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RESEARCH ARTICLE

Wind-induced flow velocity effects on nutrient concentrations at Eastern Bay of Lake Taihu, China

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Abstract Shallow lakes are highly sensitive to respond internal nutrient loading due to wind-induced flow velocity effects. Wind-induced flow velocity effects on nutrient suspension were investigated at a long narrow bay of large shallow Lake Taihu, the third largest freshwater lake in China. Wind-induced reverse/compensation flow and consistent flow field probabilities at vertical column of the water were measured. The probabilities between the wind field and the flow velocities provided a strong correlation at the surface (80.6%) and the bottom (65.1%) layers of water profile. Vertical flow velocity profile analysis provided the evidence of delay response time to wind field at the bottom layer of lake water. Strong wind field generated by the west (W) and west-north-west (WNW) winds produced displaced water movements in opposite directions to the prevailing flow field. An exponential correlation was observed between the current velocities of the surface and the bottom layers while considering wind speed as a control factor. A linear model was developed to correlate the wind field-induced flow velocity impacts on nutrient concentration at the surface and bottom layers. Results showed that dominant wind directions (ENE, E, and ESE) had a maximum nutrient resuspension contribution (nutrient resuspension potential) of 34.7 and 43.6% at the surface and the bottom profile layers, respectively. Total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) average concentrations were 6.38, 1.5, and 0.03 mg/L during our field experiment at Eastern Bay of Lake Taihu. Overall, wind-induced low-to-moderate hydrodynamic disturbances contributed more in nutrient resuspension at Eastern Bay of Lake Taihu. The present study can be used to understand the linkage between wind-induced flow velocities and nutrient concentrations for shallow lakes (with uniform morphology and deep margins) water quality management and to develop further models.

Introduction

Shallow lakes with uniform morphological and topographic characteristics are found with most successfully opposing the reduced nutrient loads as compared to relatively deeper ones (Nixdorf and Deneke 1997). Frequent wind-induced disturbances to sediment resuspension dominantly affect the sediment-water interface much higher than other factors. Internal wave and current energy help in the mixing of nutrient-rich bottom water. The currents rhythmically flow back and forth in opposing directions and are the major source of water movements of the lake in an otherwise stratified shallow lake. Many investigations on flow structure due to wind disturbances have been done (Longo et al. 2012) which shows that there can be large- to small-scale disturbance in flow structure due to the wind (Han et al. 2008). Wind speed also plays an important role in defining flow velocity below a critical value (Koçyigit and Falconer 2004, Chao et al. 2008).

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Wind-induced waves and currents have major impact on the vertical and horizontal distribution of heat, dissolved substances, and nutrient. This significantly alters the distribution and productivity of phytoplankton and fishes (Wu 1975, Kleeberg and Kozerski 1997, Wetzel 2001). Along with external sources, sediments are the major source of nutrient releasing into water bodies (Søndergaard et al. 2003, Fisher et al. 2005, Ahlgren et al. 2011, Christian 2011). The hydrodynamic intensity that leads to sediment suspension is highly dependent on the wind in shallow lakes (Maxam and Webber 2010) and in shallow estuaries (Llebot et al. 2014). The effects of strong wind-induced flow velocities on sediment suspension and nutrient release in shallow lakes have been well documented (Luettich et al. 1990, Bengtsson and Hellström 1992, Arfi et al. 1993, Qin et al. 2000, Zhu et al. 2005, Wang et al. 2015). Previous experiments have shown that the release rates of nutrient vary from place to place, depending on sediment properties and wind intensity (Zhu et al. 2011). Under dynamic (disturbed) conditions, wind-induced sediment suspension in the water column is the cause of nutrient release (in both dissolved and particulate state) at Lake Taihu (Qin et al. 2006).

Wind-induced flow velocity estimations and vertical profile distribution studies have been conducted by many researchers (Yong and Peimin 1996, Gong et al. 2005, Wang and Yu 2007, Han et al. 2008, Chen et al. 2012), but effects of wind-induced entire flow field [flow directions (consistency and reversal) comparison with wind directions] velocities on nutrient concentrations have not been considered up to now. Along with current speed, the current direction also plays an important role for suspension of nutrient in large shallow lakes. Similarly, reverse current directions are also important which have been observed in a previous study at Meiliang bay of Lake Taihu (Zheng et al. 2015). Therefore, it is important to consider wind-induced flow velocity effects on nutrient concentrations. A linear correlation between flow field and nutrient concentrations can be developed by using probability statistics of the wind-induced flow field. For this purpose, we used in situ field observations and measured the wind and flow along with nutrient concentrations at that time for developing real-world relationship between wind-induced flow velocities and nutrient concentrations. On the basis of literature study, we raised some research questions: (1) What is the percent contribution of wind field impacts on the vertical profile of flow velocities in the shallow lake with uniform morphology and deep margins? (2) What is the relationship between the surface and bottom flow velocities under the influence of wind speed? (3) What is the flow response time of the bottom to wind force at a relatively stratified profile in an elongated bay of a shallow lake? (4) And lastly, on the basis of estimated percent contribution of wind field on the vertical profile, what is the correlation between wind-induced flow velocities and nutrient concentrations at the surface and bottom profile of the lake?

On the basis of the abovementioned research questions, our objectives of the present study were to (1) evaluate wind field impacts on the water flow field in a long narrow highly wind exposed bay of a large shallow lake, (2) develop the vertical profile to evaluate wind-induced flow field impacts on the vertical profile of lake water and estimation of bottom response time, (3) obtain the probability estimation of percent contribution of wind-induced flow field effects on internal nutrient suspension, and (4) develop a linear correlation between wind-induced flow velocity (reverse flow and flow consistencies) and internal nutrient suspension. The present study will contribute to the development of new knowledge in the field of shallow lakes hydrodynamics by considering the reverse and consistent flow field relationship with wind field at vertical and horizontal profiles of lake water, which is the newly adopted mode of study.

Methodology

Study site

Lake Taihu is located in the Yangtze river delta and contains 2338 km^2 of water surface area, with an average depth of 1.9 m. Annual lake water temperature ranges between 4.8 and 29.2 °C with an average estimation of 17.3 °C (Zhao et al. 2011). Average wind speed is 4.3 m/s in summer and 0.9 m/s in winter with an annual variation of 0 to 10 m/s (Qian 2012).

Current water quality deterioration problem at Lake Taihu is due to external and internal nutrient release in lake water, and it is increasing since the last three decades (Paerl et al. 2011). Lake Taihu has been facing algal bloom since 1960 (at the Wuli bay) (Chen et al. 2003), but now it has been extended to all parts of the lake (Qin et al. 2004). Strong wind events in April and October can cause the formation and extension of algal bloom in Lake Taihu (Wu et al. 2013). Lake Taihu has an uneven spatial distribution of total phosphorus (TP) and total nitrogen (TN) (Deng et al. 2008). Eastern Lake Taihu has floating macrophytes, and it is considered as the clearest part of Lake Taihu (Zhu et al. 2013). Eastern Lake Taihu has lower concentrations of TP and TN as compared to all other parts (Wang et al. 2015). Around 0.03 mg/L of TP was observed in spring and summer of 2005 at the Eastern Bay of Lake Taihu, and TN concentrations were around 1 mg/L (Li et al. 2011).

Eastern Bay of Lake Taihu was selected for the present study, and most precise in situ field observations were conducted by using Handheld weather station PH-II (XPH Company, China) and PHWD wind transducer sensor (XPH Company, China) for wind field, Acoustic Doppler Velocimeter (HorizonADV SonTek Company, USA), Acoustic Doppler Current Profiler (ADCP Argonaut-XR, SonTek Company, USA) for flow field and hydrodynamics,

and manual methods of water sampling and analyses were used for total suspended solids (TSS), TN, and TP. Sampling location was approximately 3 km below the outflow of Taipu river and approximately 13 km upstream of Guajingkou river (a small and controlled outflow tributary of Eastern Lake Taihu. Eastern Lake Taihu is morphologically uniform with deep margins towards the north to northeastern sides of the bay, as shown in Fig. 1.

Field observations

Field investigations were conducted to study the vertical distribution of certain water quality parameters under the influence of the wind-induced flow velocities. The wind field (wind speed and direction) and flow field (vertical profile three-dimensional flow velocities) were monitored continuously from 5th June 2015 to 11th June 2015. Daily four water samples from the surface and bottom layers with 3 h sampling frequency (from 5 a.m. to 6 p.m.) were collected to examine TSS, TN, and TP concentrations.

In laboratory analyses, TSS concentrations were measured by using the membrane filtration method (Wang et al. 2015) while TN and TP concentrations were measured by using an automatic water quality analyzer (AA3, SEAL Company, Germany). Before the measurement of TN and TP concentrations, water samples were filtered by using a water circulation multifunction vacuum pump (SHP-III, SHIDING Company, China).

Three-dimensional flow velocity measurements were conducted by using Acoustic Doppler current profiler (ADCP) with operating frequency of 1500 kHz which was placed upward at the bottom of the lake inside water. The length of ADCP is 30 cm, and its blind zone/fade zone is 50 cm; therefore, it measured the three-dimensional flow velocities, 80 cm above the bottom and measured three-dimensional flow velocities of three layers named surface (0–40 cm), upper middle (40–80 cm), and lower middle (80−120 cm). ADV Ocean (operating frequency of 5 MHz) was used to measure the three-dimensional velocity of the bottom zone (195–200 cm) and was placed downward 5 cm above the bottom of lake water.

Therefore, there were four profile layers including surface (0–40 cm), upper middle (40–80 cm), lower middle (80–120 cm), and bottom layer (195–200 cm) used in the present study.

Flow directions were divided into 16 zones of north (N), north-north-east (NNE), north-east (NE), east-north-east (ENE), east (E), east-south-east (ESE), south-east (SE), south-south-east (SSE), south (S), south-south-west (SSW), south-west (SW), west-south-west (WSW), west (W), west-north-west (WNW), north-west (NW), and north-north-west (NNW). After conversion, flow directions were compared with wind directions to estimate the wind and flow consistencies and reversal for wind-induced flow velocities impact assessment. These wind and flow directions were compared and considered reverse flow if the difference between the wind
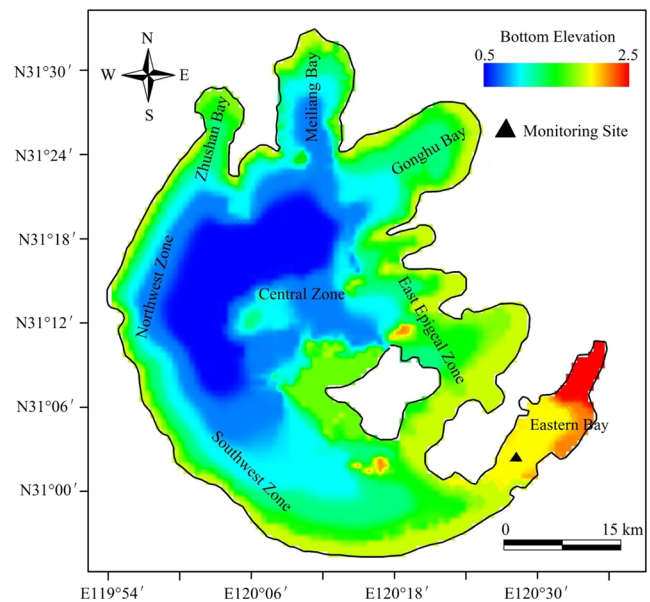

Fig. 1 Location of the study area with experimental site location at the Eastern Bay (DongTaihu) of Taihu Lake

and flow direction at a specific time was equal to or greater than 90° (Fig. 2a).

Wind field date measurements and analysis procedures

Wind speed and directions data from 5th June 2015 8:20 to 11th June 2015, 18:20 with 10 min frequency of each water sampling hour was used in the present study. After the visual analysis of wind speed data, wind speeds were divided into six intervals of 0.1–1.0, 1.1–2.0, 2.1–3.0, 3.1–4.0, 4.1–5.0, and 5.1–8.0 m/s because wind speed was found within the range of 0.1–8.0 m/s during our field observations. Wind direction data was processed and was added 180° to meet the correct estimation process because wind direction shows the direction of the wind which was "coming from" a specific direction. However, flow velocity shows that the flow was "going towards" a specific direction. Therefore, in this study, we considered the eastern wind direction which is blowing towards the east.

Wind directions were also converted into the same 16 intervals and compared with the flow directions to measure the flow consistency and reversal. Wind and flow consistencies were estimated by measuring the consistency between wind and flow direction angles; flow direction was considered consistent when the flow direction angle was within 45° left or right to the particular wind direction (see Fig. 2b). The reverse flow was considered if the difference of angle between the wind direction and flow direction at that time was equal to or greater than 90°. The schematic diagram is shown in Fig. 2 which describes the measurement procedures of reversal and consistency between the wind and flow directions.

Nutrient concentrations of the surface and bottom layers were collected from field platform and were examined at
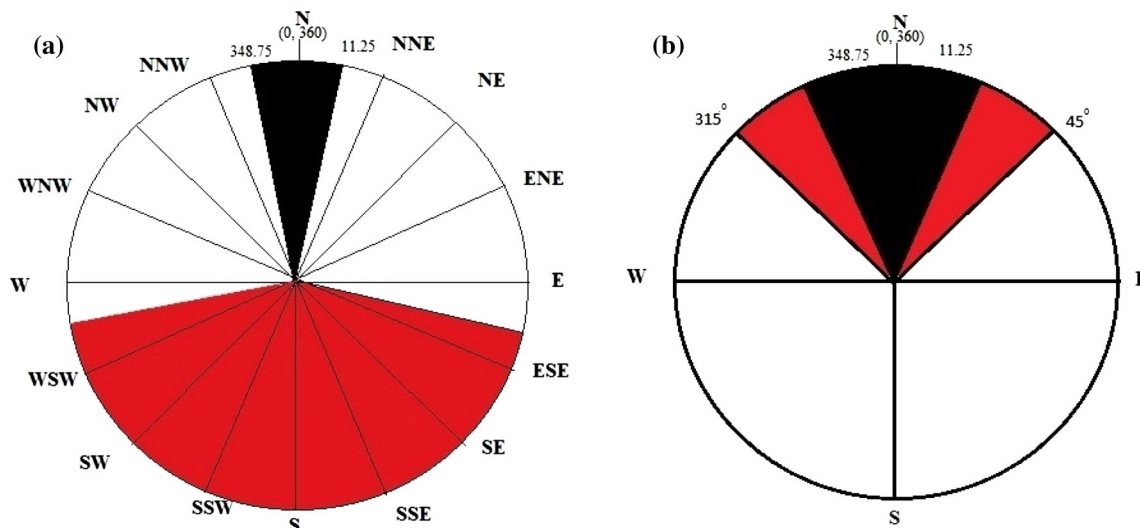
Fig. 2 Schematic diagrams explaining the research methodology to measure **a** the reverse flow calculations during North wind direction *red color* indicating the considered reverse flow directions during north wind

direction and **b** the flow consistency during North wind direction, while considering 16 major wind directions into account

Lake Taihu Laboratory (TLLER). TSS, TN, and TP were considered in the present study to evaluate the correlation between wind-induced flow velocity probabilities and nutrient concentrations.

Participation of flow field in nutrient concentrations was estimated by comparing the contribution rates of wind field-induced flow field (consistency and reversal) with the nutrient concentration. In this regard, the percent contribution of reverse probabilities of the wind field and percent contribution of consistencies of wind field at the surface and bottom layers were compared with experimental results of discussed nutrient concentrations.

A general linear fitting correlation between the nutrient concentrations and windinduced flow velocity impacts was developed in the form of an equation.

Results

Assessment of wind field impacts on flow velocities

Wind field plays an important role in hydrodynamics of shallow lakes, and hence, it has a definite impact on nutrient release. Eastern Bay of Lake Taihu has gentle wind and flow velocities as compared to other parts of the lake. Therefore, it provides the ideal conditions for studying the impacts of wind field on the flow field and hence on water quality of the lake.

Influence of wind direction on flow field

Frequency analysis of wind directions showed that East to the South was the major interval making 58.9% (ENE to S) of the total wind directions data (Fig. 3). ENE and E were found with the highest frequency of 13.1% followed by ESE (11.9%), S (9.5%), SSE (8.3%), SSW (7.1%), NNW (5.9%), and WSW (5.4%) which were major wind directions, as shown in Fig. 3 and Table 1.

On the basis of frequency analysis, the wind and flow direction consistencies were also estimated at all profile layers (e.g., if the wind direction was towards E, then flow was considered consistent when it was within 45° to 135°) (Fig. 2b).

Results showed a complex system of flows with consistencies of 40.5% (surface), 49.4% (upper middle), 41.1% (lower middle), and 23.8% (bottom layer). We found major flow consistency towards N to E quadrant (66. 7% of bottom flow and 56.5% surface flow was within 0 to 90°) and 34% frequency of wind direction was towards N to E quadrant.

Similarly, while comparing wind directions with bottom flow direction, ENE to S was major wind directions contributing 58.9% (as discussed above) with 16.7% of bottom flow consistency with those wind directions. ENE, E, and ESE make 38.1% of total wind field data, and the bottom flow consistency with these three directions was 11.9% from total flow field percentages.

Reverse flow due to major wind directions was estimated by comparing wind directions with flow directions as discussed earlier. The results indicated that reverse flow at the surface layer was found maximum towards S (75%), SSE (71%), and SSW (66.7%) wind directions. Maximum reverse flow at upper and lower middle layers was found at SSE (79%, 50%), S (81%, 56%), and SSW (66.7%, 66.7%) wind directions respectively. The bottom layer was found with maximum reverse flows as compared to other profile layers which consist of WSW (100%), SSW (91.7%), NNW (70%), S (69%), and ESE (45%) wind directions, as shown in Fig. 4.
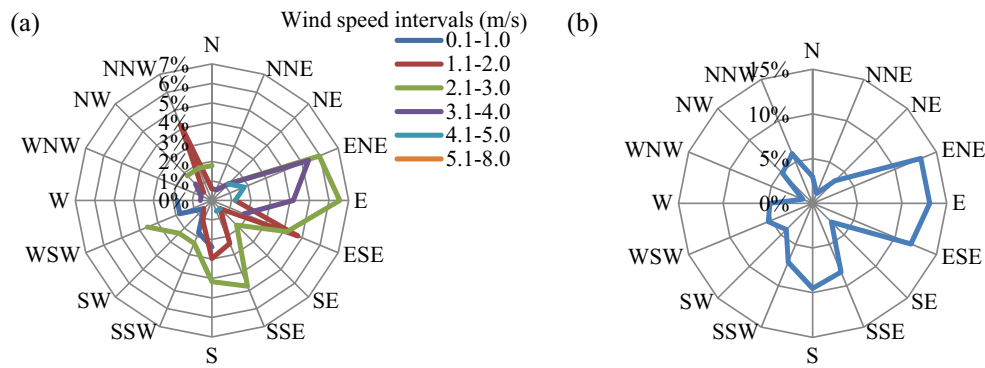
Fig. 3 Wind statistics from in situ observation with **a** histogram of wind speeds from 0.1 to 8 (m/s) showing the frequency distribution of major wind speeds during certain wind directions (with dominant wind speeds of ENE, E, and SSE) and **b** histogram of wind directions frequency distributions which is showing ESE, E, and ESE as major prevailing wind direction

Influence of wind speeds on the flow field

Reverse flow field impacts due to wind speed were estimated by comparing the results of reverse/compensation flow probability statistics of wind direction with the weighted average of wind speed intervals. The results of the analysis show that reverse flow field probabilities are directly proportional to the frequency of wind speed data, as shown in Fig. 5. Hence, wind speed interval of 2.1–3.0 m/s showed highest reverse flow field probabilities following with 1.1–2.0 and 3.1–4.0 m/s.

Surface and upper middle layers of vertical flow profile indicated high reverse flows following with bottom and lower middle layers in the wind speed interval of 2.1–3.0 m/s. Similarly, the surface, upper middle, and lower middle layers have shown high reverse flow field probabilities in 1.1–2.0 m/s wind speed interval. Upper and lower middle profiles have shown reverse flow field probabilities at the wind speed interval of 3.1–4.0 m/s.
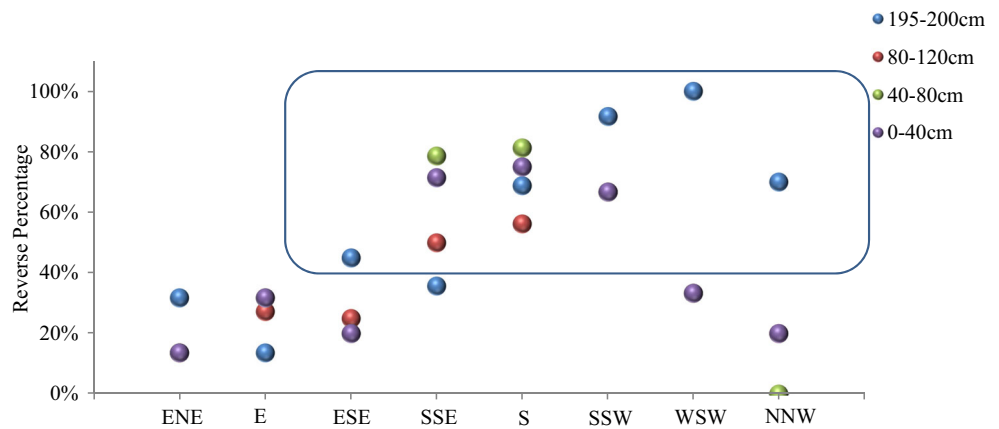
Results of reverse flow field probabilities due to different wind speed intervals have shown that the reverse flow field probabilities at lower middle layer were high due to major wind speeds following with the surface and upper middle layers. Dominant reverse flow field impacts at bottom layer were found within the wind speed interval of 2.1–3.0 m/s.

Table 1 Cumulative frequency distribution of wind speed (m/s) and wind direction with the detailed percent contributions of wind speed intervals versus wind directions to determine the major wind speed intervals and dominant wind directions at Eastern Bay of Lake Taihu

Wind direction	Wind speed (m/s)						
	0.1–1.0	1.1–2.0	2.1–3.0	3.1–4.0	4.1–5.0	5.1–8.0	Total
N	0.60	0.60	1.79				2.98
NNE	0.60			0.60			1.19
NE			1.19	1.19	1.19		3.57
ENE			5.95	5.36	1.79		13.1
E		1.19	6.55	4.17	1.19		13.1
ESE	0.60	4.76	4.17	1.79		0.60	11.9
SE		0.60	1.79		0.60		2.98
SSE		2.38	4.76	0.60	0.60		8.33
S	2.38	2.98	4.17				9.52
SSW	1.79	1.19	2.38	1.79			7.14
SW	0.60	0.60	2.38		0.60		4.17
WSW	1.79		3.57				5.36
W	1.79	2.38		0.60			4.76
WNW				0.60	0.60		1.19
NW	1.19	0.60	1.79	1.19			4.76
NNW		4.17	1.79				5.95
Total	11.31	21.43	42.26	17.86	6.55	0.60	100

All given values are percentages

Contribution rate of wind field on reverse flow field

Results of the present study provided a strong correlation between wind field and reverse flow field, and its impacts can be estimated in terms of reverse flow field probabilities. Results indicated that main wind directions and dominant wind speeds played an important role in reverse flow field generation.

Comparison between the surface and bottom flow directions showed 34.5% of the flow consistency with each other. Furthermore, reverse flow can also be related to the water level fluctuations due to windward flows and towards outflows. On the basis of hydrodynamic results, it was observed that wind-induced reverse flow field impact played a dominant role in the suspension of nutrient at Eastern Bay of Lake Taihu. Experimental results of flow and wind field showed reverse flow contribution of 40.1 and 41.3% at the surface and the bottom profile layers. Similarly, flow consistency contributed 40.5 and 23.8% at the surface and bottom profile layers, respectively. Therefore, the cumulative effects of wind force at the surface and the bottom of lake flow velocity were found to be 80.6 and 65.1%, respectively (Fig. 6).

Vertical and horizontal velocity profile distribution

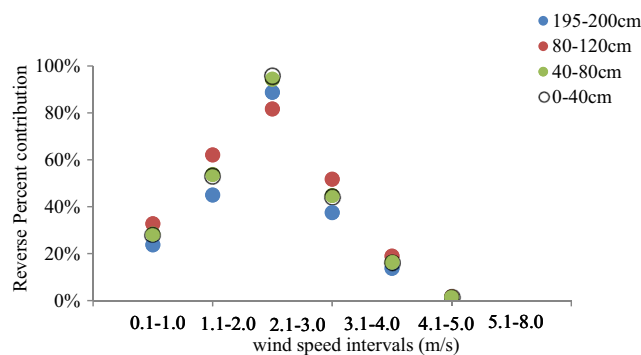A general comparison of vertical flow velocities with wind speed has been drawn to estimate the behavior and response of flow field to wind field, as shown in Fig. 7. The response of vertical and horizontal velocities profile of a surface, upper middle, and lower middle layers to wind field was good as compared to bottom profile velocities which have shown the delay response to wind field in general.

The wind and flow field consistencies and reverse flow field analysis provided a strong base in understanding hydrodynamic conditions of the study area. Wind and flow consistency analysis showed the strong relationship between wind and flow directions. Field location was approximately 3 km below the outflow of Taipu river where flow was towards the dominant directions of N to NE (Guajingkou river lying between N to E quadrant) possibly due to the morphology of the study area. Therefore, the effect of gravitational flow towards Guajingkou river and towards deep margins in the study area and the wind along with other forces (like Coriolis force) played a major role in the generation of reverse flows. Strong winds were observed two times during field experiment which caused the change in entire flow directions opposite to normal flows (time interval from 180 to 230 and 455 to 459 in Fig. 7). Firstly, on 6th June 12:03 p.m., the wind started to blow at the speed of 4.2 m/s (wind direction was NNE) and reached 6.2 m/s with a sudden change towards W to WNW direction within 30 min (Fig. 7b). This sudden wind rose towards the opposite direction with strong wind speed caused a sudden change in the entire flow field with very low frictional
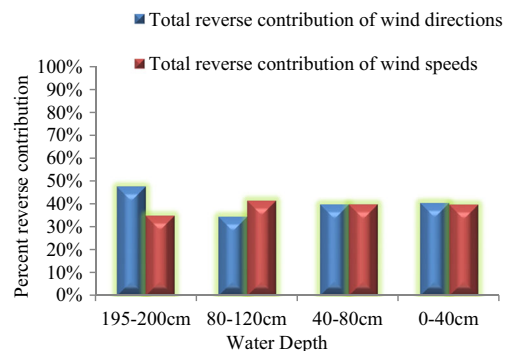

Fig. 5 Reverse flow field probabilities due to major wind speed intervals of four depth profiles at the Eastern Bay of Lake Taihu

Fig. 6 Comparison between wind speed and wind direction induced total reverse flow velocities contribution rate at four depth profile layers of the experimental site

Fig. 7 Wind induced vertical
flow profile diagram of the
surface, upper middle, lower
middle, and bottom by using in
situ field observations (10 min
interval)
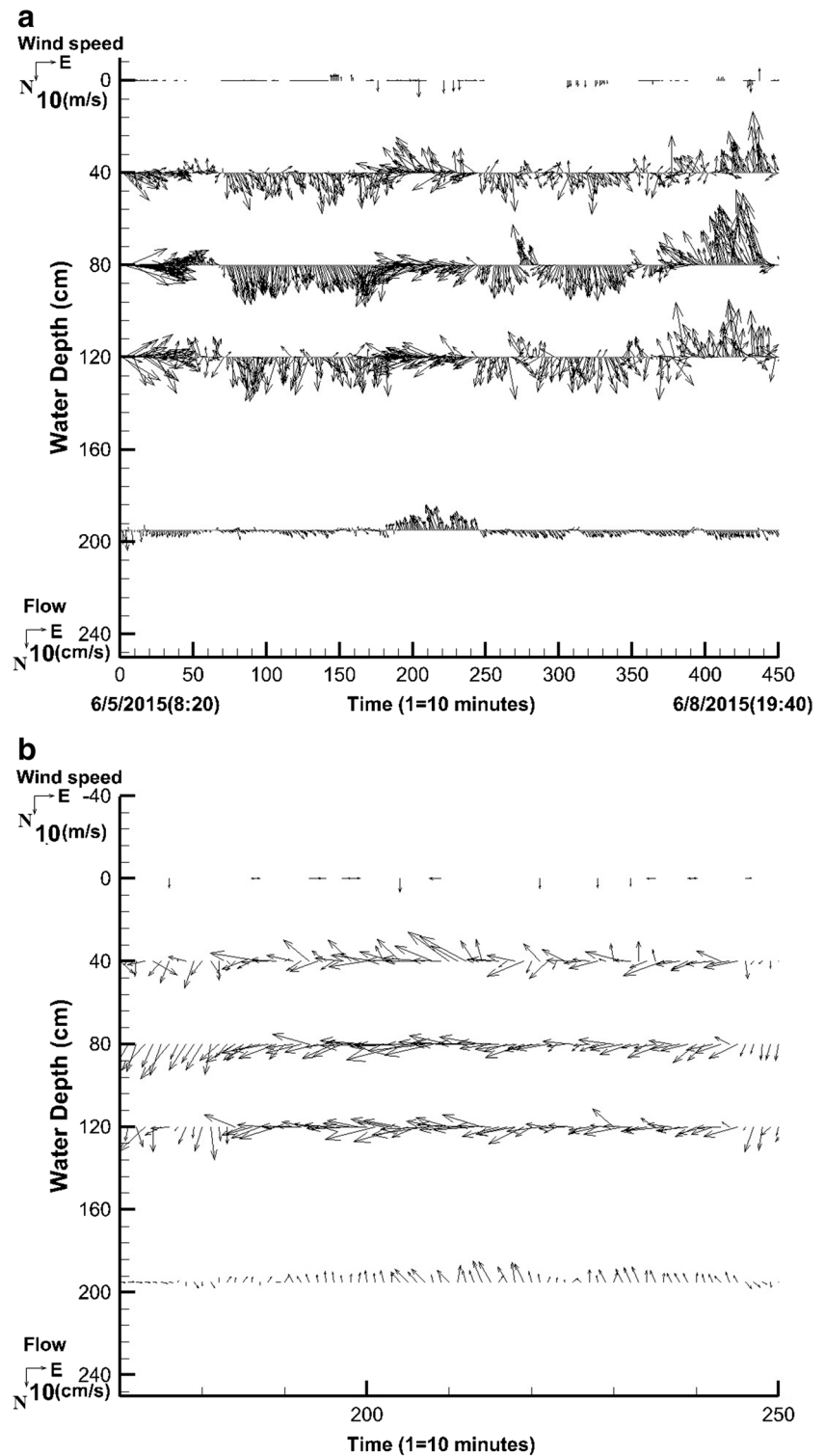
response/delay time (usual response against wind field). Secondly, similar effects were observed on 8th June 2015 when wind speed started to increase from 3.1 m/s at 13:30 and reached to 7.8 m/s at 13:50 and then decreased gradually to normal wind speed 3.3 m/s at 14:45. It started from ESE and changed towards W and WNW in that period of time. During this period, bottom flow was also found towards S to W directions but with comparatively late response/high delay time known as frictional response time. Kämpf (2015) identified the Leeward flow effects causing a surface pressure field which is leading towards the slope against wind direction in a shallow coastal homogeneous water body.
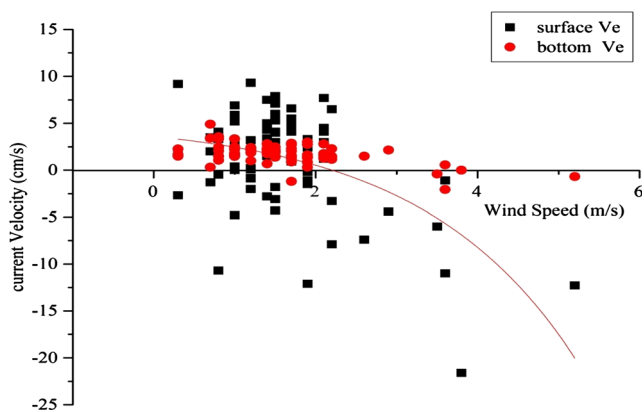
Fig. 8 Fitting correlation between eastern wind speed and current velocities at surface and bottom flow profile layers

Fig. 9 Wind field-induced TSS concentrations and contribution rates of reverse and consistent flow velocities at surface and bottom water profile layers

It was observed from the results that wind speed greater than 3 m/s affected the entire flow field. Wang et al. (2015) showed similar results (3–8 m/s) by using field and experimental data of wind speed on Lake Taihu. Reverse flow results showed the maximum reversal of flow in the entire flow field when the wind speed was within 2.0–3.0 m/s. Usually, the wind speed was low (0.1–3.0) during entire field observation which makes 75% of our total field observation data.

A linear fitting correlation was developed between the surface and bottom current velocities (Ve) with wind speed (Eastern) and found an exponential correlation, as shown in Fig. 8. The exponential correlation model statistics are as following:

$$y = y^{\circ} + A^{*}\exp\left(R^{\circ *}x\right) \tag{1}$$

Such that $y^{\circ} = 5.25 \pm 0.069$, $A = -1.65 \pm 0.04$, $R^{\circ} = 0.52 \pm 0.004$,

$Reduced$ chi$-$sqr $= 0.2085$, $R^2-(COD) = 0.99498$,

and Adj.$R^2 = 0.099497$

Wind-induced flow velocity and nutrient resuspension

Wind field impacts on flow velocity are documented at Lake Taihu (Qin et al. 2006) and other shallow lakes in the world (Chao et al. 2008, Han et al. 2008, Longo et al. 2012). Similarly, wind-induced flow velocity impacts on sediment and nutrient suspension have also been well documented at Lake Taihu (Qin et al. 2000, Zhu et al. 2005, Qin et al. 2006, Wang et al. 2015) and on other shallow lakes and estuaries of the world (Luettich et al. 1990, Bengtsson and Hellström 1992, Arfi et al. 1993, Maxam and Webber 2010, Llebot et al. 2014). The probability estimations of the present study between wind field and flow velocities showed a strong correlation at the surface (80.6%) and bottom (65.1%) profile layers of the water column. By using
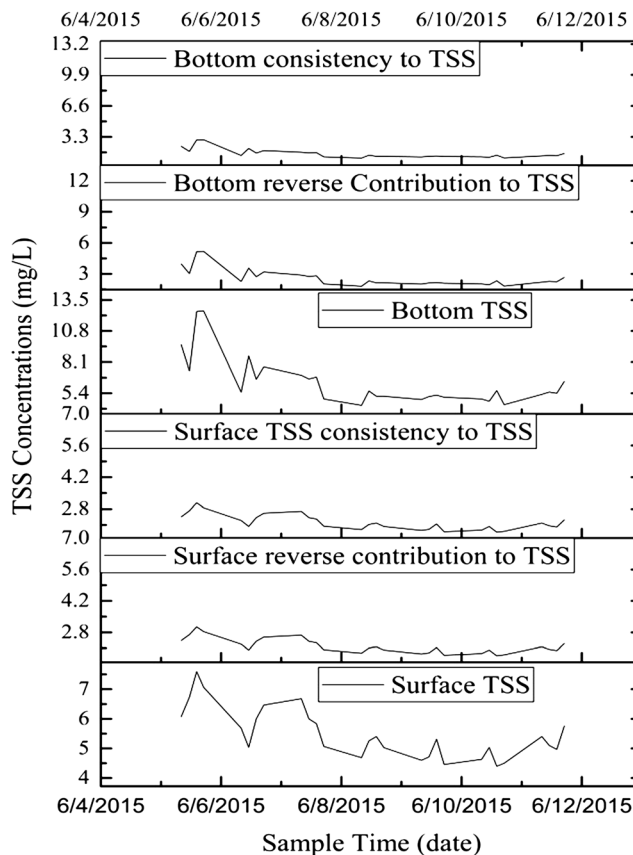
the current probabilities, a linear correlation between wind induced flow velocity and nutrient concentrations was developed.

Surface water TSS concentrations were found between 4.4 and 7.6 mg/L with an average concentration of 5.48 mg/L during field observations. Similarly, the bottom TSS concentrations were found between 4.34 and 12.55 mg/L with an average of 6.38 mg/L. Wind field-induced flow velocity effects on TSS suspensions at the surface and the bottom of the lake have been drawn in Fig. 9.

Therefore, the linear correlation between TSS and wind field induced flow impacts at the surface and the bottom of the lake by using Eq. (1) can be written as:

$$Surface \quad f(x,y) = 0.2267^{*}x + 2.246^{*}y + 4.713exp-08 \tag{2}$$

And

$$Bottom \quad f(x,y) = 1.938^{*}x + 0.8372^{*}y + 4.166exp-09 \tag{3}$$

Such that $x =$ wind field induced reverse flow velocities.

$y =$ wind field and flow field consistency, and $f(x,y) =$ total suspended solids measured concentration.

Similarly, the linear correlation of fitting between TN and TP was developed and results can be seen in Table 2.

Table 2 Linear correlation functions of TSS, TN, and TP between wind field and flow velocities showing relationship in the form of a linear equation $f(x,y) = a^*x + b^*y + c$ in which x = wind field induced reverse/compensation flow velocities, y = wind field induced flow field consistency, and $f(x,y)$ = total measured concentration

	Surface			Bottom		
	TSS	TN	TP	TSS	TN	TP
Coefficients (with 95% confidence bounds):						
A	0.2267	1.725	1.697	1.938	0.65	1.78
B	2.246	0.7614	0.7886	0.8372	3.072	1.107
C	4.713e-08	-1.87e-08	-1.882e-09	4.166e-09	−9.976e-09	2.286e-09
Goodness of fit						
SSE	2.22E-15	4.12E-16	7.17E-18	4.75E-16	1.15E-16	2.97E-17
R-square	1	1	1	1	1	1
Adjusted R-square	1	1	1	1	1	1
RMSE	9.43E-09	4.06E-09	5.36E-10	4.36E-09	2.14E-09	1.09E-09

It can be observed from the measured data that the concentration of TSS was higher at the bottom as compared to the surface TSS concentrations. 5th June 2015 was found with the highest concentrations of TSS at both profile layers. Wind speed was light to moderate (0.5 to 4.3 m/s), and wind direction was between E and ESE on 5th June 2015. TSS concentrations were 5 to 8 mg/L at the surface with a slight variation during the observation period. In contrast to surface TSS concentrations, the bottom layer was found with high variability of TSS concentrations (5 to 12.4 mg/L). Reverse flow field induced concentrations of TSS due to wind speed and direction were found between 1.5 and 2.7 mg/L at the surface and between 1.9 and 5.9 mg/L at the bottom layer of lake water. Therefore, the release rate of TSS was found with an average amount of 6.38 g/m^3 during field observations.

Nitrogen availability controls the zooplankton grazing in shallow lakes and phytoplankton populations in the deeper ones (max depth > 3 m) (Moss et al. 1997).

Average, maximum, and minimum concentrations of TN were found (1.587 and 1.5963 mg/L), (2.31 and 1.005 mg/L), and (0.982 and 1.256 mg/L) at the surface and bottom profile layers of lake water, respectively. These concentrations were found higher than the monitored 1 mg/L values in 2005 by Li et al. (2011). Therefore, the average concentration of TN increased about 0.5 mg/L in last 10 years (2005 to 2015) at the Eastern Bay of Lake Taihu. Results of measured data have shown that TN concentrations were slightly lower at surface profile layer (1.5–2.3 mg/L) as compared to the bottom layer (1.26–2.1 mg/L) of the Eastern Bay of Lake Taihu (Fig. 10a). The surface layer was found with highest concentrations on 5th June 2015, but the bottom layer TN concentrations were highest on 9th June 2015. It shows the highest discrepancy of data in terms of TN concentration at the surface and the bottom layers of Lake Taihu. Reverse flow velocity participation to TN resuspension induced by wind field (wind speed and direction) at the surface and bottom layers was between 0.4 and 0.9 mg/L, as shown in Fig. 10a.

Phosphorus is the main factor controlling phytoplankton growth in the lakes (e.g., (Golterman 1984). After reducing external nutrient loads, shallow lakes are more resistant to recovery than deeper ones (Sas 1989, Jeppesen et al. 1991, Phillips et al. 1994). The reason behind the resistance to change is mainly due to internal P release (Marsden 1989, Lijklema 1994). Phosphorus release rate from sediment is highly dependent on factors like redox reactions, adsorption/desorption, mineral phase solubility, abd mineralization of organic matter (Boström et al. 1988, Marsden 1989).

In the present study, TP concentrations were found slightly higher at the surface as compared to the bottom profile layer, as shown in Fig. 10b. Highest concentrations of TP were found due to moderate wind intensity on 9th June 2015 at both profile layers of water column (0.0445 mg/L at the surface and 0.038 mg/L at the bottom). The overall concentrations were very low at the bottom layer, except on 9th June 2015 when its value was 0.04 mg/L. Similar results of wind-induced flow velocity effects on phosphorus were obtained in an experimental study by You et al. (2007) in which maximum P suspension from sediment-water interface was the result of moderate wind-induced flow velocities instead of low and strong wind intensities. Surface layer TP concentrations were normal throughout the experiment time (0.024–0.044 mg/L). Average TP concentrations were found the same as the monitoring results of 0.03 mg/L in 2005 (Li et al. 2011). Reverse flow field participations due to wind speed and direction were between 0.005 and 0.038 mg/L, as shown in Fig. 10b.

Discussions

Reverse flow probability statistics shows that ESE, SE, SSE, S, SSW, SW, and WSW were the major wind directions found with maximum reverse flows. S and SSW wind directions were found with the maximum reverse flow at all profile layers. Dominant wind directions of SSE, S, and SSW were the key
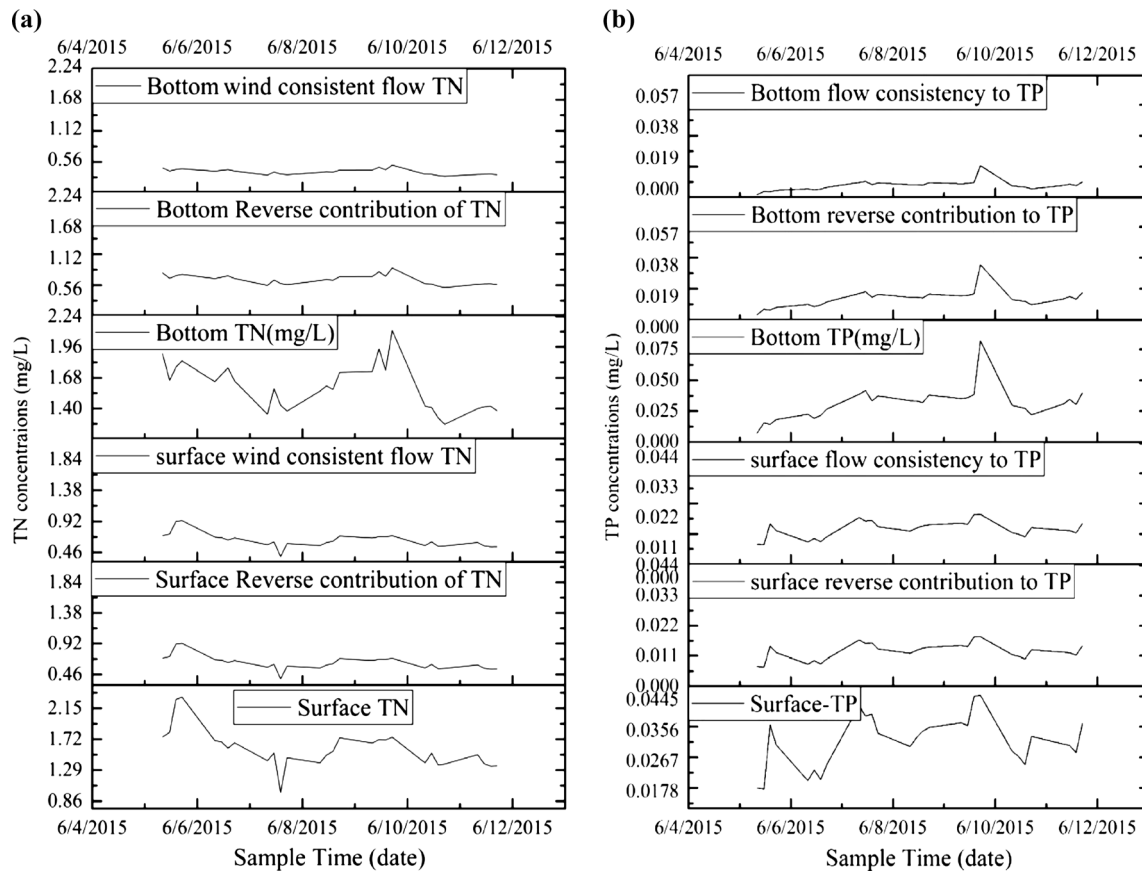
Fig. 10 Wind field induced TN **a** and TP **b** concentrations and contribution rates of reverse and consistent flow velocities at surface and bottom water profile layers

factor for the formation of compensation currents/reverse flows in all profile layers of lake water. Similarly, reverse flow was found maximum at the surface and bottom layers of vertical water profile due to dominant wind direction. On the basis of our results (as shown in Fig. 6), the wind direction has a major contribution in the generation of reverse flows at the bottom layer of the vertical profile. Similarly, wind speed has a major contribution in the generation of reverse flows at the lower middle layer of the vertical profile. While considering overall scenarios, major wind directions and dominant wind speeds have a nearly the same contribution in the generation of the reverse flow field at the surface and upper middle layers. These results have shown similarity with the results of the study of Yuanyuan (et al. 2015) at Meiling bay of Lake Taihu. Reverse flow field results at bottom layer were the same as Qin et al. (2007) but different from the surface layer of the vertical profile.

Wind field played an important role in water level fluctuations at Eastern Bay of Lake Taihu, due to which total nutrient load was directly related to wind direction. Similarly, low wind speed (0.1–3.0 m/s) makes 75% of entire field experiment, and our results showed maximum reverse flow during low wind speed. Flow consistency analysis between the surface and bottom layer and consistency analysis between wind directions and flow directions provided evidence of frictional forces (Coriolis

force and gravitational forces) playing an important role in complex flow field systems. Current velocities were positive before the wind speed of 2 m/s at the surface and 3.7 m/s wind speed at the bottom flow field (Fig. 8), and there was an exponential relation between surface and bottom flows. However, Zheng et al. (2015) found the logarithmic correlation of water currents at upper and lower vertical profile layers. Current velocities were consistent (max 5 cm/s) at the bottom but at surface current velocities were maximum (−22 cm/s) at 3.8 m/s wind speed which was also the critical wind speed (3.7–4.0 m/s) found by Zheng et al. (2015) for sediment resuspension at Lake Taihu. It was observed that frictional flow response time was directly related to the wind speed and was greater than 5 min after the start of sudden wind rose with wind speed more than 3 m/s.

The present study results showed that there were more disturbances due to low-to-moderate wind forcing which leads towards increased nutrient suspension from the bottom. This shows similarity with the results of Huang's results (Huang et al. 2016) that low-to-moderate disturbance causes the prompt release of nitrogen and phosphorus, which ultimately amplifies eutrophication in Lake Taihu.

Vertical flow velocities profile analysis showed that wind field impacts on the bottom flow velocities were relatively low which could be due to the low transfer rate of total kinetic energy from

upper layers to the bottom layer. Nystrom et al. (2007), De Serio et al. (2011), De Serio and Mossa (2015) also found the same scenario of decreasing TKE from the surface to bottom in shallow regions of coastal areas by using ADCP. The impact of gravitational or pressure gradient flow of bottom layer on the total flow field can also minimize the flow velocities at the bottom. Similarly, lower frictional response time between upper water columns and the bottom layer can also minimize the wind field impacts on bottom flow velocity; it supports the arguments provided by Fischer et al. (1979) and Llebot et al. (2014) to consider density differences and wind forcing as an adaptation to semi-enclosed water bodies (lakes and estuaries).

ENE, E, and ESE were the major wind directions found during present field experiment, showing similarity with the observations of (Wu et al. 2013). The contribution of dominant wind directions (ENE, E, and ESE), as shown in Fig. 3, was estimated by using the above-given linear relationship between wind field-induced flow field and nutrient concentrations. ENE, E, and ESE contribution of TN were 1.42, 1.08, and 0.91 mg/L at the surface and 0.961, 0.35, and 0.73 mg/L at the bottom water flow field. Similarly, ENE, E, and ESE contribution to TN concentrations were 0.19, 0.215, and 0.15 mg/L at the surface and 0.45, 0.13, and 0.113 mg/L at the bottom layer of lake water respectively. TP concentrations were slightly higher at the surface than the bottom profile layer; therefore, ENE, E, and ESE contribution in TP concentrations at the surface layer were 0.0035, 0.004, and 0.0028 mg/L and 0.0055, 0.0015, and 0.0037 mg/L at the bottom, respectively. Therefore, the overall contribution of TSS, TN, and TP due to wind field-induced flow field effects (e.g., maximum wind-induced flow field potential for nutrients resuspension) in the dominant wind directions (ENE, E, and ESE) were 34.69 and 43.59% at the surface and bottom profiles, respectively.

Conclusions

Field observations at the Eastern Bay of large, shallow, and wind-exposed Lake Taihu have been conducted to estimate wind field-induced flow velocity impacts on nutrient concentrations. Analyses of 1-week experimental data provided a strong relationship between wind field (wind speed and direction) and flow velocities at the Eastern Bay of Lake Taihu. Reverse and consistent flow probabilities were estimated through comparisons between wind field and flow velocities at four vertical layers of the water column. Reverse flow field impacts showed that main wind directions and high-frequency wind speeds played an important role in the generation of reverse flows at all profile layers of water. Vertical profile distribution has shown a delayed response time to wind field at the bottom layers of water at the semi-enclosed bay of Lake Taihu. Strong transverse gradient due to lateral/displaced water movements was observed during strong wind events of

opposite winds (cross-lake or opposite to normal flow direction) of W to WNW directions. When the wind speed was medium to slow, W, WNW, and S winds increased the exchange rate due to the effects of reverse flow and Coriolis force. There was an exponential correlation found between the surface and bottom flow directions, and frictional response time was directly proportional to the wind speed and it was more than 5 min after the start of sudden wind rose with wind speed greater than 3 m/s. The present study compared the effects of wind field-induced flow field impacts on measured TSS, TP, and TN concentrations. A linear correlation was developed between estimated wind field-induced flow velocity impacts and nutrient concentrations in the form of a linear model at the surface and bottom profile layers.

References

Ahlgren J, Reitzel K, De Brabandere H, Gogoll A, Rydin E (2011) Release of organic P forms from lake sediments. Water res 45:565–572

Arfi R, Guiral D, Bouvy M (1993) Wind induced resuspension in a shallow tropical lagoon. Estuar Coast Shelf Sci 36:587–604

Bengtsson L, Hellström T (1992) Wind-induced resuspension in a small shallow lake. Hydrobiologia 241:163–172

Boström B, Andersen JM, Fleischer S, Jansson M (1988) Exchange of phosphorus across the sediment-water interface. Phosphorus in Freshwater Ecosystems, Springer, pp 229–244

Chao X, Jia Y, Shields FD, Wang SS, Cooper CM (2008) Three-dimensional numerical modeling of cohesive sediment transport and wind wave impact in a shallow oxbow lake. Adv Water Resour 31:1004–1014

Chen Y-Y, Hu G-X, Yang S-Y, Li Y-P (2012) Study on wind-driven flow under the influence of water freezing in winter in a northern shallow lake. Adv Water Sci 23:837–843

Chen Y, Qin B, Teubner K, Dokulil MT (2003) Long-term dynamics of phytoplankton assemblages: microcystis-domination in Lake Taihu, a large shallow lake in China. J Plankton res 25:445–453

Christian E (2011) Aerobic phosphorus release from shallow lakes. Sci Total Environ 409:4640–4641

De Serio, F., Leuzzi G, Monti P, Mossa M (2011) Profile measurements of turbulence properties in coastal currents using acoustic Doppler methods. 7th International Symposium on Stratified Flows, Rome. doi:10.13140/2.1.3189.6000

De Serio F, Mossa M (2015) Analysis of mean velocity and turbulence measurements with ADCPs. Adv Water Resour 81:172–185

Deng CQ, Zhai S, Yang X, Han H, Hu W (2008) Spatial distribution characteristics and environmental effect of N and P in water body of Taihu Lake. Environ Sci 12:3382–3386 (in Chinese)

Fischer H, List E, Koh R, Imberger J, Brooks N (1979) Mixing in estuaries. Mixing in inland and coastal waters. Academic Press, New York, pp 229–278

Fisher M, Reddy K, James RT (2005) Internal nutrient loads from sediments in a shallow, subtropical lake. Lake Reserv Manag 21:338–349

Golterman H (1984) Sediments, modifying and equilibrating factors in the chemistry of freshwater. Verh Int Ver Limnol 22:23–59

Gong C-S, Yao Q, Zhao D-H (2005) Numerical simulation of wind-driven current in Xuanwu Lake. J Hohai Univ Nat Sci 33:72–75

Han H-J, Hu W-P, Jin Y-Q (2008) Numerical experiments on influence of wind speed on current in lake. Oceanologia et Limnologia Sinica 39:567–576

Huang J, Xi B-D, Xu Q-J, Wang X-x, Li W-p, He L-s, Liu H-l (2016) Experiment study of the effects of hydrodynamic disturbance on the interaction between the cyanobacterial growth and the nutrients. J Hydrodyn Ser B 28:411–422

Jeppesen E, Kristensen P, Jensen JP, Søndergaard M, Mortensen E, Lauridsen T (1991) Recovery resilience following a reduction in external phosphorus loading of shallow, eutrophic Danish lakes: duration, regulating factors and methods for overcoming resilience. Mem Ist Ital Idrobiol 48:127–148

Kämpf J (2015) Interference of wind-driven and pressure gradient-driven flows in shallow homogeneous water bodies. Ocean Dyn 65:1399–1410

Kleeberg A, Kozerski H-P (1997) Phosphorus release in Lake Großer Müggelsee and its implications for lake restoration. In: Kufel L, Prejs A, Igor Rybak J (eds) Shallow Lakes' 95, vol 119. Developments in Hydrobiology, Springer, pp 9–26. doi:10.1007/978-94-011-5648-6_2

Koçyigit MB, Falconer RA (2004) Three-dimensional numerical modelling of wind-driven circulation in a homogeneous lake. Adv Water Resour 27:1167–1178

Li Y, Acharya K, Stone MC, Yu Z, Young MH, Shafer DS, Zhu J, Gray K, Stone A, Fan L (2011) Spatiotemporal patterns in nutrient loads, nutrient concentrations, and algal biomass in Lake Taihu, China. Lake Reserv Manag 27:298–309

Lijklema L (1994) Nutrient dynamics in shallow lakes: effects of changes in loading and role of sediment-water interactions. In: Mortensen E, Jeppesen E, Søndergaard M, Kamp NL (eds) Nutrient Dynamics and Biological Structure in Shallow Freshwater and Brackish Lakes. Springer Netherlands, Dordrecht, pp 335–348. doi:10.1007/978-94-017-2460-9_30

Llebot C, Rueda FJ, Solé J, Artigas ML, Estrada M (2014) Hydrodynamic states in a wind-driven microtidal estuary (Alfacs Bay). J Sea res 85:263–276

Longo S, Liang D, Chiapponi L, Jiménez LA (2012) Turbulent flow structure in experimental laboratory wind-generated gravity waves. Coast Eng 64:1–15

Luettich RA, Harleman DR, Somlyody L (1990) Dynamic behavior of suspended sediment concentrations in a shallow lake perturbed by episodic wind events. Limnol Oceanogr 35:1050–1067

Marsden MW (1989) Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release. Freshw Biol 21:139–162

Maxam AM, Webber DF (2010) The influence of wind-driven currents on the circulation and bay dynamics of a semi-enclosed reefal bay, Wreck Bay, Jamaica. Estuar Coast Shelf Sci 87:535–544

Moss B, Beklioglu M, Carvalho L, Kilinc S, McGowan S, Stephen D (1997) Vertically-challenged limnology; contrasts between deep and shallow lakes. Hydrobiologia 342:257–267

Nixdorf B, Deneke R (1997) Why 'very shallow' lakes are more successful opposing reduced nutrient loads. Hydrobiologia 342:269–284

Nystrom EA, Rehmann CR, Oberg KA (2007) Evaluation of mean velocity and turbulence measurements with ADCPs. J Hydraul Eng 133:1310–1318

Paerl HW, Xu H, McCarthy MJ, Zhu G, Qin B, Li Y, Gardner WS (2011) Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): the need for a dual nutrient (N & P) management strategy. Water res 45:1973–1983

Phillips G, Jackson R, Bennett C, Chilvers A (1994) The importance of sediment phosphorus release in the restoration of very shallow lakes (The Norfolk Broads, England) and implications for biomanipulation. Hydrobiologia 275(1):445–456. doi:10.1007/bf00026733

Qian H (2012) The influence of wind field to the spatial distribution of chlorophyll-a concentration. Dissertation, Nanjing University of Information Science and Technology (in Chinese)

Qin B, Hu W, Chen W, Fan C, Ji J, Chen Y, Gao X, Yang L, Gao G, Huang W (2000) Studies on the hydrodynamic processes and related factors in Meiliang Bay, northern Taihu Lake, China. J Lake Sci 12:327–334

Qin B, Hu W, Gao G, Luo L, Zhang J (2004) Dynamics of sediment resuspension and the conceptual schema of nutrient release in the large shallow Lake Taihu, China. Chin Sci Bull 49:54–64

Qin B, Xu P, Wu Q, Luo L, Zhang Y (2007) Environmental issues of lake Taihu, China. Hydrobiologia 581:3–14

Qin B, Zhu G, Zhang L, Luo L, Gao G, Gu B (2006) Estimation of internal nutrient release in large shallow Lake Taihu, China. Sci China Ser D 49:38–50

Sas H (1989) Lake Restoration by Reduction of Nutrient Loading. ed. H. Sas. Academia Verlag. Hans Richarz Publikations-Service

Søndergaard M, Jensen JP, Jeppesen E (2003) Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506:135–145

Wang J, Pang Y, Li Y, Huang Y, Luo J (2015) Experimental study of wind-induced sediment suspension and nutrient release in Meiliang Bay of Lake Taihu, China. Environ Sci Pollut res 22:10471–10479

Wang Y-H, Yu G-H (2007) Velocity and concentration profiles of particle movement in sheet flows. Adv Water Resour 30:1355–1359

Wetzel RG (2001) Limnology: lake and river ecosystems. Gulf Professional Publishing

Wu J (1975) Wind-induced drift currents. J Fluid Mech 68:49–70

Wu T, Qin B, Zhu G, Luo L, Ding Y, Bian G (2013) Dynamics of cyanobacterial bloom formation during short-term hydrodynamic fluctuation in a large shallow, eutrophic, and wind-exposed Lake Taihu, China. Environ Sci Pollut res 20:8546–8556

Yong P, Peimin P (1996) Numerical simulation of three-dimensional wind-driven current in Taihu lake. Acta Geograph sin 4

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. J Environ Sci 19:1055–1060

Yuanyuan Z, Xiaodong L, Zulin H, Gongyu H, Li G, Liqiang C (2015) Study of the temporal and spatial differences of hydrodynamic characteristics of wind-induced current in Taihu Lake. Environ Protect Sci 2015–01(41):51–56

Zhao L, Zhu G, Chen Y, Li W, Zhu M, Yao X, Cai L (2011) Thermal stratification and its influence factors in a large-sized and shallow Lake Taihu. Adv Water Sci 22:844–850

Zheng S-S, Wang P-F, Chao W, Jun H (2015) Sediment resuspension under action of wind in Taihu Lake, China. Int J Sediment Res 30:48–62

Zhu G, Qin B, Gao G (2005) Direct evidence of phosphorus outbreak release from sediment to overlying water in a large shallow lake caused by strong wind wave disturbance. Chin Sci Bull 50:577–582

Zhu M, Zhu G, Yongping W (2011) Influence of scum of algal bloom on the release of N and P from sediments of Lake Taihu (in chinese). Environ Sci 2:409–415

Zhu M, Zhu G, Zhao L, Yao X, Zhang Y, Gao G, Qin B (2013) Influence of algal bloom degradation on nutrient release at the sediment–water interface in Lake Taihu, China. Environ Sci Pollut res 20:1803–1811