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RESEARCH ARTICLE

Dynamic monitoring of resuspension in the multiple eco-types of the littoral zone of a shallow wind-disturbed lake

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Abstract

Sedimentation and resuspension processes, are known to govern nutrient cycling and lake metabolic processes, but have not been well studied in littoral zones with multi-ecotypes of shallow wind-disturbed lakes. This time-series study used sediment traps to estimate the spatiotemporal changes in sedimentation and resuspension rates, during the four seasonal continuous deployment periods, in the littoral zone of Lake Taihu. The effect of sedimentation processes on nutrient accumulation was also investigated. Results showed that the sedimentation rates at six observation sites were highly variable, with gross sedimentation rates ranging from 184.83 to 2150.74 g m^{-2} day^{-1}. Almost 88% of the total observed sedimentation originated from sediment resuspension. Cyanobacterial blooms coupled with the frequently changeable wind conditions in the littoral zone, were the key factors in lacustrine sediment redistribution and a large pool of organic material accumulated during cyanobacterial blooms. Moreover, the contribution of resuspended total phosphorous and total nitrogen to the water column, were 0.22 mg L^{-1} and 0.46 mg L^{-1}, respectively. The high rate of rapid nutrient cycling observed at the sediment water interface due to resuspension, may be a key factor in maintaining eutrophication in large and shallow lakes, which is of high relevance to the future management of aquatic ecosystems.

Keywords Gross sedimentation · Sediment resuspension · Sequential sediment trap · Eutrophication lakes

Introduction

Sediment resuspension has been shown to affect sediment nutrient cycling and sedimentation, and is recognized as an important internal process in large and shallow lakes (Bloesch 1994; Tammeorg et al. 2013; Matisoff et al. 2017). In recent decades, a growing number of studies have been performed on reservoirs (Chalar and Tundisi 2015), rivers (Ganaoui et al. 2004), estuarine deltas (Sedláček et al. 2016), tidal creeks (Voulgaris and Meyers 2004) and lakes (Zhu et al. 2015; Ding et al. 2017). Conversely, relatively few studies have been performed on lake littoral zones, despite their importance as a transitional zone between lakes and their adjacent terrestrial ecosystems (Hofmann et al. 2011).

Resuspension in the littoral zone can be affected by many factors, such as natural wind and wave events (Tammeorg et al. 2013), presence of aquatic vegetation (Kaitaranta et al. 2013), river plumes from catchment run-off (Whinney et al. 2017), dredging and dredging-related activities (Qi et al. 2014). Various studies have shown that surface waves are the most important cause of resuspension in the littoral zone of lakes, due to the absence of tides, large river inflow and synoptic-scale motions in these environments (Chung et al. 2009; Hofmann et al. 2011). Wave-induced resuspension depends on wind speed, duration and direction (Evans 1994; Li et al. 2017). In some shallow lakes, wave-generated shear stress contributes more than 95% to total sediment resuspension (Li et al. 2017). Additionally, the effect of aquatic vegetation on resuspension

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has also been investigated, focusing on vegetation distribution, type and properties, due to their important role in structuring of ecosystems (Horppila and Nurminen 2005; Zhu et al. 2015; Li et al. 2016). Lake ecotypes are determined by the lakes natural geographical characteristics and differ according to their varying ecologies. Based on the hydrological conditions and distribution of vegetation, the littoral zone ecotype is classified into three types, either near-river, bare and macrophyte type. These ecotypes have significantly different turbidity levels and underwater light fields (Liu et al. 2013), indicating differences in resuspension. However, little is known about the effects of wind-induced sediment resuspension coupled with multi-ecotypes on the littoral zone of shallow lakes.

In previous decades, various methods have been used to determine sediment resuspension in large shallow lakes, such as mass balance calculations (Håkanson et al. 1989), multiple point water samplers (Hu et al. 2005), various modelling approaches (Ganaoui et al. 2004), laboratory experiments (Huang et al. 2015), using optical and acoustical instruments (Voulgaris and Meyers 2004; Li et al. 2017) and sediment traps (Zhu et al. 2015; Matisoff et al. 2017). Owing to their simplicity and widespread use, sediment traps are commonly used as standard tools for determining sediment resuspension in shallow lakes (Storlazzi et al. 2011; Whinney et al. 2017). Some operational issues do exist, such as the accuracy and efficiency of traps, required exposure time, preservation and mineralization (Håkanson et al. 1989; Zajączkowski 2002). To address these issues, a sequential sediment trap was used to estimate the sedimentation rates in a shallow wind-disturbed lake. Sampling bottles were mounted on a carousel, sequentially rotating new bottles under a collection funnel for a predetermined time interval, providing that the exposure time of sediment traps was kept adequately short (24 h).

This study focused on resuspension in the littoral zone with multi-ecotypes of a shallow wind-disturbed lake, with the hypothesis that multi-ecotypes play different roles in sediment sedimentation and resuspension. Hence, the main objectives of this study were as follows: (1) to elucidate the spatiotemporal variations in gross sedimentation and resuspension rates in the littoral zone of a shallow wind-disturbed lake, with multi-ecotypes; (2) to explore the main factors causing variation in the rates of sedimentation and resuspension; and (3) to discuss the response of nutrient accumulation to variation in sedimentation and resuspension processes in shallow wind-disturbed eutrophic lakes.

Materials and methods

Study area

Lake Taihu (30°56′–31°33′N, 119°54′–120°36′E) is the third largest shallow freshwater lake in China and is situated at the south of the Yangtze River delta, with a mean depth of 1.9 m, an area of 2338 km^2 and a water retention time of about 5 months (Qin et al. 2007). Generally, water enters the lake from the western side and exits from the southeastern side via the Taipu River, resulting in water quality being better in the south of the lake than in the north.

The study was conducted in Zhushan Bay in the north of Lake Taihu, one of the most eutrophic areas of the lake. The bay is a semi-enclosed with a water depth of 1.2–2 m and surface area of 66 km^2 (Wang et al. 2015). The main inflow rivers in the northwest are Hengtang, Taige, and Caoqiao, with significant cyanobacterial blooms and eutrophication in the region due to nutrient loading from the inflowing rivers. The study sites were situated in the western littoral zones of Zhushan Bay, except for site 1 which was located in the center of the bay (Fig. 1). Site 2 was located 250 m from the Hengtang river. Sites 1 and 2 were surrounded by the inflowing river, representing near-river areas. Sites 3 and 4 represented macrophyte areas. Site 3 was located 150 m from the western lakeshore, with 80% macrophyte coverage of the sampling area based on visual estimation (*Phragmites communis, Triarrhena sacchariflora, Arundo donax, Polygonum, Zizania caduciflora*). Site 4 was located 150 m from the western lakeshore, with 100% (visual estimation) macrophyte coverage, with the same species composition as site 3. At sites 3 and 4, macrophyte growth patterns showed sprouting in late February; growth to the water surface level in May and withering from October to December. Sites 5 and 6 were located in the south of Zhushan Bay with no observable macrophyte coverage. Sites 5 and 6 both faced the open water area and were exposed to long-lasting and sustained, strong winds, allowing sites 5 and 6 to represent bare areas.

Sampling and analyses

Gross sedimentation was determined using a sequential sediment trap (plexiglass tube, 9 cm in diameter and 50 cm in height), optimized from the method of Douglas et al. (2003). The sequential sediment trap was deployed four times, with each continuous observation period lasting 12 days (12–24 Oct 2016; 31 Dec 2016 to 12 Jan 2017; 19 Apr to 1 May 2017; and 7–18 August 2017). During each deployment, 36 sediment traps were divided into 12 times to get back at each site. All the contents within the sediment traps, including sediment, water, and organic detritus, were collected with the sampling frequency of 24 h. Three stakes were fixed at 1.5 m intervals at each site, to prevent movement of traps during extreme weather. The inlet of the trap was 0.5 m above the sediment surface and the trap was anchored using a stainless-steel shelf fixed to the stakes.

The levels of dissolved oxygen (DO), pH, temperature and water turbidity were measured in situ at each

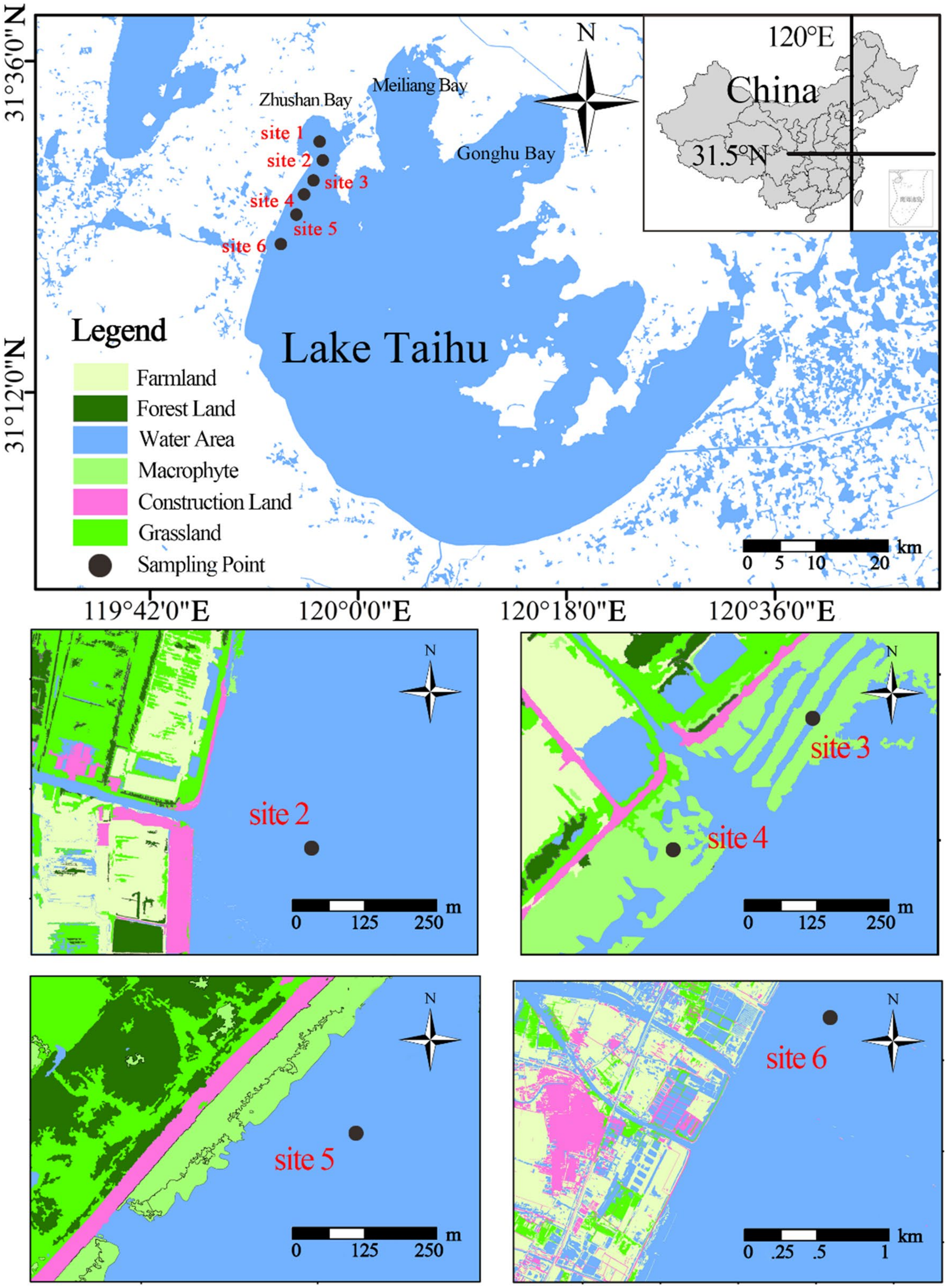

Fig. 1 Schematic diagram of the sampling sites in Lake Taihu. Site 1 was located in the central region of Zhushan Bay. Site 2 was located in the Hengtang river, 0.3 km away from the estuary. Sites 3 and 4 were located in the artificial reed area. Sites 5 and 6 were located in the south of Zhushan Bay facing the open lake area

site using a 6600V2 multi-sensor sonde (Yellow Springs Instruments (YSI) Corporation, USA). Water depth was measured using a SD5000 portable digital water depth gauge (Yijie Instrument, Shenzhen, China). High-frequency wind speed and direction data were collected at 5 min intervals for the Taihu Basin, from the hydrological information service system (http://218.1.102.99:8100/indexCloud.html). At each sampling event, surface sediment samples were collected from the 0–1 cm layer using a Peterson grab sampler and triplicate water samples were collected using a tube sampler. Sediment cores were collected using a gravity core sampler from all sites, for analysis of total nitrogen (TN) and total phosphorous (TP). Sediment cores were cut into 2 cm intervals and sediment samples were immediately transported to the laboratory in plastic sealed bags, then freeze dried at − 45 °C for 72 h. Samples were then stored at − 4 °C for less than 24 h prior to analysis.

In the laboratory, the entire contents of the traps were dried at 105 °C and weighed. The organic fraction of the dry weight of entrapped material and surface sediments (0–1 cm layer), were determined by ignition at 550 °C. Gross sedimentation was expressed as grams per day per square meter (g m^{-2} day^{-1}). Triplicate water samples from each site were filtered through GF/C filters, dried at 105 °C and weighed, then determined by ignition at 550 °C. Chemical analyses of water samples and sediment core samples (including TN and TP) were determined by spectrophotometry, following digestion with alkaline potassium persulfate according to the method of Ebina et al. (1983). The rate of nutrient resuspension at each site was estimated from the calculated resuspension rates and the nutrient content of surface sediments (0–1 cm layer).

The sediment resuspension rate was estimated using the method developed by Gasith (1975), which is applicable in shallow water bodies and has previously been applied successfully in Lake Taihu (Zhu et al. 2015). The method uses the equation:

$$R = S \times \frac{(fS - fT)}{(fR - fT)} \tag{1}$$

where R is the resuspended sediment (mg, dry weight); S is gross sedimentation (mg, dry weight); f_R is the organic fraction of surface sediment (%); f_S is the organic fraction of S (%); and f_T is the organic fraction of suspended sediment (%). The method by Gasith (1975) assumes that the organic fraction of surface sediments (f_R), is different from that of suspended sediments (f_T). In the present study, f_T was significantly higher than f_R, allowing the method of Gasith (1975) to be reliably used.

Statistical methods

Statistical analysis was performed using the Statistical Package for the Social Sciences 19.0 (SPSS 19.0). The correlations between gross sedimentation or resuspension rate and wind speed, were individually analyzed using the Pearson correlation coefficient for each observation site, at the $p < 0.05$ and $p < 0.01$ levels of significance. The differences in resuspension rates and gross sedimentation observed at different sites, were analyzed by paired sample T test, at the $p < 0.05$ and $p < 0.01$ levels of significance. Analysis of variance for repeated measurements (two-way ANOVA) was performed for gross sedimentation and resuspension rates from triplicate traps, with the following varying effects: season (four levels), observation site (six levels) and the interaction of season and site. Post-hoc comparison of means were performed using the Student–Newman–Keuls's tests.

Results

Variations of wind speed and direction

During the observation period, mean daily wind speed varied from 0.9 to 6.6 m s^{-1} and the maximum daily speed ranged from 3.6 to 11.5 m s^{-1}, indicating that wind conditions were unsteady and frequently changeable in the littoral zone of Zhushan Bay (Fig. 2). During the winter observational period, wind speeds were relatively low at less than 4 m s^{-1} and daily maximum wind speeds only occasionally exceeded 9 m s^{-1}. During the spring observational periods, the wind speed was changeable in the littoral zone, increasing from 2.6 to 5.8 m s^{-1} between 22 and 23 April 2017, then decreasing from 5.5 to 1.7 m s^{-1} between 26 and 27 April 2017. 70% of all recorded wind speeds ranged from 4 to 6 m s^{-1}, with the lowest average wind speeds observed in winter and increasing wind speeds towards summer. The prevailing wind direction was from the north during winter and from the southeast during summer.

Gross sedimentation and resuspension rate

Gross sedimentation and resuspension rates differed significantly according to both season and observation site ($p < 0.05$), with interactions also found between the two factors (Table 1). Analysis of the temporal variation in gross sedimentation, shows that there was an increase in gross sedimentation during spring and summer. The average gross sedimentation rates in spring and summer across all six observation sites were 1691.1 and 1147.9 g m^{-2} day^{-1}, respectively, while the average values were only 319.5 and 163.6 g m^{-2} day^{-1} in autumn and winter, respectively (Fig. 3). Spatially, the gross sedimentation rate was

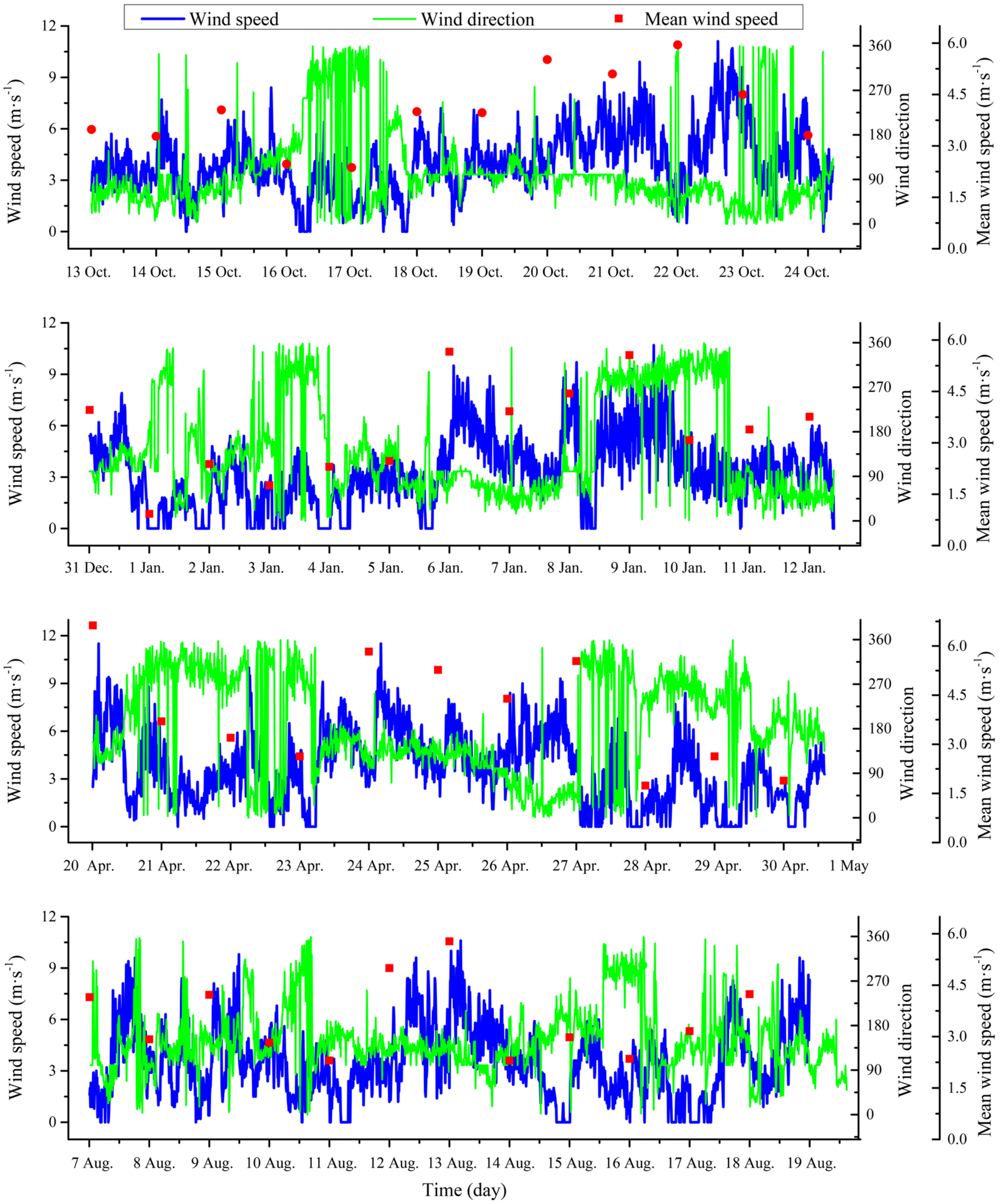

Fig. 2 High frequency wind speed data at 5 min intervals and recorded wind direction during the observation periods: **a** 12th October to 24th October 2016 (autumn), **b** 31st December 2016 to 12th January 2017 (winter), **c** 19th April to 1st May 2017 (Spring), **d** 7th August to 18th August 2017 (Summer)

consistently and markedly higher in bare areas (site 5 and 6) of Zhushan Bay, with average gross sedimentation rates almost an order of magnitude higher than at other sites in macrophyte areas of Zhushan Bay (Fig. 3). The ranked order of average gross sedimentation rates across all sites was: site 5 > site 6 > site 4 > site 1 > site 2 > site 3. It is of note, that the average gross sedimentation rate was 1423.6 g m^{-2} day^{-1} in areas containing no macrophytes and 434.7 g m^{-2} day^{-1} in macrophyte areas during the observation periods.

Continuous observation at all 6 sites revealed that gross sedimentation rates showed high daily variation during the observation period. During the four seasonal deployments

Table 1 Two-way ANOVA with gross sedimentation and resuspension rate among all 4 seasons and six observation sites

	df	Gross sedimentation		Resuspension rate	
		F value	*p* value	F value	*p* value
Season	3	4.45	0.025*	4.57	0.023*
Site	5	8.02	0.000*	7.39	0.000*
Season × Site	15	3.37	0.000*	3.70	0.000*

Values given are F and *p* statistics for n = 3 replicates

*Denotes significant *p* value ($p < 0.05$)

of the sequential sediment trap, the daily gross sedimentation rate varied from a minimum of 12.7 g m^{-2} day^{-1} to a maximum of 8193.6 g m^{-2} day^{-1} (Fig. 4). The gross sedimentation rate markedly increased from 26.8 to 7540.1 g m^{-2} day^{-1}, with an increase in mean wind speed from 2.1 to 5.8 m·s^{-1}. The four seasonal deployments of the sequential sediment trap, allowed data to be used to establish the correlation between gross sedimentation rate and mean wind speed. Results show that the correlation coefficients during autumn 2016, winter 2016, spring 2017 and summer 2017, were 0.85 ($p < 0.01$), 0.63 ($p < 0.05$), 0.83 ($p < 0.01$) and 0.94 ($p < 0.01$), respectively. Therefore, wind conditions caused a significant temporal pattern in sedimentation rates.

To examine the relationships between the variation in mean wind speed and resuspension processes, the daily resuspension rate was determined during all four deployment periods, along with monitoring of wind conditions in the littoral zone. Resuspension rates exhibited a similar seasonal pattern to gross sedimentation rates in the littoral zone, with large peaks observed in spring and summer, then abruptly decreasing from autumn to winter at all observation sites (Fig. 5). The average resuspension rate across all 6 observation sites in spring and summer, were 1644.7 and 819.5 g m^{-2} day^{-1}, respectively. Conversely, average values were only 262.1 and 134.5 g m^{-2} day^{-1} in autumn and winter, indicating that on average 88% of gross sedimentation originated from resuspended sediments. The resuspension rate also showed good correlation with mean wind speed ($r > 0.8$, $p < 0.01$), suggesting that frequent and changeable wind conditions in the littoral zone may be the precipitating factors for sediment resuspension.

Characteristics of water and sediment quality

Water quality varied significantly in the littoral zone of Zhushan Bay (Table 2). Water temperatures varied from 8.9 to 30.9 °C, while the concentration of DO ranged from 1.0 to 9.0 mg L^{-1}, with the lowest DO levels coinciding with maximum water temperatures during summer. The concentrations of TN and TP showed significant seasonal variation, with TN concentrations ranging from 2.1 mg L^{-1} in summer at site 1 and site 2, to 6.3 mg L^{-1} at site 4 (macrophyte areas), with an annual average of 3.8 mg L^{-1}. TP concentrations ranged from 0.10 mg L^{-1} in spring at site 1, to 0.55 mg L^{-1} in summer at site 4, with an annual average of 0.26 mg L^{-1}. Additionally, the ratio of TN to TP (TN/TP) in Zhushan Bay also displayed a seasonal pattern, driven by asynchronous dynamics of TN and TP. During summer and autumn, mean TN/TP ratios varied from 7.2 to 14.5, respectively, across all six observation sites, although during winter and spring, this ratio ranged from 11.5 to 36.4, respectively.

Organic matter concentrations ranged from 8.4 to 15.5% in macrophyte areas (site 3 and 4) and from 2.5 to 12.6% in bare areas (Fig. 6). The maximum observed organic matter concentrations, were found to coincide with the lowest DO concentrations during the observation period. In the inner sites of Zhushan Bay, organic matter concentrations were markedly higher than in the outer sites (site 5 and 6), with an almost 2- or threefold difference observed in Summer.

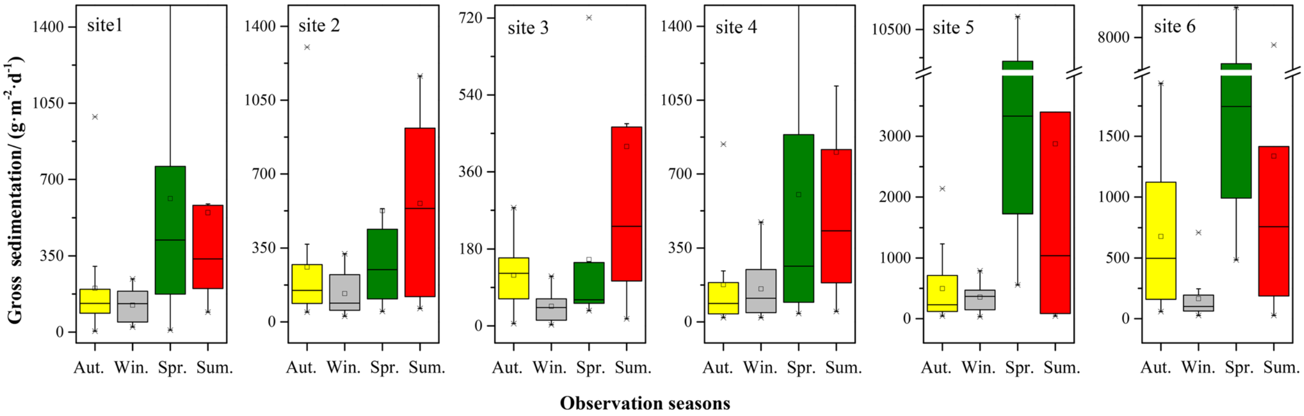

Fig. 3 Box plots showing the distribution of gross sedimentation at all 6 sites. Box encompasses 50% of the values, while small squares represent mean values. Aut., Win., Spr. and Sum., represent Autumn, Winter, Spring and Summer, respectively

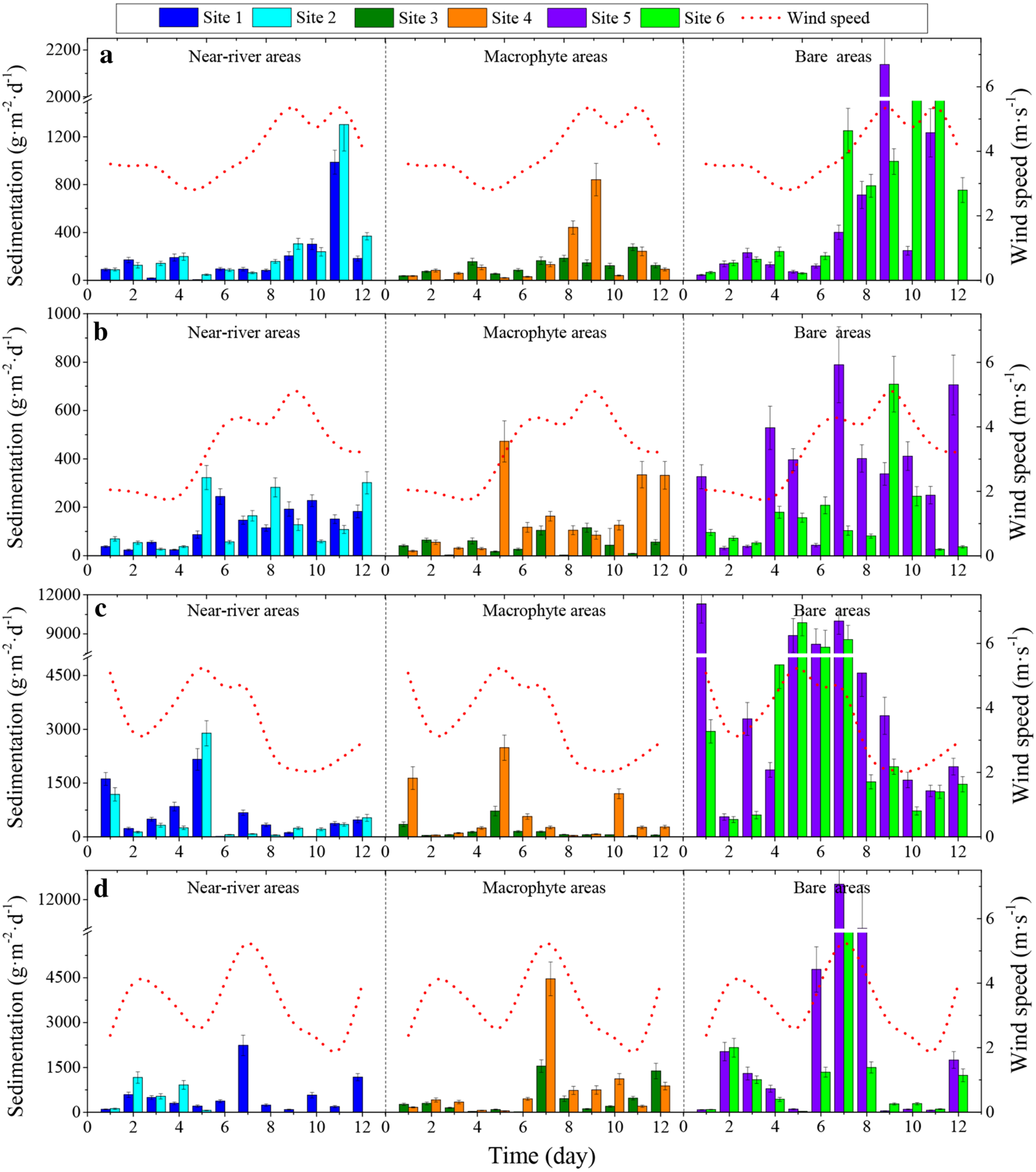

Fig. 4 Continuous observation of daily gross sedimentation rate and mean wind speeds, across all six observation sites in the littoral zone of Zhushan Bay. Horizontal coordinates represent monitoring days, numbered sequentially in a range of 1 to 12. Sites 1 and 2 indicate near-river areas; Sites 3 and 4 indicate macrophyte areas; Sites 5 and 6 indicate bare areas. **a** 12th October to 24th October 2016 (autumn), **b** 31st December 2016 to 12th January 2017 (winter), **c** 19th April to 1st May 2017 (spring), **d** 7th August to 18th August 2017 (summer). During sampling at site 2 in summer, some data were missing due to faulty sediment traps

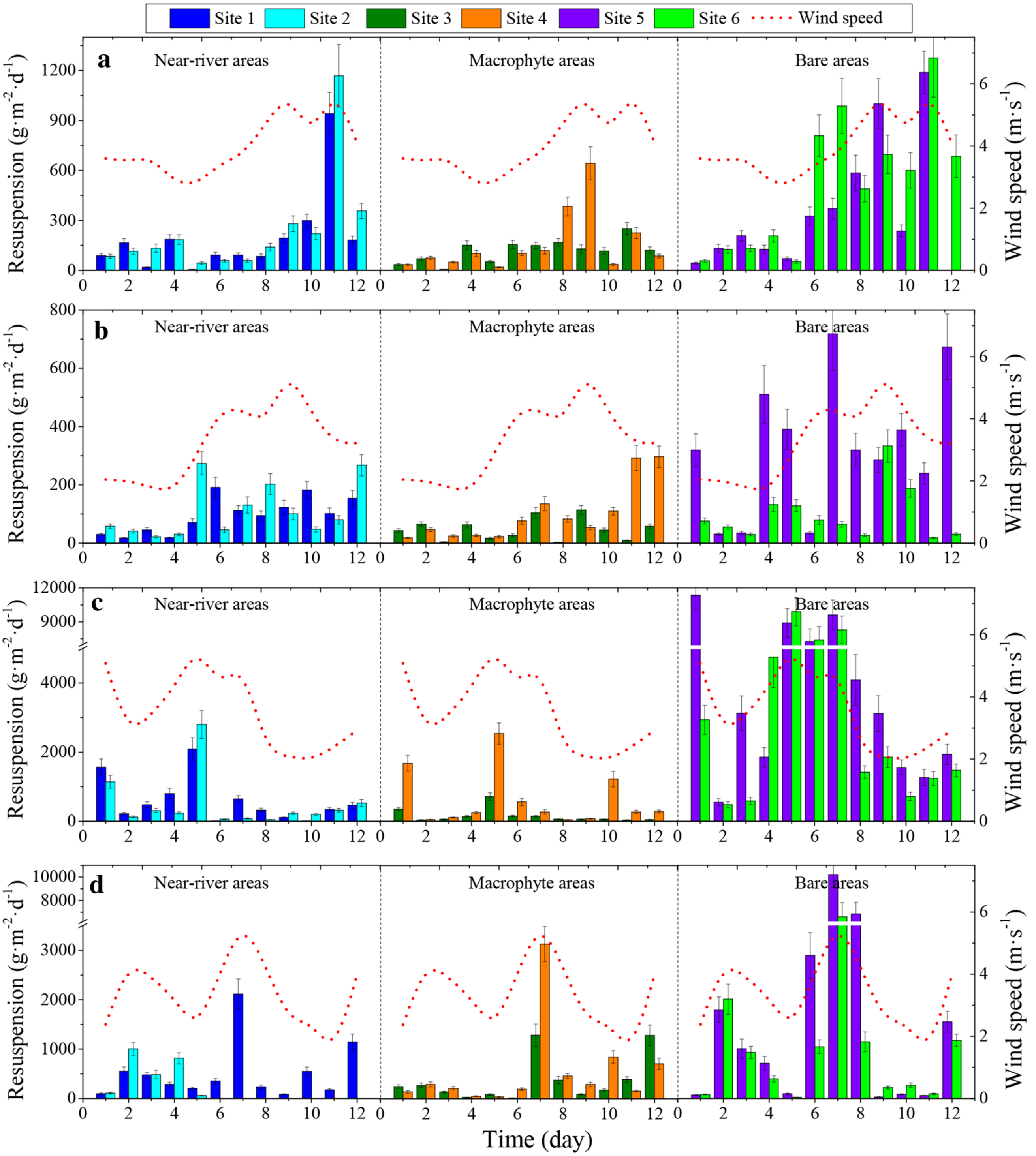

Fig. 5 Daily resuspension rate and mean wind speed during the four deployment periods, at all six observation sites in the littoral zone of Zhushan Bay. Horizontal coordinates represent monitoring days, numbered sequentially in a range of 1 to 12. Sites 1 and 2 indicate near-river areas; Sites 3 and 4 indicate macrophyte areas; Sites 5 and 6 indicate bare areas. **a** 12th October to 24th October 2016 (autumn), **b** 31st December 2016 to 12th January 2017 (winter), **c** 19th April to 1st May 2017 (spring), **d** 7th August to 18th August 2017 (summer). During sampling at site 2 in summer, some data were missing due to faulty sediment traps

Table 2 Water quality characteristics at the sampling site in Zhushan Bay, Lake Taihu, from October 2016 to August 2017

Sites	T (°C)				DO (mg L^{-1})				TN (mg L^{-1})				TP (mg L^{-1})				TN/TP			
	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.
1^{NA}	20.4	9.1	20.1	29.9	4.8	7.4	7.3	3.4	2.8	4.9	3.7	2.1	0.24	0.26	0.10	0.19	11.8	18.8	36.4	11.1
2^{NA}	20.6	8.9	20.2	30.9	3.4	7.3	6.5	2.1	3.3	4.9	3.9	2.1	0.23	0.25	0.14	0.29	14.5	19.4	28.1	7.4
3^{MA}	20.7	8.9	18.1	29.9	1.9	5.6	2.3	1.0	3.3	4.6	4.1	6.1	0.34	0.15	0.36	0.54	9.7	30.6	11.5	11.3
4^{MA}	20.7	8.9	20.1	29.9	3.3	6.3	7.5	2.2	2.8	4.5	3.1	6.3	0.27	0.18	0.11	0.55	10.6	25.0	27.5	11.4
5^{BA}	20.7	8.8	19.6	29.7	5.0	8.3	8.3	5.0	3.1	4.4	2.8	4.4	0.43	0.19	0.18	0.38	7.2	23.1	15.5	11.6
6^{BA}	20.8	8.9	20.0	30.0	6.2	9.0	8.6	5.0	2.6	4.3	2.6	3.3	0.30	0.21	0.11	0.35	8.9	20.9	23.7	9.3

Aut., Win., Spr. and Sum., represent Autumn, Winter, Spring and Summer, respectively

BA bare areas, *NA* near-river areas, *MA* macrophytes areas

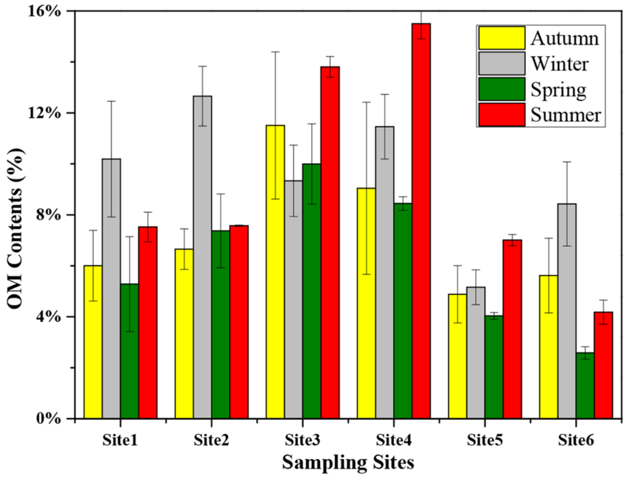

Fig. 6 Seasonal variation in organic matter concentrations, at all six observation sites in the littoral zone of Zhushan Bay. Data were obtained from surface sediment samples (0–1 cm layer)

Sediment quality also showed significant variation according to vertical distribution, with TN and TP concentrations showing similar variations, with peaks in concentrations in the surface sediment layer, followed by a decreasing trend at lower depths (Fig. 7). However, TN concentrations ranged from 437.8 to 2006.8 mg kg^{-1} in macrophyte areas, while concentrations varied between 442.3 and 942.5 mg kg^{-1} in bare areas. TN concentrations in the surface 15 cm depths of macrophyte areas were significantly larger than in bare areas. The observed TP distribution pattern was similar to that of TN in the sediments, with a high degree of enrichment in the surface layer. TP concentrations ranged from 220.1 to 1641.9 mg kg^{-1} in macrophyte areas and from 232.7 to 729.4 mg kg^{-1} in bare areas.

Discussion

The observed gross sedimentation and sediment resuspension rates, exhibited significant temporal and spatial variations depending on the different ecotypes in the littoral zone of Zhushan Bay. The gross sedimentation and resuspension rates across all sites, were generally higher during spring and summer, than during autumn and winter (Fig. 3). This phenomenon has also been reported in other lakes, for example, Bloesch and Uehlinger (1986) observed that 70–80% of the gross annual sedimentation occurred during summer. In shallow lakes, the sediment resuspension process is dominantly via wind induced orbital wave movement in the water column (Hofmann et al. 2011; Tammeorg et al. 2013). In the present study, during the observation periods, wind patterns were found to be strongly affected by the southeast monsoon. The general wind conditions were characterized by wind speeds between 3 and 5 m s^{-1} for 70% of all the observation periods, with southeastern wind directions dominant (Fig. 2). Qin et al. (2004) found that the threshold of wind speed for sediment resuspension was 4 m s^{-1} in Lake Taihu. Horppila and Niemistö (2008) reported that fluctuation in resuspension rates were strongest when winds were blowing along the longitudinal axis of the lake, which is a southeastern direction in Lake Taihu. As a result, gross sedimentation and resuspension rates showed significant seasonal variation, with the highest values reported in spring and summer. Hence, lacustrine sediment redistribution is mainly associated with wind speed and direction.

In addition, due to the influence of the dominant wind direction (south-easterly), a high mass of algal and aquatic plant residues accumulated in the littoral zone of Zhushan Bay. Similarly, Tammeorg et al. (2013) reported that the substantial increase in resuspension rates observed during August, were significantly affected by phytoplankton populations. Similar variation patterns in resuspension activity have also been reported in eutrophic Lake Arresø, Denmark (Søndergaard et al. 1992). Authors reported that this phenomenon was due to organic matter accumulation

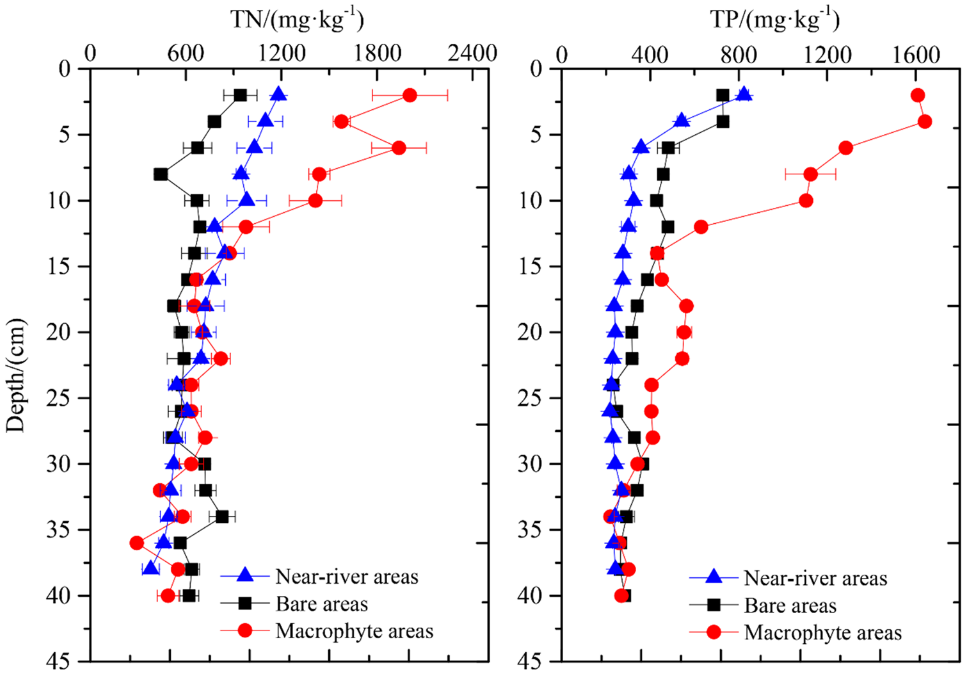

Fig. 7 Vertical distributions of TN and TP concentrations in sediment cores at 2 cm intervals, sampled from near-river area (site 1), bare area (site 6) and macrophyte area (site 3) in the littoral zone of Zhushan Bay. Values represent mean ± SD from triplicate analyses

in sediments during summer. Macrophyte areas create new sedimentation environments and have been found to induce changes in existing sediment environments. In many shallow eutrophic lakes, cyanobacterial blooms can be generally driven by the wind, causing accumulation in the littoral zone or entrapping algae in emergent macrophytes, forming a dense scum of 10–30 cm in thickness (Xing et al. 2011). Cyanobacterial blooms produce a high level of organic matter, composed of numerous functional groups and can act as a flocculant, or combine with inorganic particulates (Zhang et al. 2016). These findings suggest that the rapid gross sedimentation rates observed in the littoral zone of Zhushan Bay were at least partially attributed to cyanobacterial bloom events during spring and summer.

It is of note, that during the sampling periods the average gross sedimentation rate was significantly higher in areas containing no macrophytes, than in macrophyte areas ($p < 0.01$, Figs. 4, 5). The correlation coefficients between wind speed and resuspension rate were 0.55, 0.46, 0.37, 0.42, 0.48 and 0.49 for sites 1–6, respectively. The near-river areas (sites 1 and 2) and bare areas (sites 5 and 6) had higher correlation coefficients than macrophyte areas (sites 3 and 4), which indicates that macrophytes have an effect on the wind speed-resuspension relationship. Previous studies have found that in other shallow lakes, the presence of macrophytes induced a substantial effect on reducing sediment resuspension rates (Li et al. 2016). Evans (1994) reported an order-of-magnitude estimate, that the long-term contribution of resuspended material to the total flux of particulate matter was 85%. In the present study, results showed that on average 88% of gross sedimentation originated from resuspended sediment. Therefore, the lowest gross sedimentation rate coincided with the lowest sediment resuspension rate occurring in macrophytes areas. The observed effects may due to the different structural properties and distribution patterns of macrophytes. The ratio of resuspension rates in the growth season (spring and summer) versus the degradation season (autumn and winter), were 9.77 and 7.60, at sites 5 and 6 (bare areas), respectively. In comparison, the ratios were only 3.19 and 4.01, at sites 3 and 4 (macrophyte areas), respectively. Dense summer macrophyte growth can increase the retention of fine particles and organic matter, due to the hydraulic resistance from the vegetation (Li et al. 2016). Therefore, macrophytes induce a strong influence on variability of sediment resuspension rates in different regions. Previous studies have also shown that macrophyte community type and density, can have a significant effect on the stabilization of sediments against wave activity and resuspension (James 2004; Horppila et al. 2013; Zhu et al. 2015). Therefore, besides wind speed, the structure and seasonal development of macrophyte communities are also key factors in the reduction of sediment resuspension.

Sediments are an important component of lake ecosystems, due to the dynamic variation between acting as a source and a sink (Pejrup et al. 2013). Under the conditions of sedimentation, sediments absorb substances in lake water, serving as a sink for nutrients and pollutants. In resuspension dominated environments, the substances retained in the sediment are desorbed and released back into the water column, providing a source of nutrients and pollutants within lakes. Previous studies have proposed that wind-induced sediment resuspension is a causative factor in maintaining eutrophic conditions in large and shallow lakes (Tammeorg et al. 2013). This phenomenon has been reported in Lake Winnipeg (Matisoff et al. 2017) and Lake Kinneret (Eckert et al. 2003), with the present study further supporting this conclusion. When the wind-force is imposed on the lake, it drives sediment resuspension, with nutrient release from pore water to overlying water, following sediment resuspension. Hydrodynamic disturbance therefore enhances nutrient absorption by suspended particulates. After the withdrawal of wind force, the suspended mass re-deposits on sediment surface, returning some of the released nutrients back to the sediment until further wave or wind force is applied for resuspension and nutrient release (Qin et al. 2004). The estimates for the contribution of TP and TN to the water column due to resuspension, were significantly higher in the present study (TP increased by 0.22 mg L^{-1} and TN increased by 0.46 mg L^{-1}) than the values previously estimated by Zhu et al. (2015) in Lake Taihu (TP increased by 0.05 mg L^{-1} and TN increased by 0.34 mg L^{-1}). The observation sites for Zhu et al. (2015) were located in Gonghu Bay, where shorter effective fetch lengths are observed than in Zhushan Bay. It is of note, that the sediment trap exposure time (14-day interval) was longer than in the present study (24-h interval), which may be a contributing factors to the lower level of flux reported previously (Zhu et al. 2015). Long exposure times enhanced the release and mineralization of organic matter and nutrients, reducing the organic fraction of gross sedimentation. Previous studies have shown that bi-weekly loss of material may account for 10% of the retained sample (Chalar and Tundisi 2015; Whinney et al. 2017). Therefore, prolonged exposure times are not optimal and repeated daily or weekly sample recoveries should be planned in shallow lakes. The high level of nutrient loading coupled with high resuspension rates in spring, may facilitate algal bloom formation. Kling et al. (2011) reported that a dramatic rise in severe algal blooms coincided with a large increase in internal phosphorus loading in the lake. Ding et al. (2018) investigated the contribution of internal phosphorous loading over a 1-year field sampling study, in a eutrophic bay of Lake Taihu. Results showed that TP release from sediments accounted for 54% of the increase in TP in the water column, during the pre-bloom period. Similar results were observed in Lake Dianchi, where almost 77% of TP and 72% of TN inputs were from internal loading processes (Wu et al. 2017). Frequent resuspension processes in shallow lakes, accompanied by high internal loading, may be factors responsible for the delay in recovery of eutrophic lakes following reduction of pollution inputs. In addition, the ecotype plays a vital role in nutrient cycling and dynamics in the littoral zone of aquatic ecosystems. For example, in macrophyte areas, macrophytes can utilize nutrients from both the water column and sediments. Conversely, in near-river and bare areas, nutrient dynamics were determined by wind-driven sedimentation and resuspension processes. It is of note, that TN and TP concentrations in the upper surface layer of water (to a 15 cm depth) in macrophyte areas, were markedly larger than in near-river and bare areas (Fig. 7). This phenomenon has been previously attributed to two aspects, firstly, the death and decomposition of macrophytes and trapped phytoplankton are a critical nutrient sink in macrophyte areas (Lu et al. 2018), which is consistent with the variation in organic matter concentrations observed in the present study (Fig. 6). Secondly, macrophyte coverage inhibits sediment resuspension, lowering the release of nutrients from the sediment. Alternatively, strong wave motions may erode the upper 10 cm depth of sediments in regions void of macrophytes (Qin et al. 2004), which enhances the release of nutrients from the sediment. Therefore, the effect of sediment resuspension and macrophyte coverage on water quality should receive greater research attention, to support the effective management of aquatic ecosystems.

Conclusions

This study investigates sediment resuspension rates in varying ecotypes, in the littoral zone of a shallow lake. Results show that gross sedimentation and resuspension rates exhibit significant temporal and spatial variations. The gross sedimentation and resuspension rates were generally higher during spring and summer, than during autumn and winter. Spatially, bare and near-river regions exhibited higher gross sedimentation and resuspension rates than the macrophyte areas. The main causes identified for variation in gross sedimentation and resuspension rates at different observation sites, were wind speed and macrophyte coverage. In addition, sedimentation patterns were found to correlate with the accumulation of nutrients, with almost 88% of gross sedimentation originating from resuspended sediment. Frequently occurring resuspension processes in shallow lakes, were accompanied by high rates of internal loading and these may be relevant factors in the delay in recovery of lakes from eutrophic conditions.

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