Hydrodynamics in association with the eutrophication in large shallow lake Taihu, China

By Boqiang Qin

China has 2,693 natural lakes with areas over 1.0 km²; about 23.5% of these lakes and 25.9% of their area are located in the middle and lower reach of the Yangtze River (MLYR) and eastern coastal area. All these lakes are shallow and freshwater lakes with high productivity, often suffering from nutrient enrichment and harmful algal blooms.

Lake Taihu, China

Introduction

Lake Taihu is a typical large shallow lake, with an area of 2,336 km^2 and length (from North to South) 68 km and width (from the East to West) 56 km, a mean depth of 1.9 m and a maximum depth of less than 3 m. It is situated in the delta of the Yangtze River (Figure 1), one of the most industrialized and urbanized areas in China. It is a polymictic system and occasionally frozen in winter. This lake has long suffered from eutrophication and toxic cyanobacterial blooms (*Microcystist* spp.) since the 1990s. Several ecological systems are co-existing in this lake. The northern part of the lake is an algae dominant system, characterized by a relatively higher depth and lower transparency. The eastern part of the lake is a macrophyte dominant system, characterized by shallow depth and high clarity. The pelagic zone is frequently turbid due to the long fetch (Figure 1). There are 27 large rivers or canals connected to Lake Taihu. Most runoff is from the mountainous west and southwest basin, while most wastewater discharged in the lake is from the northern and northwestern basin.

In this article, we discuss the lake hydrodynamics in association with the spatial and temporal changes of water quality, internal nutrient loading, harmful algal blooms, numerical simulation and prediction, and future perspective of lake management.

Hydrodynamic characteristics of Lake Taihu

In large shallow lakes, because of their long fetch, wind-induced waves develop well, resulting in frequent sediment resuspension and release of historically accumulated nutrients (nitrogen (N) and phosphorus (P)). Sediment resuspension exerts a profound influence on underwater light and primary production, and further influences the composition and function of the ecosystem via the bottom-up effect. Wind-induced hydrodynamic disturbances entrain dissolved oxygen (DO) at the water-sediment interface, which then impacts the degradation and mineralization of organic matter. The interconnection between in-lake biogeochemical processes and lake morphology is largely unexplored.

With the deployment of several Doppler current meters (SonTek Inc., USA) during the summer of 2015, we found that water currents in Lake Taihu range from 0~20 cm/s with an average less than 10 cm/s, mainly driven by winds. The significant wave height is about 41 cm. Most wind-induced waves are of high frequency and low energy, short distance propagation and fast energy dissipation. Because of the monsoonal climate, dry and cold northwesterly winds dominate in the winter, and humid and warm southeasterly winds in the summer. Thus, summer (July to September) total nitrogen (TN, mg/L), total phosphorus (TP, mg/L) and chlorophyll a (Chla, μg/L) concentrations are distributed non-uniformly, increasing from the southeast to the northwest.

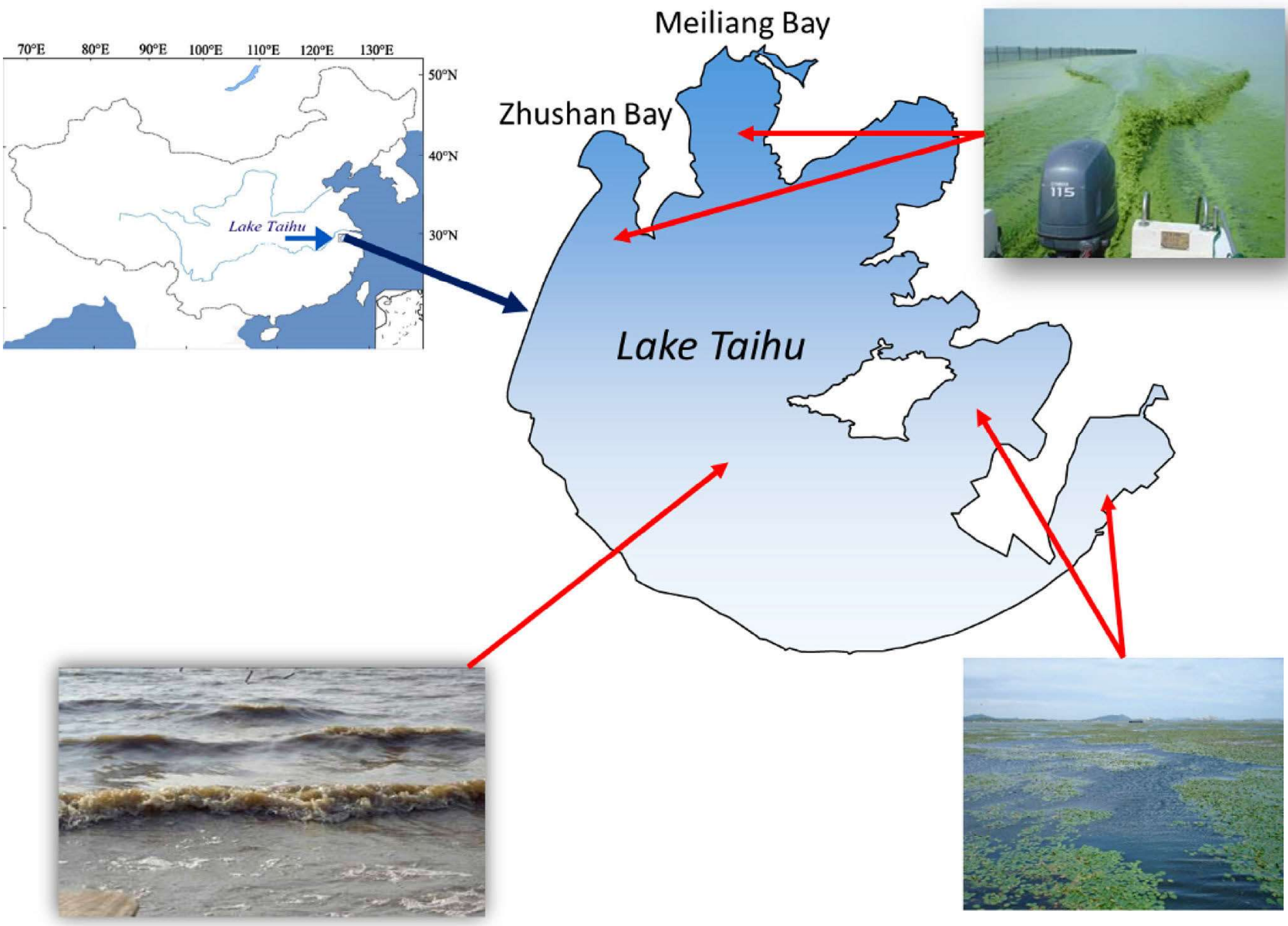

Figure 1 | Location and a variety of ecological conditions of Lake Taihu.

There are four forcings driving the water currents, i.e. wind stress, Coriolis force, pressure gradient stress (originating from the wind driven upwelling) and bottom friction stress[1]. During the low wind speed periods, the mean values of the wind stress, Coriolis force, pressure gradient stress and bottom frictional stress have nearly the same magnitude (Figure 2)[1]; during high wind speed periods, the mean wind stress (170.8x10^{-6} m/s^2 for unit mass) and pressure gradient stress (153.9x10^{-6} m/s^2 for unit mass) are overwhelming (Figure 2)[1]. For the low and the high wind speed periods, statistical analyses of the current velocity showed that their mean periodicity was 80 hour and 24 hour, respectively[1]. The former is caused by seiche which is associated with the southeasterly summer monsoon jet, and the latter is caused by the so-called land-water breeze which is driven by the thermal contrast between the land and the lake (wind blows from land to lake in nighttime and inverts in daytime during summer). In addition, even if Lake Taihu is very shallow, the water current at the surface is in different direction from that at the bottom, forming a two layer structure[1]. Thus, it would not be realistic to assume that this shallow lake is vertically homogeneous and employ a single-layer two-dimensional hydrodynamic model to simulate its circulation.

In shallow lakes, frequent wind-driven sediment resuspension significantly increases the concentration of total suspended solids (TSS) in the water column, altering underwater light conditions. The TSS concentration changes dramatically with water depth and wind speed in Lake Taihu (Figure 3). During the strong wind period (ranging between 5.7 and 8.0 m/s), the TSS concentration near the bottom could increase by over 100-fold compared with the TSS near the surface or the TSS during periods of calm or little wind (Figure 3), which suggests that shallow systems could also be stratified with respect to some water quality parameters.

Field observations and calculations suggest that the sediment resuspension in shallow lakes is mainly driven by waves, rather than by currents. In Lake Taihu the shear stress produced by waves was 1 or 2 orders of magnitude higher than that of the currents[2]. Based on flume experiments, the critical shear stress for sediment resuspension was determined to be approximately 0.017~0.25 N/m^2 . When the wavelength to water depth ratio (L/D) was approximately 2–3, wave propagation was affected by lake bottom friction and sediment erosion occurred; when L/D > 3, the interactions between the waves and the bottom sediment increased to induce massive erosion and sediment resuspension[3].

Internal loading in Lake Taihu

As a large and shallow lake, Lake Taihu has a relative long water residence time (WRT) and high ability to retain nutrients, especially phosphorus. Approximately 60-70% of the external P load was retained inside the lake[4]. In contrast to small and deep lakes, legacy phosphorus in the sediment of large and shallow lakes is readily mobilized and released into the overlying water (Figure 4). Thus, the phosphorus concentration of the water column in a shallow lake is determined not only by the external input from the watershed, but also by the legacy nutrients in the sediments[5]. Due to the small capacity and extensive exposure to sediments, shallow lakes are highly susceptible to nutrient enrichment and eutrophication.

To investigate the influence of hydrodynamics on nutrient mobilization from sediments in shallow lakes, we conducted a series of flume-experiments to examine the wind-induced wave impact on sediment resuspension and nutrient release. We collected some surface sediments in Meiliang Bay, northern Lake Taihu, laid it at the bottom of the flume, and fully disturbed it to cause its resuspension, then left it for days to form natural stratigraphy[2]. Several waves with prescribed periods and frequencies were then imposed in the flume. We found that a great amount of sedimentary phosphorus was released into the overlying water in the form of particulate, not in the form of soluble phosphorus which mobilizes from sediment mainly via diffusion through the concentration gradient between the porewater and overlying water[6]. The occurrence of cyanobacterial blooms could alter some physicochemical features, such as the elevation of the pH value due to photosynthesis and the depletion of dissolved oxygen (DO) resulting from the increase of labile organic matter, both of which promote the phosphorus mobilization from sediment to the overlying water. During the year with intense cyanobacterial blooms, the internal P loading from sediment could be as high as 90% of the external loading in Lake Taihu[5].

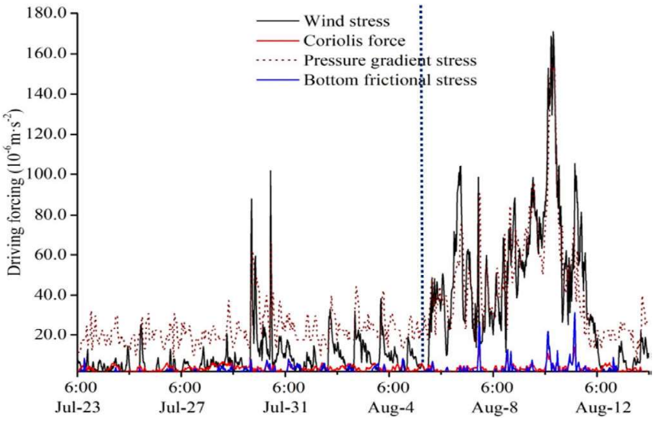

Figure 2 | Changes in wind stress, Coriolis forces, pressure gradient stress, and bottom frictional stress in the center of Lake Taihu between 23 July 2015 and 14 August 2015.

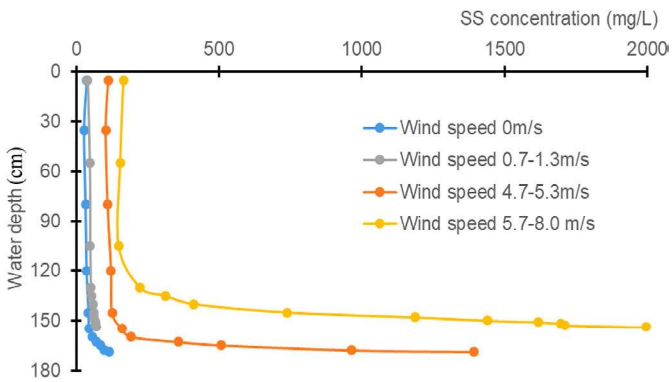

Figure 3 | Solid suspension (SS) concentration profile changes with wind speed. Four wind episodic observations at Meiliang Bay, Lake Taihu: calm condition (June 6, 2003), breezy wind (0.7-1.3 m/s) (October 3, 2002), high wind (4.7-5.3 m/s) (June 13, 2003), strong wind (5.7-8.0 m/s) (October 6, 2002).

Eutrophication and algal blooms in Lake Taihu

When the cyanobacterial blooms first appeared in 1990s in Lake Taihu, it was depicted as a ghost coming and going without trace, because the algal patchiness drifted in space quickly. The reason for this is the highly changeable currents that are driven by the wind, which make it extremely difficult to monitor and track with traditional monitoring methods using a limited number of sites and low sampling frequency (monthly or weekly). Remote sensing was then introduced to monitor the spatial distribution of algal blooms and relevant parameters in this large lake[7]. Remote sensing monitoring revealed that the algal bloom extent and frequency during 2003-2018 in Lake Taihu was increasing in intensity. Because of climate warming and nutrient enrichment, the phenology of phytoplankton blooms was earlier in the spring and ended later in the autumn than before[8, 7].

Numerical simulation of algal blooms in Lake Taihu

Based on field observations, we found that the wind drag stress can greatly influence the results of the simulation of water currents[9]. In addition, including the wave-induced radiation stress in the simulation can significantly improve the ability of the model to simulate currents correctly[9]. Numerical simulations show that the extent, location, and movement of algal bloom patches in the pelagic zone is determined by the wind-induced water current convergence and divergence[10]. Vertical movement of cyanobacterial colonies is an outcome of the balance between downward entrainment and upward buoyance originating from the gas vesicles of cyanobacteria. Further, water quality and algal bloom forecast has been accomplished by incorporating a water quality model and phytoplankton growth and mortality model into the three-dimensional hydrodynamic model. This short-term algal bloom forecast and early warning system has been applied in Lake Taihu[11]. With the input of weather forecasts, hydrological parameters, and nutrient concentrations for the next few days, the phytoplankton biomass and its spatiotemporal distribution can be predicted. The algal bloom intensity, including its extent and location, in the next half-week could be forecasted and reported to relevant administrative agencies[11, 12]. Predicted bloom occurrences and locations were verified against hindsight remote sensing data or manual observations The precision of these predictions was overall higher than 80%[11].

Lake eutrophication management in China

In order to control wide-spread water pollution, a series of laws and regulations have been issued aiming at water pollution prevention, including the revised Law of Prevention and Control of Water Pollution (revised in 2007 and 2017, issued by The National People's Congress), The Action Plan for the Prevention and Control of Water Pollution (Issued by the State Council in 2015), etc.

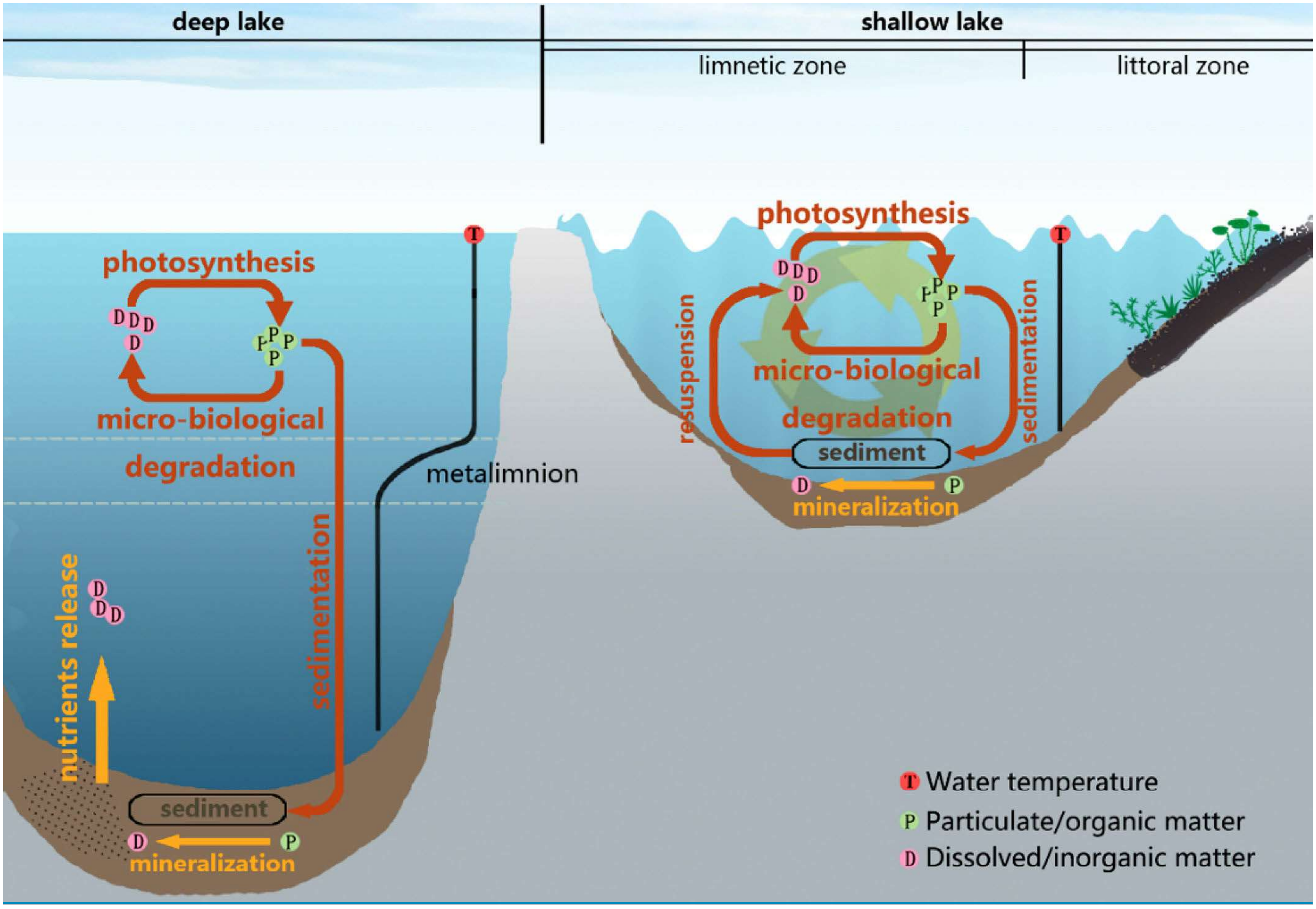

Figure 4 | Differences in nutrient recycling between deep and shallow lakes. The presence of a thermocline during summer in deep lakes prevents nutrient recycling from the hypolimnion to the epilimnion, whereas in shallow lakes, destratification by turbulence causes the coupling of organic matter decomposition and mineralization to nutrient recycling from the sediment to overlying water and promotes phytoplankton proliferation.

These efforts have overall improved the water quality of rivers across the nation. However, eutrophication of lakes and cyanobacterial blooms have not been reversed, particularly in shallow lakes in the Yangtze River basin[13, 14], because of its low flush rate and delayed response to effluent diversion in the watershed than in the rivers. Lake Taihu has received an unprecedented amount of restoration investment. However, cyanobacterial blooms still recur and persist every summer. This is attributed to three reasons. The first is the low standard for treated wastewater discharges and the lack of non-point source pollution control, which led to a considerable amount of external loading into the lake; the second reason is that less effort has been invested in internal loading reduction due to the difficulty of managing large amounts of polluted sediments; the third reason is climate warming, which has led to cyanobacterial bloom persistence and has promoted nutrient recycling from the bottom sediments to the overlying water.

Due to the high population density and economic development around Lake Taihu, it is expected that the synergistic stresses from economic development and climate warming on the lake ecosystem will not be relieved in a short period. Long-term improvement of water quality and sustainable management of the lake ecosystems in the Yangtze River Basin requires a meta-coupled, nature-based approach integrating social sciences, engineering, and natural systems to achieve sustainable development[14].

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