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A field-scale investigation of nutrient and sediment reduction efficiencies of a low-technology best management practice: Low-grade weirs

B.H. Baker[a,*], R. Kröger[b], J.D. Prevost[c], T. Pierce[d], J.J. Ramirez-Avila[e], J.M. Prince Czarnecki[a], D. Faust[a], C. Flora[f]

[a] Department of Wildlife, Fisheries and Aquaculture, Mississippi State University, MS 39762, United States
[b] Covington Civil and Environmental, LLC, 2510 14th Street, Suite 1010, Gulfport, MS 39501, United states
[c] Delta F.A.R.M., PO Box 276, Stoneville, MS 38776, United States
[d] Environmental Protection Agency Gulf of Mexico Program Office, 2510 14th Street, Suite 1212, Gulfport, MS 39501, United States
[e] Department of Civil and Environmental Engineering, Mississippi State University, MS 39762, United States
[f] United States Department of Agriculture Agricultural Research Service, Stoneville, MS 38776, United States

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ABSTRACT

Increasing awareness of hypoxia in ocean regions across the globe has led to creation of nutrient reduction strategies targeting this coastal problem. In the Mississippi River Basin, the Governor's Action Plan has called for a 45% load reduction of both nitrogen (N) and phosphorous (P) to reduce the Gulf of Mexico hypoxic zone. One documented best management practice (BMP) for nutrient reduction is low-grade weirs (hereafter "weirs"). Recent studies have highlighted advantages of using low-grade weirs in agricultural ditches for controlled drainage by increasing hydraulic residence time (HRT) and mitigating nutrient loading from storm water and sedimentation. This study aimed to assess the ability of weirs to reduce nutrients in agriculture runoff at field-scale in the Mississippi Delta. Nutrient load reductions were observed in drainage ditches with and without weirs. However, nutrient and sediment loads varied widely, with observed load reductions ranging from −885 to 96% and −1 to 65% for total inorganic N and total inorganic P, respectively, in ditches with weirs. Maximum nutrient load reductions highlight that systems, with and without weirs, have the capability to reduce nutrients under certain conditions, while minimum nutrient reductions highlight when drainage ditch capacity limitations were exceeded. Differences in nutrient and sediment concentrations between storm- and low-flow samples ranged from 28 to 97%, indicating water velocity as the driving force behind observed differences. Seasonal analysis of nutrient runoff revealed significantly higher concentrations of total inorganic N, total inorganic P, and total suspended solids in the spring ($p = 0.003$, $p < 0.0001$, and $p < 0.0001$, respectively), while an N also increased in the fall ($p = 0.007$). Differences in annual sediment and P trends showed lower concentrations in systems with weirs. While this investigation highlighted both the successes and limitations of utilizing low-grade weirs as a BMP, results suggest that capture capacity of BMPs should be tailored to drainage acreage and site variability.

1. Introduction

Global crop demands are forecasted to increase between 100–110% from 2005 to 2050 (Tilman et al., 2011), requiring the intensification of agricultural production to meet demands. As agricultural intensification in the last 35 years has already resulted in a 6.87- and 3.48-fold increase in nitrogen (N) and phosphorus (P) fertilization, linear expansion of past trends project approximately 3-fold increases in N and P associated with continued population expansion (Tilman, 1999). Increased fertilizer applications to agricultural landscapes result in higher nutrient loading to receiving surface waters (Donner, 2003) leading to eutrophic conditions in coastal ecosystems. This issue is of particular concern in the Gulf of Mexico, where nutrient losses from agricultural landscapes in the Mississippi–Atchafalaya River Basin have led to increased nutrient

* Corresponding author. Current address: Water Quality Laboratory, Thompson Hall 253, Mississippi State University, Starkville, MS 39762, United States. Fax: +1 662 325 4763.
E-mail address: beth.baker@msstate.edu (B.H. Baker).

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loading to downstream surface waters and the occurrence of an annual coastal hypoxic zone in the Gulf of Mexico (Rabalais et al., 2002; Rabalais, 2011). The need to reduce nutrient loading to the Gulf of Mexico has led to the establishment of a goal to reduce riverine total N and P loads by 45% (USEPA, 2008; GOMA, 2009) and an increased allocation of resources and research initiatives to implement innovative management strategies to achieve those nutrient reductions.

Serving as primary conduits for agricultural runoff, ditch systems, are essential features for adequate drainage to maintain crop production. Found throughout the Lower Mississippi Alluvial Valley, ditch systems have been shown to transport nutrients and other agricultural pollutants to downstream waters (Moore et al., 2001a,b; Randall and Vetsch, 2005; Needelman et al., 2007; Smith et al., 2008). Additionally, drainage ditches function to control water Table levels, influencing chemical and biological processes (Needelman et al., 2007) and have been examined as a management practice for nutrient remediation (Moore et al., 2001a,b; Cooper et al., 2002; Moore et al., 2010). Recent studies have demonstrated the ability of drainage ditches to mitigate nutrient runoff (Kröger et al., 2007, 2008a; Moore et al., 2010). Furthermore, utilizing controlled drainage structures within ditch systems has been identified as having additional benefits for nutrient management (Evans et al., 1995).

Best management practices (BMPs) in the form of controlled drainage have been implemented on the agricultural landscape to reduce nutrient concentrations and loads to receiving waters by reducing drainage outflows (Gilliam et al., 1979; Evans et al., 1992, 1995; Borin et al., 2001). Controlled drainage is a practice in which a structure, such as a variable-height riser, is used to manage the water level in a drainage outlet (Evans et al., 1995). Low-grade weirs (hereafter referred to as weirs) have been utilized in lieu of traditional control drainage practices (e.g., variable-height risers) to reduce effluent nutrient loads in recent studies. Kröger et al. (2008a) demonstrated that weirs had the potential to facilitate more efficient management of systems via flexible spatial configurations within the drainage ditch rather than stationary outflow control structures. Semi-controlled experiments showed increases in hydraulic residence time (HRT) (Kröger et al., 2008b) and reduced nitrate concentrations (Kröger et al., 2011, 2012) in systems with weirs. Results of a field-scale investigation of a single drainage ditch with weirs installed showed similar effects on HRT and nutrient reductions of N and P constituents ranging from 14 to 67% (Littlejohn et al., 2014). Additional investigation of the potential use of weirs for controlled drainage at the field scale is warranted for replication.

The objective of this study was to quantify nutrient reduction efficiencies of weirs in drainage ditches receiving agriculture runoff at the field-scale. The experiment was conducted in the Mississippi Delta, a highly productive agricultural region of large economic importance to the State of Mississippi. The Mississippi Delta is located in northwestern Mississippi and is part of the larger Mississippi River Basin. The hypothesis of this study was that the implementation of weirs in agricultural drainage ditches would alter hydraulic residence time and denitrification, resulting in enhanced nutrient load and concentration reductions compared to ditches without weirs. Nutrient concentrations and loads were monitored in drainage ditches with and without weirs within working row-crop agricultural landscapes. Goals of weir implementation and nutrient monitoring aim to highlight the effectiveness of these structures for water quality improvement. This investigation also aims to demonstrate how innovative, low-technology nutrient reduction strategies can decrease nutrient contributions to coastal ecosystems.

2. Materials and methods

Study sites were located in in the Mississippi Delta, an area formed by alluvial deposits of the Mississippi River and its tributaries (Fisk, 1951). Sub-watersheds were chosen because of their priority status within a Mississippi River Basin Healthy Watersheds Initiative and listing on the Mississippi Department of Environmental Quality 303(d) list of impaired waters (Upper Yazoo-Hydrologic unit code 08030206). A total of six agricultural drainage ditches were chosen for experimental sites located in Humphreys and Yazoo Counties, MS (Fig. 1). Of the six ditches, two were reference ditches with no weirs (hereafter referred to as Ref-A and Ref-B), two were ditches with two weirs installed in each (hereafter referred to as W2-A and W2-B), and two were ditches with four weirs installed in each (hereafter referred to as W4-A and W4-B). Ditches were characterized by their physical differences and soil types (Table 1). Physical differences included the respective watershed drainage area around each ditch, as well as the drainage ditch dimensions.

Precision surveys of the agricultural drainage area were conducted to calculate the fall of each ditch via elevation surveys with laser level (Spectra Precision LL300, Westminster, CO, USA). The fall of each ditch was used to determine weir placement and height to efficiently manage hydrologic flow, residence times, and reductions in nutrient losses from these primary drainage ditches downstream. The target goal was to maintain 0.03 m of grade fall per 30.5 m of ditch length to ensure sufficient field drainage (engineering standard for drainage ditches in the lower Mississippi Alluvial Valley as the landscape has little natural fall). Weir placement aimed to maximize water retention in the system while limiting weir height to reduce flood risks, where the holding capacity behind one weir reached the next upstream weir. Weir placement was agreed upon by Delta Farmers Advocating Resource Management (F.A.R.M), Mississippi State University, and landowners prior to installation. Delta F.A.R.M installed weirs with help from landowners between August 2011 and November 2011.

Low-flow grab samples were collected (if water was flowing) every three weeks during the growing season (March–October) and every six weeks during the dormant season (November–February), while storm-flow samples were collected on a per-rain-event basis. Both storm- and low-flow samples were collected from January 2011 through July 2013. At outflows from each ditch, automated ISCO 6712 water samplers (24 bottle, polyethylene, HACH, Loveland, CO, USA) fitted with Module 720 velocity and water level loggers were installed (Fig. 2). ISCO samplers were calibrated and programmed to trigger sample collection once water depth increased 10 cm from baseflow levels; 900 mL samples were collected every 10 min for the first hour of every rain event (to catch the peak of the hydrograph) and every hour thereafter if the rain event continued. The maximum number of samples collected via ISCO sampler per rain event was 24. Passive samplers, made of PVC pipe (custom in-house fabrication) were also installed next to each ISCO sampler at fixed heights (200–1200 mm above the sediment surface) and at all subsequent sampling locations within drainages ditches as the primary water collection method to capture the rising limb of a storm hydrograph. Passive samplers had a storage capacity of 650 mL and self-seal once filled. At outflows, passive and ISCO samples were averaged to better represent water quality throughout storm hydrographs via determination of event mean concentrations. To monitor water level, a designated LevelTroll® (In-Situ Inc., Ft. Collins, CO, USA) was stationed at each sample site, and a Baro Troll® (In-Situ Inc., Ft. Collins, CO, USA) was deployed as an atmospheric reference. Sample sites were located just downstream of weirs prior to outlets in ditches with weirs.

All water samples were handled, collected, and transported according to United States Environmental Protection Agency quality assurance/quality control guidelines (USEPA, 2002). Water