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EUTROPHICATION IN LAKES

Effects of hydrodynamics on phosphorus concentrations in water of Lake Taihu, a large, shallow, eutrophic lake of China

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Abstract To understand the effect of hydrodynamical process on water phosphorus concentration, wind, wave, and several water quality indices were observed in Meiliang Bay, a shallow and eutrophic bay locates in north of Lake Taihu. During the 7 day observation period, wind speed and significant wave height were recorded more than 3 h per day, and water samples were collected in five water-depth layers once a day. Hydrodynamical disturbance had no significant correlationship with the water quality at the top layer when the significant wave height was smaller than 30 cm, but it significantly increased suspended solids (SS) concentration of the bottom water layer. Concentrations of nutrients showed no positive correlationship with SS concentration in the water body. Intensive sediment resuspension may not have occurred when the hydrodynamic stress on sediment was only a little higher than the critical stress for sediment resuspension. A new method for confirming the critical stress for intensive sediment resuspension and nutrient release still needs to be developed. The range of the water quality indices was quite high during the seven days of observation. High variation seems to be a common character of large shallow lakes like Taihu.

Keywords Shallow lake · Hydrodynamics · Eutrophication · Phosphorus · Algae bloom · Lake Taihu

Introduction

In shallow lakes, wind-induced waves frequently disturb the water-sediment interface, and often cause intensive sediment resuspension. Strong winds may cause significant increases of suspended solids (SS) concentration in overlying water (Aalderink et al., 1984; Carper & Bachmann, 1984; Luettich et al., 1990; Qin et al., 2000; Zhu et al., 2004; Zhu et al., 2005b). The intensive sediment resuspension may increase the internal release of nutrients from sediment (Søondergåard et al., 1992), but sometimes it may also help deposit soluble nutrients into the bottom sediments by sorption and precipitation (Gunatilaka, 1982). Simulated experiments also indicated that hydrodynamics may have both positive and negative effects on sediment nutrient release (Kristensen et al., 1992; Fan et al., 2001). Therefore, effects of hydrodynamical processes on the

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Eutrophication of shallow lakes with special reference to Lake Taihu, China

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exchange of nutrients between sediment and water are quite complicated.

Lake Taihu is the third largest freshwater lake in China (Qin et al., 2007). Water quality of Lake Taihu has been deteriorated quickly since the 1960's due to the drastic effects of anthropogenic activities (Dokulil et al., 2000). The nutrition status of Meiliang Bay (a bay in the northern Lake Taihu) changed from oligo-mesotrophic stage with low algal biomass before 1981 to a eutrophic condition with blooms of *Microcystis* during 1988–1995, and a hyper-eutrophic conditions with the dominance of *Planctonema* and total phosphorus up to 200 mg m^{-3} during 1996–1997 (Chen et al., 2003). Sediment investigations also showed a strong effect of municipal drainage on the water quality of northern bay of Lake Taihu (Qu et al., 2001). At present, the dominant phytoplankton species of Lake Taihu are *Microcystis, Anabaena, Melosira, Cyclotella and Cryptomonas*. *Microcystis* spp. occupies 85% of algae biomass and forms an algal bloom each summer (Chen et al., 1997). Zooplankton grazing is inadequate to control the algae bloom of *Microcystis* (Chen & Nauwerck, 1996; McNaught et al., 1997). Pen fish culture and reconstruction of floating, leave-floating, and submerged plants may benefit water quality improvement (Li & Yang, 1995; Hu et al., 1998; Pu et al., 1998), but are difficult to carry out in a large area like Meiliang Bay.

Wave processes occur frequently in Lake Taihu due to its shallowness and special shape. For example, from 1997 to 1999, daily maximum wind speeds (calculated as hourly average wind speed) higher than 5 ms^{-1} occurred 89.5% of the time, and wind speeds higher than 8 ms^{-1} occurred 34.2% of the time (Fan et al., 2004). A simulation study on Lake Taihu sediment showed that water disturbance caused soluble reactive phosphorus (SRP) release from sediment which was 8–10 times higher than release under undisturbed conditions (Fan et al., 2001). Wave flume experiments showed that the critical shear stress (0.03–0.04 N m^{-2}) that leads to extensive sediment resuspension in Lake Taihu could be induced by a 4–6 ms^{-1} southeast wind event (Qin et al., 2004). Nutrients released from sediment resuspension caused by wind-induced wave may be the main type of internal load of nutrients in Lake Taihu (Qin et al., 2004), but there is little knowledge about the amounts of suspended sediment and released nutrients and also the form of released nutrients in the lake due to the great difficulty in making field observations.

The objectives of this paper are to present field observations on hydrodynamics, wind, water chemistry and algae biomass in Lake Taihu, and to discuss the effect of hydrodynamics on nutrient release from sediments.

Materials and methods

Field observation description

Meiliang Bay locates in the north of Lake Taihu, with an area of 130 km^2. The observation site was selected in the centre of Meiliang Bay to minimize the effect of lake shore on hydrodynamics. Near the observation site, is a regular water quality observation site of Taihu Laboratory for Lake Ecosystem Research (TLLER), which has been monitored every month since 1991. The water depth was 2.4 m at the observation site and did not change significantly during the observation period. On 10th July 2003, a steel-tube platform was set up in the observation site. A wave-meter with three sensors was fixed on the observation platform for wave measurement. An Acoustic Doppler Profile (ADP) was fixed on the platform for lake current measurement. And a Davis meteorological station was fixed on the platform for wind-speed and direction measurement. All of the data were downloaded to computer regularly. A 20 cm long sediment core was collected and sliced to sub-sample each 2 cm depth. Water content (WC, %), bulk density (g cm^{-3}), porosity (%) and loss on ignition (LOI, %) of each sub-sample were measured within 3 h. At the same time, a polymethyl-methacrylate peeper interstitial water sampler with 36 cm long, 1 cm thickness and 0.45 μm membrane was laid at the observation site. After 7 days, the peeper sampler was pulled out and the interstitial water was sampled immediately in each centimeter for Fe^{2+}, PO_4^{3-} and NH_4^+ analysis. Redox potential (Eh) of the interstitial water was immediately measured, too. The meteorological station did not work well the first day, resulting in the loss of some data, so data of wind-speed and direction per hour from the TLLER standard weather station were used for that period.

From 11 July to 17 July, lake water was sampled at 13:00 each day at the five layers (20, 50, 100, 200, and 230 cm). For each water sample, about 100 ml was filtered in the field by 0.45 μm aperture GF/F filter membrane for measuring dissolved total phosphorus (DTP), soluble reactive phosphorus (SRP), ammonia nitrogen (NH_4^+-N), and dissolved organic carbon (DOC). A 250 ml water sample was fixed by alkaline potassium iodide (KI) and manganese sulfate ($MnSO_4$) for dissolved oxygen (DO) determination. Another 1000 ml unfiltered water sample was preserved for total phosphorus (TP), suspended solids (SS) and chlorophyll a (Chl-*a*) analysis. All of the water samples were sent to TLLER for chemical analysis within 2 h. Organic matter in SS was evaluated by loss on ignition (LOI) on the GF/C filter membrane.

Chemical analysis methods

For TP and DTP analysis, water sample was digested by alkaline potassium persulphate in high pressure sterilization pot at 120°C. Then phosphate concentration was determined by molybdenum–antimony–ascorbic acid colorimetry with a Shimadzu UV 2401 spectrophotometer. SRP and NH_4^+-N were determined by colorimetry with Skalar flow-injection analyzer (detection limit for phosphate is 0.001 mg P l^{-1}). DO was determined by sodium hyposulfite titration. DOC was analyzed by I/O 1020A TOC Analyzer. SS was determined by a gravimetric method with Whatman GF/C filter membrane filtration and oven-dried the filtrating residua over 4 h at 105°C. LOI of SS was also determined by gravimetric method with 550°C ignite the SS contained GF/C membrane over 5 h. To determine Chl-*a* concentration, 250 ml water sample was filtered through 0.45 μm pore size synthetic fabric membrane. Chl-*a* concentration was determined by colorimetry after the residue on the membrane was frozen, grinded and extracted by ethanol.

Statistic methods

One way ANOVA analyses of water quality among different wave conditions with Scheffe's method and Tukey's method were carried out by SPSS 11.0 statistical software. Correlation analysis among observed indices was also done by SPSS 11.0.

Results

Physicochemical characteristics of sediment and interstitial water

Eh of interstitial water showed a steep decline in the top 7 cm layer of sediment (Fig. 1), and remained constant in the layer deeper than 7 cm. Concentration of Fe^{2+} showed a continuously increasing trend with depth (Fig. 1), suggesting there is a sharp concentration gradient of Fe^{2+}. This may owe to the release of Fe^{2+} from interstitial water to more oxidation overlying water with increased Eh. Concentration of PO_4^{3-} also showed an increasing trend from overlying water to sediment depth. A peak value at 5–7 cm depth may indicate that internal release of P from sediment by diffusion occurred mainly in the surface 7 cm. The alkaline phosphate activity (APA) and organic phosphorus decomposing bacteria (OPDB) also showed a peak value at about 7 cm and declined to background value at sediment depths over 11 cm in the sediment of Lake Taihu (Wang, 2004). The sediment properties and chemical forms of phosphorus changed drastically in the depth of 5–15 cm in an investigation of vertical distribution of physicochemical characteristics and phosphorus chemical forms of sediment in four sub-lake areas of Lake Taihu (Zhu et al., 2003). Therefore, 7 cm depth of sediment in Lake Taihu may be the peak value of activity of anaerobic bacteria for organic matter and phosphorus regeneration from organic debris. However, no significant increase of NH_4^+ concentration occurred in interstitial water of the top 15 cm except in the surface 1 cm.

Water content, LOI percentage, porocity and bulk density of sediment also indicated that the surface 7 cm sediment is quite different from the

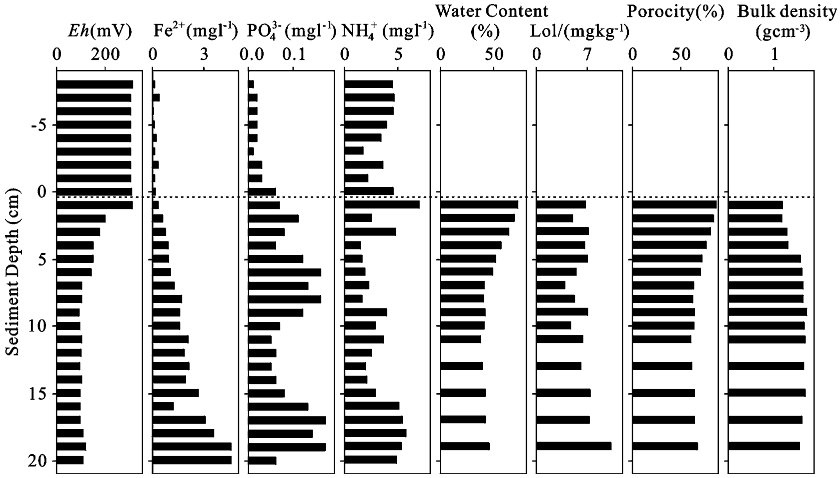

Fig. 1 Vertical distribution of Eh, Fe^{2+} concentration, PO_4^{3-} concentration, NH_4^+ concentration in interstitial water and physicochemical characteristics of sediment of observed site

deeper sediment. Qin et al. (2004) investigated the vertical distribution of physiochemical characteristics of sediment in the whole Lake Taihu and found that the surface 5–15 cm sediment was significantly different from the deeper layer. They concluded that the top 5–15 cm sediment was the active layer participating in the material cycling of Lake Taihu. Thereby, hydrodynamic processes in Lake Taihu may mainly affect the top 5–15 cm sediment that affects nutrient exchange with lake water.

Wind and wave conditions during field observation

During the observation, wind speed varied from 0 ms^{-1} to 7.0 ms^{-1}. Significant wave height varied from 5.85 cm to 28.25 cm. No strong wind-wave process occurred during the observation. The mean wind speed and direction between 12:30–13:30, mean significant wave height per hour of 10:00–11:00, 11:00–12:00, 12:00–13:00 per day, and the weighted mean value of the 3 h are presented in Table 1. Generally, the hydrodynamical disturbance intensity was divided into three kinds of situation according to significant wave height: Over 25 cm at 13th July, 12–20 cm on 16th July, 12th July, and 15th July, and lower than 12 cm on 17th July, 14th July, and 11th July.

The intensity of wind-induced waves was affected significantly by wind direction, though the observation site was located in the central of Meiliang Bay. The wave heights were significantly lower on 12th July, 15th July and 16th July than on other dates because of northeast and southeast winds (Fig. 2). A small hill near the east shore of Meiliang Bay and a relatively short wind-fetch-length explain this observation.

Suspended solids concentration and its LOI percentage

No significant differences of SS concentrations were observed among the 7 days when the SS concentrations of the top four layers were used to denote the condition of water body. However, SS concentrations in the bottom layer were quite different among the different wave conditions. The SS concentration of the bottom layer water was the highest value (154 mg l^{-1}) in 13th July. It is consistent with the strongest wind-induced wave during sampling than the other days (Fig. 2). This result shows that hydrodynamic disturbances did not have significant effects on the top water in Lake Taihu because the significant wave height was lower than 20 cm. This wave intensity may be too common and frequent in Lake Taihu to cause distinguished differences among different wind-induced wave processes.

Concentration of LOI in SS showed a similar trend to that of SS concentration. Generally, there were no significant differences of LOI

Table 1 Wind speed and H_s during the field observation

Date	Wind speed/direction/(ms^{-1})			H_s /(cm)			
	10:00–11:00	11:00–12:00	12:00–13:00	10:00–11:00	11:00–12:00	12:00–13:00	Weighted mean value[a]
11-July	4.1/307	2.1/55	1.2/7	15.14	10.63	6.95	9.54
12-July	3.4/132	2.7/134	2.0/129	19.33	18.52	12.91	15.85
13-July	2.3/235	1.2/239	6.1/278	20.35	26.46	27.05	25.74
14-July	3.3/119	2.1/106	1.8/114	13.82	10.82	8.83	10.32
15-July	3.5/302	4.0/34	4.6/14	12.18	12.57	11.90	12.17
16-July	4.8/71	6.2/60	6.3/70	15.98	17.10	20.28	18.50
17-July	2.3/246	1.9/233	1.1/246	13.48	10.58	8.88	10.21

[a] Weighted mean value of H_s was calculated as following: H_s (mean value) = (H_s (10:00–11:00) + 2 × H_s (11:00–12:00) + 3 × H_s (12:00–13:00))/6

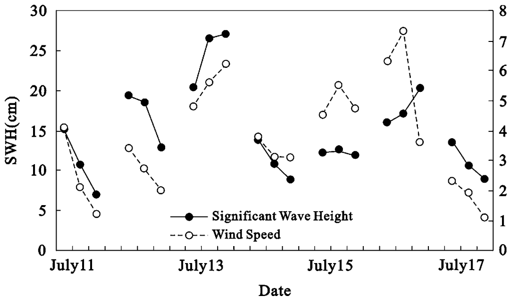

Fig. 2 Wind speed and significant wave height three hours before each days water sampling

concentration in the top four layers among the first 6 days. However, LOI concentration in the top four layers was significantly higher during the last days. This result could be caused by the algae bloom that occurred during the last day. The concentration of Chl-*a* also confirmed this presumption.

Nutrients, DO, and Chl-*a* concentrations

Vertical distributions of TP, DTP and SRP concentrations are presented in Fig. 3. For TP, there was no difference among different days except for 11 July, which was quite low compared to the next 6 days. For DTP, there was no difference among the 7 days. SRP was remarkably high on 15th July. And for NH_4^+, the last 3 days were significantly higher than the first 3 days. For Chl-*a* and DO, the last day is markedly higher than the previous days.

Correlation analysis indicated that there was not any significantly correlation between hydrodynamical disturbance intensive and water quality indices in the top four layers of water. DTP concentration correlated with SRP concentration in the top four layers ($r = 0.83$, $n = 7$), and in the bottom layer ($r = 0.79$, $n = 7$). LOI concentration correlated with Chl-*a* concentration and DO concentration in the top four layers, which means the water DO and organic suspended solids are determined by algae biomass.

SS and LOI concentrations in bottom layer were significantly affected by the intensive hydrodynamical disturbance ($r = 0.83$, $n = 7$). However, there was no significant relationship between SS and the intensive hydrodynamic disturbance in the top four layers. It suggested that wind-induced wave may have caused surface sediment resuspension, but the effect was limited in the bottom layer.

Discussion

Effects of wind-induced wave disturbance on phosphorus release from sediment in shallow lake

Do wind-induced waves cause phosphorus release from sediment to overlying water in shallow lakes? Our observations in Meiliang Bay suggest that they do not. However, we can not conclude that sediment resuspension will not affect nutrient concentrations in overlying water. In fact, field

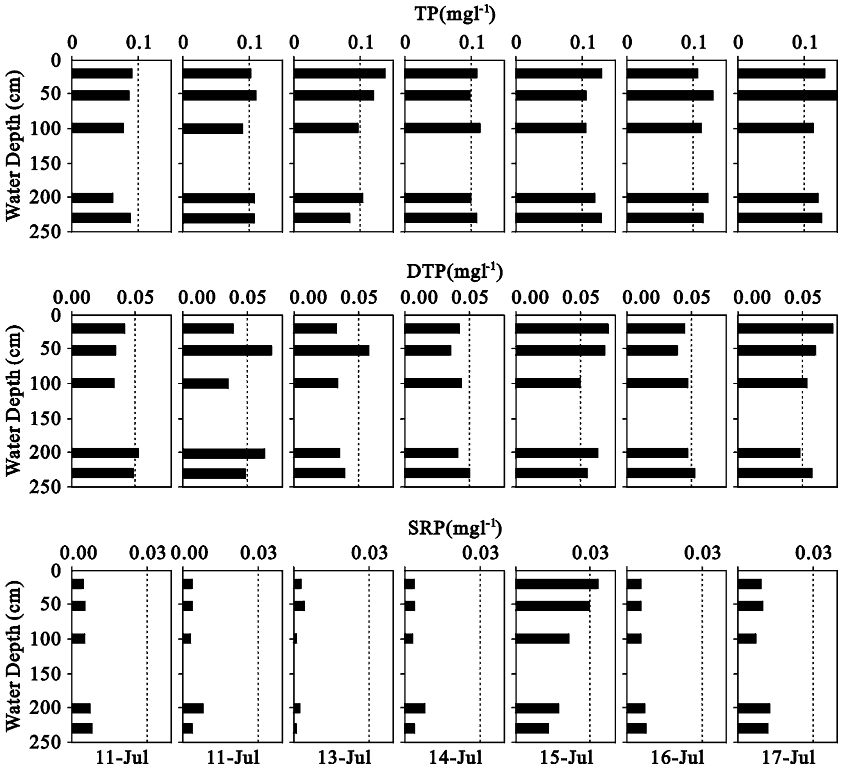

Fig. 3 Vertical distribution of TP, DTP and SRP concentrations in overlying water

observations have indicated that strong wind could increase TP, DTP and SRP concentrations in lake water as the wind speed was over 12 ms^{-1} in Lake Taihu (Zhu et al., 2004, 2005b). However, no significant release of phosphorus from sediment was found in this field observation, perhaps due to the relative low wind speed. In the wave flume experiments, Qin et al. (2004) found that the critical shear stress that leads to extensive sediment resuspension in Lake Taihu was about 0.03–0.04 N m^{-2}, equivalent to a wind speed in situ up to 4 ms^{-1}. The stress of wind-induced wave calculated minute by minute using observed data varied between 0.01 N m^{-2} and 0.11 N m^{-2}, and its peak value occurred between 18:00–18:30, 16th July. But intensive sediment resuspension still was not observed. This result suggests that the critical shear stress of 0.03–0.04 N m^{-2} isn't the correct stress for extensive sediment resuspension, but is simply the stress needed for surface sediment particles to begin to move up. According to hydraulic judging criteria, critical stress for sediment resuspension means the surface sediment particles begin to gradually float upward. In another wave flume experiments, Zhu et al. (2005a) found that SS concentration increased from 2.5 mg l^{-1} without any waves to 13.6 mg l^{-1} when wave height just exceeded the critical wave height (5.93 cm). But SS concentration increased to 224 mg l^{-1} as wave height increased to 13.29 cm. This means that sediment won't suspend extensively as the wave height become a little higher than the critical wave height. The wave height that will cause intensive sediment resuspension by field observation and simulated flume experiment is still not known.

In other field observations of hydrodynamical processes in Meiliang Bay, SS concentration in overlying water increased significantly when the wind-speed over 6.5 ms^{-1} in Meiliang Bay (Qin et al., 2000). SS concentration was about 120 mg l^{-1} with wind-speed over 6.5 ms^{-1}. The SS concentration was over 400 mg l^{-1} in top layer water with wind speed over 12 ms^{-1} (Zhu et al., 2004, 2005b). At the same time, TP, DTP, SRP concentration in the top layer water increased significantly, too. These results indicate that the wind-speed needs to be between 7 and 12 ms^{-1} for intensive sediment resuspension. However, wind speed seldom exceeded 6.5 ms^{-1} in this field observations. Thus, SS and nutrients concentration in overlying water had not significantly varied with the intensity of hydrodynamical disturbance perhaps due to lower wave height than the critical wave height for intensive sediment resuspension.

Sediment resuspension does not always increase phosphorus concentration in overlying water in shallow lakes. Correlative analysis indicates that concentrations of DTP correlate inversely with SS concentration ($r = 0.83$, $p < 0.05$). The reason is that surface sediments are often oxidized in large shallow lakes. The surface floc is in constant equilibrium with the water column. When the surface floc suspended to overlying water, it absorbs dissolved phosphorus from water phase. This phenomenon was also found in shallow Lake Yangebup (Linge & Oldham, 2004).

Although a positive correlationship between water SS concentration and intensity of hydrodynamic disturbance was not observed in this field observation, it should be noted that a relative strong wave occurred in the third day, with subsequent nutrient concentration increases in the fifth day followed by an algae bloom on the seventh day. However, cause and effect relationships among the three phenomenons are still unclear.

Variation of water quality indices in large shallow lake

Water quality indices of shallow lake are highly variable because of the spatial and vertical inhomogeneity of water quality, as well as the violent influence of hydrodynamical disturbance. Most of the observed water quality indices varied drastically in the 7 days of observation (Fig. 4). For example, DTP concentration in the surface 20 cm layer water varied between 0.34 mg l^{-1} and 0.77 mg l^{-1}, SRP varied between 0.002 mg l^{-1} and 0.033 mg l^{-1}, NH_4^+–N varied between 0.056 mg l^{-1} and 0.832 mg l^{-1}, and Chl-*a* varied between 33 mg l^{-1} and 117 mg l^{-1} during the seven observation days.

Compared to the monthly monitored data from 2000 to 2003, considerable variation of the water quality indices occurred among the observed 7 days (Fig. 4). This observation suggests that monthly monitored data may be inadequate to reflect the water quality variation in large shallow lakes like Lake Taihu. For example, the cycle time of phytoplankton colony is generally a week. Thus, Chl-*a* concentration must be quite different between water sampling events depending on the

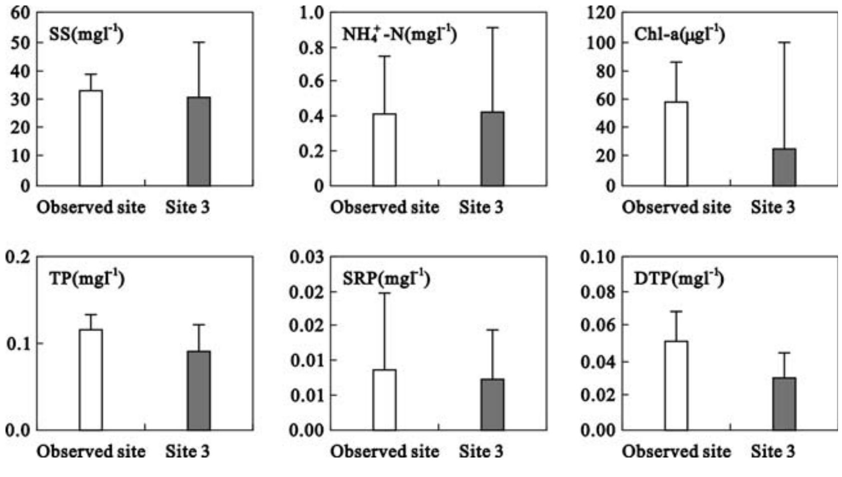

Fig. 4 Variation of the observed surface 20 cm water quality indices during the 7 days and that of the monthly monitored data at No. 3 regular monitoring site of TLLER

presence or absence of an algae bloom. Additionally, wind speed and direction during water sampling can affect water quality indices, such as Chl-*a* concentration, phytoplankton structure (Chen et al., 2003). Therefore, one must be careful in using monthly monitored data to explain water quality change in large shallow lakes.

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