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First report of the successful operation of a side stream supersaturation hypolimnetic oxygenation system in a eutrophic, shallow reservoir

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ABSTRACT

Controlling hypolimnetic hypoxia is a key goal of water quality management. Hypoxic conditions can trigger the release of reduced metals and nutrients from lake sediments, resulting in taste and odor problems as well as nuisance algal blooms. In deep lakes and reservoirs, hypolimnetic oxygenation has emerged as a viable solution for combating hypoxia. In shallow lakes, however, it is difficult to add oxygen into the hypolimnion efficiently, and a poorly designed hypolimnetic oxygenation system could potentially result in higher turbidity, weakened thermal stratification, and warming of the sediments. As a result, little is known about the viability of hypolimnetic oxygenation in shallow bodies of water. Here, we present the results from recent successful tests of side stream supersaturation (SSS), a type of hypolimnetic oxygenation system, in a shallow reservoir and compare it to previous side stream deployments. We investigated the sensitivity of Falling Creek Reservoir, a shallow (Z_{max} = 9.3 m) drinking water reservoir located in Vinton, Virginia, USA, to SSS operation. We found that the SSS system increased hypolimnetic dissolved oxygen concentrations at a rate of ~1 mg/L/week without weakening stratification or warming the sediments. Moreover, the SSS system suppressed the release of reduced iron and manganese, and likely phosphorus, from the sediments. In summary, SSS systems hold great promise for controlling hypolimnetic oxygen conditions in shallow lakes and reservoirs.

1. Introduction

Hypolimnetic hypoxia (defined as dissolved oxygen concentrations <2 mg/L; Wyman and Stevenson, 1991) in lakes and reservoirs degrades water quality and can prevent recovery from eutrophication (Cooke and Kennedy, 2001; Cooke et al., 2005; Wetzel, 2001). Maintaining an oxygenated environment in the bottom waters prevents the release of nutrients and

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reduced metals – namely, phosphorus (P), iron (Fe), manganese (Mn) – and their accumulation in the hypolimnion (Matthews and Effler, 2006; McGinnis and Little, 2002; Mortimer, 1941). Controlling these nutrients and metals is essential for improving water quality. Phosphorus can stimulate algal growth and exacerbate eutrophication (Schindler, 1977; Schindler et al., 2008; Smith, 1982), while Fe and Mn in the hypolimnion can cause taste, odor, and color problems for drinking water suppliers (AWWA, 1987; Zaw and Chiswell, 1999). Ultimately, maintaining an oxygenated hypolimnion is paramount for controlling these nutrients and metals and simplifying the water treatment process.

Hypolimnetic oxygenation systems are commonly used to increase dissolved oxygen (DO) concentrations in the hypolimnia of lakes and reservoirs (Beutel and Horne, 1999; Singleton and Little, 2006). Hypolimnetic oxygenation systems aim to maintain thermal stratification while adding oxygen to bottom waters (Beutel and Horne, 1999). Two primary advantages of hypolimnetic oxygenation systems are higher oxygen solubility in comparison to hypolimnetic aeration systems, and higher oxygen transfer efficiencies (percent uptake of delivered oxygen; Beutel and Horne, 1999). As a result, >30 hypolimnetic oxygenation systems have been deployed in lakes and reservoirs around the world, as documented in the literature (Liboriussen et al., 2009; Noll, 2011; Singleton and Little, 2006; Yajima et al., 2009; Zaccara et al., 2007).

Despite its promise, the process of hypolimnetic oxygenation has three major potential drawbacks – destratification, hypolimnetic warming, and induced sediment oxygen demand – that must be taken into account when designing a system. First, hypolimnetic oxygenation aims to raise the oxygen content of the hypolimnion without destratifying the overlying water column (Ashley, 1985). Such mixing could result in the entrainment of nutrients that were once isolated in the hypolimnion to the epilimnion, resulting in elevated nutrient concentrations in the photic zone and increased nutrient availability. Furthermore, partial destratification increases the hypolimnetic volume over which oxygen must be delivered to maintain desired DO concentrations, leading to inefficiency and added costs. Second, hypolimnetic oxygenation aims to avoid warming of the hypolimnion, which could lead to premature overturn, and poses a potential problem for benthic, cold-water organisms (Beutel and Horne, 1999; Wu et al., 2003). Third, hypolimnetic oxygenation may also stimulate increases in sediment and water column oxygen uptake, thereby accelerating hypolimnetic oxygen depletion and diminishing overall performance of the system (Bryant et al., 2011; Gantzer et al., 2009b). Although somewhat counter-intuitive, hypolimnetic oxygenation systems can increase oxygen demand by stimulating aerobic decomposition and chemical demand (Gantzer et al., 2009b; Lorenzen and Fast, 1977; Moore et al., 1996).

There are several different types of oxygenation systems that are commonly deployed in deep (>10 m) lakes and reservoirs. These primarily include bubble-plume diffusers (linear and circular) and submerged down-flow bubble contact chambers such as the Speece Cone (reviewed by Beutel and Horne, 1999; Singleton and Little, 2006). However, these types of systems are generally only deployed in deep lakes and reservoirs because shallow (<10 m) water bodies lack sufficient depth to ensure that bubbles of injected oxygen dissolve in the hypolimnion or that thermal stratification is not disrupted by system operation (Beutel, 2006; Cooke et al., 2005). Thus, for implementing hypolimnetic oxygenation in shallow lakes and reservoirs, a technique known as side stream supersaturation (SSS) represents a potential alternative (Beutel and Horne, 1999).

SSS may hold great promise for successful hypolimnetic oxygenation of shallow ecosystems. This technique involves withdrawing hypolimnetic water from the lake, injecting concentrated oxygen gas at high pressure, and returning the oxygenated water to the hypolimnion (Singleton and Little, 2006). Due to the small hypolimnetic volume in shallow water bodies, SSS systems may be more effective than other systems in increasing hypolimnetic DO concentrations because they can add more oxygen with low water flow rate, thereby causing less mixing and maintaining thermal structure.

In a comprehensive review of published studies and other reports, we found that side stream systems have been deployed thus far in at least five lakes or reservoirs and three river or tidal ecosystems worldwide (Table 1). We note the difference in our review between side stream systems that inject oxygen into the hypolimnion of water bodies at saturated concentrations (hereafter, side stream hypolimnetic oxygenation) and SSS systems, which inject oxygen at supersaturated concentrations.

The outcome of the previous side stream and SSS deployments has been mixed. While the earliest known deployment in Ottoville Quarry in 1973 (Z_{max} = 18 m) demonstrated that a side stream system could successfully increase hypolimnetic DO concentrations without destratification of the water column (Fast et al., 1975, 1977), later deployments of side stream systems, one an SSS, in Attica Reservoir (Fast and Lorenzen, 1976; Lorenzen and Fast, 1977), Lake Serraia (Toffolon et al., 2013), and Lake Thunderbird (OWRB, 2012, 2013), all exhibited premature destratification (Table 1). Consequently, there has been no successful deployment of a side stream or SSS system in a shallow (<10 m) lake or reservoir to date.

Given that most lakes and reservoirs worldwide are small and shallow (Downing et al., 2006; Scheffer, 2004), and that improving water quality is a major goal worldwide (MEA, 2005), we investigated the utility of SSS application in a shallow drinking water reservoir. We had two primary objectives. First, we assessed if the SSS system could successfully overcome induced sediment oxygen demand to increase hypolimnetic DO concentrations without triggering destratification or sediment warming. Second, we evaluated how well the system prevented the release of Fe, Mn, and P from the reservoir sediments.

2. Materials and methods

2.1. Study site

Falling Creek Reservoir (FCR) is a small, eutrophic drinking water reservoir near Vinton in Bedford County, southwestern Virginia, USA (37° 18′ 12″ N, 79° 50′ 14″ W). FCR is operated and