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Effectiveness of a bubble-plume mixing system for managing phytoplankton in lakes and reservoirs

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ABSTRACT

Bubble-plume mixing systems are often deployed in eutrophic lakes and reservoirs to manage phytoplankton taxa. Unfortunately, inconsistent outcomes from bubble-plume (induced) mixing are often reported in the literature. The present study investigates the response of phytoplankton to induced mixing using a whole-reservoir field experiment and a three-dimensional hydrodynamic model (Si3D) coupled with the Aquatic EcoDynamics (AED) model through the framework for aquatic biogeochemical modelling (FABM). The coupled Si3D-AED model is validated against a 24-h field mixing experiment and subsequently used for a numerical parametric study to investigate phytoplankton responses to various induced mixing scenarios in which the phytoplankton settling rate, phytoplankton growth rate, reservoir depth, and mixing system diffuser depth were sequentially varied. Field observations during the mixing experiment suggest that the total phytoplankton concentration (measured in μg/L) across the reservoir was reduced by nearly 10% during the 24-h mixing period. The numerical modeling results show that phytoplankton concentration may be substantially affected by the functional traits of the phytoplankton and the deployment depth of the mixing diffuser. Interestingly, the numerical results indicate that the phytoplankton concentration is controlled by reduced growth rates due to light limitation in deep reservoirs (> 20 m), whereas settling loss is a more important factor in shallow reservoirs during the mixing period. In addition, the coupled Si3D-AED model results suggest that deploying the mixing diffuser deeper in the water column to increase mixing depth may generally improve the successful management of cyanobacteria using bubble-plume mixing systems. Thus, the coupled Si3D-AED model introduced in the present study can assist with the design and operation of bubble-plume mixing systems.

1. Introduction

Bubble-plume mixing systems, a type of water quality management system, are increasingly deployed to manage phytoplankton in lakes and reservoirs (Imteaz and Asaeda, 2000; Heo and Kim, 2004; Visser et al., 2016). Many studies have reported that turbulent mixing induced by mixing systems may mitigate water quality problems, including algal blooms and hypolimnetic hypoxia (e.g., Huisman et al., 2004; Imteaz et al., 2009; Gerling et al., 2014; Lehman, 2014).

Despite their increasing use by water managers, there has been little guidance as to how to best deploy and operate mixing systems for phytoplankton management. As a consequence, many mixing systems have been unable to prevent phytoplankton blooms, which are increasing globally due to climate and land use change, and can result in scums, odors, and toxins in drinking water supplies (Brookes and Carey, 2011; Carey et al., 2012). A study conducted by Nürnberg et al. (2003) showed that improper continuous mixing and aeration throughout a year may increase surface phytoplankton blooms due to increased upwelling of nutrients. Furthermore, poor design and operation of a mixing system may destratify a water body before fall turnover, impairing water quality. Toffolon et al. (2013) reported that mixing which aimed to increase dissolved oxygen (DO) in a shallow reservoir caused undesired premature destratification and even reduced the hypolimnetic DO concentration. Thus, careful consideration of the intensity, duration, and frequency of mixing is required for successful deployment of this type of water-quality management systems.

Additionally, the appropriate depth of deployment for mixing systems may vary based on taxon-specific phytoplankton traits and water body depth. Different phytoplankton taxa (e.g., cyanobacteria, green

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algae, or diatoms) respond differently to vertical mixing (Huisman et al., 2004; Lehman, 2014). Generally reservoir managers try to promote the growth of diatoms and limit the growth of cyanobacteria (Bielczyńska, 2015; Visser et al., 2016) because cyanobacteria are primarily responsible for harmful blooms in fresh water bodies (Carey et al., 2012). Their positive buoyancy due to gas vesicles allows cyanobacteria to dominate in the surface waters, maximizing incoming light for their growth (Visser et al., 1997; Huisman et al., 2004). Many studies have reported that the growth rate of bloom-forming cyanobacteria decreases due to the light limitation that occurs when turbulent mixing induced by mixing systems entrains cyanobacteria into deeper water (e.g., Nürnberg et al., 2003; Huisman et al., 2004). Field and numerical modelling studies suggest that vertical mixing prevents the growth of cyanobacteria but favours diatoms, which would otherwise quickly sink out of the photic zone in the absence of mixing due to their dense silica frustules (Huisman et al., 2005). As a result, induced mixing may result in a shift of the dominant taxa from bloom-forming cyanobacteria to diatoms. Therefore, particularly in deep water bodies with large aphotic zones, mixing may affect phytoplankton concentration by changing the competition for light among different species (Reynolds, 2006).

In shallow water bodies, however, the aphotic zone is much thinner (e.g., Nürnberg et al., 2003). Phytoplankton cells may settle out quickly on the sediments of shallow water bodies, setting up a scenario where settling rates, rather than light-dependent growth rates of different phytoplankton groups, may determine the overall outcome of mixing (Condie, 1999). Thus, the depth of a lake or reservoir may be an important factor controlling the outcome of mixing in water bodies. An optimum mixing depth controlled by the diffuser depth and mixing intensity may exist for a given water body, achieving a balance between managing phytoplankton taxa while simultaneously preserving thermal stratification.

To determine how best to deploy and operate water-quality management systems, we operated a bubble-plume mixing system in a shallow drinking water supply reservoir to examine its effects on phytoplankton. We used the experimental results to calibrate a 3-D hydrodynamic model (described in Chen et al., 2017) and then modelled multiple scenarios in which we sequentially manipulated the settling rate, phytoplankton growth rate, reservoir depth, and diffuser depth for idealized phytoplankton (cyanobacteria and diatom) cells. Our goal was to understand the effects of bubble-plume mixing on phytoplankton dynamics and improve the management outcomes following deployment of bubble-plume mixing systems in lakes and reservoirs.

2. Methodology

2.1. Study site

The study site is eutrophic Falling Creek Reservoir (FCR) in Vinton, Virginia, USA (37°18′12″N, 79°50′14″W). FCR is managed by the Western Virginia Water Authority (WVWA) for drinking water supply. The bathymetry of FCR is shown in Fig. 1. The reservoir has two water-quality management systems (a side-stream supersaturated hypolimnetic oxygenation system, SSS, and a bubble-plume epilimnetic mixer, EM) installed to deal with summer hypoxia and phytoplankton blooms, respectively.

The SSS system is designed to increase DO in the hypolimnion and suppress the release of soluble iron, manganese and phosphorus from the sediments, without destratifying the reservoir. The purpose of the EM system is to simultaneously mix and deepen the mixed layer, thereby disrupting the growth of surface bloom-forming phytoplankton taxa (e.g., cyanobacteria) by decreasing their access to light. Detailed descriptions of the SSS and EM systems are provided in previous studies (Gerling et al., 2014; Chen et al., 2017).

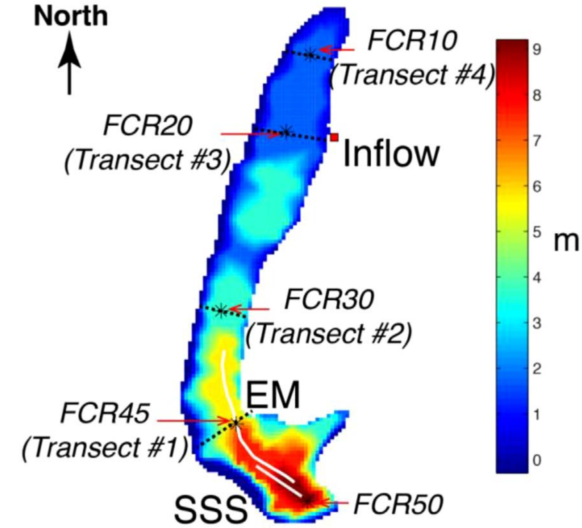

Fig. 1. FCR bathymetry and sampling locations. White lines near the deepest site of the reservoir, FCR50, show the locations of the SSS and EM systems. Black dashed lines in the contour show the location of Transects #1–#4.

2.2. Field experiment

Mixing experiments were carried out during summer 2016 to investigate the effect of bubble-plume mixing on phytoplankton dynamics across the water body. The schedule of operation for the EM system is shown in Table 1. The EM system was operated continuously over a 24-h period, whereas the SSS system remained in operation throughout the study.

There were five monitoring locations (FCR10, FCR20, FCR30, FCR45, and FCR50) in the thalweg from the upstream of the reservoir to the downstream (Fig. 1). The four upstream locations had corresponding transects (#1–#4), each consisting of nine monitoring points evenly distributed laterally across the reservoir, as indicated by the black dashed lines in Fig. 1. In total, there were 37 monitoring locations where vertical profiles were collected during the experimental period.

Temperature, dissolved oxygen (DO), and chlorophyll-a profiles were collected with an SBE 19plus high-resolution (4 Hz sampling rate) Conductivity, Temperature, and Depth (CTD) profiler (Sea-Bird Scientific, Bellevue, WA, USA) attached with a WETLabs ECO-FL fluorometer (Sea-Bird Scientific, Bellevue, WA, USA). The vertical resolution measured by the CTD was at ~ 0.1m for each of the 37 monitoring profiles from the water surface to the bottom. One-minute resolution meteorological data were obtained from an *in-situ* weather station deployed on the dam of FCR (Campbell Scientific Inc., UT, USA). The quality of the data collected by the weather station was checked against meteorological data measured at Roanoke Airport, which were downloaded from the National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA, www.ncdc.noaa.gov).

Table 1
Experimental schedule for the EM system.

DoY	178	179	180
EM	OFF	ON	OFF