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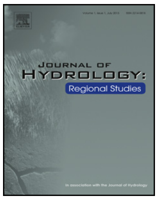

Small reservoir effects on headwater water quality in the rural-urban fringe, Georgia Piedmont, USA

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ABSTRACT

Small reservoirs are prevalent landscape features that affect the physical, chemical, and biological characteristics of headwater streams. Tens of thousands of small reservoirs, often less than a hectare in size, were constructed over the past century within the United States. While remote-sensing and geographic-mapping technologies assist in identifying and quantifying these features, their localized influence on water quality is uncertain. We report a year-long physicochemical study of nine small reservoirs (0.15–2.17 ha) within the Oconee and Broad River Watersheds in the Georgia Piedmont. Study sites were selected along an urban-rural gradient with differing amounts of agricultural, forested, and developed land covers. Sites were sampled monthly for discharge and inflow/outflow water quality parameters (temperature, specific conductance, pH, dissolved oxygen, turbidity, alkalinity, total phosphorus, total nitrogen, nitrate, ammonium). While the proportion of developed land cover within watersheds had positive correlations with reservoir specific conductivity values, agricultural and forested land covers showed correlations (positive and negative, respectively) with reservoir alkalinity, total nitrogen, nitrate, and specific conductivity. The majority of outflow temperatures were warmer than inflows for all land uses throughout the year, especially in the summer. Outflows had lower nitrate concentrations, but higher ammonium. The type of outflow structure was also influential; top-release dams showed higher dissolved oxygen and pH than bottom-release dams. Water quality effects were still evident 250 m below the dam, albeit reduced.

1. Introduction

The prevalence of small reservoirs is increasingly recognized across diverse landscapes (Downing et al., 2006; Lehner et al., 2011; McDonald et al., 2012; Verpoorter et al., 2012, 2014). Often less than a hectare in size, small reservoirs are used for water supply (*e.g.*, irrigation, stock watering, fire suppression), recreation (*e.g.*, fishing, boating), aesthetic amenity (*e.g.*, residential, golf courses), and hydrologic and sediment control (*e.g.*, flood mitigation, low-flow augmentation, sediment retention) (Winer, 2000). While the rate of new reservoir construction in the United States has declined recently, new

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reservoirs are being constructed in developing regions (*e.g.*, India, Africa) to provide community assets that assist with water independence by harvesting runoff (Annor et al., 2009; Oblinger et al., 2010; Teka et al., 2013).

This study focuses on the effects of small reservoirs on downstream water quality. Similar to wetlands and larger reservoirs, small reservoirs temporarily store stormwater that is gradually released, thus delaying and mitigating peak flows (Larm, 2000; Guo, 2001; Ravazzani et al., 2014). Small reservoirs can also increase evaporative water losses due to increased surface area and higher water temperatures (Tanny et al., 2008), leading to altered flows compared to a watershed lacking reservoirs. Modified downstream flows are especially commonplace during drought conditions when low reservoir volumes and high evaporation prevent water from discharging downstream. Reservoirs also affect water quality, which requires evaluation of "whether or not water is usable, or whether or not the surrounding environment may be endangered by pollutants in the water" (Engman and Gurney, 1991). We hypothesize that the increased number and total area of reservoirs has a seasonal impact on downstream water quality.

Temperature is often a critical water quality parameter and major determinant of aquatic organism occurrence and productivity (Gosink, 1986; Gooseff et al., 2005; Geist et al., 2008). Temperature regulates chemical-reaction rates and influences the solubility of ecologically important gases and minerals. Similarly, dissolved oxygen concentrations are also important for metabolic reasons, as well as controlling redox reactions (Chang et al., 1992; Jager and Smith, 2008). During stratified or partially-stratified conditions, reservoirs alter temperature and dissolved oxygen depending on water depth, with the reservoir becoming warmer and more oxygenated near the surface, and cooler and anaerobic at depth (Dripps and Granger, 2013). Downstream water temperature and dissolved oxygen concentrations vary depending on whether reservoir releases occur from the surface or near the bottom of the water column (Willey et al., 1996; Neumann et al., 2006).

Specific conductance is an electrical measure of total dissolved solids (TDS). Anaerobic conditions in stratified reservoirs lead to redox reactions that release manganese, iron, and other metals that increase TDS. Also, leaking sewer and septic systems lead to higher TDS in more-developed landscapes (Rosen, 2003). pH is a unit used to represent the concentration of dissolved hydrogen ions, H^+, while alkalinity is a measure of the ability of water to neutralize acidity. Photosynthetic activity alters reservoir pH and this activity can be markedly different in streams and reservoirs. Within reservoirs, photosynthetic CO_2 uptake increases pH, while respiration and decomposition decreases pH.

Turbidity describes the reduction in water clarity caused by suspended particles within the water, which affects water temperature and productivity. Reservoirs alter turbidity by slowing water velocity, allowing suspended particles to settle and preventing downstream sediment transport (Verstraeten and Poesen, 2000). Based on one study, reservoirs may have sequestered as much as one-third of the eroded sediments in the United States (Smith et al., 2002). Yet, suspended organic matter (*e.g.* phytoplankton, seston) can increase turbidity in lakes and reservoirs.

Nitrogen and phosphorus are common limiting nutrients for aquatic primary producers (Jansson et al., 1994; Yin and Shan, 2001; Paul, 2003; Downing et al., 2008). Nutrient loading in aquatic systems can stimulate primary production and cause algal blooms in the photic zone, and low dissolved oxygen and high CO_2 below the photic zone (Downing et al., 2008; Torgersen and Branco, 2008). Reservoirs alter nitrogen and phosphorus forms by redox and biological mechanisms, and also sequester them in stream and reservoir sediments, which can be resuspended within the water column when disturbed (Yin and Shan, 2001; David et al., 2006; Jacinthe et al., 2012; Powers et al., 2013).

Reservoirs modify habitats for aquatic species because they fragment aquatic habitats, which isolates species from headwater streams and affects species richness and genetic dispersal (Freeman et al., 2007). Many native species have evolved to survive in specific habitats, so that alteration of flows (*e.g.*, residence time) and water quality (*e.g.*, temperature, dissolved oxygen, pH, nutrients) can promote expansion of generalist invasive and exotic species (Johnson et al., 2008).

Small-reservoir water quality alteration primarily focuses on the performance of reservoirs used as surface-water hydraulic-control features (Winer, 2000). Water quality studies of small reservoirs show patterns similar to those exhibited by larger reservoirs, such as reducing sediment and nutrient loads (Bennion and Smith, 2000; Gal et al., 2003; Fairchild et al., 2005; Fairchild and Velinsky, 2006; Wiatkowski, 2010). The density of small reservoirs may affect the degree of water quality impacts. For example, watershed-scale studies in South Africa comparing regions with high and low reservoir densities have shown that a high density of small dams significantly reduces overall water quality (Mantel et al., 2010). Additionally, the range of reported water quality alteration is large and the "predictive ability for the function of reservoirs within specific hydrologic watersheds is poor" (Torgersen et al., 2004). Examination of the function of urban ponds for stormwater and pollution management has been identified as an important research need (Hassall, 2014).

The relationship between land use and water quality has long been established in the literature (Omernik et al., 1981; Osborne and Wiley, 1988; Herlihy et al., 1998). Land use near or adjacent to freshwater is of great importance, particularly for instream habitat structure and organic matter inputs. However, considering the entire contributing watershed (or *catchment*) often provides the best predictive link between land use and freshwater conditions such as nutrient supply, sediment delivery, and hydrology (Allan, 2004). Water bodies within urbanized watersheds typically have elevated nutrient concentrations, higher specific conductance, and flashier hydrographs (Sutherland et al., 2002; Walsh et al., 2005; Hughes and Mantel, 2010). Agricultural watersheds often have higher nutrient concentrations, sediment loads, turbidities, pesticides, and herbicides (Allan et al., 1997).

Interactions between freshwater ecology and the patchwork of watershed land covers and land uses can be explained using the *gradient paradigm (*Schoonover et al., 2005). The gradient paradigm proposes that the geography and form of environmental variation is ordered, and this structure governs the spatial functioning of ecosystems within that environment (McDonnell and Pickett, 1990). This suggests that ecosystem function is not just a consequence of land use, but also of the