Small Reservoir Impacts on Stream Water Quality in Agricultural, Developed, and Forested Watersheds: Georgia Piedmont, USA

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Abstract. Small reservoirs are prevalent landscape features and an important component of headwater hydrology. Tens of thousands of small ponds, most less than a hectare, were constructed over the past century within the United States. While remote-sensing and geographic-mapping technologies assist in quantifying these features, their influence on water quality is less well understood. This study reports the results of a year-long physicochemical study of nine ponds (0.15-2.17 ha) within the Oconee and Broad River watersheds in the Georgia Piedmont. Study sites were selected along an urban-to-rural gradient (i.e., three each of developed, agricultural, and forested) and were sampled monthly for pond discharge as well as inflow and outflow water-quality parameters (pH, temperature, specific conductance, dissolved oxygen, turbidity, alkalinity, total phosphorus, total nitrogen, nitrate, ammonium). While not representative of all ponds, this study provides reference conditions for pond water quality and examines downstream impacts within divergent land uses in the Georgia Piedmont. Results indicate small reservoirs have a significant impact on stream water quality and that this impact varies significantly based on the type of dam structure (top-release vs. bottom release).

INTRODUCTION

The prevalence of constructed ponds and reservoirs is increasingly recognized across diverse landscapes (Downing et al. 2006; Lehner et al. 2011; McDonald et al. 2012; Verpoorter et al. 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 features (e.g., residential, golf courses), and hydrologic control (e.g., flood mitigation, low-flow augmentation) (Winer 2000). Ponds are constructed in developing regions (e.g., India, Africa) to provide community assets that assist with water independence by harvesting runoff (McClain 2013).

The effects of ponds are broadly recognized but not precisely quantified. Similar to wetlands and larger reservoirs, ponds temporarily store stormwater that is subsequently released, thus delaying and mitigating peak flows. Yet, ponds can increase evaporation water losses due to greater surface area, higher temperature, and amplified wind effects (Tanny et al. 2008), leading to altered flows during drought conditions compared to a watershed lacking ponds. Ponds also affect water quality, which is a comprehensive concept describing “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). Water quality valuation includes physical, chemical, and biological properties.

Temperature is 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 reaction rates and influences the solubility of ecologically important gases and minerals. Similarly, dissolved oxygen (DO) concentrations are vitally important and determine oxygen availability for organic and inorganic compounds (Chang et al. 1992; Jager and Smith 2008). Ponds alter temperature and DO depending on water depth, with ponds becoming warmer and more oxygenated near the surface, and cooler and anoxic at depth. Downstream water temperature and DO concentrations vary depending on whether the pond outflows come from the top or bottom of the water column (Willey et al. 1996, Neumann et al. 2006).

Specific conductance is an electrical measure of the total dissolved solids. Anoxic conditions in stratified ponds leads to redox reactions that release manganese, iron, and other metals that increase conductances. Also, leaking sewer and septic systems lead to higher conductances in more-developed landscapes. 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. Ponds alter pH through changes in photosynthetic activity, where increased photosynthetic consumption of CO_2 increases pH, while decomposition and respiration decreases pH. Turbidity describes the decrease in water clarity caused by suspended particles within the water, which affects water temperature and productivity. Ponds alter turbidity by slowing water velocity, causing suspended particles to settle, and preventing downstream sediment transport. Based on one study, ponds may have sequestered as much as one-third of the eroded sediments in the United States (Smith et al. 2002; Verstraeten and Poesen 2000). Yet, ponds may increase turbidity by the production of seston, which is suspended organic matter such as algae.

Nitrogen and phosphorous are common limiting nutrients for aquatic primary producers (photo-autotrophs) in aquatic habitats (Jansson et al. 1994; Yin and Shan 2001; Paul 2003; Downing et al. 2008). Influxes of nitrogen and phosphorous stimulate primary production and cause algal blooms. Algal decomposition lowers dissolved oxygen, and increases CO_2 releases to the atmosphere (Downing et al. 2008; Torgersen and Branco 2008). Ponds alter nitrogen and phosphrous states through temperature and biological mechanisms. Additionally, phosphorous often binds with sediment and may be sequestered in benthic sediments (Yin and Shan 2001).

Water quality alteration by ponds modifies habitat for species. As aquatic species have evolved within certain habitats, manipulation of water quality characteristics such as temperature, pH, or nutrient availability can promote expansion of generalist invasive and exotic species (Johnson et al. 2008). Reservoirs constructed on-stream fragment aquatic habitat, affecting species richness and genetic dispersal, as species are isolated from headwaters (Freeman et al. 2007).

With the increased recognition of both point and non-point source contributions to water quality, the cumulative influences of tens of thousands of ponds should be considered. Small reservoir water quality alteration is primarily studied via reports on the performance of ponds used as surface water hydraulic control features (Winer 2000). Other studies of small reservoir impacts on water quality indicate similar patterns exhibited by large reservoirs such as reducing the loads of phosphates, nitrates, nitrites, ammonia, TSS, and TDS (Bennion and Smith 2000; Gal et al. 2003; Fairchild et al. 2005; Fairchild and Velinsky 2006; Wiatkowski 2010).

However, 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 values are large and therefore the predictive ability for the function of ponds within specific hydrologic watersheds is poor (Torgesen et al. 2004). Examination of water quality alteration within a set of small reservoirs within the Georgia Piedmont provides a baseline for evaluating the effects of ponds on water quality in the southeastern United States, including seasonal variations in water quality changes over an annual cycle.

METHODS

Monthly discharge and water quality data were collected from streams flowing into and out of nine small reservoirs from September 2012 through October 2013. In addition, near-shore samples were also collected directly from the reservoir. Temperature, DO, specific conductance, and pH were collected *in situ* using a Hydrolab Quanta water quality multiprobe. Turbidity was tested using a Hach 2100P Portable Trubidimeter. Alkalinity was calculated using a LaMotte Environmental Test Kit and direct reading titration method for total alkalinity in terms of $CaCO_3$. In addition, monthly water samples were collected at each monitoring location in the stream thalweg 50 cm below the stream surface. Samples were sent to the UGA Chemical Analysis laboratory for analysis of ammonia, nitrite, total nitrogen, and total phosphorous. Discharge was also recorded at each site for calculation of nutrient loads. During the same period, HOBO Water Temp Pro v2 dataloggers recorded temperature every fifteen minutes at each stream location. Dataloggers were secured within the thalweg using bricks and rope.

RESULTS AND DISCUSSION

Of the 108 site visits, 70 complete sets of upstream, pond, and downstream data were collected. This is because ephemeral streams were occasionally dry during the warm summer months. In addition, low inflows and high evaporation rates caused some reservoirs to release no water downstream.

By comparing upstream and downstream parameter values, we identified several significant patterns in water quality alteration by small reservoirs (Fig. 1-2). Figures show the change in each parameter (upstream value subtracted from the downstream value = change.) Positive change values indicate an increase in the parameter. Negative change values indicate a decrease in the parameter. Zero change values indicates no change (upstream and downstream are the same).

Figure 1: Small reservoir impacts on downstream dissolved oxygen (mg/L), temperature (°C), pH, turbidity (NTU), alkalinity (mg-$CaCO_3$/L) and specific conductance (mS/cm).

Reservoirs with top-release dam structures often exhibit different downstream trends than bottom-release structures. For example, the concentration of dissolved oxygen (DO) was significantly lower in water from the bottom of the reservoir water column. Downstream DO rates were lowered by as much as 4.9 mg/L. The lower DO rates relate to the low oxygen environment in the hypolimnion and the consumption of oxygen by bacterial respiration in the reservoir benthos. In contrast, top-release reservoirs that discharge water from the reservoir surface typically increased DO concentrations. The increase in DO from top-release reservoirs is caused by increased aeration of water by exchange of oxygen with the air and increased oxygenation as a by-product of photosynthesis by algae within the photic zone.

Temperature alteration also exhibited unique patterns based on dam structure. While nearly all reservoirs moderately increased downstream temperatures throughout the year, top-release dam structures exhibited significantly higher temperature increases in the warm March-October months. This is likely because lake stratification did not allow mixing between the heated epilimnion and cooler benthic waters.

Turbidity and alkalinity followed similar patterns. Both parameters generally increased downstream from reservoirs, particularly in association with bottom-release reservoirs, during the warmer and lower streamflow June-November period. Top-release reservoirs minimally increased downstream turbidity and alkalinity and occasionally even decreased these values.

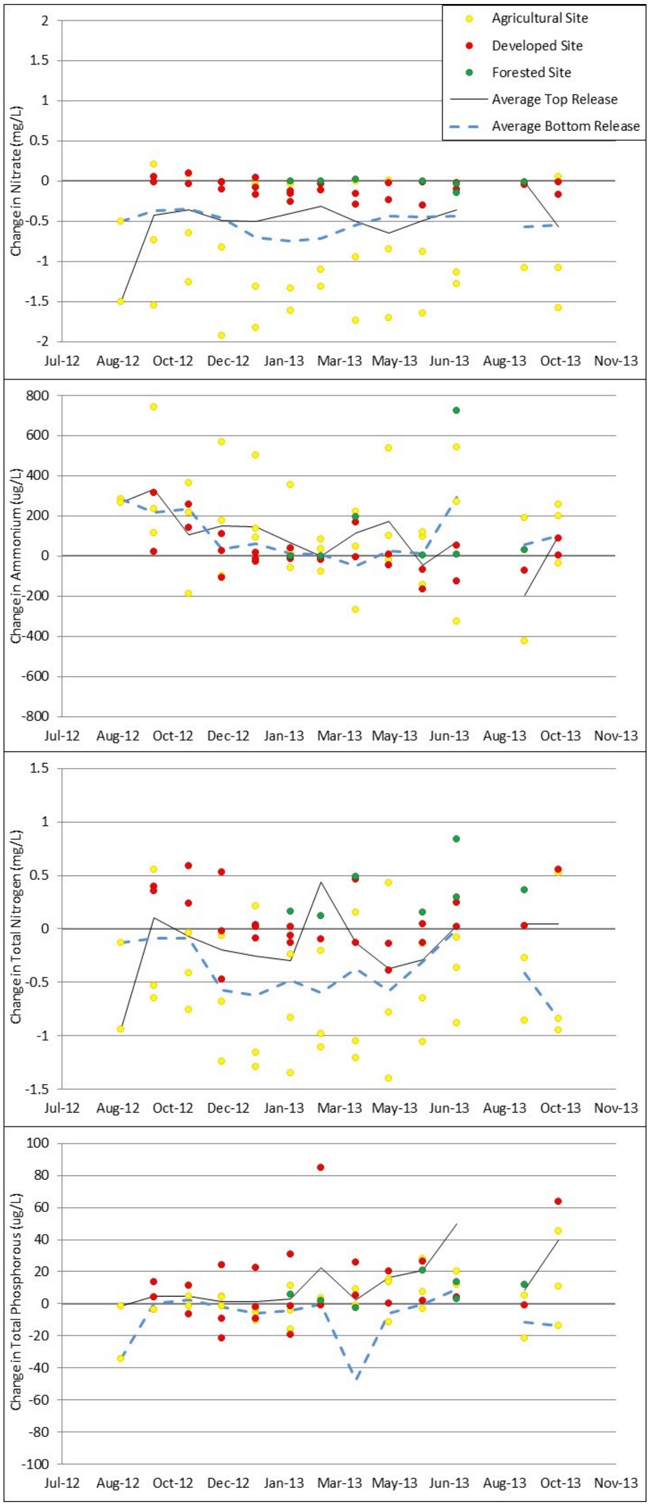

Figure 2: Small reservoir impacts on downstream nitrate (mg/L), ammonium (μg/L), total nitrogen (mg/L), and total phosphorous (μg/L).

Specific conductance was not strongly affected by the dam-release structure as top- and bottom-release reservoirs had similar downstream trends. Specific conductance increased downstream from reservoirs during the August-November period. However, during other months, downstream specific conductance values were similar to upstream values.

Modification of nutrient concentrations exhibited interesting trends, as well. Nitrate concentrations consistently decreased downstream from ponds (Fig. 2). The decrease in nitrate was most pronounced for agricultural sites with high incoming upstream nitrate levels. It is likely that growth of algal and aquatic plant biomass removed the nitrate from the system. In contrast, ammonium concentrations increased downstream from reservoirs. Ammonium increases were highest during the initial August-October period with warmer weather and lower rainfall.

The agricultural ponds had the highest increase in ammonium. Increased ammonium may have resulted from organic matter decomposition. Total nitrogen typically decreased downstream, especially for agricultural sites. Finally, total phosphorous slightly increased downstream from top-release dams and decreased below bottom-release dams. However, the total phosphorous often did not change substantially, except during unique events. The few high phosphorous events may be related to localized resuspension of sediments caused by animal activity or maintenance within either the streams or ponds.

CONCLUSIONS

The difference in physicochemical parameters upstream and downstream from small reservoirs demonstrates that these constructions play an important role in headwater water quality. In addition, the type of dam water release structure plays a dominant role in the type and extent of water alteration. As small reservoir creation continues both within the U.S. and abroad, the impacts of these constructions must be considered by individual land owners, water managers, and policymakers.

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