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Contribution of spring and summer hydrodynamic conditions in the eutrophication process at Lake Taihu, China

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Contribution of different hydrodynamic conditions caused nutrients released and algal blooms growth and deteriorates water quality. Important factors related to climate variation, such as water temperature, precipitation, wind, solar radiation, and human activities can influence trophic conditions in the water column. A field survey was conducted at Meiliang Bay during spring and summer seasons and in diverse hydrodynamic conditions. The study aimed to investigate the variation of wave shear stress generated by strong wind and vessels. The measurement results showed that the shear stress increased in direction with increasing wind speed and significant wave heights. Wave shear stress τ has a maximum value = 0.2 Nm^2 during weak wind 1.5-2.5 m/s and significant wave height = 0.20 m while, it has a maximum value = 0.8 Nm^2 with strong wind range from 4.5 to 10 m/s corresponding with the significant wave height which has maximum value = 0.65 m in 2014. Also, wave shear stress τ has maximum value = 0.25 Nm^2 with maximum significant wave height = 0.6 m during passages vessels in 2016. It ranges from -0.8 to 0.8 Nm^2 with maximum wave amplitude value U = 0.4 m/s passages heavy ship in 2018. The results indicated that the bottom layer has a major impact, with strong winds and vessels' induced waves. Furthermore, the shear stress generated by those forces impacted directly on the boundary of the lake and caused sediment resuspension leading to release nitrogen. The outcomes of this paper give a clear idea about the processes happening in the lake.

Key words: Vessels, hydrodynamic, waves, shear stress, Meiliang Bay, Lake Taihu.

INTRODUCTION

Climate change can cause increasing temperatures and evaporation while decreasing water obtainability. In addition, climate change can increase surface runoff causing floods, and may also result in deteriorated water quality. Sensitive factors for climate variation, for example, water temperature, precipitation, wind, solar radiation and human activities can also influence trophic conditions in water pole (Nazari-Sharabian et al., 2018). Differences in hydrodynamics among lakes have been related with variances in morphological geometries and the neighbouring topographies in addition to hydro-meteorological and geochemical influences (Sharip et al., 2018). Shallow lakes are characterised by intermittent resuspension of sediments which happens when the bottom shear stress exceeds the critical shear stress (Li et al., 2017b). Li et al. (2017a) studied the impact of wind field-induced flow velocity at the Eastern Bay of Lake Taihu and found that wind field is a significant factor causing resuspension of sediments and nutrients. Waves and currents generated shear stresses are the active forces at the deep water that influence sediment distribution, micro-topography, and habitat. Bottom shear stresses and its forcing processes mobility events were different spatially and temporally in the Middle Atlantic (Dalyander et al., 2013). Chao et al. (2008) developed a three-dimensional numerical model for simulating cohesive sediment transport in water bodies where wind-induced currents and waves are important and the results showed that the sediment is resuspended by the actions of wind waves and by shear stress generated and transported by wind-driven flow. Linares et al. (2018) indicated that the oscillations on bottom shear stress in freshwater estuaries in the Great Lakes are induced meteorologically and can increase it by an order of magnitude in comparison with river - dominated flow conditions. Pang et al. (2006) showed that lake current had relatively significant effects on the sediment solids concentrations (SSC) at littoral zone of Lake Taihu, while SSCs at the central area of the Lake was mainly influenced by waves. Waves are the most important factor for controlling sediment resuspension processes. Their effects are more noticeable in the shoreline zone than the middle zone due to the waves interacting directly with the shoreline (Qin, 2004; Gabel et al., 2017). The wave's interactions affect sediment surface, biota, cause resuspension, erosion, transport of particles, the release of nutrients, methane reallocation and stress on zoobenthos affecting their diversity, abrasion of biofilms from stones, and the spread of aquatic macrophytes (Luettich et al., 1990; Hawley, 2000, Eriksson et al., 2004; Bussmann, 2005; Peters, 2005; Scheifhacken, 2006). Pollution of Lake Taihu is resulting from anthropogenic development in the Lake Taihu Basin. Lake Taihu has knowledgeable several ecological problems meanwhile the1960s, mainly eutrophication and cyanobacterial blooms (Qin et al., 2007; Paerl et al., 2011; Jiang et al., 2018).

Anthropogenic nutrient over-enrichment, coupled with rising temperatures and an increasing frequency of extreme hydrologic events are accelerating eutrophication and encouraging algal blooms. These consequently affect water supplies, fisheries, recreation, tourism, and property values (Paerl et al., 2011; Ma et al., 2019). The watershed nutrient management struggles to control algae blooms in huge quantities and cover the lake by reducing P inputs. But the N loading has also increased, supporting blooms of non-N2 fixers, and changing lake nutrient resources and cycling characteristics (Qin, 2004; Qin et al., 2007; Paerl et al., 2011). Water quality parameters associated with limitation factors change according to the real state and sensitivities of water parameters (Jiang et al., 2018). Trophic level index (TLI) and water quality index (WQI) methods are used in the lake to determine the eutrophication levels and the status of water quality (Wang et al., 2019). Anthropogenic activities affect the ecological stability of Lake. Studying water quality parameters is very important for solving the problems in the ecosystem. Nutrients and pollutants are transmitted and accumulate in Meiliang Bay. The obejectives of this study are therefore to: 1) to study the variation of wave shear stress according to the inducer, and 2) to assess the water quality by hierarchical cluster in spring and summer seasons.

MATERIALS AND METHODS

Description of study site

Field observations were recorded in Meiliang Bay, which is located at (31°25′7.41″N, 120°12′46.90″E; Figure 1) in three periods (April, 2014; May, 2016, and July, 2018) in the summer seasons with different hydrodynamic conditions. Meiliang 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 (Liu et al., 2014; Gao et al. 2017; Li et al. 2017b). It is extremely eutrophic, as indicated by cyanobacteria blooms during summer leading to severe water quality problems (Gao et al., 2017; Li et al., 2017b). Meiliang Bay has average annual wind speed 4.5 m/s , with dominant summer wind from the southeast and dominant winter wind from the northwest (Wu et al., 2013; Gao et al., 2017; Li et al., 2017b).

Field observation pattern instruments

The instrument's patterns were used in three field observations as shown in Table 1. According to the Chinese standard methodology for lake eutrophication surveys (Jin, 1990).

This method is corresponding to the American standard methods (APHA, 1998), for water quality parameters (James et al., 2009).

Water quality sampling

Water quality samples were transported to Taihu Laboratory Lake Ecosystem Research, Chinese Academy of Sciences (TLLER) for filtration to obtain suspended particulate matter (SPM) substance by

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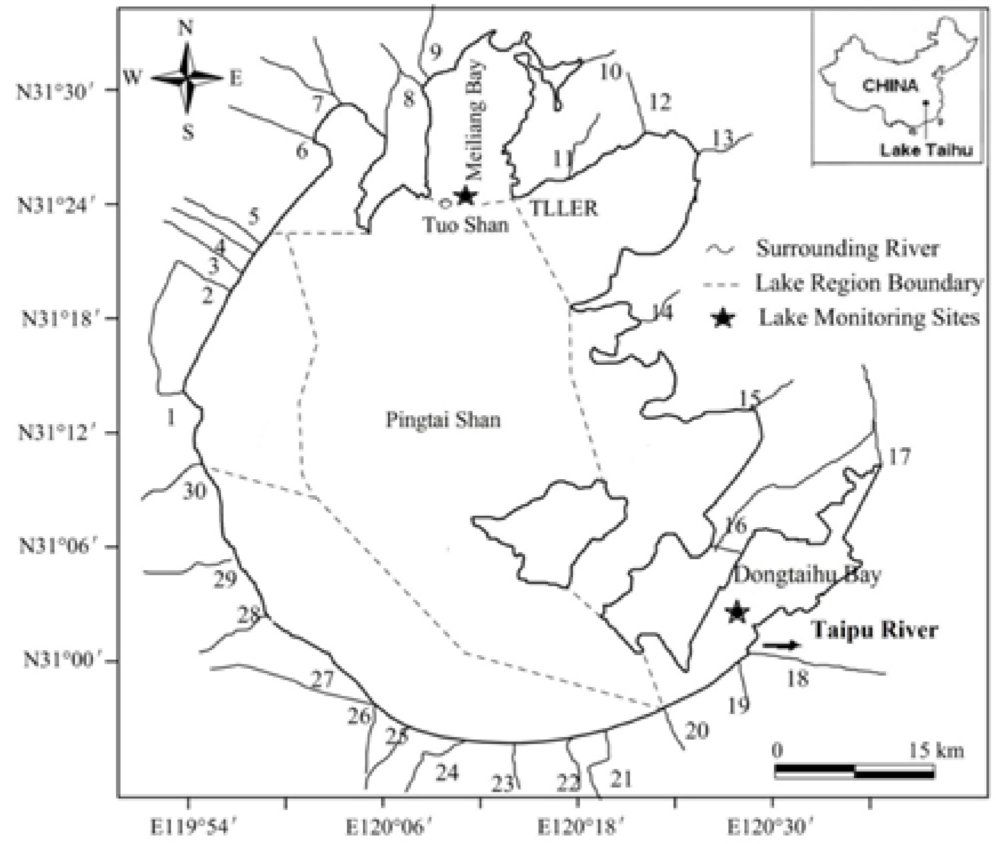

Figure 1. Location of Study area with descriptions of sampling sites of Lake Taihu.

Table 1. Instruments pattern were used in Meiliang Bay.

Detailed parameters of A. Meteorological data		Instruments	Position of instruments
A.1 wind field	Wind speed	PH-Handheld weather stations 5 min	5 m above the water surface
		TLLER weather stations, 1 h	20 m above the sea level
	Wind direction	TLLER weather stations, 1 h	20 m above the sea level
	Wave (wave height H、 period T)	RBRduo T.D wave, 5 min	1.77 m above the bottom
1			
B.2 Conventional physical and chemical indicators	The concentration of suspended sediment (SS)	OBS-3A, 3 min	0.95 m below the water surface; 2.65 m under the water surface
	Water temperature (WT) Dissolved oxygen (DO) mg/L pH; conductivity	YSI 6600, YSI ProPlus10 min	2.3, 0.5 m below the water surface
	TN; NH_3^+-N; NO_3—N; NO_2^--N; DTN; TP; PO_4^{3-}; DTP& Chl-a B.4 Algae concentration.	3 h	20cm below the water surface; 10cm above the bottom

filtering only 250 ml of water through cellulose acetate membranes (0.45 µm), then the analyses including total nitrogen (TN), total dissolved nitrogen (TDN), dissolved inorganic nitrogen (DIN; ammonium (NH_4^+) + (NO_3^-) + (NO_2)), total phosphorus (TP), total dissolved phosphorus (TDP) and Phosphate (PO_4) were performed. Other parameters, including pH, water temperature (T), dissolved oxygen (DO), total dissolved solids (TDS) and electrical conductivity (EC) were obtained by using a multi-parameter instrument EXO2 sonde Yellow Springs Instrument (YSI) 6600 and YSI ProPlus. As well as, Synchronous, high-frequency measurements of wind, currents, waves, and Sediment resuspension concentrations (SSCs) were carried out in this study.

The observation tools included an RBR duo T.D wave tide gauge, PH-II Handheld weather stations, a PHWD wind direction sensor, and a bottom-mounted holder equipped with an Acoustic Doppler current profiler (ADP Argonaut-XR), Acoustic Doppler Velocimeter (ADV Ocean, Son Tek Inc.), and Optical Backscatter Sensor (OBS) turbidity meter. The wind parameters were measured using PH-II Handheld weather stations and a PHWD wind direction sensor fixed above the surface of the lake.

Wave data collection

Wave parameters were analysed following the general wave data Equation 1:

$$W_s = \left(\frac{dH^2}{2\pi}\right) tanh\frac{2\pi h}{w_s} \tag{1}$$

Wave parameters were analysed following the general wave data equation (1):
W_s is a reference to the significant wavelength, H is the significant wave period, and h is the depth points we observed. The maximum orbital velocity of a wave near the bottom layer u_w (m/s) can be expressed as Equation 2 following the method by Madsen (1976) and Whitehouse (2000)

$$O_w = \frac{\pi E_s}{L_s\, sin\left(\frac{2\pi e}{Ps}\right)} \tag{2}$$

Where E_s means the effective wave height (meters), L_s the wavelength (m), P_s is wave period, and e is the depth points in the meter.

Shear stress collection

Shear stress created by waves was calculated by the following Equation 3 (Grant and Madsen 1979):

$$\tau w = 0.5\rho f_w O_w^2 \tag{3}$$

The abbreviation τ_w is shear stress (N/m^2), ρ indicated to the density of water (kg/m^3), O_w the maximum wave orbital velocity near the bed (calculated by Equation 2), and the wave f_w friction coefficient related to the lake bottom roughness and Reynolds number. The f_w calculated as follows (Jiang et al., 2000; Li et al., 2017b; Shih et al., 2017).

General hydrophysiology

The spatial and temporal variation of the water surface quality was evaluated by using a Multivariable method during different hydrodynamic effects. The Multivariate hierarchical cluster analysis (HCA) agreements the use of a mathematical explanation of the relationship to group several measures into the same section or between the diverse sections. Considering the temporal and spatial variations in Lake water quality and determining the factors that affect water quality can assist researchers in establishing significance for sustainable water management (Chen and Lu, 2014). Samples categorised according to their parameters. All the selected variables Temperature (Temp)°C, Dissolved oxygen (DO)mg/L, Salinity (SAL), pH, Chlorophyll-a(Chl-a) µg/L, Turbidity (Turbid) NTU were utilised in this statistical analysis. The results of all samples were statistically analysed by software Origin pro-2018.

RESULTS AND DISCUSSION

In Lake Taihu, It is known that the wave height increased when the wave period is increased. While wave shear stress has no significant by the wave period (Ding et al., 2018). Data from near bottom of the lake by using high-frequency instruments expose that the shear stress has different critical means values in spring and summer seasons in the same site according to the inducers of waves. The measurement results showed that the shear stress increased in direction with increasing wind speed (m/s) and significant wave height (m) (Figure 2). Also, the data analysis shows that different hydrodynamic results express the influence that happened during generated wave shear stress by different forces in the eutrophic shallow Lake in China. Wave shear stress τ has maximum value = 0.2 (Nm^2) during weak wind 1.5-2.5 m/s and significant wave height = 0.20 (m) while wave shear stress τ has maximum value = 0.8(Nm^2) with strong wind range between 4.5 to 11 (m/s) corresponding with the significant wave height which has maximum value = 0.65 (m) in 2014. Also, wave shear stress τ has maximum value = 0.25 (Nm^2) with maximum significant wave height = 0.6 (m) during passages high-speed vessels in 2016. Wave shear stress τ has a maximum value range from - 0.8 to 0.8 Nm^2 with maximum wave amplitude value U = 0.4 m/s during blowing water by heavy ship in 2018 (Figure 3).

Waves under strong wind forcing have action on the boundary of water and stimulated sediment resuspension, while the critical shear stresses caused by waves and currents have the same degree with weak wind forcing (Qin, 2004; Wei et al., 2019). Zheng et al. (2015) explore the variations of the current speed, wave parameters and sediment resuspension under different wind speeds in Lake Taihu and found that there were exponential distributions between the mean wind speed and wave parameters and between the mean wind speed and current speed.

The scholars found that with increasing surface wind, a consistent increase in the concentration and particle size of the Suspended Particulate Matter (SPM) in the water column. The disturbance of the water column can lead to sediment disturbance and nutrients released larger than steady conditions. The resuspension process has a significant correlation with the release of nutrients from sediment. Waves are the main reason for sediment resuspension generated by shear stresses in the central part of the shallow lake and Meiliang bay (Asmaa, 2019).

For a few days field observation, by using Yellow Springs Instrument (YSI), (Table 2) shows that the comparisons of means physical parameters were confirmed the trophic state in Lake Taihu during three

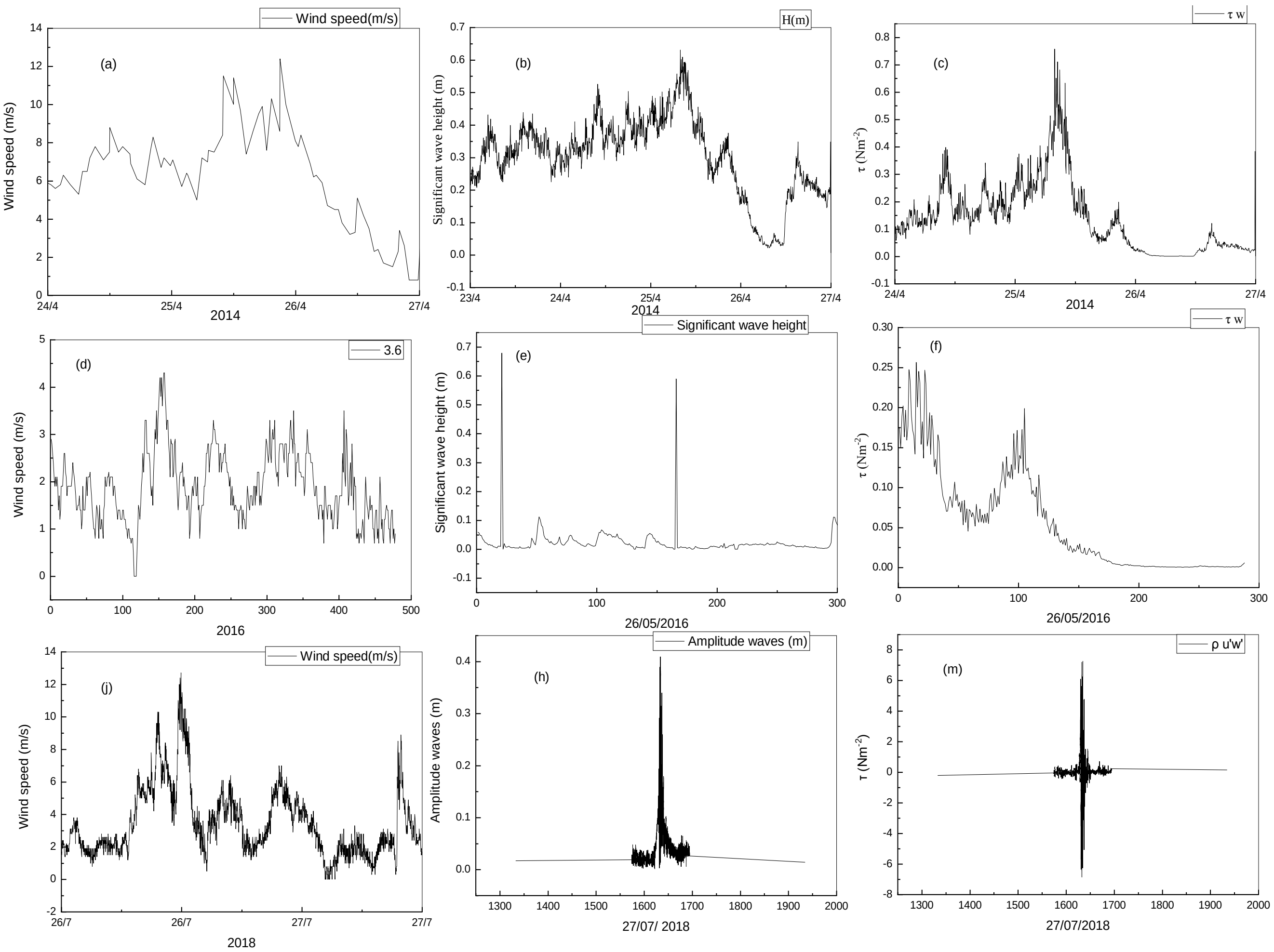

Figure 2. Different hydrodynamic conditions showing wind speed (m/s); significant wave height (m); wave shear stress (N/m^2) in April 2014; May 2016 and July, 2018.

summer seasons under different hydrodynamic conditions. The means of Total dissolved solids (TDS), Dissolved Oxygen (DO)/mg/L, Salinity (SAL), Chlorophyll-a (Chl-a) ug/L, Turbidity (NTU) and Blue-green algae BGA-PC 1 (µg/L) are gathered with Multivariate analysis. From the table, the means comparisons of physical parameters show that the highest mean values were in 2014 and the lowest mean values were in 2018.

Euclidean distance was used in this analysis and categorize the water samples. Euclidean distance estimates if the samples can be grouped into statistically different hydrochemical groups that could be important in the physical background. The figure shows the groups, which were categorized in the water samples in the seasons.

In the diagram of Hierarchical Cluster Analysis, there was only one cluster appear in the three field observations and the most representative observation and the Least representative Observation was summarized in Table 3. The dendrogram tree of water quality parameters for 40 samples selected for analysis has descriptive in Table 4. In April, 2014, the means of water quality parameters were of the temperatur was 16°C the dissolved oxygen was 23.01 mg/dL, salinity was 0.33 PPT, pH was 9.15, Turbidity was 60.545(NTU), and Chllorophyl was 4.95 µg/L. While, in May, 2016 the means of water quality parameters were of temperature (°C) was 19.6, the dissolved oxygen was 7.65 mg/dL, Salinity was 0.25 PPT, pH was 8.5, Turbidity was 37.32 NTU, and Chllorophyl was 5.68 µg/L. Also, in July, 2018 the means of water quality parameters were of temperature (°C) was 33.56, the dissolved oxygen was 10.55 mg/dL, Salinity was 0.24 PPT, pH was 10.26, Turbidity was 19.96 NTU, and Chllorophyl was 3.81 ug/L.

Figure 4 shows that the means of nutrients: total phosphorus (TP), total dissolved nitrogen and phosphatase have similar values while total Nitrogen (TN), total dissolved nitrogen (TDN), Ammonia (NH_4) and Phosphate (PO_4) have the maximum means values and more sensitive for resuspension in the water with the

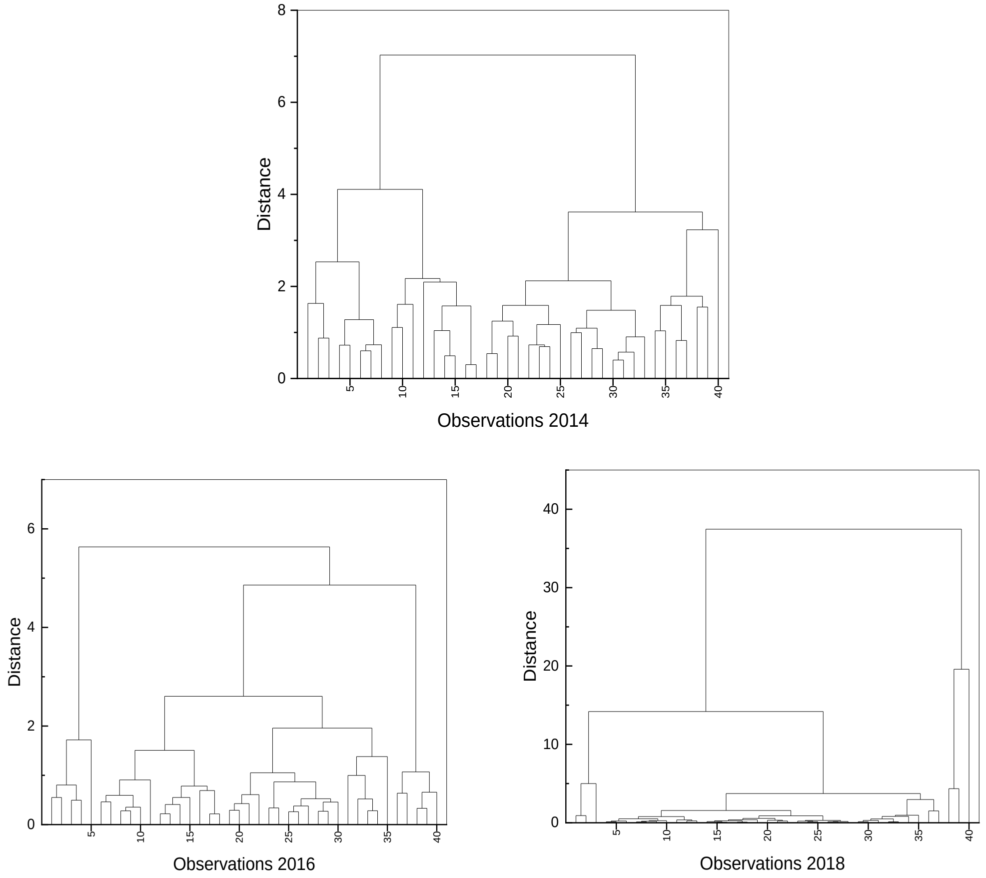

Figure 3. Diagram of hierarchical cluster analysis for water quality physical parameters during spring and summer seasons.

Table 2. Descriptive statistics of physical parameters of water quality in the spring and summer seasons.

Parameter	N.analysis	Mean	SD	Sum	Minimum	Medium	Maximum
TDS1/ 2014	4	0.46	1.29	1.85	0.457	0.465	0.47
TDS2/2016	4	0.34	0.006	1.37	0.340	0.34	0.34
TDS2/2018	Na	Na	Na	Na	Na	Na	Na
DO1/2014	4	8.76	0.091	35.07	8.676	8.75	8.89
DO2/2016	4	8.05	1.96	32.22	5.247	8.58	9.79
DO3/2018	4	10.21	0.005	40.86	10.21	10.215	10.22
Sal1/ 2014	4	0.35	0.005	1.40	0.35	0.35	0.36
Sal2/ 2016	4	0.25	0.004	1.02	0.25	0.25	0.26
Sal3/2018	4	0.24	0	0.96	0.24	0.24	0.24
Chllo-a1/2014	4	13.33	2.25	53.34	11.27	12.93	16.21
Chlo-a 2/2016	4	5.067	0.78	20.27	3.96	5.25	5.79
Chlo-a 3/2018	4	4.05	0.08	16.22	4	4.02	4.18
Turbidity 1	4	120.8	32.10	483.49	93.93	111.04	167.48
Turbidity 2	4	32.64	4.17	130.58	28.29	32.1	38.09
Turbidity 3	4	16.05	1.61	64.21	14.64	15.73	18.12
BGA-PC 1 µg/L	4	3961.8	1801.1	15847.4	1837.05	3905.10	6200.2
BGA-PC 2 µg/L	4	8126.3	7207.4	32505.4	2034.63	5972.8	18525.049
BGA-PC 3 µg/L	4	0.46	1.290	1.85963	0.457	0.465	0.47

Table 3. Most representative observation and the least representative observation.

Field observations time	Cluster	Most representative observation	Least representative observation
April, 2014	1	17	1
May, 2016	1	13	3
July, 2018	1	9	21

Table 4. Descriptive statistics of dendrogram of water quality parameters in 2014, 2016, and 2018 seasons.

Parameter	N analysis	Mean	S. deviation	Sum	Min.	Med.	Max.
2014							
Temp °C	40	16.99	0.119	679.9	16.8	17	17.2
DO/mg/L	40	23.01	3.861	920.4	15.22	23.7	30.35
SAL	40	0.33	0	13.2	0.33	0.33	0.33
pH	40	9.151	0.007	366.0	9.13	9.15	9.16
Turbidity	40	60.545	1.183	2421	58.5	60.3	63.8
Chl ug/L	40	4.95	0.695	198	3.5	5.05	6
2016							
Temp	40	19.6	0.047	786.67	19.61	19.65	19.82
ODO	40	7.65	0.263	305.97	7.26	7.615	8.16
SAL	40	0.25	0.003	10.05	0.25	0.25	0.26
pH	40	8.49	0.093	339.66	8.4	8.465	8.76
Turbidity	40	37.32	2.88	1492.8	31.1	37.3	42.7
Chl ug/L	40	5.68	0.407	227.25	4.84	5.71	6.56
2018							
Temp	40	33.56	0.026	1342.411	33.534	33.55	33.604
ODO	40	10.55	0.018	422.01	10.53	10.54	10.58
SAL	40	0.24	1.69	9.6	0.24	0.24	0.24
pH	40	10.26	0.064	410.41	10.17	10.26	10.38
Turbidity	40	19.96	11.15	798.47	13.32	15.89	67.66
Chl ug/L	40	3.810	0.098	152.43	3.64	3.81	4

strong wind and vessels conditions. Eutrophication changed in the equilibrium of the aquatic ecosystem and lead to the damage of the water ecosystem and the steady decline of its functions. Consequently, the impact on water quality characteristics appears worse in the transparency of the water. Therefore, the sunlight penetrates the water body and photosynthesis plants under the water layers will be decreasing totally. Water eutrophication caused the supersaturation of nutrients which means lack of dissolved oxygen in the water and this is very dangerous to aquatic animals. Also, Algae produces toxins and increases organic matter; the organic matter in the water produces harmful gases, which are toxic for the fish and seashell (Qin et al. 2007, Yang et al. 2008, Qin 2009, Wang and Wang 2009). Scholar's investigations found that the algae produced toxins, such as Cyanotoxins, were detected in the Yangtze River, in addition to many reservoirs and lakes of Yellow River valleys, apart from Dianchi Lake, Lake Taihu and Lake Chaohu (Ye et al. 2007, Yang et al. 2008).

The major influencing factors on water eutrophication include nutrient enrichment, hydrodynamics, environmental factors such as temperature, salinity, carbon dioxide, element balance, etc., and microbial and biodiversity. Waves and currents play an important role in sediment resuspension and internal nutrient release in large, shallow lakes. The turbidity started to increase at wind speeds of approximately 4 m/s and significantly increased when wind speeds exceeded 6 m/s. Wave-generated shear stress contributed more than 95% to sediment resuspension and that only in weak wind conditions (<4 m/s) and the shear stresses generated by currents and waves contributed equally. Other scholars found similar results by Ding et al. (2018), Jalil et al. (2019), and Asmaa

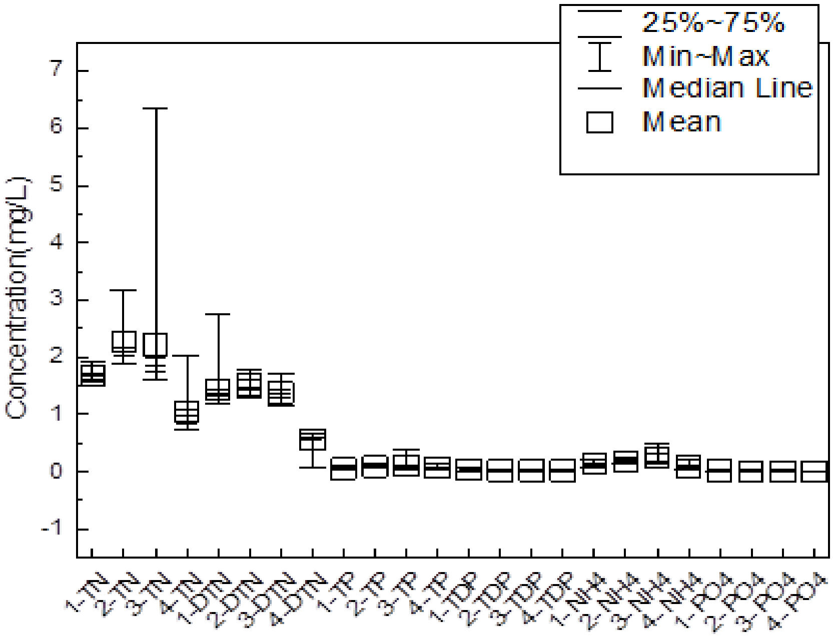

Figure 4. Box plot of the compression of concentration nutrients during suspension processes in fourth Hydrodynamic conditions in Meiliang Bay: 1- weak wind in 2014, 2- strong wind in 2014; 3- Vessels in 2016 and 4- Weak wind in 2018.

(2019).

Most of the previous sediment dynamics observations have been done in rivers and open channels where sediment resuspension is mainly caused by current-induced shear stress (Wang et al., 2014). However, it has been shown that wind-induced wave contributes significantly to the sediment resuspension process in shallow lakes, ponds, and nearshore of the lakes. Wave-generated shear stress contributed more than 70% to sediment resuspension in shallow lakes (Sheng, 1979; Wang et al., 2014). Understanding the mechanisms of water eutrophication is important and will help with the prevention of water eutrophication. Water eutrophication in lakes, reservoirs, estuaries, and rivers is prevalent around the world, specifically in developing countries such as China (Yang et al., 2008; Qin, 2009).

The results of the compressions method evaluate the spatial and temporal variation of the water surface quality of Meiliang Bay. The statistical analysis of all the selected variables Temperature (Temp)°C, Dissolved oxygen (DO)/mg/L, Salinity (SAL), pH, Chlorophyll-a (Chl-a) µg/L and Turbidity (Turbid) NTU are confirmed the trophic state (Table 2) and categorises statistically two different hydrochemical groups that could be important in the physical background. The compressions method provided similar results that corresponded with the lake's real trophic cases. Strong evidence that the regression relationship between chlorophyll-a, dissolved oxygen with P-value = 0.00, and pH levels in Meiliang bay are significantly time-dependent and correlated when algal growth increased the dissolved oxygen decreased in the seasons. Hypoxia is the result of low Dissolved oxygen content (≤2 mg/L) in shallow lakes and it lies at the variable depth of water profile causing eutrophication in shallow lakes (Zhou et al., 2013). This Bay is facing severe water quality and algal bloom problems (Zhu et al., 2013; Liu et al., 2014) which is directly related to the wind-induced vertical mixing of nutrients and reduced amount of dissolved oxygen causing increased hypoxia. Our finding is similar to the study found by Khan and Ansari (2005) which demonstrated that the pH and dissolved oxygen affecting water eutrophication and both factors are very important.

Also, increased the maximum means values of total Nitrogen (TN), total dissolved nitrogen (TDN), Ammonia (NH_4) and Phosphate (PO_4) with strong wind and vessels this indicated that during different hydrodynamic conditions the most nutrient released from the bottom layer in the lake by those forces is nitrogen and sensitive for resuspension in the water. Furthermore, the results revealed that nitrogen is the critical limiting factor to algal growth and eutrophication in Lake Taihu, this finding corresponds to the studies found by Alongi et al. (2003), Paerl et al. (2011). Moreover, Cheng and Li (2006) shown that the eutrophication or red tide happens when N concentration in water reaches 300 µg/L and P concentration reaches 20 µg/L. The trophic mean state in Meiliang Bay in the three summer seasons nearby the same but in 2014 is the strongest than 2016 and a noticeable decline in 2018. This result may be because of climate changed or the heavy rain during the field observation period.

Conclusion

The present study studied the compressions between different hydrodynamics conditions. Filed observations were in summer seasons at various hydrodynamic forces in Meiliang Bay Lake Taihu. The results indicated that the bottom layer has a significant impact on strong winds and vessel waves. Furthermore, when the shear stress generated by those forces, it impacted directly on the boundary of the lake and caused sediment resuspension leading to release nitrogen. The worst water quality was in summer season in 2014 and 2016, and then entirely decline in 2018. These results may be due to Typhon or heavy rain during the collection of data. The new method of hierarchical cluster analyses and variance was used to assess the water quality in different hydrodynamic conditions. The outcomes of this paper give a clear idea about the processes happening in the lake and which force is more effective on the boundary and released nutrients that encourage algal blooms in these seasons.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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