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Effects of rainfall patterns on water quality in a stratified reservoir subject to eutrophication: Implications for management

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HIGHLIGHTS

- Effects of rainfall patterns on water quality were systematically investigated.
- Duration of anoxic conditions at the bottom greatly influenced by rainfall patterns
- Rainfall patterns affect phytoplankton biomass and community structure.
- Water-lifting aerators were employed successfully for reservoir restoration.
- Optimized management strategies are recommended.

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ABSTRACT

The seasonal variation of hydrological conditions caused by shifting rainfall patterns observed in recent years has significant effects on water quality. High-volume inflows following heavy rainfall events that significantly disturb stratification lead to increased dissolved oxygen (DO) at the bottom of the reservoir, inhibiting the release of nutrients from sediments and causing a rapid reduction of algal biomass in the reservoir. However, the duration and extent of these effects depend not only on the frequency and intensity of heavy rainfall events but also on the period of thermal stratification in the reservoir. The effects of heavy rainfall events on water quality during three typical stratification periods of the reservoir were systematically investigated using extensive field data. The continuous heavy rainfall that occurred in September 2011 (stratification began to diminish) completely mixed the reservoir and produced a high concentration of DO along with a low phytoplankton concentration throughout the reservoir until stratification occurred the following year. Conversely, several days were required for anoxic conditions (in the hypolimnion) and cyanobacterial blooms to reappear after the storm runoff that occurred during the stable period of stratification (August 2012). In addition, the heavy rainfall that occurred in May 2013 accelerated the formation of an anoxic zone at the bottom of the reservoir and promoted cyanobacterial blooms due to the high nutrient input and the increased water temperature after the storm runoff ended. Water-lifting aerators (WLAs) were employed in the Shibianyu Reservoir to inhibit algal growth and to control the release of nutrients. Based on our field observations and theoretical analyses, optimized management strategies are recommended to improve water quality in the reservoir under different rainfall patterns at a reduced cost.

1. Introduction

Rainfall patterns are categorized by their amount and distribution, and regional differences in climatic and hydrological conditions lead to the existing diversity of global rainfall patterns (Cinco et al., 2014; Fernández-Montes et al., 2014; Zhang et al., 2014). The total amount of rainfall is expected to increase because of global warming. Studies show that heavy rainfall events are predicted to occur more often in the near future, while the total amount of precipitation is predicted to change slowly (de Lima et al., 2013; Xu et al., 2011). Correspondingly, the increasing intensity and frequency of storm-rainfall events will lead to a decrease in the number of typical rainfall events and to prolonged dry periods between events because the total rainfall is not expected to substantially change in a given area (Peng et al., 2013; Zhang and Cong, 2014). Rainfall events represent disturbances to water bodies because they initiate changes in the environment and hydrological conditions. Changes in rainfall patterns, particularly the time of occurrence, along with the frequency and intensity of extreme rainfall events have significant effects on the physical and chemical characteristics of reservoirs (Girmay et al., 2009; O'Neil et al., 2012; Wang et al., 2012a).

Precipitation drives runoff (Cantón et al., 2011). Generally, rainfall volume and inflow volume are correlated, especially during the flood

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period when a sufficient amount of rain falls to saturate the catchment (Ran et al., 2012). In a stratified reservoir, high inflow volumes can significantly reduce water column stability because vertical disturbance is intensified by water flow. However, the effects depend on the hydrodynamics after the inflow water enters the reservoir. Generally, reservoir hydrodynamics are regulated by the density difference between the inflow and the water impounded in a reservoir. In freshwater systems, suspended matter and water temperature are thought to be the primary factors controlling water density (Marti et al., 2011; Rueda et al., 2007). The occurrence and duration of rainfall events have significant effects on the inflow water temperature, while rainfall intensity is considered the primary force driving the inflow of sediment into a certain area (Thothong et al., 2011; Qin et al., 2010).

Many productive reservoirs in tropical and warm temperate regions are stratified for most of the year. This stratification could lead to long periods of anaerobic conditions at the bottom of the reservoir and result in a significant deterioration of water quality as reduced (chemical) species continue to be released from the sediments and enter the hypolimnion (Beutel et al., 2008; Fan and Kao, 2008). Significant turbidity currents following extreme rainfall events have been observed and reported for many reservoirs (Wang et al., 2012b). These high-density inflows coupled with a large amount of suspended matter and dissolved oxygen entering the bottom of the reservoir can immediately increase dissolved oxygen levels and effectively restrain the release of pollutants (Huang et al., 2014a; Liu et al., 2014; Ma et al., 2011). However, the duration and extent of the effects greatly depend on the time of occurrence of extreme rainfall events, but there is limited information on this important issue. The seasonal succession of phytoplankton biomass and communities is greatly influenced by rainfall patterns (Reichwaldt and Ghadouani, 2012; Xiao et al., 2011). Generally, high inflow volumes during rainfall events lead to a reduction of algal biomass due to high flushing rates and an increase of diversity due to the reduction of the previously predominant algae (Rigosi and Rueda, 2012). However, the high nutrient input into the reservoir by storm runoff will favor cyanobacteria (Becker et al., 2010). Few studies have investigated the time required for cyanobacterial blooms to reappear after storm runoff, which is also greatly influenced by the occurrence time of extreme rainfall events.

Cyanobacterial blooms that accompany the release of nutrients from bottom sediments during summer stratification have become a common problem for most stratified eutrophic reservoirs. Artificial mixing is increasingly used to control cyanobacterial blooms while simultaneously inhibiting the release of nutrients from bottom sediments (Toffolon et al., 2013; Upadhyay et al., 2013). However, seasonal variations in rainfall patterns have complicated optimized management of the reservoir. In this research, which is based on extensive field studies, we performed a detailed analysis of the effects of rainfall patterns on water quality in a deep reservoir subject to eutrophication during three typical stratification periods. Our objective was to establish an understanding of how changes in rainfall patterns affect hydrological conditions, stratification structure, water quality, and the succession of phytoplankton in a stratified reservoir subject to eutrophication. The results are important for the development of optimized management strategies to maintain water quality under different rainfall patterns at a reduced cost.

2. Materials and methods

2.1. Study site

The Shibianyu Reservoir (33°51′52″–34°00′25″N; 108°53′08″–109°02′20″E) is a deep, canyon-shaped reservoir located in the southwestern part of Xi'an City in the Shaanxi Province, Northwestern China (Fig. 1). Xi'an is the capital of Shaanxi Province, which has a population of 8.6 million people. The Shibianyu Reservoir was constructed in 1975 and began to supply water to Xi'an City in August 1990; it has

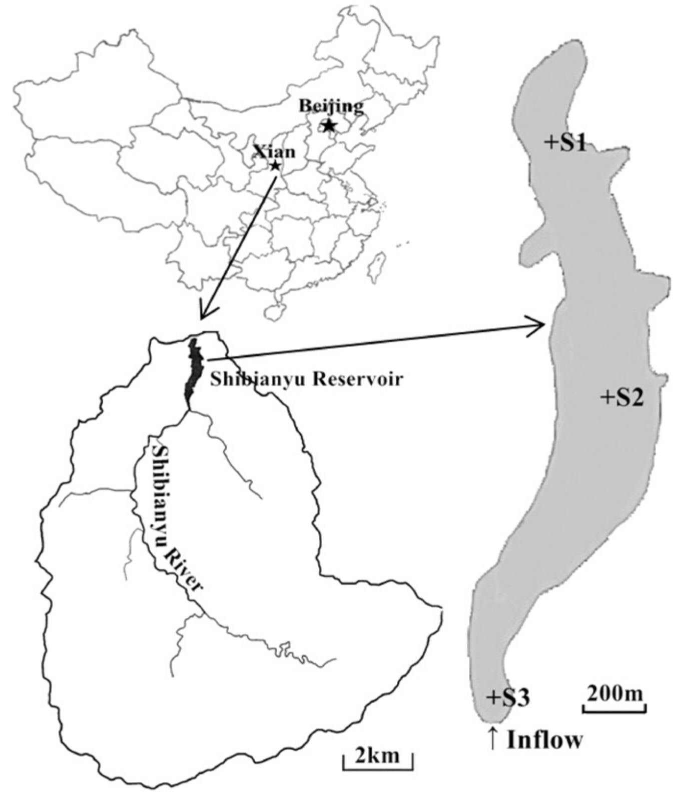

Fig. 1. Illustration of Shibianyu Reservoir showing locations of the sampling and monitoring sites.

developed into a multi-operational business for controlling floods, generating electricity, and supplying water. The reservoir has a total capacity of 28.1 million m^3 and supplies 30 million m^3 of water to Xi'an City annually. At capacity, the reservoir has mean and maximum depths of 32 m and 60 m, respectively. Typical for a temperate monsoon climate, the reservoir has a high average temperature of 22–24 °C in summer and a low mean temperature of −2 to −4 °C in winter.

Originating from the Qinling Mountain, the Shibianyu River is the main tributary of the Shibianyu Reservoir (Fig. 1). This river is 30 km long, with a catchment area of 132 km^2. The landscape upstream and surrounding the reservoir is largely unmodified and consists primarily of hills covered with forest with limited human activity, ensuring that the inflow water is in good condition most of the time. However, the inflow water quality deteriorates during storm rainfall periods due to soil erosion, with high concentrations of suspended matter and nutrients that are transported into the reservoir (Huang et al., 2014b).

As the city's alternate water resource, Shibianyu Reservoir's water quality is an important factor ensuring urban water security. The Shibianyu Reservoir is a stratified eutrophic reservoir, with annual average concentrations of total nitrogen (TN) and total phosphorus (TP) of 2.8 mg/L and 0.041 mg/L, respectively (Huang et al., 2014b). Cyanobacterial blooms in the surface water and the release of endogenous pollution from bottom sediments during the stratification period strongly influence the reservoir water quality. Two WLAs have been installed in the Shibianyu Reservoir to improve water quality. However, the seasonal variation of rainfall patterns significantly affects the water quality in the Shibianyu Reservoir in many aspects, thus influencing the methods used for optimized management. Three sampling sites were selected in the reservoir to investigate the changes in water quality influenced by rainfall events. S1 is located in the deep water area of the reservoir and is 250 m from the reservoir dam. The depth of the site varies between 23 and 60 m in response to water level fluctuations of the Shibianyu Reservoir throughout the year. S2 is located in the transition area and is 1200 m from the reservoir dam, with minimum and