ARTICLE IN PRESS

Environmental Pollution xxx (2017) 1–12

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

The role of wind field induced flow velocities in destratification and hypoxia reduction at Meiling Bay of large shallow Lake Taihu, China☆

Abdul Jalil [a, b], Yiping Li [a, b, *], Wei Du [b], Wencai Wang [b], Jianwei Wang [b], Xiaomeng Gao [a], Hafiz Osama Sarwar Khan [b], Baozhu Pan [c], Kumud Acharya [d]

[a] Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, Hohai University, Nanjing, 210098, China
[b] College of Environment, Hohai University, Nanjing, 210098, China
[c] Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an, 710048, China
[d] Division of Hydrologic Sciences, Desert Research Institute, Las Vegas, NV 89119, USA

ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form
23 September 2017
Accepted 28 September 2017
Available online xxx

Keywords:
Hypoxia
Thermal destratification
Wind field
Anoxia
Vertical velocity

ABSTRACT

Wind induced flow velocity patterns and associated thermal destratification can drive to hypoxia reduction in large shallow lakes. The effects of wind induced hydrodynamic changes on destratification and hypoxia reduction were investigated at the Meiling bay (N 31° 22′ 56.4″, E 120° 9′ 38.3″) of Lake Taihu, China. Vertical flow velocity profile analysis showed surface flow velocities consistency with the wind field and lower flow velocity profiles were also consistent (but with delay response time) when the wind speed was higher than 6.2 m/s. Wind field and temperature found the control parameters for hypoxia reduction and for water quality conditions at the surface and bottom profiles of lake. The critical temperature for hypoxia reduction at the surface and the bottom profile was ≤24.1C° (below which hypoxic conditions were found reduced). Strong prevailing wind field (onshore wind directions ESE, SE, SSE and E, wind speed ranges of 2.4–9.1 m/s) reduced the temperature (22C° to 24.1C°) caused reduction of hypoxia at the near surface with a rise in water levels whereas, low to medium prevailing wind field did not supported destratification which increased temperature resulting in increased hypoxia. Non-prevailing wind directions (offshore) were not found supportive for the reduction of hypoxia in study area due to less variable wind field. Daytime wind field found more variable (as compared to night time) which increased the thermal destratification during daytime and found supportive for destratification and hypoxia reduction. The second order exponential correlation found between surface temperature and Chlorophyll-a (R^2: 0.2858, Adjusted R-square: 0.2144 RMSE: 4.395), Dissolved Oxygen (R^2: 0.596, Adjusted R-square: 0.5942, RMSE: 0.3042) concentrations. The findings of the present study reveal the driving mechanism of wind induced thermal destratification and hypoxic conditions, which may further help to evaluate the wind role in eutrophication process and algal blooms formation in shallow water environments.

Outcome: Wind field is the key control factor for thermal destratification and hypoxia reduction. 24.1C° is the critical/threshold temperature for hypoxia, Chlorophyll-a and NH_3-N concentrations of the shallow freshwater lake.

1. Introduction

The concentration of dissolved oxygen (DO) is the major component of algal growth in large shallow eutrophic lakes. Hypoxia is the condition of reduced DO concentration (≤2 mg/L), which is the major indicator of eutrophication due to its occurrence at variable depths in shallow lakes (Zhou et al., 2013). Lake depth plays an important role for studying water quality scenarios in lakes (Jalil et al., 2016). Thermal stratification and wind induced vertical mixing controls the hypoxic conditions in large shallow eutrophic lakes.

Wind field has certain impacts of destratification and hypoxia

☆ This paper has been recommended for acceptance by Dr. Harmon Sarah Michele.

* Corresponding author. College of Environment, Hohai University, 1 Xikang road, Nanjing, 210098, China.
E-mail address: jalil_ahmed21@hotmail.com (Y. Li).

https://doi.org/10.1016/j.envpol.2017.09.095
0269-7491/© 2017 Published by Elsevier Ltd.

reduction in the eutrophic estuaries as studied on Cape Cod Bay, USA, (Geyer, 1997), Chesapeake Bay, USA (Chen and Sanford, 2009; Chen et al., 2009; Li and Li, 2012; Li et al., 2015; Scully, 2010, 2013; Wang et al., 2016b) and the long island sound, USA (O'Donnell et al., 2008; Wilson et al., 2008). Wang et al. (2016b) studied the role of wind directions on destratification and hypoxia reduction. He found that downwelling (easterly) wind direction caused greater destratification and hypoxia reduction than the upwelling wind direction (westerly) in the Chesapeake Bay estuary.

Wind field plays its role as a control parameter to define the hydrodynamics and water quality scenarios in large shallow lakes (Jalil et al., 2017; Li et al., 2017a). The frequent nutrient release is the result of wind force due to its dominant role in defining flow velocities and current structure in shallow lakes and estuaries (Chen et al., 2012; Longo et al., 2012). A study by Li et al. (2017a) showed that dominant wind speeds and dominant wind directions play a major role in the generation of reverse flows at vertical profile at the eastern bay of large shallow lake Taihu. Schoen et al. (2014) studied the wind-driven circulation patterns of an estuarine lake St Lucia, South Africa, with dominant wind directional switching and found that these circulations cause intermittent water exchange and mixing between the lake basins. Hypoxia and anoxia have been found to be the major reason of black bloom in freshwater lakes (Stahl, 1979; Yang et al., 2008). Shen et al. (2014) investigated the reasons of black bloom at Gonghu Bay of large shallow lake Taihu and found that black blooms can be characterized by low dissolved oxygen concentrations (close to 0 mg/L) along with low oxidation-reduction potential and relatively low pH of overlying water. Whereas, higher Ferrous (Fe^{2+}) and Sulfide ($\sum S^{2-}$) concentrations were found the major reason of black color of bloom at Lake Taihu. Jalil et al. (2017) investigated the impact of wind field induced flow velocity at the eastern bay of lake Taihu and found that wind field has a major contribution in resuspension of sediments and nutrients. Results of the study by (Jalil et al., 2017) indicated that strong wind field caused reverse flow field in non-prevailing wind directions. The water, atmosphere interactions were investigated to measure the momentum transfer coefficients by using eddy covariance at Lake Taihu in a study by (Xiao et al., 2013). Results of the study indicated that transfer coefficients decreased with increasing wind speed for weak winds and approached constant values for strong winds. The presence of submerged macrophytes reduced the momentum transfer (drag) coefficient significantly. At the two sites (Meiling bay and Dapukou shoreline area) free of submerged macrophytes, the 10-m drag coefficients under neutral stability at the wind speed of 9 m/s had been found 38 and 34% greater than the prediction by the Garratt model for the marine environment which shows that, at the same wind speed, the water surface of the lake was rougher than the ocean surface (Xiao et al., 2013).

Several studies have been conducted to evaluate the impact of wind field on hypoxic conditions in estuaries (as cited above), but no clear understanding of wind field impacts on shallow lake hypoxic conditions has been developed. Moreover, it is also an important aspect for scientists to understand the mechanisms leading towards destratification and hypoxia reduction due to wind field generated forces. Different wind directions have different degrees of impact on destratification and vertical mixing in large shallow lakes. Longitudinal, lateral and direct wind straining are the dominant mechanisms which could be evaluated for studying destratification and hypoxia reduction studies in large shallow lakes. The present study hypothesized that there could be medium to large scale effect of wind field on the hypoxia occurrence and distribution in the vertical profile of large shallow eutrophic lakes. We also hypothesized that dominant wind directions can play their dominant role in hypoxia reduction and destratification at vertical profile of large shallow eutrophic lakes. For this purpose, we selected a large shallow highly eutrophic bay of Lake Taihu to investigate the vertical prevalence of hypoxia in the water, with surface fully covered with algae. Therefore, the objectives of the present study were to 1) investigate the effects of wind field on the flow structure and mixing processes, 2) explore the effect of thermal structure/temperature on the prevalence and distribution of hypoxia at vertical profile of the lake water, 3) and develop the relationship between dominant wind directions and hypoxic conditions at large shallow highly eutrophic lake.

2. Materials and methods

2.1. Study area

Present study field experiment was conducted at Meiling bay from 22nd May 2014 to 29th May 2014 to study hypoxic conditions and to understand the wind field impact on hypoxia reduction during the bloom period because Lake Taihu faces algal bloom in late May every year (Shen et al., 2014). Meiling Bay is a semi-enclosed bay with a surface area of 129.3 km^2, 1.9 m average depth and is located northern part of Lake Taihu (Gao et al., 2016; Huang, 2004). This bay is facing severe water quality and algal bloom problem (Gao et al., 2016; Liu et al., 2014; Zhu et al., 2013) which is directly related to the wind induced vertical mixing of nutrients and reduced amount of dissolved oxygen causing increased hypoxia. Annual average wind speed varies from 3.5 m/s to 5.0 m/s whereas summer dominant wind direction is South-eastern and winter dominant wind direction is Northwestern (Wu et al., 2013) in this bay. Meiling bay have a medium depth of the surface mixed layer (MLD) of water as compared to other bays (Gonghu Bay, Zhushan Bay, Xukou Bay and East Taihu Bay) of the lake (where diurnal stratification had been formed easily) due to combined effects of thermal and hydrodynamic forces (Zhao et al., 2012). The diurnal stratification has been observed due to combined effects of hydrodynamic changes induced by wind and heat exchange between air and water surface at lake taihu (Zhao et al., 2012). The in situ field observations were conducted at Tuoshan Bay which is located at the mouth of Meiling Bay (Fig. 1). The total water depth varied from 2.66 cm to 2.88 cm during our field experiment. The location of field experiment was at the edge of Meiling bay where the width of the bay is approximately 8.4 km whereas, the rivers/tributaries entering into Meiling bay are approximately 12.75 km upstream of the experiment site. The shape of the bay is elongated but due to its large width there was no clear impact of shape or width/edges on hydrodynamics of the lake found in the present study. The major water exchanges between the Meiling bay and central lake taihu are due to wind induced forces (due to onshore winds from central lake to Meiling bay and due to natural flow and offshore winds from Meiling bay towards central lake). The Mixed layer depth in the Meiling bay is nearly medium as compared to central lake having deepest mixed surface layer due to thermal destratification and hydrodynamic forces as mentioned by (Zhao et al., 2012).

2.2. Field observations

In the present study, we used Acoustic Doppler Current Profiler (ADCP Argonaut-XR, SonTek Company, USA) with 10 min monitoring frequency to measure 3-dimensional flow velocities and directions (depth profiles of 50, 100, 150 and 200 cm) with a 50 cm range of each profile.

ADCP has pressure sensor which accurately adjusts with water level changes to measure required data. ADCP was placed vertically upward to measure 3-dimensional flow velocities and directions

Please cite this article in press as: Jalil, A., et al., The role of wind field induced flow velocities in destratification and hypoxia reduction at Meiling Bay of large shallow Lake Taihu, China, Environmental Pollution (2017), https://doi.org/10.1016/j.envpol.2017.09.095