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Decline in water level boosts cyanobacteria dominance in subtropical reservoirs

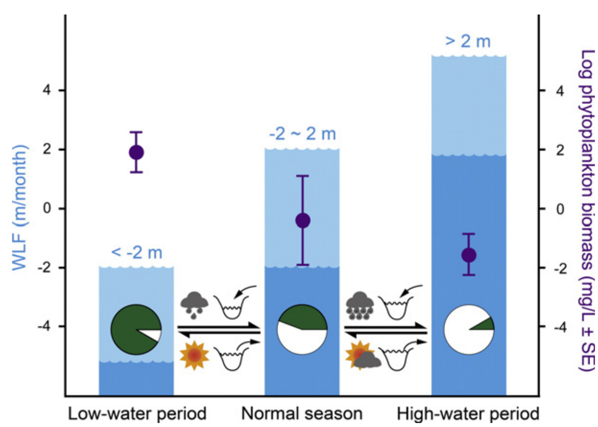
Jun Yang [a,b], Hong Lv [a], Jun Yang [a,*], Lemian Liu [a], Xiaoqing Yu [a], Huihuang Chen [a]

[a] *Aquatic Ecohealth Group, Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*

HIGHLIGHTS

- Effects of water level fluctuations (WLF) on phytoplankton community dynamics were analyzed in four subtropical reservoirs.
- Both human-induced and climate-driven declines in water level can boost cyanobacteria dominance.
- Water level management can be widely used in small and medium-sized reservoirs for water quality protection.

GRAPHICAL ABSTRACT



Conceptual diagram of the effect of climate change and human activity on water level fluctuations (WLF) and phytoplankton biomass (mean biomass ± SE). Light blue shading indicates uncertainty of WLF. Green pie charts represent the percentage of cyanobacteria to total phytoplankton biomass.

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ABSTRACT

Globally aquatic ecosystems are likely to become more vulnerable to extreme water fluctuation rates due to the combined effects of climate change and human activity. However, relatively little is known about the importance of water level fluctuations (WLF) as a predictor of phytoplankton community shifts in subtropical reservoirs. In this study, we used one year of data (2010–2011) from four subtropical reservoirs of southeast China to quantify the effects of WLF and other environmental variables on phytoplankton and cyanobacteria dynamics. The reservoirs showed an apparent switch between a turbid state dominated by cyanobacteria and a clear state dominated by other non-cyanobacterial taxa (e.g., diatoms, green algae). Cyanobacterial dominance decreased, or increased, following marked changes in water level. Multiple regression analysis demonstrated that pH, euphotic depth, WLF, and total phosphorus provided the best model and explained 30.8% of the variance in cyanobacteria biomass. Path analysis showed that positive WLF (i.e. an increase in water level) can reduce the cyanobacteria biomass either directly by a dilution effect or indirectly by modifying the limnological conditions of the reservoirs in complex pathways. To control the risk of cyanobacterial dominance or blooms, WLF should be targeted to be above +2 m/month; that is an increase in water level of 2 m or more. Given that WLF is likely to be of more frequent occurrence under future predicted conditions of climate variability and human activity, water level management can be widely used in

* Corresponding author.
E-mail address: jyang@iue.ac.cn (J. Yang).

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small and medium-sized reservoirs to prevent the toxic cyanobacterial blooms and to protect the ecosystem integrity or functions.

1. Introduction

China is the largest dam-building country in the world, with the total estimated storage capacity of reservoirs being triple that of natural lakes (Yang and Lu, 2014). Reservoirs are highly dynamic environments and changes in the hydrological characteristics and shifts in ecosystems state may threaten biodiversity and cause large losses of sustainable ecosystem goods and services (Johnson et al., 2001; Palmer, 2010). There are large gaps in understanding of both the physical and ecological feedbacks which occur in subtropical reservoirs (Evtimova and Donohue, 2014). Phytoplankton assemblages are key components in determining ecosystem stability, and they are among the classic examples of populations undergoing switches between alternative stable states in shallow lakes (Scheffer and Carpenter, 2003), yet the patterns of succession and the factors driving these temporal patterns in subtropical reservoirs remain poorly understood (Xiao et al., 2011; Lv et al., 2014).

Shifts in phytoplankton community are often thought to be a result of changes in nutrient load and light regime (Tilman et al., 1982; Jensen et al., 1994; Jochimsen et al., 2013). However, strong shifts in phytoplankton communities may also be associated with hydrological changes (Beaugrand, 2004; Loverde-Oliveira et al., 2009; Cobbaert et al., 2014, 2015). One of the major factors is water level fluctuations (WLF), which are controlled by both natural conditions (e.g., meteorological and catchment characteristics) and local human activities (e.g., artificial water transfer) (Paillisson and Marion, 2011; Jeppesen et al., 2015). The effect of WLF on ecological processes and community patterns is now incontrovertible (Supplementary Table S1). Due to both global climate change and changes in freshwater demands, increased WLF have become an important disturbance to many aquatic ecosystems, especially reservoirs in the subtropical monsoon climatic region.

Previous studies have shown that WLF is an important driver of the shifts between clear-water and turbid states in shallow lakes (Scheffer and Jeppesen, 2007). The limnological conditions, such as nutrient dynamics and stratification patterns, may significantly change with WLF in reservoirs (Naselli-Flores and Barone, 2005; Wang et al., 2011). WLF has also been identified as a main driver of phytoplankton biomass and composition in rivers, lakes, and reservoirs (Naselli-Flores and Barone, 1997; Mac Donagh et al., 2009; Wang et al., 2011; Zhu et al., 2013), and may affect the distribution and temporal variation of phytoplankton communities (Kimmel et al., 1990; Palijan, 2012). In addition, WLF can significantly reduce the benthic algal biomass and alter the taxonomic and trophic structure of benthic assemblages in standing waters (Evtimova and Donohue, 2014, 2016). This has led to the suggestion that WLF could be a useful management tool to improve freshwater quality (Naselli-Flores and Barone, 2005; Geraldes and Boavida, 2005). Although artificial management and manipulation of water levels have been widely practiced in the past decades (Liu et al., 2012; Visser et al., 2016), the impact of alternating high and low water levels on alternative stable states of phytoplankton communities, especially cyanobacteria dynamics in subtropical reservoirs, are not well known.

Previous studies have largely focused on unraveling the mechanisms behind regime shifts in shallow lakes (Scheffer et al., 1997; Carpenter, 2003; Scheffer and Jeppesen, 2007) or exploring WLF and other environmental variables (such as nutrients and temperature) as important drivers of phytoplankton community structure in freshwater ecosystems (de Emiliani, 1997; Lv et al., 2014). However, the extent to which WLF is a predictor of cyanobacteria blooms in subtropical reservoirs is still unclear (Zohary and Ostrovsky, 2011). Here we examine the phytoplankton communities in four subtropical drinking water reservoirs which are presently characterized by clear water, high water level and turbid, low water level states. Clearly formal experiments are usually the best approach for identifying mechanisms in scientific research - however these are very difficult to carry out in systems used for a city's water supply. Therefore in this study we use the statistical analyses of observational data to attempt to infer plausible mechanisms for predicting and modifying cyanobacteria dominance. The data sets allowed us to test and quantify WLF as an important predictor of cyanobacteria dominance in reservoirs. We hypothesized that by influencing the light availability, nutrient loads, and other limnological variables, WLF would be a significant predictor of cyanobacteria dynamics in subtropical reservoirs. We also developed a quantifiable WLF target for restoring impaired water quality caused by toxic cyanobacteria. Based on our findings, we recommend a potential water level-based management tool to control cyanobacterial blooms in subtropical reservoirs.

2. Material and methods

2.1. Study area

Our study included four reservoirs: Hubian (24°30′ N, 118°10′ E), Shidou (24°42′ N, 118°00′ E), Bantou (24°40′ N, 118°01′ E), and Tingxi (24°48′ N, 118°08′ E). All of these reservoirs are located around Xiamen city, Fujian province, southeast China (Fig. 1), and are important sources of drinking water for the city (Yang et al., 2012). These four reservoirs are located along an urban-to-rural gradient, extending from urban Hubian, to more rural sites in the nearby hills. Shidou, Bantou, and Tingxi Reservoirs all have forested catchments with Bantou having the most human modification of these three sites (having some buildings, small scale agriculture and plantation forestry scattered amongst the more semi-natural woodland). The area is subject to a subtropical humid monsoonal climate and has a highly seasonal precipitation pattern - which results in seasonal WLF of the reservoirs. Annual means of historical temperature and total precipitation (1956–2011) are 21 °C and 1468 mm, respectively. The rainy season is usually from May to September, while the dry season lasts from October to April.

The general characteristics of the study reservoirs are presented in Table 1. Typically, the highest water level occurs in summer and autumn and the lowest in winter and spring. However, Hubian Reservoir showed high water levels in the dry season because it was strongly affected by the artificial water transfers from the Jiulong River. Hubian Reservoir also has the shortest water retention time among the four studied reservoirs. Bantou is the smallest reservoir in volume, while Shidou is the largest reservoir with the longest water retention time. Tingxi Reservoir has the most pristine watershed, with nearly 100% of forest coverage. All of the four reservoirs were classified as light eutrophic ($50 < TSI \leq 60$) or middle eutrophic ($60 < TSI \leq 70$) based on their trophic state index (TSI) values (Yang et al., 2012; Lv et al., 2014).

2.2. Sampling and sample analysis

Surface water samples were collected at monthly intervals from May 2010 to April 2011. We selected three sampling stations from the riverine, transitional, and lacustrine zones in each reservoir (Lv et al., 2014). In each sampling site, 2.5 L of water samples were collected for recording biological communities and 0.5 L for physical and chemical analyses. Water temperature (WT), electrical conductivity (EC), dissolved oxygen (DO), and pH were determined *in situ* using a Hydrolab DS5 multi-parameter water quality analyzer (Hach, Loveland, CO, USA). Secchi depth (SD) was measured with a 30-cm diameter Secchi disk. Total nitrogen (TN) and total phosphorus (TP) were analyzed