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Balancing lake ecological condition and agriculture irrigation needs in the Mississippi Alluvial Valley

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ABSTRACT

The Mississippi Alluvial Valley includes hundreds of floodplain lakes that support unique fish assemblages and high biodiversity. Irrigation practices in the valley have lowered the water table, increasing the cost of pumping water, and necessitating the use of floodplain lakes as a source of water for irrigation. This development has prompted the need to regulate water withdrawals to protect aquatic resources, but it is unknown how much water can be withdrawn from lakes before ecological integrity is compromised. To estimate withdrawal limits, we examined descriptors of lake water quality (i.e., total nitrogen, total phosphorus, turbidity, Secchi visibility, chlorophyll-*a*) and fish assemblages (species richness, diversity, composition) relative to maximum depth in 59 floodplain lakes. Change-point regression analysis was applied to identify critical depths at which the relationships between depth and lake descriptors exhibited a rapid shift in slope, suggesting possible thresholds. All our water quality and fish assemblage descriptors showed rapid changes relative to depth near 1.2–2.0 m maximum depth. This threshold span may help inform regulatory decisions about water withdrawal limits. Alternatives to explain the triggers of the observed threshold span are considered.

1. Introduction

The Mississippi Alluvial Valley (MAV) between Cairo, Illinois and Baton Rouge, Louisiana includes hundreds of floodplain lakes created by the meandering of prehistoric river systems, the Mississippi River, and other contemporary rivers that flow through the valley to join the Mississippi River (Baker et al., 1991; Miranda, 2016). The valley supports unique biotic assemblages that represent an important component of North American biodiversity. Nearly 50 species of mammals, 45 species of reptiles and amphibians, and 37 species of mussels occur in the MAV (Brown et al., 2000). Additionally, 136 species of fish depend on the river and floodplain system (Schramm et al., 2016), and roughly 100 fish species have been documented in floodplain lakes and backwaters (Baker et al., 1991; Dembkowski and Miranda, 2014). Beyond providing habitat, lake and wetland systems in the MAV have been described to enhance water quality by providing services such as acting as sediment and nutrient sinks; greenhouse gas mitigation; carbon sequestration; recreation including fishing, hunting, and boating; and assisting in flood control (Walbridge, 1993; King and Keeland, 1999; Jenkins et al., 2010).

Beginning in the 1850s, much of the bottomland hardwood forests that covered the MAV have been cleared and wetlands have been drained to facilitate agricultural use of the rich alluvial soils. Although most rivers have not been dammed within the valley, they have been modified by channelization and levee construction (Baker et al., 1991), and by impoundments above the valley. Agricultural development has reduced forests in the valley to about 20% of their original area, with half of the remaining forests occurring inside the Mississippi River's mainstem levee system (Forsythe, 1985). Deforestation and agriculture have altered runoff and increased sedimentation. These modifications have severely constrained channel migrations, to a point that no new abandoned channels are being created, whereas existing lakes are filling and losing depth at alarming rates of 1–7 cm $year^{-1}$ (Ritchie et al., 1979; McHenry et al., 1982; Cooper and McHenry, 1989; Wren et al., 2008). Within the valley, agricultural non-point source runoff of nutrients and agrochemicals have decreased water quality (Rebich, 2004) resulting in additional stress placed on aquatic communities (Kleiss et al., 2000). These anthropogenic landscape transformations have degraded the environmental quality of floodplain lakes and altered biotic characteristics.

An additional threat to floodplain lakes beyond degraded environment quality, is their use as source of water for irrigation. Currently,

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approximately 65% of the farmland in the MAV is irrigated to maintain maximum yields (Kebede et al., 2014) and this percentage has been increasing over time. A major issue facing agriculture producers is the unsustainable water withdrawal from the Mississippi River Valley alluvial aquifer for irrigation during the growing season when precipitation is minimal (Clark et al., 2011). Use of the aquifer is almost exclusively (98%) for irrigation of agricultural fields (Arthur, 2001). Since the 1970s, groundwater volumes in the aquifer in Mississippi alone have decreased at a rate of approximately 12,335 ha-m year^{-1} due to an increase in irrigated area (Thornton, 2012). Decreasing water levels in the aquifer have resulted in producers and agriculture conservationists turning to creating new water sources (e.g., tailwater recovery systems; on-farm storage reservoirs; Omer, 2017), considering interbasin water transfers (Muzzi, 2000), or using existing surface water sources (e.g., floodplain lakes) for irrigation. These efforts are reflected by the number of surface water use permits awarded, which more than doubled between 2005 and 2011 from 116 to 283 in the Yazoo Basin alone (YMD, 2005, 2011).

Existing sources, such as floodplain lakes, could provide a substantial water resource for producers in the Mississippi Alluvial Valley. However, use of these natural sources of water could further threaten the ecological integrity of lakes already impacted by a century of deforestation and hydrological modifications that support agriculture (Alfermann and Miranda, 2013). Due to their small size and relatively shallow depth, floodplain lakes have limited capacity particularly in late-summer and early-fall when evapotranspiration is high and rainfall is low. It is during this time of the year when water for irrigation is commonly pumped from floodplain lakes. Using lakes as a water source could prove to be detrimental to local biota which are already stressed due to decreased water quality caused by agriculture runoff with elevated concentrations of nutrients, suspended solids, and agrochemicals (Rebich, 2004). Decreasing the volume of these systems during an already stressful time of the year could further degrade lake abiotic and biotic conditions by exacerbating water quality problems and altering habitat availability and accessibility. It has been established that lake depth influences fish assemblages, algal production, and the physical and chemical characteristics of water in floodplain lakes of the region (Miranda, 2011).

Whereas, the relationships between lake depth, physicochemical variables, and fish assemblage metrics have been described (e.g., Miranda, 2011; Dembkowski and Miranda, 2014; Goetz et al., 2015), to our knowledge no attempt has been made to quantify critical depth thresholds that can be used by agricultural interests and agency regulators to minimize impacts of water withdrawals to lake water quality or biotic characteristics. Critical thresholds may occur when the response of a variable relative to lake depth is not linear, but changes at some threshold. At this threshold level, the effect of lake depth weakens, strengthens, or otherwise stabilizes (Toms and Lesperance, 2003; Toms and Villard, 2015). By providing evidence-based targets, lake depth thresholds can inform and guide regulatory decisions designed to maintain or improve lake health while allowing rationed water withdrawals to help support agricultural, industrial and municipal uses. With this goal, our objective was to examine the relationships between water depth, physicochemical variables, and fish assemblage descriptors to determine if and where critical depth thresholds occur in floodplain lakes of the MAV.

2. Methods

To address our objective, we examined various physicochemical variables and fish assemblages relative to lake depth. We considered a hierarchy of descriptors stretching from nutrient concentrations, to water clarity, primary production, and fish assemblage attributes.

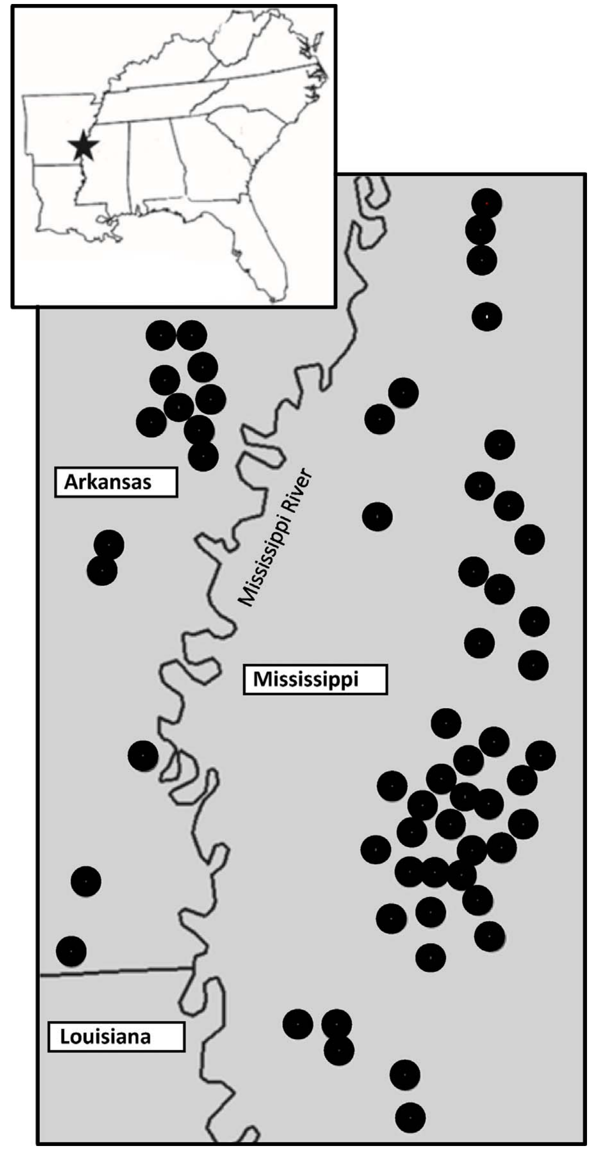

Fig. 1. Location of 59 floodplain lakes within the Mississippi Alluvial Valley. Inset identifies the study region in the southeastern United States.

2.1. Data collection

In all, 59 floodplain lakes (Fig. 1) representing about 10% of lakes in the region (Baker et al., 1991) were included in this study. The lakes are associated with the Arkansas, Ouachita, and White rivers in Arkansas, and Yazoo, Coldwater, Tallahatchie, and Big Sunflower rivers in Mississippi. All lakes were channel remnants of varying lengths. The set of study lakes was selected based on accessibility and representation of a broad range of maximum depths. Average land use within a 1-km concentric band around each study lake (lake-specific watersheds could not be defined because of the lack of sufficient topographic relief in the region) included 48% (range 0–77) agriculture, 30% (2–100) forest cover, and 6% (0–38) wetlands (Dembkowski and Miranda, 2014). To partially control for diel variability and seasonal fluctuations, nutrients, water clarity, and primary production were measured between 1100 and 1330 h, and fish collections were made between 600 and 1200 h. To control for seasonal variability, surveys were conducted during July to early-August. This period includes the time of the year in the study region with peak primary production, limited rainfall, reduced connectivity between lakes and neighboring rivers, and when water is pumped out of the lakes. Lakes were sampled once in 2006–2012; 19 of