JOURNAL OF ENVIRONMENTAL SCIENCES XX (2018) XXX–XXX

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JOURNAL OF ENVIRONMENTAL SCIENCES
www.jesc.ac.cn

Destratification and oxygenation efficiency of a water-lifting aerator system in a deep reservoir: Implications for optimal operation

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ARTICLE INFO

Article history:
Received 6 July 2017
Revised 15 December 2017
Accepted 18 December 2017
Available online xxxx

Keywords:
Reservoir
Thermal stratification
Numerical simulation
Water-lifting aerator
Mixing
Oxygenation

ABSTRACT

Thermal stratification is a common phenomenon in lakes and reservoirs and has a significant influence on water quality dynamics. Heihe Reservoir is a canyon-shaped reservoir in Shaanxi Province with strong thermal stratification. Therefore, eight water-lifting aerators (WLAs) were installed in this reservoir, which could overcome thermal stratification and increase oxygenation with gas flows between 20 and 50 m^3/hr, and oxygenate the hypolimnion with gas flows less than 20 m^3/hr. To examine the destratification efficiency of the WLA system, we used a three-dimensional hydrodynamic module based on MIKE 3 to simulate the thermal structure of Heihe Reservoir and compared the simulations with measured data. Results showed that operation of the WLA system promoted water mixing and effectively oxygenated the hypolimnion. Through the established energy utilization assessment method, the energy utilization efficiency of the WLA system was between 5.36% and 7.30%, indicating the capability of the technique for destratification in such a large reservoir. When the surface water temperature dropped to the theoretical mixed water temperature calculated by the energy utilization assessment method, reducing gas flow could save energy. This would prevent anaerobic conditions from occurring in the bottom water and maintain good water quality in Heihe Reservoir.

Introduction

Thermal stratification occurs commonly in reservoirs and lakes (Rangel-Peraza et al., 2012; Wang et al., 2012) and results in substantial hypolimnetic oxygen depletion, which has a negative impact on aquatic systems and water quality (Beutel et al., 2008; Elçi, 2008; Visser et al., 2016). Lakes and reservoirs in tropical and subtropical zones undergo seasonal thermal stratification, which divides the water column into the epilimnion, metalimnion, and hypolimnion (Gantzer et al., 2009b; Huang et al., 2014). The density gradient in the metalimnion prevents dissolved oxygen transport from the surface to the deep-water region, which can result in an anaerobic condition in the hypolimnion (Mackenthun and Stefan, 1995; Zhang et al., 2015). Long periods of anoxia lead to significant deterioration of water quality, because nutrients and metals continue to diffuse to the hypolimnion from sediments, and trigger algal blooms (Beutel, 2006; Gerling et al., 2014; Mcginnis and Little, 2002; Visser et al., 2016).

There are two major strategies for solving anoxia problems in the hypolimnion: one is to break thermal stratification by using artificial mixing techniques (Ma et al., 2015b; Visser et al., 2016),

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https://doi.org/10.1016/j.jes.2017.12.021
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and the other is to directly oxygenate the hypolimnion with hypolimnetic oxygenation systems (Chen et al., 2016; Gantzer et al., 2009b). Hypolimnetic oxygenation retains thermal stratification, thus protecting the biocoenosis in deep water (Bryant et al., 2011; Gantzer et al., 2009a; Toffolon et al., 2013). Nonetheless, thermal stratification usually promotes the growth of toxic cyanobacteria, which could deteriorate water quality and pose risk to public safety (Liu et al., 2012; Wynne et al., 2008). For *in situ* water quality improvement in reservoirs, artificial mixing techniques can overcome thermal stratification, and these techniques serve two functions: oxygenation and control of algal blooms (Li et al., 2013; Lundgren et al., 2013; Ma et al., 2015b). However, comprehensive studies on these techniques and their application in reservoirs are limited.

The water-lifting aerator (WLA) is a type of artificial mixing apparatus that overcomes thermal stratification and oxygenates the hypolimnion. The WLA system contains air compressors, gas holders, air supply pipe, and water-lifting aerators. Compressed air is transported through the air pipe to every water-lifting aerator, while the gas holders maintain the air pressure. This technique had been applied in some reservoirs, and some promising results were obtained. In previous studies, Ma et al. (2015a, 2015b) presented two different operation modes and researched the effect of the WLA system on endogenous pollution control and algae control in Heihe Reservoir and Shibianyu Reservoir. Zhou et al. (2017) indicated that the operation of this system could inhibit sediment release efficiently in Heihe Reservoir. Shi et al. (2016) researched the effect of the WLA system on the removal of dissolved sulfides and volatile organic sulfur compounds (VOSc) in Zhoucun Reservoir. Zhou et al. (2016) concluded that the WLA system enhanced indigenous aerobic denitrifiers and removed the total nitrogen effectively in Zhoucun Reservoir. The effect of the WLA system on destratification is an important topic to be investigated. Field observations combined with numerical simulation have become more important and widely used in researching the thermal regime of reservoirs, and a series of hydrodynamic models used to study the thermal regime of lakes and reservoirs have yielded some useful conclusions (Han et al., 2000; Kong et al., 2016; Samal et al., 2012; Trolle et al., 2011).

In this study, eight WLAs were installed in Heihe Reservoir, which is the most important fresh water source for Xi'an City. We used a three-dimensional hydrodynamic module based on the MIKE 3 software to simulate the thermal structure of the Heihe Reservoir, and study the effects of the WLA system on destratification. We also calculated the energy utilization of this system and discussed an optimized operation scheme to provide feasible management strategies for reservoir managers.

1. Study site

Heihe Reservoir (34°42′–34°13′ N; 107°43′–108°24′ E) is a large canyon-shaped reservoir located in Zhouzhi County, approximately 86 km southwest of Xi'an in Shaanxi Province, northwestern China (Fig. 1a). Xi'an is the capital city of Shaanxi Province, and has a population of 8.4 million people. The Heihe Reservoir is the most important fresh water source for Xi'an, with a daily water supply of 8.0×10^5 m^3. When full, the reservoir has a surface area of 4.55 km^2, a total capacity of 2.0×10^8 m^3, and mean and maximum depths of 44 and 94 m, respectively. Generally, the normal high and minimum water levels are 594 m and 520 m above sea level (a.s.l.), respectively. Originating from the Qinling Mountain, the Heihe River, which drains a catchment area of 1481 km^2, is the main tributary of the Heihe Reservoir. The upstream and surrounding landscapes of the reservoir are largely unmodified hills covered by forests that show little human activity.

2. Field observations

Field sampling campaigns were conducted from 2012 to 2016 to investigate water quality changes at sampling site S1 (34°02′44.39″ N; 108°12′23.17″ E). S1 was located at the middle of WLA-1 and WLA-5, in the deepest area of Heihe Reservoir and close to the intake tower. Another sampling site S0 (33°58′30.43″ N; 108°08′48.64″ E) was located at the inlet of the Heihe River to collect inflow hydrologic data, including inflow rate and water temperature (Fig. 1a). Vertical profiles of temperature and dissolved oxygen (DO) were measured every 2–3 m from the surface (0.5 m below the surface) to the bottom (0.5 m above the sediments) at S1 using a Hydro-lab DS5X (Hach, USA).

Daily hydrological and climatic data included outflow rate, water level, air temperature, radiation, precipitation, and evaporation from 2012 to 2016. The relationship between reservoir capacity and water level was obtained from the automatic weather station and Heihe Reservoir Administration Bureau.

3. Introduction of improved water-lifting aerators in Heihe Reservoir

Improved WLAs were installed in Heihe Reservoir, and the sketch and layout of the WLA system are shown in Fig. 1b and c. A previous study described the working principle of the WLA system (Ma et al., 2015a). The WLA system has two important functions: destratification and oxygenation. A large air piston does not form when gas flow is less than 20 m^3/hr, and the primary function is to oxygenate the hypolimnion. When the gas flow was between 20 and 50 m^3/hr, a large air piston would form and lead to mixing of the water body. The WLA system operated in the fall from 2013 to 2016 and successfully served the function of mixing the water bodies.

4. Numerical simulation model

We used a three-dimensional hydrodynamic module based on MIKE 3 to simulate the thermal structure of the Heihe Reservoir. MIKE 3 was developed by the Danish Hydraulic Institute (DHI) and had been successfully used to model many reservoirs and bays (Liu et al., 2007; Xing et al., 2013; Zeinoddini et al., 2015). In this study, the simulated domain included the Heihe River and Heihe Reservoir from sampling site S0 to the reservoir dam. We measured the bathymetry of the domain and generated unstructured triangular meshes with a maximum area of 0.02 km^2 and a minimum angle of 30°. To enhance computational efficiency, we used a variable vertical grid divided by a combined sigma z-level