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Hydrodynamic mechanisms underlying periodic algal blooms in the tributary bay of a subtropical reservoir

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ABSTRACT

Periodic algal blooms in certain tributary bays of the Three Gorges Reservoir (TGR) have become a serious environmental problem. A three-year observational study of the water velocity, temperature, nutrients and chlorophyll *a* (Chl.*a*) in Xiangxi Bay (XXB), a which is tributary of the TGR, was undertaken to identify the mechanisms underlying algal blooms. The results showed that, in the Xiangxi Bay, bottom-layer intrusive current (BLIC) happened in winter, middle-layer intrusive current (MLIC) occurred in spring and summer, and surface-layer intrusive current (SLIC) happened in autumn. The MLIC could cause a extraordinary thermal stratification. In addition, these density currents carried large amounts of nutrients into XXB, thus inducing eutrophication. The Critical Depth Hypothesis (CDH) implied that algal blooms in XXB would occur continuously when the MLIC happened. As the hydrodynamics in the TGR could be affected singnificantly by the change of the water level, water level operations may represent a method to control algal blooms.

1. Introduction

The reservoir behind the Three Gorges Dam (TGD), which is the world's largest hydropower station (Stone, 2008) and is located on the Yangtze River (YR) in Hubei Province, China, has been regulated with a top water level of 175 m above sea level since October 26, 2010. This regulation changed the hydrological conditions and has serious impacts on the local environment and ecosystems (Fu et al., 2010; Shen and Xie, 2004; Stone, 2008). Algal blooms represent one of the most severe challenges (Fig. 1) because they impair the aquatic ecosystem and threaten drinking water quality (Liu et al., 2012; Zheng et al., 2017). Thus, algal blooms have become a social and environmental problem in the Three Gorges Reservoir (TGR).

Generally, nutrient enrichment, water discharge, flow velocity, turbulence, and changing climate are factors that influence algal blooms (Kawara et al., 1998; Mitrovic et al., 2003; Reynolds, 1986; Steinberg and Hartmann, 1988; Tarczyn'ska et al., 2001). In the TGR, scholars initially suggested that nutrient enrichment driven by changes in regional land use and management could represent the primary causes of these blooms (Ye et al., 2009). However, later studies found that nutrients in the mainstream ofthe TGR slightly decreased after the construction of the TGD (Huang et al., 2014; Luo et al., 2011) and that nutrients in the tributary bays primarily originated from the mainstream of the TGR (Luo et al., 2007; Yang et al., 2015). A slower flow velocity could represent another efficient cause (Xu et al., 2010) because the velocity in the tributaries was 1.00–3.00 m/s before construction of the TGD and less than 0.05 m/s later the TGD (Fu et al., 2010; Zhang et al., 2006). Accordingly, the "critical flow velocity" (Li et al., 2005) and "retention time" (Xu et al., 2010) concepts were applied to predict the occurrence of algal blooms. However, due to the complex hydrodynamics in the tributaries (Holbach et al., 2013; Yang et al., 2010), verifying the the "critical flow velocity" and "retention time" using the traditional experimental and model methods is difficult (Huang et al., 2008).

The inducement of algal blooms could certainly be attributed to the TGD, because blooms did not occur in that area before construction of the TGD (Fu et al., 2010). Dams directly change the hydrology and then indirectly influence the eco-environmental conditions and cause certain

Abbreviations: BLDC, bottom-layer downslope current; BLIC, bottom-layer intrusive current; CDH, Critical Depth Hypothesis; Chl.a, Chlorophyll *a*; CJ, site in the mainstream of the Three Gorges Reservoir; Cl^-, chloridion; $C_{sed.}$, suspended sediment concentration; EEFO, eco-environmental friendly operation; g, the gravitational acceleration; Inflow, site in the upstream river of the Xiangxi Bay; K_d, light attenuation coefficient; LBDCs, layered and bidirectional density currents; MLIC, middle-layer intrusive current; N^2, square buoyancy frequency value; Na^+, sodion; PAR, photosynthetically active radiation; Si, dissolved silicon; SLIC, surface-layer intrusive current; T, temperature; TGD, Three Gorges Dam; TGR, Three Gorges Reservoir; TN, total nitrogen; TP, total phosphorus; v, flow velocity; XX00-XX10, eleven sites in the Xiangxi Bay; XXB, Xiangxi Bay; XXR, Xiangxi River; YR, Yangtze River; Z, water depth; Z_{eu}, euphotic depth; Z_{mix}, mixed layer depth; ρ, water density

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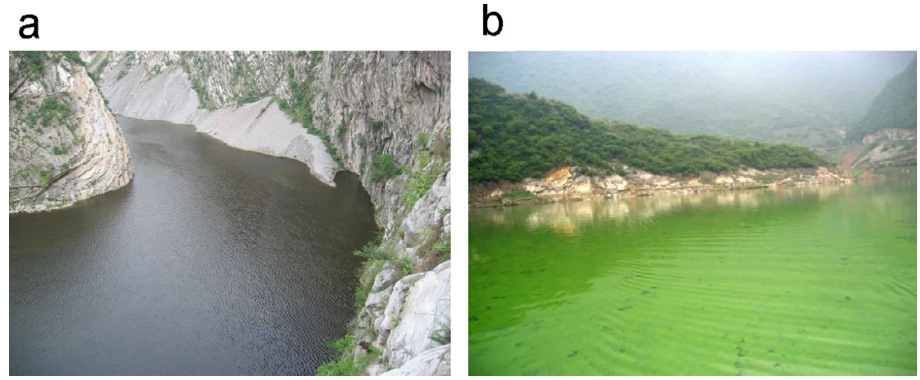

Fig. 1. Examples of water bodies covered by different algal blooms in XXB: (a) Black water caused by *Peridiniopsis* sp. and (b) Green water caused by *Microcystic aeruginosa.* (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

problems, such as algal blooms. In reality, the hydrodynamics in certain tributary bays of the TGR present complex bidirectional currents rather than a simple flow from upstream to downstream (Holbach et al., 2014; Ji et al., 2017), which is different from the situation observed in other reservoirs worldwide. Thermal stratification (Yu and Wang, 2011) and vertical mixing (Liu et al., 2012) caused by those currents might have a great effect on the appearance or disappearance of algal blooms.

However, the exact temporal relationship between hydrodynamics and algal blooms has not been clarified. Our three-year monitoring research project in the Xiangxi Bay (XXB) was conducted to 1) clarify the hydrodynamic conditions and interpret their effects on thermal stratification and nutrient transportation, 2) identify the mechanism underlying the algal blooms in this hydrodynamic background, and 3) provide suggestions for improving water quality in the TGR.

2. Materials and methods

2.1. Sampling sites and parameter measurement s

The Xiangxi River (XXR) is the largest tributary close to the TGD in Hubei Province (Fig. 2b) (Yang et al., 2015). Since the initial impoundment of the TGR in 2003, different phytoplankton species have dominated in the XXB during different seasons (Liu et al., 2012; Wang et al., 2011a). For example, *Peridiniopsis* sp. algal blooms occur in spring (Fig. 1a), whereas *Microcystic aeruginosa* algae blooms form in summer (Fig. 1b). To monitor spatial and temporal variations in the environmental parameters, eleven sampling sites were set at approximately 3-km intervals in XXB and were numbered XX00-XX10 (Fig. 2c). Moreover, two sites located at the mainstream of the TGR and the upper reach of XXB were classified as “CJ” and “Inflow”, respectively. The parameters and their measurements are shown in Table 1.

2.2. Data analyses and the ion tracer method

The mixed layer depth (Z_m) was considered the depth at which the water temperature (T) was 0.5 °C lower than that at the surface (Montégut et al., 2004). The light attenuation coefficient (K_d) was derived from the slope of the semilog plot of irradiance versus depth. The euphotic depth (Z_{eu}) was determined as the depth at which the photosynthetically active radiation (PAR) was 1% of the value at the

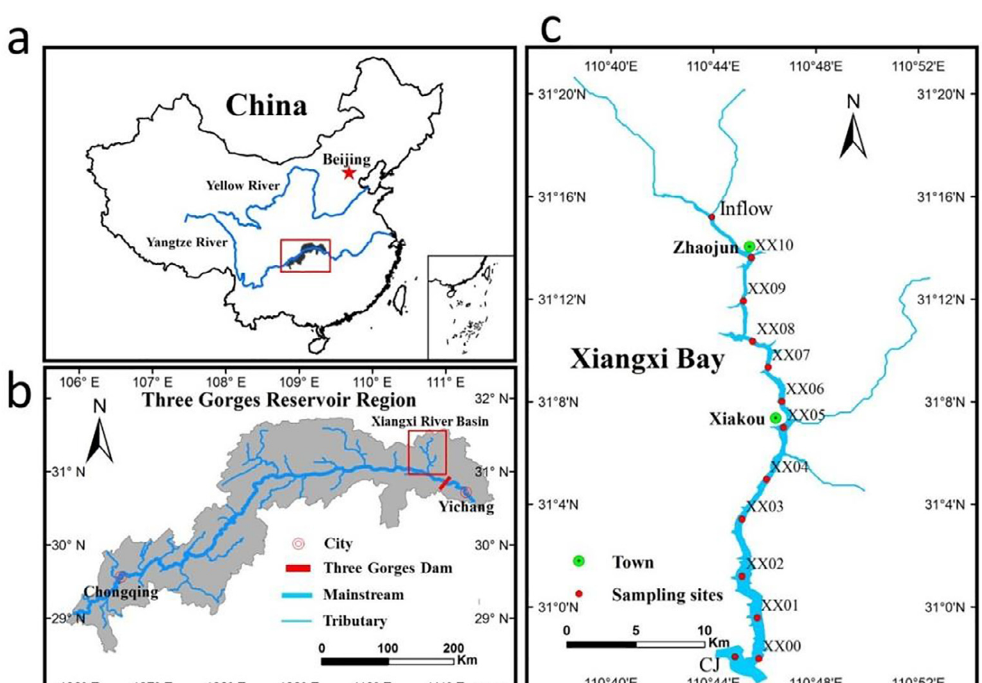

Fig. 2. (a) Location of the TGR in China. (b) TGR region. (c) Location of eleven sampling sites in XXB (from XX00 to XX10) and another two sites along the YR mainstream (CJ) and upstream of XXB (inflow).