The influence of hydraulic characteristics on algal bloom in three gorges reservoir, China: a combination of cultural experiments and field monitoring

The influence of hydraulic characteristics on algal bloom in Three Gorges Reservoir, China: A combination of cultural experiments and field monitoring

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Abstract:

It is essential to understand the mechanism of algal bloom and develop effect measures to control the hazard in aquatic environment, such as large reservoirs. In this study, a series of experiments, along with field observation from 2007 to 2016, were carried out to identify the hydrodynamic parameters that drive the algal bloom in the Three Gorges Reservoir (TGR), China, and their threshold values were determined. The results show that algae concentration was markedly diluted with a short retention time, and the threshold value of the retention time to avoid algal bloom was approximately less than 3 days. With strong stratification, the algae concentration was able to approach to the level of algal bloom in 10 days, even when the water temperature is lower than 12 ℃. The ratio of mixing depth to euphotic depth (Zm/Ze) had significant negative correlations with both algae concentration and algae specific growth rate (SGR). The field monitoring data indicated that Zm/Ze is an important hydrodynamic parameter which sensitively affects algae growth and concentration. This study made the first attempt to determine Zm/Ze >2.8 to restrain algal bloom in the TGR. Our findings shed light on the influence of critical depth on the algal bloom in the TGR, and the results can serve to control algal bloom in reservoirs through discharge operation.

Key words： Flow velocity, Water retention time, Zm/Ze, Critical depth hypothesis, Reservoir regulation, Three Gorges Reservoir

1 Introduction

To meet the increasing need of renewable energy and flood control, reservoirs have received large attentions, especially in developing countries (Yuksel, 2010; Bilgili et al., 2018). In China, nearly 100,000 reservoirs have been built (Li et al., 2018b). Due to increasing nutrient input, however, eutrophication and algal bloom have seriously affected the ecosystem and water quality in Chinese reservoirs (Huang et al., 2020; Yang et al., 2012). Particularly, in the Three Gorges Reservoir (TGR) behind Three Gorges Dam - the world’s largest dam, algal bloom have been observed in most tributary bays since the initial water storage in 2003 (Fu et al., 2010; Stone, 2008). The dominant algal species have changed from diatom and dinoflagellates to the recent toxic cyanobacterial (Zheng et al., 2017). The high frequency and wide distribution of algal bloom in the TGR have seriously affected the aquatic ecosystem and people living in the catchment (Hao et al., 2019). Therefore, it is vital to identify the driving factor of the algal bloom and develop effect measures to control the hazard in the TGR and other reservoirs (Yang et al., 2013c).

Some studies has been conducted to explore the key environmental factors affecting the algal bloom, such as material factors (e.g. nutrients (Goldman et al., 1979; Litchman et al., 2004; Cai et al. 2020), carbon (Goldman et al., 1979; Huang et al., 2018)), energy elements (e.g. light (Diehl, 2002), temperature (Robarts and Zohary, 1987)) and biological elements (e.g. zooplankton (Gilbert, 1988; Rasconi et al., 2014), bacteria, macrophytes (Fussmann, 1996), viruses (Lehahn et al. 2014)). The hydrodynamic changes caused by dams can create a suitable environment for algal growth and even algal bloom in reservoirs. In general, interception of the dams affects the hydrodynamic conditions mainly by decreasing the flow velocity, increasing the water retention time, and enhancing the water stratification (Xu et al., 2011; Cheng et al., 2019b).

Despite their wide spread in the TGR, algal blooms rarely occur in cold winter and do not appear in the mainstream (Fu et al., 2010). As local climate conditions and nutrients in the reservoir water have little differences pre- and post- dam construction (Li et al., 2019), the changed hydrodynamic regime is considered by many researchers as the main driver for the algal bloom (Li et al., 2018a; Missaghi et al., 2016; Yang et al., 2018b). Therefore, the effect of the varying hydrodynamic conditions on the algal bloom is the pivot to study the mechanism of algal bloom and develop the control measurements in the TGR (Yang et al., 2013c; Yin et al., 2014). At present, most researchers consider the lower flow velocity in the reservoir tributaries as the key factor to induce the algal bloom (Dai et al., 2013; Sha et al., 2015; Yin et al., 2014). Some scholars have explored the relationship between flow velocity and algae growth and identified a ‘critical flow velocity’ to control algal bloom (Long et al. 2011; Wang et al., 2009a). However, some experiments have indicated that flow velocity cannot inhibit the algae biomass, but on the contrary benefit the propagation of algae (Huang et al., 2008), suggesting that there may be no ‘critical flow velocity’ affecting the algal growth in the TGR. This result was also proved by the experiments of reservoir regulation in the TGR, the water draining through the dam made little mitigation of the algal bloom (Wang et al., 2009b; Zheng et al., 2011). Therefore, lower flow velocity in the TGR might not be fundamental factor causing agal bloom in the TGR. Other researchers suggested that less renewable water body was more likely to cause algal blooms (Bartoli et al., 2018; Cha et al., 2017). Based on this theory, some models have been developed to predict algal blooms (Wan et al. 2013; Kim et al., 2021). In deep waters, water stratification was considered as an important factor affecting algal blooms (Cantin et al., 2011; Ouellet and Beisner., 2014; Ptacnik et al., 2016); light intensity was also suggested as an important factor; Zm/Ze can combine water stratification and light (Reynolds et al.,1983; Diehl et al. 2002; Stockenreiter et al., 2021). At present, most studies have focused on breaking the thermal stratification to control algal blooms (Visser et al., 2016; Saros et al., 2016). However, the results of these studies cannot be directly applied to the TGR. After the dam construction, intrusive currents widely appeared from mainstream to tributaries (Yang et al., 2018). These density currents significantly changed the hydrodynamic conditions, along with carrying large amounts of nutrients into the tributaries. Due to the unique hydrodynamic phenomena in the tributary bays of TGR, the threshold values of hydrodynamic parameters derived from other rivers may not be directly applicable in the TGR. After all, the relationship between hydrodynamic conditions and algal bloom still remains unclear in the TGR and more studies are still required.

To fill the knowledge gap, this research focused on three hydrodynamic parameters: flow velocity, water retention time and vertical thermal stratification. Along with 10-years field observation of algal bloom in the TGR, a series of controlled experiments were carried out to explore the relationship between these parameters and algae growth. In addition, critical parameter for algal bloom in the TGR were analyzed to investigate the mechanism and thresholds affecting algal bloom. The main aims of this study are to 1) determine the influence of flow velocity, water retention time, and stratification on algae growth; 2) explore the mechanism of algal bloom derived by hydraulic characteristics; and 3) identify a hydraulic parameter and its threshold to control the algal bloom in the TGR. The findings can reveal the mechanism of algal bloom and provide a technological support to mitigate the hazard.

2 Materials and methods

2.1 Experimental designs

2.1.1 Effects of different flow velocities on the algae growth

Studies have found the effects of flow velocity on algae growth (Ferris and Lehman, 2007; Mitrovic et al., 2011). Especially, algae flourish in a water body with slow flow velocity (Song et al., 2018). In order to research the relationship between flow velocity and algal growth, similar to Horner’s design (1990), an open channel raceway was installed, with the channel of 7.00 m, the width of 0.38 m and depth of 0.70 m (Fig. 1). Considering the maximum flow velocity in the TGR of 1.2 m/s (Xu et al., 2011), six parallel groups were set up at flow velocities of 0.00 m/s, 0.30 m/s, 0.50 m/s, 0.70 m/s, 0.90 m/s, and 1.20 m/s, respectively, in this experiment. Two replicate experiments were performed for each group. More details about the nutrient and light condition can be found in Section 2.2.

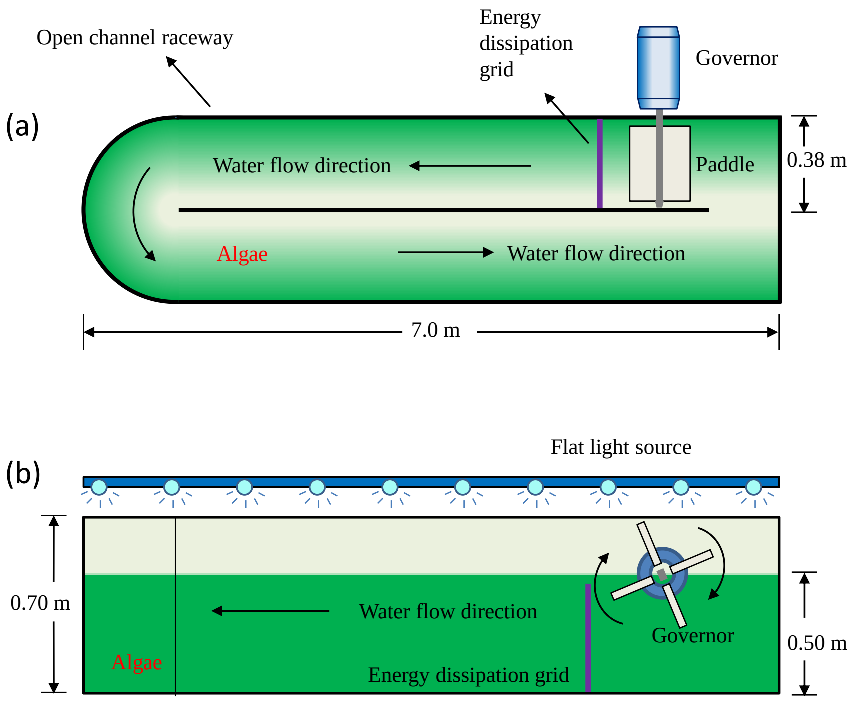

Fig. 1. (a) Planform and (b) sideview of the open channel raceway. Water flow velocity was driven and controlled by the paddle of electric machine governor (a). The light for algal culture is from fluorescent tube (b). The water depth is 0.50 m.

2.1.2 Effects of different water retention time on algae growth

To estimate the effects of different water retention times on algae growth, an experimental device was designed (Fig. 2), which was consisted of a series of glass incubator jars and a black storage tank filled with nutrient solutions. The jars were filled with solution (see Section 2.2 for more details) with a volume of 0.0567 m^3 (diameter of 0.38 m and a spillway at the height of 0.50m). Nutrient solution with no algae was continuously dripped into the jars from the storage tank through pipes, and valve on the pipe controlled the drip rate to change water retention time. To avoid the adherence and sinking of algae, air was aerated into the jars to well mix the water. Six parallel group experiments were conducted at varying retention time of 1 day, 2 days, 4 days, 6 days, and 12 days, and a non-exchange group (without adding nutrient, the infinite two on the left Fig. 2), respectively. Two replicate experiments were performed for each group. More details about nutrient and light condition are reported in Section 2.2.

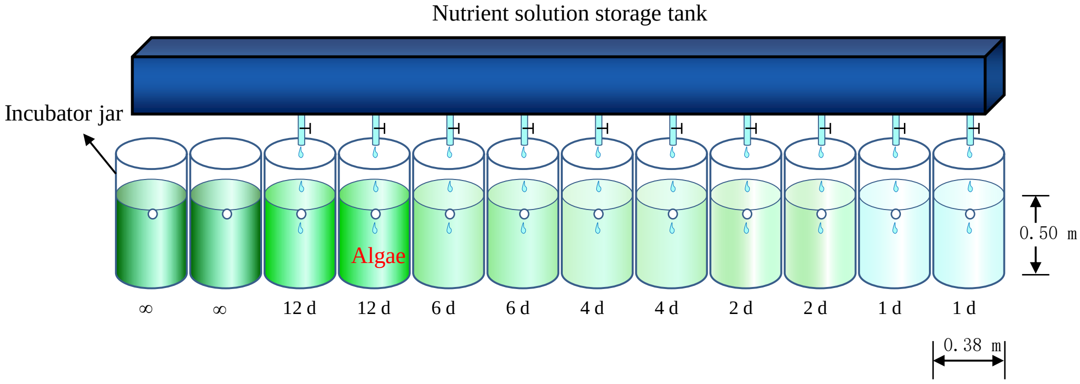

Fig. 2 Sketch of the water retention time experimental devices. Retention time of each jar was controlled by valve on the pipe connected to the storage tank. The light source was held on the front of the jars.

2.1.3 Effects of different stratified structures on algae growth

To research the effects of different stratification structures on algae growth, a series of field enclosure experiments were carried out in Xiangxi Bay (XXB), a tributary in the TGR. The enclosures were made of transparent polyethylene (PE) tubes with a thickness of 1.5mm, a diameter of 0.68m, but varying lengths (Fig. 3). The experiments were conducted in February when the water turbulence was strong enough to support a complete vertical mixing. In the meantime, the euphotic depth maintained around 11.2 m. The stratification of water body was achieved by adjusting the length of the enclosures in vertical direction (Fig. 3). Six parallel groups were set at varying stratification structures (the ratio of mixing depth and euphotic depth, Zm/Ze) of 0.2, 0.4, 0.9, 1.3, 1.8 and 2.7, respectively. Two replicate enclosures were performed for each group. More details about nutrient and light condition can be found in Section 2.2.

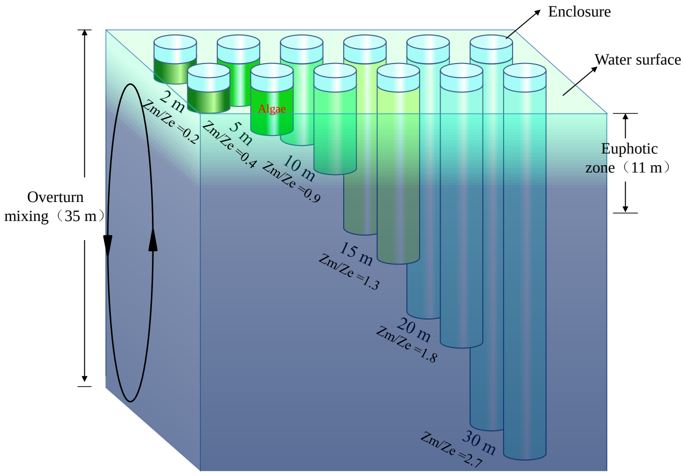

Fig. 3 Sketch of the experimental enclosures used to research the effects of different stratification structures on algae growth. Those enclosures were connected by a floating platform, and the tops of enclosures were 0.5 m above the water surface. Natural sunlight was the light source for algae growth.

2.2 Culture conditions for algae growth in the experiments

For the experiments of flow velocity (Fig. 1) and water retention time (Fig. 2), tap water was firstly standing for two days before being used, and then solutions of KNO_3, KH_2PO_4•$2H_2O$ and Na_2SiO_3•$9H_2O$ were added into water and the concentrations of total nitrogen (*TN*), total phosphorus (*TP*) and dissolved silicon (*D-Si*) were adjusted to 5.0 mg/L, 0.5 mg/L and 5.0 mg/L, respectively. The initial pH was set at 8.6 by adding the solutions of NaOH. Water temperature was controlled to be 20±1℃ by using the adjustable insulated electric heating rod. Light source was fluorescent lamp and the intensity was maintained at 2700 lx, and the illumination time was 12 hours per day.

In the water retention time experiment (Fig. 2), the dominant species of the algal bloom in the TGR *Microcystis aeruginosa* and *Chorella pyrenoidosa* were used in the experiments, and they were obtained from the Freshwater Algae Culture Collection at the Institute of Hydrobiology (Wuhan, China).

In the field (*in situ*) enclosure experiment (Fig. 3), the reservoir water was pumped into those enclosures, and no extra algae and nutrients were added.

2.3 Measurements of environmental parameters in the experiments

During the experiments, water temperature (*WT*) and water depth (*WD*) were measured by using the water quality analyzer HYDRO Lab DS5 (HACH, Loveland, CO, USA). Two bottles of water sample (300 mL) for each experimental group were collected every day. One bottle of water sample was used to determine total nitrogen (*TN*), total phosphorous (*TP*) and dissolved silicon dioxide (*D-Si*) in laboratory following China's national standard methods "Water and Wastewater Monitoring and Analysis Methods, fourth ed." (Wang et al., 2002); the other one was firstly filtered through a cellulose acetate fiber membrane (0.45μm), the filtered water sample was used to measure nitrite (NO^-_3-N) and phosphate (PO^-_4-P), and the left membrane was analyzed for Chlorophyll *a* (*Chl.a*) concentration following China's national standard methods (Wang et al., 2002). In the experiments of flow velocity (Fig. 1) and water retention time (Fig. 2), the light intensity was measured by using an illuminometer (TES-1339, China). In the enclosure experiments (Fig. 3), the underwater photosynthetically active radiation (*PAR*) was measured by using a light sensor (LI-1400, USA).

2.4 Field Monitoring

2.4.1 Monitoring sites and sampling overview

Xiangxi River (XXR) is the largest tributary close to the TGD in Hubei Province (Fig. 4), which is approximately 94 kilometers long and located in a subtropical continental monsoon climate. When the TGR is operated at a water level of 175 m, a 40 km reach is covered by the backwater from the estuary, called as the Xiangxi Bay (XXB). Since the initial storage in 2003, various phytoplankton species have dominated XXB in different seasons (Liu et al., 2012; Ye and Cai, 2011). In order to research the relationships between algal bloom and hydraulic characteristics, we have done a 10-year field monitoring in the algal bloom area (Xiakou station, Fig. 4). 11 sites (at intervals of approximately 3 km) were selected from the estuary to the end of the backwater (Gaoyang Town) on the mainstream of the XXB, indicated as XX00-XX10 (Fig. 4). One more site was selected at the mainstream of the Yangzte River to represent the reservoir mainstream, indicated as CJXX.

At all monitoring sites, hydrodynamics, physical, K and biological parameters were measured, including water depth (*WD*), water temperature (*WT*), light intensity (*LI*), light attenuation coefficient (*Kd*), and Chlorophyll a (*Chl.a*).

2.4.2 Measurements of environmental parameters in field monitoring

The measurement methods of *WD, WT, LI,* and *Chl.a* were the same as section 2.3. *Kd* was derived from the slope of the semilog plot of irradiance versus depth.

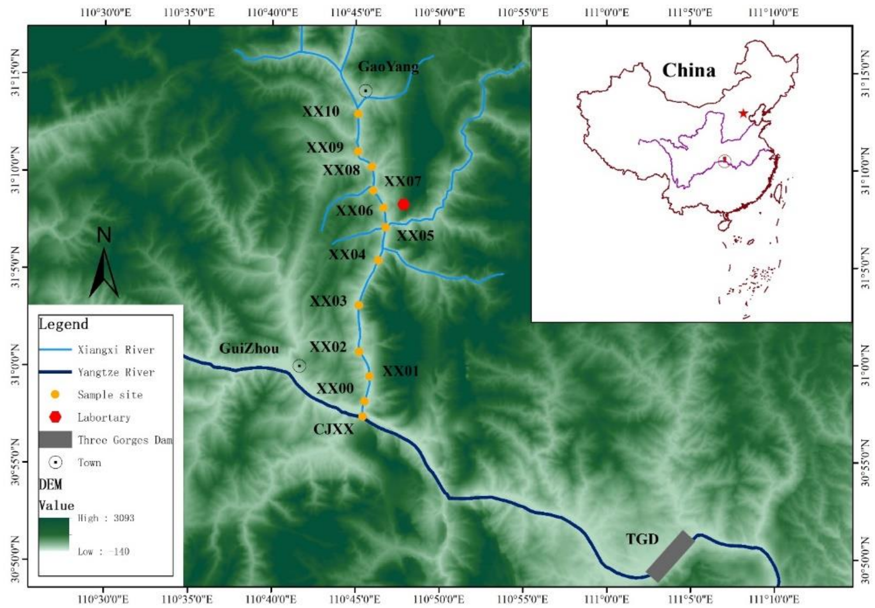

Fig. 4 Location of sampling sites in the Xiangxi Bay (XXB) of the Three Gorges Reservoir (TGR), China

2.5 Data analysis

Water retention time was calculated by dividing the volume of the container by the sum of water inflow to the container (Tarczyn´ska et al., 2001; Xu et al., 2011),

$$T_r = V/Q$$

where T_r was the water retention time (day); V was the volume (cm^3) of jar and Q was the water flow discharge (cm^3/s) of the drippy nutrient solutions from the pipes.

Mixing depth (Zm) was calculated according to the method of Montégut et al. (2004), which was the depth where water temperature was 0.5°C lower than the surface layer. Euphotic depth (Ze) was calculated following the theory of Beer-Lambert (Khanna et al., 2009; Sakshaug et al., 1997), which was the depth where the light intensity was 1% of the surface water light. The Ze was defined as

$$Z_e = \frac{1}{K_d} \ln (100/1)$$

where K_d was the underwater attenuation coefficient of light (m^{-1}).

The algae specific growth rate (SGR) was defined as

$$\mu = \frac{\ln B_t - \ln B_0}{t}$$

where B_t was the *Chl. a* concentration of algae after a period of time t, B_0 was the initial *Chl. a* concentration, and t was the duration time of an algae growth phase.

All linear regression and significance test analyses were conducted in software R.

3 Results

3.1 Characteristics of algae growth under different flow velocities

Under different flow velocities, *Chl.a* concentrations in all groups appeared a similar pattern: increased first and declined later (Fig. 5(a)). Since nutrients for algae growth were provided only once in the beginning of the experiment, algae grew to the peak then gradually restricted by the nutrient supplement. Therefore, in this paper, only the increasing periods of *Chl.a* concentrations that mentioned above were taken as a complete growth cycle and analyzed, in order to exclude the impacts of other microorganisms in the later period.

In this experiment, the *Chl.a* concentrations under the flow velocities of 0 and 0.3m/s were largely similar: both peaked on day 11 with values of 70.30 μg/L and 72.55 μg/L, respectively, and then decreased gradually. At the flow velocity of 0.50m/s, the *Chl.a* concentrations peaked at 96.44μg/L on day 21 and then plunged to 30.00μg/L two days later, very different from other flow velocity conditions. At the flow velocity of 0.70 m/s, *Chl.a* concentrations reached the peak on day 16 with a value of 125.67μg/L, which was the maximum value of all 6 groups. At the flow velocities of 0.90 and 1.20 m/s, *Chl.a* concentrations showed similar patterns. In general, algae grew rapidly at low flow velocities, but the peaks of *Chl.a* concentration at low flow velocities were lower than those at high flow velocities.

The algae SGR under different flow velocities were shown in Fig.5 (b). The maximum of *Chl.a* concentrations had a positive correlation with flow velocities (R^2=0.563, p<0.05), but the correlation between the SGR means and flow velocities was insignificant (R^2=0.001, p>0.05), indicating that algae biomass could be higher under a relatively larger flow velocity, but the flow velocity did not dominate algae growth rate in the TGR.

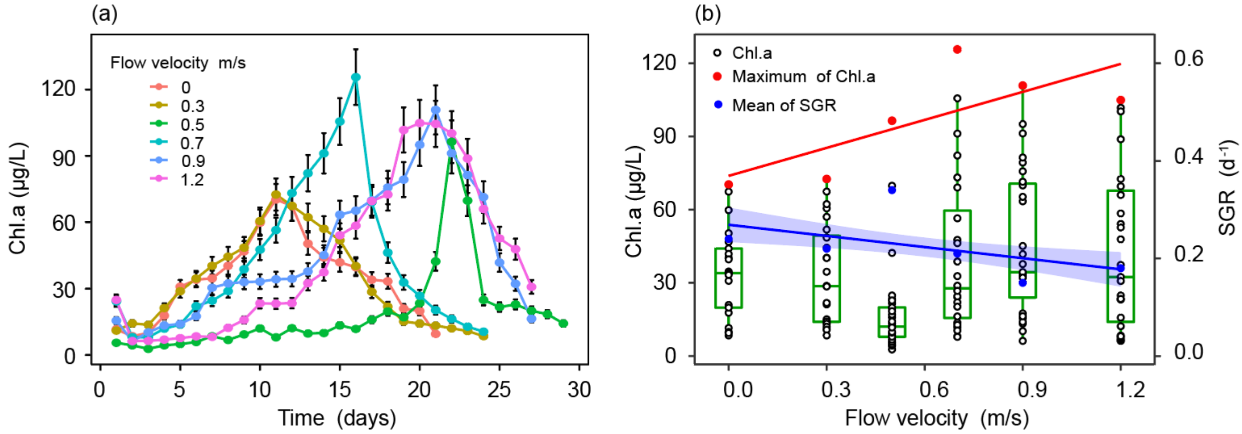

Fig. 5 Relationships between flow velocities and *Chl. a* concentration (a) and algae specific growth rate (SGR) (b).

3.2 Characteristics of algae growth under different water retention time

The characteristics of *Chl.a* concentrations under different water retention time were shown in Fig. 6 (a). *Chl.a* concentrations under the group of non-exchange increased from day 6 and reached a peak value (589.01μg/L) on day 12, which was similar to those under the flow velocity of 0 m/s (Fig. 5). Because nutrients were supplied in this experiment in order to coincide with other water retention time conditions, the peak value of *Chl.a* concentration was much higher than that under the situation of 0 m/s (Fig.5). At the retention time of 12 days, *Chl.a* concentration started to increase from day 6 and reached the maximum (288.38μg/L) on day 11, and then stabilized afterwards. Under the retention time of 6 days and 4 days, the peak values of *Chl.a* concentrations both appeared on day 11, 198.22μg/L and 114.30μg/L, respectively. By contrast, at water retention time of less than 2 days, the *Chl.a* concentrations stabilized at low levels, without obvious peak.

In Fig. 6(b), the longer water retention time was, the higher peak values of the *Chl.a* concentration were, showing a significant power function relationship (R^2=0.843, p<0.05). However, there was no significant correlation between the water retention time and SGR (R^2=0.001, p>0.05). Notably, the maximum of SGR reached 0.69 d^{-1} under the water retention time of 1 day, indicating that algae growth may not be restrained by the small water retention time, but the algal concentration in the jars can be diluted by the dripped nutrient solution without algae.

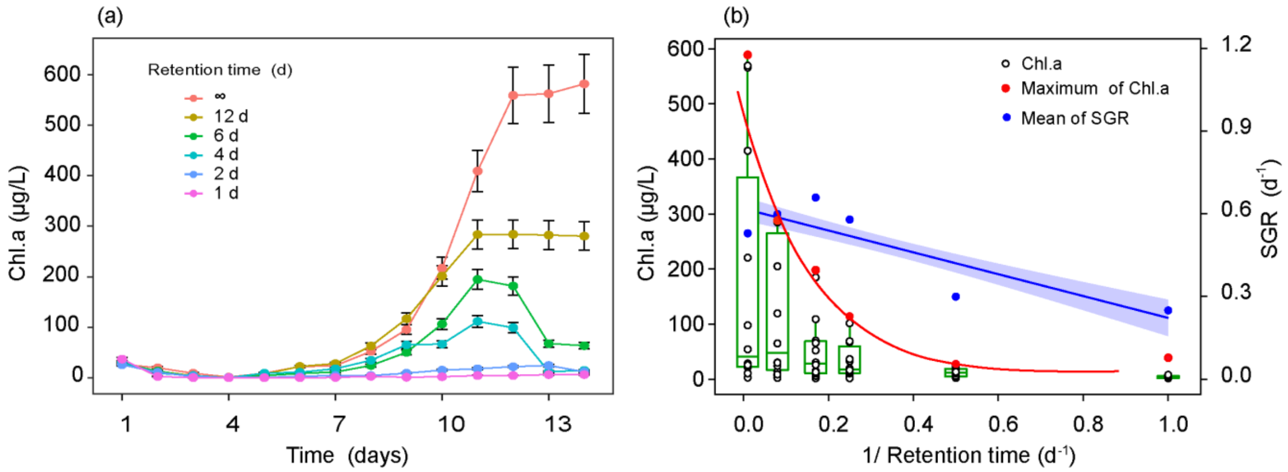

Fig. 6 Relationships between water retention times and *Chl. a* concentrations (a) and algae specific growth rate SGRs (b)

3.3 Characteristics of algae growth under different water stratification structures (Zm/Ze)

The changes of *Chl.a* concentrations under different Zm/Ze ratios were shown in Fig. 7(a). When Zm/Ze was 0.2, *Chl.a* concentrations reached the peak of 87.54μg/L on day 13, which was also the maximum of all experimental conditions. Under the condition of Zm/Ze=0.4, the peak value (11.41μg/L) appeared on day 16. When the Zm/Ze was 0.9, the peak value was 4.91μg/L, which was just a little bit higher than the initial value of 0.9μg/L. However, when Zm/Ze ratios were larger than 1.0, *Chl.a* concentrations maintained at a lower level and were less than 0.97μg/L, which were similar to those in the water outside the enclosures.

As shown in Fig. 7(b), *Chl.a* concentrations had a significant power function correlation with the Zm/Ze (R^2=0.904, p<0.05). In addition, the means of SGR had a significant negative correlation with Zm/Ze (R^2=0.767, p<0.05), suggesting that algae can grow much faster in a strong stratified water rather than in the mixed water. Hence, water mixing could markedly restrain the algae growth in the TGR.

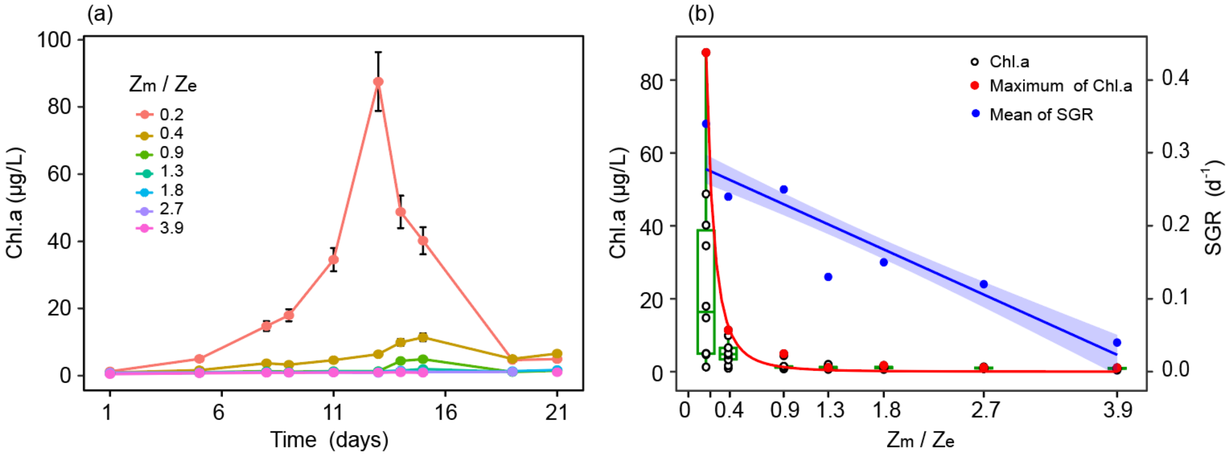

Fig. 7 Relationship between the Zm/Ze and *Chl.a* concentrations (a) and algae SGRs (b)

3.4 Filed monitoring

In the tributary bays of TGR, algal blooms occurred in spring, summer and autumn. There were significant differences in the dominant algal species between seasons, and the succession of algal species was strongly influenced by the intrusive density current. In spring, thermal stratification began to appear in the water body and bottom layer intrusive density currents occurred; diatom and green algae were the dominant species during this period. In summer, intense light and shallower mixing depth resulted in the dominance of *Microcystis aeruginosa* and anabaena. In autumn, surface layer intrusive density current induced strong vertical mixing in the water column, with the increase in mixing depth, and Chlorella and Cyclotella dominated during this period.

Considering the complex algal species succession, *Chl.a* was monitored from 2007 to 2016 in XXB of the TGR. The relationship between *Chl.a* concentrations and Zm/Ze was shown in Fig. 8. Obviously, with the decrease of Zm/Ze, the *Chl.a* concentrations grew. The maxima of *Chl.a* concentrations appeared in the range of Zm/Ze<1, and *Chl.a* concentrations maintained at low levels when Zm/Ze>2. Considering *Chl.a* concentration of 30.00μg/L as the threshold of algal bloom in the TGR (Zheng et al., 2006), the corresponding critical Zm/Ze was 2.8.

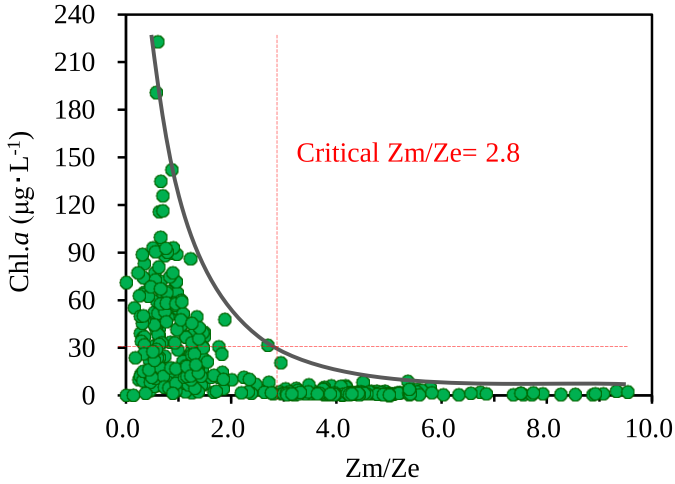

Fig. 8 Relationship between the *Chl.a* concentrations and Zm/Ze based on the field monitoring data from 2007 to 2016 in the XXB of TGR. Considering *Chl.a* concentration of 30.00μg/L as the threshold of algal bloom in the TGR, the corresponding critical Zm/Ze was 2.8.

4 Discussion

4.1 Hydrodynamic parameters to drive algal bloom in tributary bays of the TGR

Algal bloom have been observed since the initial water storage of the TGR (Stone, 2008). Before 2008, the algal bloom mainly occurred from February to May and the dominant algae species were diatom and *dinoflagellate*. Whereas, since the toxic *cyanobacterial* bloom occurred in June 2008, different kinds of algal blooms appeared from February to September every year (Zhu et al., 2013). Generally, the dominant species of algae presented a clear seasonal characteristics, and algal bloom rarely happened in winter when temperature was low (Fu et al., 2010). Due to the small changes of nutrients and weather conditions pre and post of building TGD (Li et al., 2019), the changed hydrodynamic regime caused by the water storage of the TGR was considered to be the dominant factor driving algal bloom in tributary bays (Li and Liao, 2003).

After the water storage of the TGR, the direct and obvious change of hydrodynamics in the reservoir was the decreased flow velocity. Average velocity reduced from previous 2.00 m/s to 0.17 m/s in the mainstream, and from 1-3 m/s to 0.05 m/s in the tributary bays, for example, XXB (Xu et al., 2011). The effect of flow velocity on algae bloom has received increasing attention, and a critical flow velocity hypothesis (CFH) was proposed to illuminate the mechanism of algae growth (Mitrovic et al., 2002; Mitrovic et al., 2011; Li et al., 2013; Zhang et al., 2017). According to the CFH, when water flow velocity is below the threshold, algae grows faster; when the flow velocity is above the threshold, algae growth will be restrained (Fig. 9 (a)). This was supported by our experimental results (Fig. 5(a)). Koch (1993), Long (2011), and Song (2018) have calculated the flow velocity thresholds, and most of them have determined a low flow velocity which was suitable for the algae growth. However, to the best of our knowledge, no study has tested the hypothesis that large flow velocity will restrain the algae growth. On the contrary, it has been widely proposed by the industry of algae cultivation that algae could obtain sufficient light and grow faster when flow velocity reaches 2.0-3.0 m/s (Lundquist et al., 2010; Sawanta et al., 2018). In fact, the decrease in flow velocity affects the sediment deposition (Humborg et al., 1997), water body renewal (Kawara et al., 1998) and nutrients retention (Dillon and Rigler, 1974), which can markedly affect the algae growth. Therefore, the relationship between the hydrodynamics and algal bloom is more complicated than only the flow velocity.

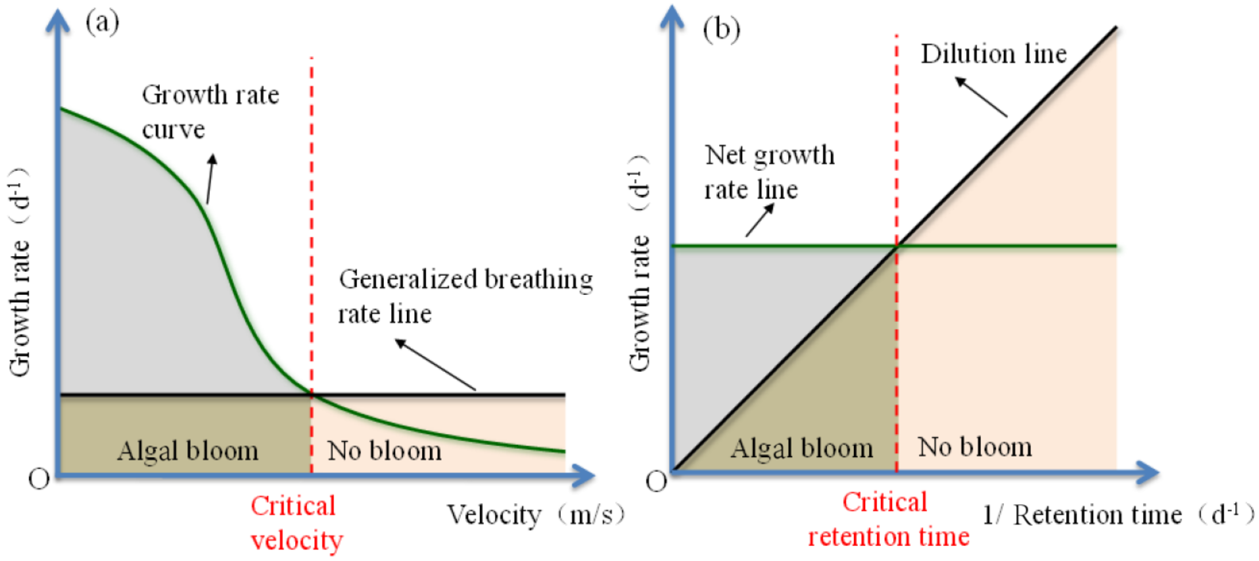

Fig. 9 Schematic diagrams of critical flow velocity hypothesis (a) and critical water retention time hypothesis (b)

Based on the theory of CFH, some researchers explored the threshold value of the critical velocity to support reservoir regulation to control the algal bloom (Wang et al., 2009a; Yin et al., 2014). However, the field monitoring showed no significant relationship between flow velocity and algal bloom, and some indoor controlled experiments found that large velocity cannot restrain, but on the contrary could promote the algae growth (Huang et al., 2008). In our flow velocity experiment, the *Chl.a* concentrations decreased with the increasing flow velocity. However, the correlation between the SGR means and flow velocities was insignificant, which means that the maxima value of *Chl.a* concentrations under different flow velocities did not decrease with the increase in flow velocity (Fig. 5). Our results also show that algae grew well even under a velocity of 1.20 m/s, the maximums of algae biomass exhibited a positive correlation with the velocities, and flow velocity did not affect the algae biomass eventually. In addition, algal bloom in the TGR were not alleviated with the application of the CFH theory in the reservoir operation (Wang et al., 2009b). Therefore, the CFH theory is invalid to explain the mechanism of the algal bloom in the TGR.

Previous scholars suggested that water retention time could have large effects on algal bloom (Bakker and Hilt, 2016; Reid and Hamilton, 2007). Recently, some researchers found that algal bloom only occurred in the less renewal water body (Bartoli et al., 2018), which means that water retention time was an important hydrodynamic parameter determining algal bloom, so called critical water retention time hypothesis (CRH) (Fig. 9 (b)). An increasing number of studies reported that water retention time could significantly affect the appearance and disappearance of the algal bloom. For example, in Asahi reservoir, Japan, algal bloom only occurred when water retention time was over two weeks (Kawara et al., 1998). In Sulejów reservoir, Poland, Cyanobacterial bloom broke out at water retention time of 60-120 days (Tarczyn´ska et al., 2001). In the Morrow Lake, USA, the threshold of retention time for algal bloom was about 5 days (Reid and Hamilton, 2007). In Hanjiang River, China, algal bloom could be restrained when water retention time (measured by flow discharge) was larger than 350-500 m^3/s (Cheng et al., 2019a; Xin et al., 2020).

Our results indicate a significant negative correlation between water retention time and algae biomass. When water dilution rate equaled to algal growth rate, the critical retention time was about 3 days. When retention time exceeded three days, algae started growing faster (Fig. 6). However, according to the ratio of inflow to storage capacity of TGR, the minimum retention times in the mainstream and tributary bays were 5 days and 10 days during the flood season (Cheng et al., 2019b; Holbach et al., 2015; Zhang et al., 2010), which both exceed the threshold value of 3 days in the experiment (Fig. 6). However, the algal bloom did not happen in the mainstream of TGR. In winter, water temperature was still suitable for algae growth in tributary bays (exceed 12℃), as shown in the enclosure experiments (Fig. 7). In addition, the water retention times of tributary bays were generally over 100 days in dry season from November to April (Cheng et al., 2019b). According to the CRH, the risk of the algal bloom could be much higher in winter, but in fact algal bloom were rarely observed (Dai et al., 2013; Yang et al., 2018b). The field observation in the TGR were all contrary to the indoor experimental results in this study (Fig. 6). Hence, the CRH could not completely illustrate the mechanism of appearance and disappearance of the algal bloom in the TGR. Therefore, the relationship between hydrodynamic conditions and algal bloom in the TGR was of large discrepancy with rivers, for example, Hanjiang River in China (Xin et al., 2020) and Darling River in Australia (Mitrovic et al., 2011)) and lakes, such as Tai Lake (Guo, 2007; Qin et al., 2013) and Chao Lake (Yang et al., 2013b) in China.

Thermal stratification, a typical physical phenomenon in deep lakes and reservoirs, has also been reported to be related to the algal bloom (Gary and Wojciech, 1998). For example, the vertical turbulence is restricted by the thermal stratification, thus most algae can stabilize in the near-surface water, propagate abundantly with the sufficient light and form algal bloom eventually. A study in 40 reservoirs found that water stratification was the main driver of algal bloom in reservoirs (Glenn and Larelle, 2008). In addition, the dominant algae can migrate vertically or keep suspending in the stratified water, thus the vertical distribution of algae usually present a large spatial heterogeneity in deep reservoirs (Eppley, 1972). Some algae species have advantages in competing for nutrients and light, so the phytoplankton components may change according to the different conditions of vertical mixing and stratification (Yoshiyama et al., 2009). Based on the above studies, some scholars suggested that vertical turbulence was a major hydrodynamic factor affecting the growth and composition of algae (Abraham, 1998; Estrada and Berdalet, 1997), and several models have also been developed to predict the algal bloom based on the vertical turbulence (Huisman et al., 1999; Klausmeier and Litchman, 2001; Mellard et al., 2011). The 'critical depth hypothesis (CDH)' (Sverdrup, 1953) established a typical pattern of water turbulence and algal bloom (Fig. 10). This hypothesis revealed the relationship between the primary productivity of phytoplankton and water stratification: the growth of phytoplankton was promoted when the mixing depth was lower than the critical depth, but the growth was restrained on the contrary condition. Considering the trophic factors, environmental factors, and hydrodynamic conditions, this hypothesis revealed the mechanism of algal bloom, and it has been wildly applied in many studies (Townsend et al., 1992;

Giovannoni and Vergin, 2012; Arteaga et al., 2020).

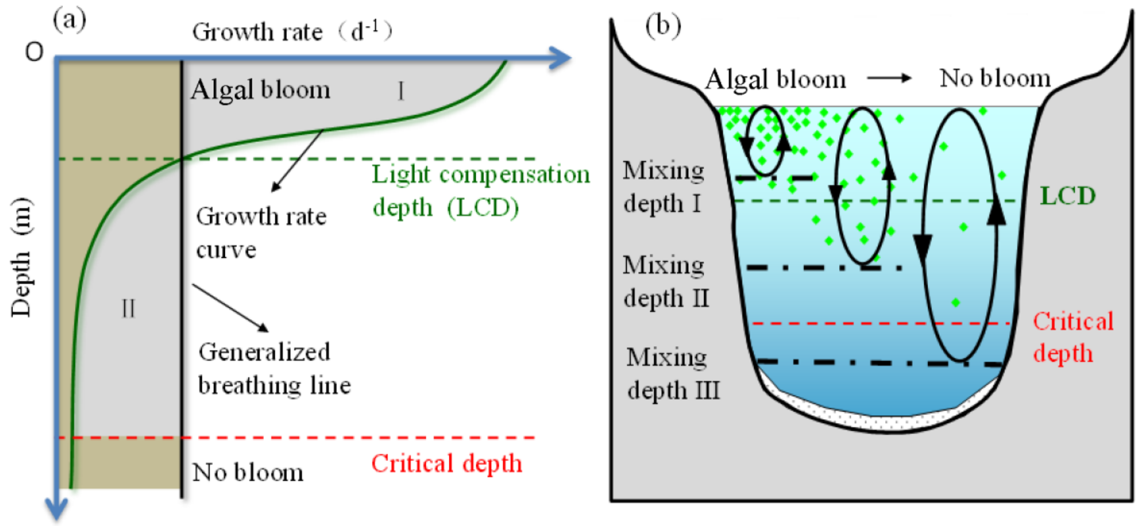

Fig. 10 Critical depth hypothesis (a) and relationships between stratified structures and algal blooms in deep water (b),

On account of the enormous inflow in the mainstream of TGR, the water body was mixed except the area with a weak thermal stratification near the TGD (Long et al., 2016). However, in the tributary bays, thermal stratification happened from March to September very year due to bidirectional density currents, which was reported to be closely relate to the algal bloom (Liu et al., 2012). In the *in situ* enclosure experiment of this study, *Chl.a* concentrations exceeded the threshold of algal bloom (over 30 μg/L) within 10 days if the mixing depth was shallow enough (Zm/Ze <0.2), even in February when the water temperature was lower than 12℃, as shown in Fig. 7. On the contrary, when the mixing depth was relatively larger (Zm/Ze >1.0), *Chl.a* concentrations maintained at a lower level. According to the field monitoring in the TGR, algae bloom always appeared in spring and disappeared in autumn, which was well corresponded to the decrease and increase of mixing depth (Yang et al., 2013c). Field monitoring of long time series (3 years) and short time series (1-2 weeks) both showed that increase of mixing depth was accompanied by decrease of *Chl.a* concentration (Yang et al., 2013c), which supported the experimental results in the current study. Therefore, according to the CDH, our enclosure experiments and field monitoring results, thermal stratification caused by the bidirectional density currents is the dominant factor to drive the algal bloom in tributary bays of the TGR, and the Zm/Ze can be recommended as a hydrodynamic parameter to predict algal outbreak and manage the hazard. In the mainstream of the TGR, although field monitoring showed that the nutrients were suitable for algal growth, it was speculated that algal bloom would not occur due to the mixing water body and a high value of Zm/Ze (>5) according to the CDH (Yang et al., 2018a), which was consistent with the *in situ* observation in the TGR.

Although CDH was suggested to be modified by the dilution–recoupling hypothesis (Behrenfeld, 2010), the significant negative correlation between the algal growth and Zm/Ze (Fig. 7) confirmed the validity of CDH for algal bloom in the tributary bays of the TGR.

4.2 Management strategy for algal bloom in the TGR

Algal bloom has been a large environmental challenge in the TGR. *Chl.a* concentration of 30.00μg/L has been considered as the threshold of algal bloom in the TGR (Zheng et al., 2006). According to the relationship between *Chl.a* and Zm/Ze in TGR, the corresponding Zm/Ze was 2.8 based on the long-term field monitoring data (Fig. 8). Notably, the *in situ* mesocosm experiment was conducted in February when diatom was the dominant algae specie in XXB. And the result in Fig.8 was a comprehensive statistic which included all kinds of algal species that have appeared during different algal bloom periods in the XXB, thus the threshold was more extensive comparing with the experiment with a single algae specie. Especially, for some flagellate algae which could migrate in the stratified water, the Zm/Ze would be much bigger. In order to cover all algal blooms in the tributary bays of TGR, according to Fig. 8, the threshold of the hydrodynamic parameter was determined as Zm/Ze>2.8 to restrain the algal bloom.

Clearly, the fundamental solution to control the algal bloom in the TGR is to reduce the nutrients in the water (Shan et al., 2019; Yang et al.,2013a). However, as the upstream watershed of the TGR is vast, an outstanding effect can hardly be achieved in a short period, without significant impact on local industry, agriculture and life (Fu et al., 2010; Yang et al., 2012). According to our results, the algae bloom could be controlled effectively by disrupting the water stratification, with Zm/Ze>2.8. To control algal bloom in small areas (less than 1 km^2), the mixing depth can be increased through water-lifting aerator technology (Yang et al., 2010). To mitigate algal bloom in large areas (more than 1 km^2), reservoir regulation method can be considered by disrupting the water stratification (Lian et al., 2014; Zheng et al., 2011). Some studies have started to explore the method to enlarge the daily water level fluctuations and water body exchanges in the mainstream and tributaries through reservoir regulation to reduce the nutrient concentrations and control the algal growth (Sha et al., 2015; Zhou, 2006). Other studies raised a 'tide-types' method of eco-environmentally friendly operation (EEFO) (Yang et al., 2013c), which suggested to change water level of reservoir in a short time to control algal bloom by enlarging water exchanges, increasing the suspended sediment and breaking the water stratification in tributary bays (Yang et al., 2010). However, the specific hydrodynamic target through which to quantify the reservoir regulation and control algal bloom has not been widely achieved by previous studies. Based on our findings, however, achieving Zm/Ze>2.8 thorough proper water level regulation can be considered as a measure to control algal bloom in the TGR.

4.3 Advances of studying algal blooms in the TGR

While algal blooms have been studied for many years, the relationship between hydrodynamic parameters and algal blooms in the TGR is still not yet fully understood. To the best of our knowledge, this study advanced the research of algal blooms in the TGR in the following three respects:

Firstly, most studies have focused on the effect of a single hydrodynamic parameter on algae growth. Hydrodynamics is a complex process, so a single parameter cannot be sufficient to represent the whole process. Our study included three hydrodynamic parameters (flow velocity, water retention time, and stratified structure) to identify the most sensitive parameter affecting algae growth.

Secondly, Zm/Ze was explored in previous studies (Reynolds et al.,1983), but their results cannot be directly applied in the TGR. After the dam construction, intrusive currents were found from mainstream to tributaries (Yang et al., 2018). These density currents markedly changed the hydrodynamic conditions and carried large amounts of nutrients into the tributaries. Considering the unique hydrodynamic phenomena in the tributary bays of TGR, the threshold values of hydrodynamic parameters derived from other rivers may not be applicable in the TGR and studies in the TGR, particularly *in situ* field studies, are indispensable.

Thirdly, field monitoring was conducted *in situ* in TGR for nearly 10 years. The long-term *in situ* monitoring data are rare and they recorded the wide variety of dominant algae species between different seasons and the evolution of algal blooms after the dam construction. Considering the impact of density currents, the long-term field monitoring data are more reliable in guiding reservoir algal regulation.

4.4 Limitations and future research

Similar to many studies, there are some limitations in the current study. In this study, a critical value of Zm/Ze is proposed to control algal blooms in triburary bays of TGR. It would be of great interest to take further investigation to reveal the mechanism of algal blooms induced by the stratified water body. Two dominant algae, *Microcystis aeruginosa* and *Chorella pyrenoidosa,* were studied in our controlled experiments, while the dominate algae species evolves between the seasons in the XXB. Therefore, further experiments including more algae species and considering the seasonal changes can provide a more precise plan to control algal bloom in the TGR. Furthermore, climate change has caused worldwide impacts on water environment. More studies are needed to understand the impact of climate change on algal bloom in the TGR, particularly the extreme weathers including droughts (Lai et al., 2020; Zhao et al., 2017).

5 Conclusions

Algal bloom has been a huge environmental problem in aquatic ecosystems, including the world largest hydropower reservoir TGR. In this study, a series of controlled experiments and field monitoring from the year of 2007 to 2016 were conducted to determine the effects of hydraulic characteristics on algal bloom in TGR. The main conclusions were drawn as follows:

(1) There was an insignificant negative relationship between flow velocity and algal growth rate. Short water retention time did not affect the algae growth, but had an obvious dilution effect on the algae biomass. The threshold of critical water retention time was about 3 days to control algal bloom.

(2) The ratio of mixing depth and euphotic depth (Zm/Ze) had significant negative correlations with both algae concentration and algae growth. When the mixing depth was shallow enough, even in the cold winter, algae propagated rapidly and formed algal bloom.

(3) Water stratification is the dominant driver for algal bloom in the XXB of TGR. Zm/Ze is a credible hydrodynamic parameter affecting algae bloom sensitively. In order to control algal bloom in the tributary bays of TGR, the threshold of Zm/Ze > 2.8 is recommended.

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