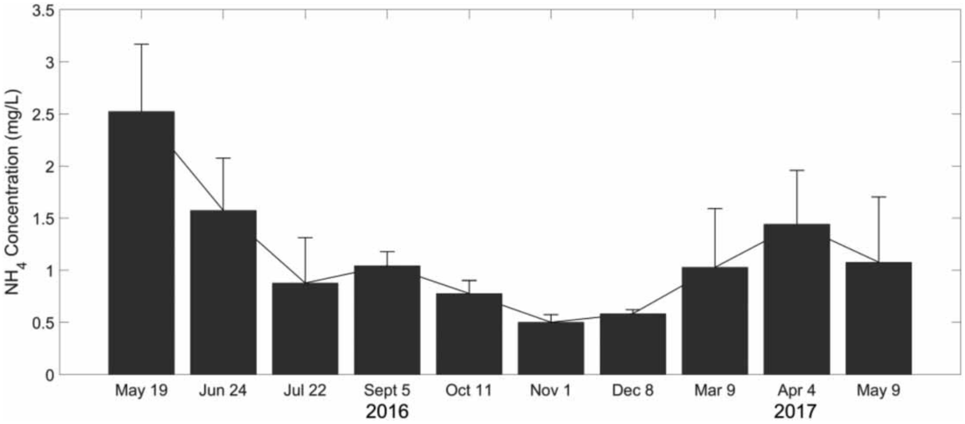

Figure 6 | The NH_4 concentration in Yangshapao during the study.

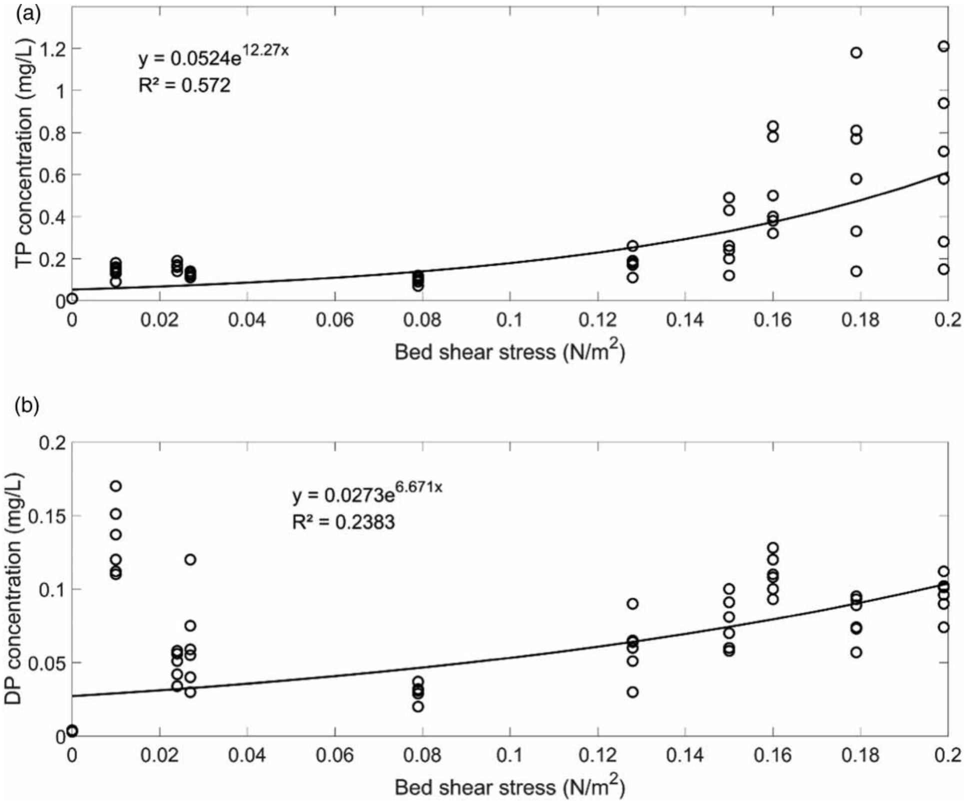

Figure 7 | (a) The relationship between TP and bed shear stress; (b) the relationship between DP and bed shear stress.

waterbodies is high in shallow lakes and reservoirs (Terry *et al.* 2017). On the one hand, DO concentration varies with seasonal temperature (Xu & Xu 2016). On the other hand, DO variation in shallow lakes will be relatively different from that in deep lakes to be impacted by the wind (Deng *et al.* 2018). Table 2 reveals that the DO is significantly associated with shear stress, probably because the wind will disturb the sediment, and the sediment oxygen will be released into the overlying water in shallow lakes and reservoirs (Chen *et al.* 2019). The rising DO concentration will

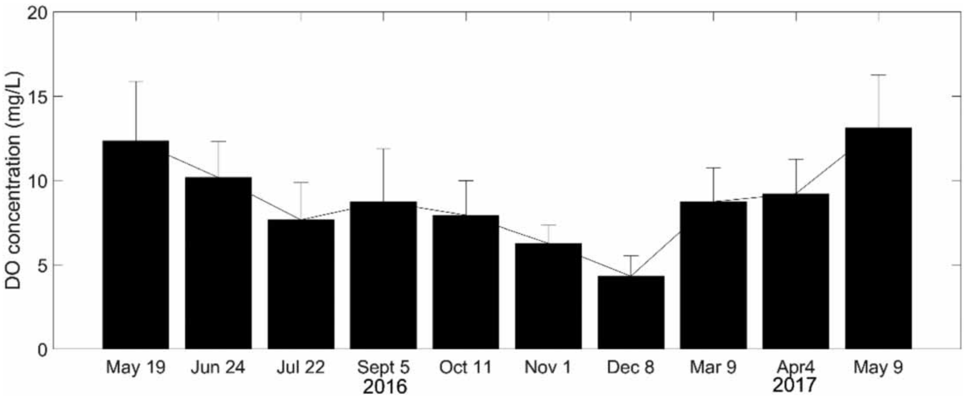

Figure 8 | The DO concentration in Yangshapao during the study.

facilitate phosphorus and nitrogen release into the water body (Müller *et al.* 2016). The data in this research also demonstrated that the DO is noticeably associated with TP, TN and NH_4 (Table 2).

As there are many factors (water depth, nutrients, water temperature, PH, DO, concentration gradient, redox potential, organisms) affecting phosphorus concentration in lakes and reservoirs, and there are interactions among various factors, if all the factors are taken into account then that will make the problem too complicated. This paper focuses on the impact of wind speed on nutrient release, while other factors are not fully considered. Those will be the focus in the next research work.

CONCLUSIONS

This research supplements the variation law of nutrients in high latitude shallow reservoirs under the action of wind disturbance. Based on the measured data for nutrients in Yangshapao Reservoir, and the wind speed being transformed into the shear stress to describe the disturbance effect of wind speed on sediment, the variation law of nutrients under wind disturbance in Yangshapao Reservoir was studied. The results show that wind-induced disturbances result in the resuspension of sediment, leading to significant increase in TP, NH_4 and TN in the overlying water, but small effects on DP. Bottom shear stress is also significantly correlated with DO concentration, while wind will up-regulate the DO concentration in the water body as well as promote nutrient release into the water body. The nutrient content in Yangshapao Reservoir varies significantly with seasons, and it will facilitate proliferation of possibly dangerous algae, especially for an ecosystem adopted as a drinking water supply during the windy period of the year. This characteristic of nutrients in the reservoir should be fully considered in the course of reservoir management.

REFERENCES

Bormans, M., Maršálek, B. & Jančula, D. 2016 Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: a review. *Aquatic Ecology* **50** (3), 407–422.

Chao, X., Jia, Y., Shields Jr., F. D., Wang, S. S. Y. & Cooper, C. M. 2008 Three-dimensional numerical modeling of cohesive sediment transport and wind wave impact in a shallow oxbow lake. *Advances in Water Resources* **31** (7), 1004–1014.

Chen, N., Wu, Y., Chen, Z. & Hong, H. 2015 Phosphorus export during storm events from a human perturbed watershed, southeast China: implications for coastal ecology. *Estuarine, Coastal and Shelf Science* **166**, 178–188.

Chen, L., D'Aoust, P. M., Rennie, C. D., Poulain, A., Pick, F., Wang, R. & Delatolla, R. 2019 Numerical investigation on the impact of wind-induced hydraulics on dissolved oxygen characteristics in a shallow stormwater pond. *Water Quality Research Journal* **54** (4), 309–325.

Cyr, H., McCabe, S. K. & Nürnberg, G. K. 2009 Phosphorus sorption experiments and the potential for internal phosphorus loading in littoral areas of a stratified lake. *Water Research* **43** (6), 1654–1666.

Deng, J., Paerl, H. W., Qin, B., Zhang, Y., Zhu, G., Jeppesen, E., Cai, Y. & Xu, H. 2018 Climatically-modulated decline in wind speed may strongly affect eutrophication in shallow lakes. *Science of The Total Environment* **645**, 1361–1370.

Dyer, K. R. 1986 *Coastal and Estuarine Sediment Dynamics*. John Wiley and Sons, Chichester, UK.

Hamilton, D. P. & Mitchell, S. F. 1996 An empirical model for sediment resuspension in shallow lakes. *Hydrobiologia* **317** (3), 209–220.

Havens, K. E., Jin, K. R., Iricanin, N. & James, R. T. 2007 Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. *Hydrobiologia* **581**, 25–42.

Hawley, N. & Lesht, B. M. 1992 Sediment resuspension in Lake St. Clair. *Limnology and Oceanography* **37** (8), 1720–1737.

Horppila, J. & Nurminen, L. 2005 Effects of different macrophyte growth forms on sediment and P resuspension in a shallow lake. *Hydrobiologia* **545** (1), 167–175.

Huang, J., Ge, X. & Wang, D. 2012 Distribution of heavy metals in the water column, suspended particulate matters and the sediment under hydrodynamic conditions using an annular flume. *Journal of Environmental Sciences* **24** (12), 2051–2059.

Huang, L., Fang, H., He, G., Jiang, H. & Wang, C. 2016 Effects of internal loading on phosphorus distribution in the Taihu Lake driven by wind waves and lake currents. *Environmental Pollution* **219**, 760–773.

Jin, K. R. & Ji, Z. G. 2004 Case study: modeling of sediment transport and wind-wave impact in Lake Okeechobee. *Journal of Hydraulic Engineering* **130** (11), 1055–1067.

Kang, L., He, Y., Dai, L., He, Q., Ai, H., Yang, G., Liu, M., Jiang, W. & Li, H. 2019 Interactions between suspended particulate matter and algal cells contributed to the reconstruction of phytoplankton communities in turbulent waters. *Water Research* **149**, 251–262.

Khare, Y., Naja, G. M., Stainback, G. A., Martinez, C. J., Paudel, R. & Van Lent, T. 2019 A phased assessment of restoration alternatives to achieve phosphorus water quality targets for Lake Okeechobee, Florida, USA. *Water* **11** (2), 327.

Marsden, M. W. 1989 Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release. *Freshwater Biology* **21** (2), 139–162.

Mei, C. C., Fan, S. J. & Jin, K. R. 1997 Resuspension and transport of fine sediments by waves. *Journal of Geophysical Research: Oceans* **102** (C7), 15807–15821.

Müller, S., Mitrovic, S. M. & Baldwin, D. S. 2016 Oxygen and dissolved organic carbon control release of N, P and Fe from the sediments of a shallow, polymictic lake. *Journal of Soils and Sediments* **16** (3), 1109–1120.

Nürnberg, G. K., Tarvainen, M., Ventelä, A. M. & Sarvala, J. 2012 Internal phosphorus load estimation during biomanipulation in a large polymictic and mesotrophic lake. *Inland Waters* **2** (3), 147–162.

Orihel, D. M., Baulch, H. M., Casson, N. J., North, R. L., Parsons, C. T., Seckar, D. C. M. & Venkiteswaran, J. J. 2017 Internal phosphorus loading in Canadian fresh waters: a critical review and data analysis. *Canadian Journal of Fisheries and Aquatic Sciences* **74** (12), 2005–2029.

Shen, J., Yuan, H., Liu, E., Wang, J. & Wang, Y. 2011 Spatial distribution and stratigraphic characteristics of surface sediments in Taihu Lake, China. *Chinese Science Bulletin* **56** (2), 179–187.

Teeter, A. M., Johnson, B. H., Berger, C., Stelling, G., Scheffner, N. W., Garcia, M. H. & Parchure, T. M. 2001 Hydrodynamic and sediment transport modeling with emphasis on shallow-water, vegetated areas (lakes, reservoirs, estuaries and lagoons). *Hydrobiologia* **444** (1–3), 1–23.

Terry, J. A., Sadeghian, A. & Lindenschmidt, K.-E. 2017 Modelling dissolved oxygen/sediment oxygen demand under ice in a shallow eutrophic prairie reservoir. *Water* **9** (2), 131.

Thomann, R. V. & Mueller, J. A. 1987 *Principles of Surface Water Quality Modeling and Control*. Harper & Row Publishers, New York, USA.

Withers, P. J. A. & Jarvie, H. P. 2008 Delivery and cycling of phosphorus in rivers: a review. *Science of The Total Environment* **400** (1–3), 379–395.

Xu, Z. & Xu, Y. J. 2016 A deterministic model for predicting hourly dissolved oxygen change: development and application to a shallow eutrophic lake. *Water* **8** (2), 41.

You, B. S., Zhong, J. C., Fan, C. X., Wang, T. C., Zhang, L. & Ding, S. M. 2007 Effects of hydrodynamics processes on phosphorus fluxes from sediment in large, shallow Taihu Lake. *Journal of Environmental Sciences* **19** (9), 1055–1060.

Zhou, Z., Huang, T., Li, Y., Ma, W., Zhou, S. & Long, S. 2017 Sediment pollution characteristics and *in situ* control in a deep drinking water reservoir. *Journal of Environmental Sciences* **52**, 223–231.

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