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Hydrochemical controls on reservoir nutrient and phytoplankton dynamics under storms

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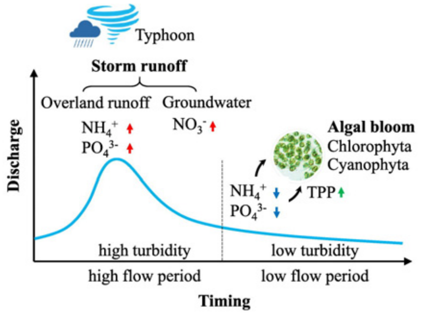
HIGHLIGHTS

- Hydrochemical controls on reservoir nutrient and phytoplankton were examined.
- NH_4-N and DRP enriched from storm runoff but removed by phytoplankton.
- Chl-*a* variation was mainly controlled by turbidity, NH_4-N, DRP, TP and discharge
- The Cyanophyta bloom was fueled by phosphate and ammonium rather than nitrate.

GRAPHICAL ABSTRACT



Reservoir nutrient and phytoplankton response to storms

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ABSTRACT

Eutrophication and undesired algal blooms in surface water are common and have been linked to increasing nutrient loading. Effects of extreme events such as storms on reservoir nutrient and phytoplankton remain unclear. Here we carried out continuous high-frequency measurements in a long and narrow dam reservoir in southeast China during a storm period in June–July 2015. Our results show a strong nutrient-phytoplankton relationship as well as a very rapid response to storm runoff. We observed an increase in total suspended matter (TSM), ammonium (NH_4-N), and dissolved reactive phosphate (DRP), with a sharp decline in chlorophyll-*a* (Chl-*a*) in the high flow periods. Afterward, Chl-*a*, total phytoplankton abundance and Cyanophyta fraction elevated gradually. Nitrate was diluted at first with increasing discharge before concentration increased, likely following a delayed input of groundwater. Physiochemical parameters and Chl-*a* were evenly distributed in the water column during the flooding period. However, 10% of NH_4-N and 25% of DRP were removed in surface water (0–1 m) when an algal bloom (Chl-*a* $> 30\ \mu g\ L^{-1}$) occurred 10 days after peak discharge. Conversely, total particulate P (TPP) of surface water was 58% higher than in the deeper water. Dynamic factor analysis (DFA) revealed that TSM, NH_4-N, DRP, total P and discharge significantly explain Chl-*a* variations following storms ($C_{eff} = 0.89$). These findings highlight that the reservoir ecosystem was vulnerable to pulse input from storm runoff and the Cyanophyta bloom was likely fueled by phosphate and ammonium rather than nitrate.

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1. Introduction

Eutrophication and harmful algal blooms are increasingly common in aquatic ecosystems worldwide (Heisler et al., 2008; Smith et al., 2006). Harmful algal blooms are typically triggered by excess inputs of the normally limiting nutrients nitrogen (N) and phosphorus (P) (Paerl, 2008), and are considered the greatest inland water quality threat to public health and environmental risk (Brooks et al., 2016; Gobler et al., 2012). Numerous works have addressed the spatio-temporal variation of nutrient and phytoplankton and chlorophyll-*a* (Chl-*a*) in freshwater ecosystems (such as reservoirs and lakes) and have highlighted the close relationship between riverine nutrient loading and phytoplankton biomass in reservoirs or lakes through measurement and modelling approaches (Kane et al., 2014; Mamun and An, 2017; Mo et al., 2016; Reartes et al., 2016). Internal nutrient release via diffusion and sediment resuspension may also contribute to algal blooms (Pearce et al., 2017; Søndergaard et al., 2003). Phytoplankton dynamics are site-specific and might be controlled by hydrological conditions and abiotic and biotic variables (Kuo and Wu, 2016). Understanding the nutrient cycling processes and key factors controlling phytoplankton succession and undesired algal bloom at various time scales is essential to develop site-specific strategies to mitigate eutrophication of aquatic ecosystems.

Climate change is predicted to have many diverse effects on lake and reservoir water quality and ecosystem functioning worldwide, due to changes in watershed hydrology and nutrient loading, water temperature, mixing regime, internal nutrient dynamics, and other factors (Paerl et al., 2016; Sin and Jeong, 2015; Wang et al., 2015). For example, rainfall-induced nutrient fluctuations in surface water affect phytoplankton communities and cause cyanobacteria blooms that are likely to occur in wet years (Qiu et al., 2016). Hydrochemistry and trophic state have changed in a large reservoir in the Brazilian northeast region under intense drought conditions (Santos et al., 2016). Enhanced stratification will influence nutrient availability and phytoplankton functional groups in deep reservoirs (Becker et al., 2009). However, most research on the effects of environmental change in freshwaters has focused on incremental changes in average conditions, rather than fluctuations caused by extreme events such as floods which need to be addressed to develop more accurate and predictive bio-assessments of the effects of fluctuations (Tweedley et al., 2016; Voynova et al., 2015; Woodward et al., 2016). Climate change is likely to increase tropical/subtropical cyclones and accompanying heavy storms, especially in subtropical East Asia (Webster et al., 2005; Wu et al., 2005). To date, the nutrient and phytoplankton dynamics in response to pulse inputs from storm runoff and key drivers controlling the formation of algal blooms are less documented.

Our previous research in southeast China has characterized the effect of major storms on the fluxes and processes related to nutrients being brought from the North Jiulong River catchment towards the estuary (Chen et al., 2012; Chen et al., 2015). We hypothesized that a reservoir ecosystem will be sensitive to pulse input of particulate matter and nutrient availability via storm runoff. Such storms were expected to increase the bioavailable nutrient forms (nitrate, ammonium, phosphate and organic nutrients) across the catchment but to different extents, depending on source supply and their transport paths (surface/subsurface runoff, and in-stream mobilization). Here we used opportunistic observational studies on the storm-driven runoff in a small dam reservoir (Xipi) in the middle North Jiulong River. We carried out high-frequency sonde measurement, daily sampling at the surface, and three-day sampling of the water column before, during and after storms that occurred in June–July 2015. The main questions we seek to address here are how storms change hydrochemistry and processes driving phytoplankton (Chl-*a*) variability. The specific objectives of this study were 1) to explore reservoir nutrient dynamics and nutrient-phytoplankton coupling in response to storm runoff, and 2) to determine the major factors controlling Chl-*a* evolution and algal bloom.

2. Materials and methods

2.1. Study area

The Jiulong River is a subtropical river located in southeastern China (Fig. 1), with a drainage area of 14,741 km^2. There are two main tributaries, the North River and West River. The watershed is under the Asian monsoon climate, subject to strongly seasonal variation of precipitation and temperature. The recorded mean annual air temperature is 20.9 °C, and annual precipitation is 1400–1800 mm, 75% of which occurs between May and October. Six major dams have been constructed along the main stem of the North River. Land use in the North River watershed includes 70% forest and upland orchards, 18% arable land and 5% urban and residential land. Pig farming in the upper stream area (Longyan city) has increased markedly since the late 1990s (Chen et al., 2013). The other counties (Zhangping, Hua'an) are predominantly agricultural and forest land and have a relatively low population intensity.

Xipi Reservoir is one of several cascade dam reservoirs located in the middle of the North River (Fig. 1). It began impounding water in 2008 for the purpose of hydropower generation and flood control, and now has a channel length of 8.5 km and mean width of 125 m. The same reservoir has previously been studied from perspectives of N and P cycling (Chen et al., 2014a; Lu et al., 2016; Zhou et al., 2016) and seasonal nutrient-phytoplankton dynamics (Mo et al., 2016). This study focuses on the effects of storm runoff on nutrient and phytoplankton in the lacustrine zone (0–2.5 km upstream of Xipi Dam). The main body of the reservoir has an open water area of 0.34 km^2, mean and maximum depth of 15 m and 28 m, a capacity of 389×10^4 m^3, and a relatively short HRT of less than a day (typical for a “run-of-the-river” reservoir). For a more detailed description of the study site see Mo et al. (2016). The dam is partly or completely opened during storm periods for flood controls depending on water level.

2.2. Sampling campaign and lab analysis

To capture nutrient and phytoplankton dynamics in reservoir water in response to storm runoff, daily measurements were conducted from June 18 through July 15, 2015 at site X3 in the lacustrine zone (Fig. 1). Surface (0.5 m) water was collected, filtered and stored in polyethylene bottles at a local house. The final sample collected on July 15 was excluded due to failure in sample storage. Vertical water samples were collected every three days at 1 m depth intervals using a SL-2A handheld electric deep water sampler (DEWALT® DC 740). A calibrated YSI sondes (6600, USA) was deployed at site X3 (1 m below water surface) to obtain hourly water temperature, pH, DO, turbidity, and chlorophyll. The YSI sondes was also used to measure the profile of the water column in three-day sampling.

All samples were filtered through a Waterman GF/F membrane, and frozen (−20 °C) until analysis. Nutrient forms analyzed included nitrate (NO_3–N), nitrite (NO_2–N), ammonium (NH_4–N), dissolved reactive phosphorus (DRP), dissolved total nitrogen (TDN) and phosphorus (TDP), and total particulate phosphorus (TPP) with total suspended matter (TSM). NO_3–N, NO_2–N, NH_4–N and DRP were analyzed by segmented flow automated colorimetry (San++ analyzers, the Netherlands), using standard procedures and methods (Rice et al., 2005). DIN was defined as the sum of NO_3–N, NO_2–N and NH_4–N. TDN and TDP were determined as NO_3–N and DRP following oxidization with 4% alkaline potassium persulfate. Dissolved organic P (DOP) was obtained by subtracting DRP from TDP, and dissolved organic N (DON) was obtained by subtracting DIN from TDN. The pre-weighed and filtered GF/F membranes were oven-dried (105 °C) to constant weight, and concentrations of TSM were determined gravimetrically. The oven-dried membranes were analyzed for TPP after being combusted in a muffle furnace (550 °C for 1.5 h) and extracted with HCl. The precision for nutrient analysis was estimated by repeated determinations of 10% of the