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Nutrient Mitigation Capacity of Low-Grade Weirs in Agricultural Drainage Ditches

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By

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Installation of low-grade weirs in agricultural drainage ditches is being evaluated as an innovative, and cost effective, management practice that decreases nutrient concentrations and loads by increasing water volume and hydraulic residence time of the ditch. Results revealed that weirs significantly increased (P = 0.029) hydraulic residence time (HRT) and ditch water volumes, leading to considerable reductions in outflow water volumes (61%). Furthermore, ditches with weirs achieved greater (P = 0.09) cumulative outflow load reductions (96%) and greater (P = 0.029) concentration reductions during the biogeochemical reduction phase of the experiment. Similarly, field research from Terrace Ditch in Yazoo County, MS yielded significant percentage concentration reductions for baseflow (53%), stormflow (63%), and load (65%). Results from the experimental approach and field scale research offer promising insight into the future of low-grade weir's establishment as an additional best management practice in agricultural landscapes.

DEDICATION

I dedicate my research to my grandfather, Charles M. Veazey, a 1961 graduate of Mississippi State University. His MSU pride, love and unwillingness to let yet another grandchild become an Ole Miss Rebel started a journey years ago that brought me to where I am today. "Wrap it in Maroon and White Papaw!"

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CHAPTER I

INTRODUCTION

The increasing global population has placed added stress on farmers in the U.S. and abroad to expand and produce more crops, likely leading to an increase in use of inorganic fertilizers. Consequently, increased fertilizer use could result in higher loads of nutrients being delivered from agricultural soils to surface receiving waters (Donner, 2003). This delivery may ultimately lead to a 2.5-fold increase in nitrogen (N) driven eutrophication (Tilman *et al.*, 2001) and greatly increase transfer of N, primarily nitrate (NO_3^-), by rivers to estuaries and oceans (Vitousek *et al.*, 1997). Nitrate transfer and increased eutrophication is of particular concern in the Mississippi River Basin (MRB) and the Gulf of Mexico because of the substantial agriculture production found throughout the basin (Kröger *et al.*, 2008a).

The MRB encompasses portions of 14 states whose land use is dominated by 90% agriculture production. Due to its high-intensity agricultural–economic system, a portion of the MRB is referred to as the nation's "breadbasket" (Turner and Rabalais, 2003). The MRB has a total watershed area of approximately 3 million km^2, covering nearly 40% of the lower contiguous U.S., and accounting for approximately 90% of the freshwater inflow to the Gulf of Mexico (Day *et al.*, 2003) . Nitrogen exports from the MRB are receiving increased attention. In particular, mitigating harmful effects of increased NO_3^- loadings on the Gulf of Mexico has been considered (Dodds and Welch, 2000; Schilling and Zhang, 2004). Having farmers implement best management practices (BMPs) represents one possible method for reducing N concentrations and loads produced by agriculture from reaching adjacent water bodies (Gilliam *et al.*, 1979; Gilliam and Skaggs, 1986; Evans *et al.*, 1992; Borin *et al.*, 2001).

Best management practices permit economical and viable agricultural production while achieving the least possible impact on the environment, including water quality. Management practices aimed at reducing nutrients can be divided into three categories: avoiding, controlling, and trapping, with most BMPs focused on the controlling and trapping nutrients. Examples of such management practices include: cover crops, no till, buffer strips, vegetative barriers, nutrient management, and controlled drainage (CD). Controlled drainage is a management practice found in northeast Italy (Borin *et al.*, 2001), southern Sweden (Wesstrom *et al.*, 2001), and North Carolina (Evans *et al.*, 1992; 1995). It has received global recognition as an additional BMP aimed at reducing nutrient concentrations and loads in drainage ditches from reaching downstream aquatic ecosystems (Kröger *et al.*, 2008a).

Drainage ditches are integral components of the MRB's agricultural landscape that contribute to transportation of non-point source pollutants into surface receiving waters, as well as acting as unique ecosystems that integrate characteristics of streams and wetlands (Needelman *et al.*, 2007). Drainage ditches consists of hydric soils, are subject to hydrological fluctuations and can support a diverse community of hydrophytic vegetation (Kröger *et al.*, 2008b). Due to these wetland characteristics, drainage ditches are truly the forgotten links between the agricultural landscape and surface receiving waters (Moore *et al.*, 2005). Studies have shown that managers can greatly decrease nutrient loads exiting the agricultural landscape and entering adjacent aquatic ecosystems by using drainage ditches through CD practices (Cooper *et al.*, 2002; Kröger *et al.*, 2008a; 2008b).

Controlled drainage practices have been used in many different agricultural situations to reduce velocity and volume of outflow solutes, decrease water table depths, and increase storm water mitigation and sediment retention (Wesstrom *et al.*, 2001; Wright *et al.*, 2001; Needelman *et al.*, 2007; Kröger *et al.*, 2011). The most common CD practice in use is the slotted board riser, which uses outlets in drainage ditches to reduce erosion impacts during isolated periods of high rainfall (Skaggs *et al.*, 1994; Lalonde *et al.*, 1996; Kröger *et al.*, 2011). This practice has two major disadvantages because the riser is: 1) limited in temporal operation and 2) spatially isolated to the ditch outlet. However, because certain drainage ditches are hundreds of meters long, use of low-grade weirs installed in a stratified spatial arrangement within agricultural ditches has been proposed as an alternate CD strategy by Kröger *et al.*(2008a; 2008b)

Low-grade weirs are structures consisting either of an earthen dam covered with rip-rap or a concrete structure similar to a slotted board riser, both of which are designed to be installed at multiple locations within the drainage ditch. Installation of low-grade weirs at multiple spatial locations throughout the agricultural landscape is considered an innovative yet cost effective strategy. This spatial arrangement, theoretically, would be advantageous compared to conventional slotted board risers as it should increase water volumes within drainage ditches creating multiple opportunities for NO_3^- reduction. This arrangement also should increase water depths adjacent to the ditch rather than just at the ditch outlet therefore increasing water levels across a larger spatial area (Kröger *et al.*, 2008a). Increasing the water depth keeps more soil in a saturated state, producing anaerobic conditions that promote biogeochemical processes such as nitrification, denitrification, ammonia volatilization, and plant assimilation (Gilliam *et al.*, 1979; Gilliam and Skaggs, 1986; Lalonde *et al.*, 1996; Reddy and Delaune, 2008).

Altering the biogeochemical processes of drainage ditches through increased water depth and hydraulic residence time (HRT) within the ditch has been shown to reduce nutrient concentrations (Gilliam *et al.*, 1979; Gilliam and Skaggs, 1986; Lalonde *et al.*, 1996). Evans (1992) stated that CD significantly reduced N being transported at the edge of the field due to decreased outflow volume as well as denitrification. Kröger et al. (2011) demonstrated that during a high volume runoff event, NO_3^- concentrations were significantly reduced between inflow and outflow for slotted board riser and low-grade weir drainage systems. The authors further stated that reductions in NO_3^- were likely due to saturated soil conditions which led to a reduction in redox potential and encouraged denitrification. Low-grade weirs offer advantages over conventional CD practices by being installed to avoid possibly flooding fields and crops during large storm events, yet still providing continuous nutrient reduction opportunities throughout the year (Kröger *et al.*, 2008a). However, further information is needed to determine the nutrient reduction capacities of low-grade weirs in an experimental setting, as well as in a functional drainage ditch receiving runoff from an agricultural landscape under intensive row crop production.

The aim of this study was to assess nutrient mitigation capacities of low-grade weirs by using constructed drainage ditches in a replicated experiment and scaling up to a functioning drainage ditch in the Lower Mississippi Alluvial Valley, specifically the Mississippi Delta. Specific objectives of this research are to: 1) assess, experimentally, the ability of low-grade weirs to reduce NO_3^- concentrations and loads in agricultural drainage ditches, 2) demonstrate the nutrient reduction capabilities at a field scale demonstration site and 3) determine if weirs enhance the nutrient mitigation capacity in drainage ditches through improved nutrient reduction activity.

My hypotheses are: 1) in the experimental setting, ditches with low-grade weirs will decrease NO_3^- concentration and loads greater than ditches without weirs; and 2) the field demonstration site will decrease NO_3^- concentration and loads similar to the experimental setting and will provide evidence of seasonal variability in decreases as well as relate importance of demonstration scale research to small scale manipulations. Furthermore, weirs will enhance the overall nutrient mitigation capacity of the drainage ditches through improved nutrient reduction activity.

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CHAPTER II

EXPERIMENTAL EVALUATION OF LOW-GRADE WEIRS FOR NITRATE CONCENTRATION AND LOAD REDUCTION

Introduction

Drainage ditches are ubiquitous features of agricultural landscapes that provide important functions needed for profitable and sustainable crop production (Kröger *et al.*, 2008a). These systems act as major conduits between surface and subsurface flow of nitrogen (N) from the agricultural landscape and downstream aquatic ecosystems (Moore *et al.*, 2005). In the Mississippi River Basin (MRB), this has profound implications on hypoxia in the Gulf of Mexico (Rabalais *et al.*, 1996; Kröger *et al.*, 2008a). However, agricultural drainage ditches function in the same manner and provide benefits similar to natural wetlands (Mitsch and Gosselink, 2000a) because they contain the three main characteristics common to all wetlands: 1) periods of inundation due to fluctuating hydroperiods, 2) hydric soils, and 3) hydrophytic vegetation (Kröger *et al.*, 2009). Using these wetland characteristics, installation of controlled drainage (CD) structures within drainage ditches increases the hydraulic residence time, thus promoting greater removal of nitrate (NO_3^-) through biogeochemical processing (Gilliam *et al.*, 1979; Skaggs *et al.*, 2005; Kröger *et al.*, 2008b).

Controlled drainage is a water management strategy in which a structure is positioned in the drainage ditch to regulate drainage flow (Evans *et al.*, 1995; Evans, 2008). In the past, slotted board risers have been the most common form of structure used for CD (Skaggs and Gilliam, 1981; Madramootoo *et al.*, 1993; Lalonde *et al.*, 1996). This structure gives the manager the ability to control the drainage flow by determining height of the board(s) within the riser. As a result, it controls volume of outflow and load of solutes. Lalonde *et al*. (1996) found that flash- board risers reduced drain flow and NO_3^- concentrations by 58-63% and 60-76%, respectively. Slotted board risers, however, are only installed at ditch outlets and are normally used during isolated temporal periods of when rainfall frequency and intensity are at their highest (Kröger *et al.*, 2011). Therefore, use of low-grade weirs installed in a stratified spatial arrangement within the ditch has been proposed as an alternate CD strategy.

Low-grade weirs provide advantages over conventional CD (i.e., slotted board riser) by maintaining desired benefits continuously throughout the year and being installed to avoid flooding fields and crops during large storm events (Kröger *et al.*, 2008a). Effectiveness of CD practices, however are greatly influenced by their design and management (Kröger *et al.*, 2008a). Low-grade weirs are structures theoretically designed to retain a certain volume of water based on slope and cross sectional area of a given ditch (Kröger *et al.*, 2011). When installed into a drainage ditch at multiple locations, low-grade weirs should alter the ditch's aquatic biogeochemical processes by decreasing flow velocities, thus increasing sediment retention and nutrient reduction rates.

Kröger *et al.* (2008a) found that CD increased the probability of aquatic biogeochemical processing conducive to wetland ecosystems by increasing residence times within the drainage ditches, thus allowing longer periods of times for nutrient mitigation and sediment retention. Kröger *et al.* (2011) demonstrated that during a high volume runoff event, low-grade weirs reduced NO_3^- loads up to 98%. The authors further stated that the NO_3^- concentration reductions were likely due to saturated soil conditions which led to a reduction in redox potential and encouraged a biogeochemical process known as dentrification. These studies highlight the potential dynamics of low-grade weirs for improving NO_3^- reductions by creating a wetland ecosystem conducive to nutrient removal.

The primary objective of my study was to assess the ability of low-grade weirs to reduce NO_3^- concentrations and loads in drainage ditches under a controlled experimental setting. The replicated experiment was completed using constructed drainage ditches under a regulated flow regime, with a simulated nutrient runoff event delivered simultaneously to both ditches with weirs and ditches without weirs. Comparison of the weir versus non-weir systems will lead to a better understanding of NO_3^- reduction capacities of this particular CD system being studied, which will ultimately provide insight to the nutrient reduction capacities of low-grade weirs in a field scale setting.

Materials and Methods

Study site

This study was conducted at the Arkansas State University (ASU) Agricultural Research Facility (35˚ 50' 32.92" N, 90˚ 42' 15.87" W) which is located approximately 1.5 km east of the ASU campus in Jonesboro, AR. Eight drainage ditches were constructed in 2006, hydro-seeded in 2007 and 2008, and now consist of well-established vegetative communities dominated by *Typha latifolia* (L). The ditches have a mean width and length of 1.8 m and 58.7 m, respectively, with 0.1% slopes along their length.

Each of the eight ditches contained an independent, adjustable inflow and outflow hydraulic structure (Fig. 2.1). An electric powered groundwater well supplied a large retention pond containing eight standpipes attached to ball valves acting as inflows to each ditch. Valves were used to control inflow rate and amount of water entering each ditch system. Each ditch also contained standpipes that acted as outflow structures, which were lowered to simulate summer drainage conditions during the experiment.

Four ditches were chosen randomly to contain weirs (Fig. 2.1), with each chosen ditch containing two weirs, for a total of eight weirs. Each weir was comprised of a prefabricated constructed concrete retention structure, commonly referred to as a Scurlock Weir© (Fig. 2.2). This particular weir was designed to be a mobile unit that a farmer could easily relocate to a more suitable area if needed. Once installed within the ditch, height of each weir was determined based on slope of the ditch. Ditch slopes and weir heights were determined using a Trimble Laser Theodolite Unit® (Trimble Navigation Limited, Sunnyvale, CA) with a fixed base station. Ditch widths, lengths, and depths were determined using meter tape and a meter stick and these measurements were used to calculate total ditch and weir volumes (Table 2.1).

Simulated storm event

A single simulated storm runoff event was delivered to each ditch continuously for eight hours (Fig 2.1). Prior to delivery, three water samples were collected from the retention pond to measure background concentrations of NO_3^- (0.325 ± .04 mg/L) to determine overall inflow NO_3^- concentrations for each ditch. Water from the retention pond provided the source of inflow throughout the experiment and inflow rates from the retention pond were measured prior to the experiment (Table 2.1). Flow rates were determined in triplicate for each ditch using the bucket method, which is a simple technique that determines flow by timing accumulation of water to a known water volume level (15 L bucket). One mixing chamber contained the NO_3^- slurry that was supplied to each ditch and was standard for all eight ditches. The slurry consisted of 9.19 kg of potassium nitrate (KNO_3) mixed with 1514 L of water, producing an estimated slurry concentration of 1000 mg/L NO_3^-. The slurry was delivered simultaneously to each ditch through Tygon® tubing (Saint- Gobain Corp. Paris, France) by high flow model QD pumps (Fluid Metering Inc., Syosset, NY), individually calibrated for each ditch. Volume of slurry delivered from the QD pumps (Table 2.1) varied based on the water inflow rates of each ditch.

Nitrate sampling

Prior to NO_3^- sampling, Industrial Red Dye 106000 (Bright Dyes, Kingscote Chemicals®) was dispensed into each ditch to calculate differences in HRTs between weir and non-weir ditches. Temporal sampling of each ditch was based on the observed HRT (Table 2.1) of each ditch. Increased sampling frequency occurred on the rising limb of each respective ditches breakthrough curve, and sampling occurred every half hour post breakthrough. Overall target ditch inflow NO_3^- concentrations were 10 mg/L, thus inflow QD rates of NO_3^- concentrations were calculated using initial volumes of each ditch. Target ditch inflow NO_3^- concentrations were determined using a series of calculations. Multiplying the NO_3^- slurry concentration (mg/L) by QD pump rate (L/min) yielded a QD NO_3^- concentration measured in mg/min. Dividing the QD NO_3^- concentration (mg/min) by inflow rate of water being delivered from the retention pond (L/min) yielded our target ditch NO_3^- concentrations measured in mg/L.

Water samples were collected in 250 mL polyethylene cups (Fischer Scientific®, Pittsburgh, PA), at the outflows of each ditch, immediately placed on ice and transported back to the Water Quality Laboratory at Mississippi State University for nutrient analysis within 24 hours. Samples were stored at 4˚ C until analysis was completed. A total of 100 mL of each sample was filtered using 0.45-µm cellulose filters (Whatman®, Dassel, Germany) and NO_3^- concentrations were determined using the cadmium reduction flow injection analysis with an 8500 Quikchem Lachat (HACH®, Loveland, Colorado).

Water Quality Parameters

Additional water quality parameters were collected during the experiment using YSI® (Yellow Springs Instruments, Ohio, US) automated datasondes placed in four ditches (two with weirs and two without) to determine differences in water quality parameters of dissolved oxygen (DO) (mg/L), water temperature (º C), pH, specific conductance (µS/cm) and water column oxidation reduction potential (ORP) (mV). Datasondes logged water quality parameters continuously every 20 minutes for the duration of the experiment. Similarly, every hour an on-site calibrated handheld YSI® instrument was used to determine water temperature, specific conductance, DO, and pH behind each weir, within each ditch without weirs, and also the retention pond.

Statistical Analysis

Estimated inflow NO_3^- concentrations were calculated for each ditch by dividing the QD pump NO_3^- concentration by the total inflow rate of water from the retention pond. Loads were calculated by multiplying the calculated inflow NO_3^- concentration and total inflow rate (i.e. sum of inflow from QD pump and retention pond). Multiplying outflow NO_3^- concentrations by the total inflow rate generated an outflow load. A cumulative outflow load for each ditch was determined by multiplying the calculated outflow load by the total volume of water that had entered the system over a specific sampling interval. Therefore, differences in cumulative outflow loads between the two systems were determined. Differences in overall outflow concentrations and loads were obtained from weir and non-weir ditches and these values were used to determine differences in percentage reduction of concentration and load values between the two systems.

Depending on normality (Shapiro-Wilk) of the data distributions, a paired t-test for means ($\alpha = 0.05$) or Mann-Whitney Rank Sum test was performed using Sigma Plot® 12.0 (Systat Software Inc., Chicago, IL) to determine if any significant difference was present for volume, HRT, concentrations, loads, and YSI data collected between weir and non-weir ditches. Using the same analysis, NO_3^- reduction during the hypothesized biogeochemical reduction phase of the experiment also was compared between weir and non-weir ditches.

A repeated measures analysis of vairance was used to determine if significant differences between weir and non-weir ditches existed through time for NO_3^- percentage concentration reduction. In JMP® 8.1 (SAS 2008, Cary, NC), a standard least squares model was fit using sampling time and treatments (weir and non-weir) as effects. The first three sampling periods for each ditch (i.e., 30 min, 60 min, 90 min) were used for this analysis due to variation in number of samples collected for each ditch. The repeated measures ($\alpha = 0.05$) output generated differences between time and time*treatment interactions.

Results

Mean DO concentrations (P = 0.01) as well as percentage DO saturation (P = 0.04) differed significantly between the retention pond, non-weir and weir ditches. The retention pond had the greatest mean DO (10.1 ± 1.1 mg/L) concentration. Ditches with weirs, however, had significantly (P = 0.04) less DO concentrations (6.6 ± 0.3 mg/L) than non-weir ditches (7.7 ± 0.5 mg/L). Additionally, pH, water temperature, and conductivity showed no statistical differences ($P \geq 0.05$) between weir and non-weir ditch systems.

Average inflow rates were measured prior to the experiment and yielded no significant difference (P = 0.377) between weir ditches (29.28 ± 0.49 L/min) and non-weir ditches (30.09 ± 0.62 L/min). Inflow rates were only measured once due to data from a previous experiment, at the ASU facility, showing no statistical correlation between water depth (i.e., head pressure) in the retention pond and inflow rates during the experiment. Nitrate concentrations were delivered continuously for eight hours to both weir and non-weir ditches at a mean exposure of 13.37 ± 0.36 mg/L delivered from the nutrient slurry with an additional mean NO_3^- concentration 0.325 ± 0.04 mg/L delivered from the retention pond. Seven of the eight ditches contained minimal amounts of water at the beginning of the experiment because of a rainfall event prior to the experiment. Ditch volumes were measured at full capacity during the experiment revealing that ditches containing weirs (7424.4 L) yielded statistically greater (P = 0.029) median water volumes than non-weir ditches (1401.2 L). A significant statistical difference (P = 0.029) also was observed for median HRTs between ditches with weirs (249 min) than non-weir ditches (48 min).

During the experiment, median outflow NO_3^- concentrations were significantly ($P \leq 0.001$) less in ditches with weirs (1.6 mg/L), than those without weirs (2.1 mg/L). Significantly greater ($P = 0.029$) median reductions in outflow water volumes were measured, with a 61% reduction in ditches with weirs and a 14% reduction in non-weir ditches. Similarly, ditches with weirs had statistically less ($P < 0.001$) median outflow loads (47.87 mg/min) than non-weir ditches (63.23 mg/min). The statistically lesser concentrations and loads found in ditches with weirs could be attributed to their statistically greater ($P \leq 0.001$) median NO_3^- percent concentration and load reductions (87%) compared to ditches without weirs (83%). Correspondingly, NO_3^- concentration reductions during the hypothesized biogeochemical reduction phase of the experiment were significantly greater ($P = 0.029$) for ditches containing weirs (Fig. 2.3). These reductions could have influenced the significantly lesser ($P = 0.009$) mean cumulative outflow loads demonstrated by ditches with weirs (5703 ± 2959 mg) compared to non-weir ditches (23810 ± 3797 mg).

The repeated measures ($\alpha = 0.05$) output from the standard least squares model reported that time was a significant main effect, with the 90 minute interval yielding statistically lesser NO_3^- percentage concentration reductions ($F_{2,23} = 14.93$, $P \leq 0.001$; Fig. 2.4) for weir and non-weir ditches. However, there were no significant differences reported for the effects of treatment ($F_{1, 23} = 0.1761$, $P = 0.67$) or time*treatment ($F_{2, 23} = 1.4714$, $P = 0.26$).

Discussion

Agricultural land use in the southeastern U.S. requires artificial drainage for sustainability and profitable crop production (Kröger *et al.*, 2008a) and innovative CD has received increasing attention as a mechanism to improve nutrient reduction in surface receiving waters. Wesström *et al.* (2001) reported that CD had a significant hydrological and environmental effect during the 2 years of measurement, reducing the total drain outflow by 79% in Year 1 and 94% in Year 2. The total reduction in NO_3^- losses corresponded with the reduced outflow rates, with 78% reduction of NO_3^- in Year 1 and 94% reduction in Year 2 (Wesström *et al.,* 2001). Similarly, the current study found that ditches with weirs reduce total drain outflow by 61% compared to 14% by non-weir ditches. These outflow drain reductions resulted in greater NO_3^- cumulative load reductions in ditches with weirs (96%) compared to non-weir ditches (85%). The key to these nutrient reductions, in the case of low-grade weirs installation, is to provide numerous locations for hydrological manipulations and control (Kröger *et al.*, 2011).

Altering the hydrological functions (i.e., HRT and ditch water volume) is a vital component for nutrient removal in drainage ditches (Mitsch *et al.*, 2001). In the current study, median water volumes for ditches with weirs were six times greater (7424 L) than the water volume in non-weir ditches (1401 L). Similarly, the HRT for ditches with weirs (249 min) was approximately five times greater than the HRT for ditches without weirs (48 min). These two components could have potentially contributed to the greater overall reduction of NO_3^- that was demonstrated in ditches with weirs.

Increased retention times and greater storage capacity are important in the effective removal of NO_3^- (Kovacic *et al.*, 2006). Kröger *et al*. (2011) compared low-grade weirs with the traditional CD strategy of slotted board risers; stating that equal water volumes between low-grade weirs and slotted board risers yielded no statistical differences in nutrient concentration and load reductions. However, our study demonstrates that ditches with low-grade weirs, compared to ditches lacking any form of

CD structure, had a greater water volume than ditches without weirs and yielded significantly greater concentration and load reductions in ditches with weirs (87%) compared to non-weir ditches (83%).

The capacity to hold water volumes for longer periods of time can lead to soils characterized by waterlogged conditions, producing a reduced environment that influences biogeochemical transformations (Mitsch and Gosselink, 2000b). During the current experiment, a greater NO_3^- concentration reduction (8.2%) during the hypothesized biogeochemical reduction phase of the experiment occurred for ditches containing weirs. The biogeochemical percentage reduction phase occurs once the system's HRT has been reached and dilution is no longer acting on the nutrient concentration in the water column. This theoretical phase is based on various assumptions occurring throughout the duration of the experiment: 1) the ditches' inflow and outflow rates are equal, 2) ditch water volumes are constant, 3) evaporation and transpiration are constant, and 4) water loss to soil discharge is negligible. Pathways such as, nitrification, denitrification, ammonia volatilization, and plant assimilation could have all led to biogeochemical reductions detected in ditches with weirs (Reddy and Delaune, 2008). Few, if any, researchers have developed or reported a complete nutrient budget for wetland systems that includes measurements of all biogeochemical pathways (Mitsch and Gosselink, 2000b).

Results from the ASU experiment highlight the dynamics of low-grade weirs and their potential to reduce nutrient concentrations and loads from agricultural landscapes. To determine significance of these results, a comparison between the experimental approach at ASU and a field scale approach is needed. Kovacic *et al.* (2000) reported that constructed wetlands reduced NO_3^- loads from agricultural drainage by 34 and 44%.

Variability in the reductions, over the three year study, was due in large part to the unregulated flow traditionally experienced in agricultural landscapes (Kovacic *et al.,* 2000). Therefore, validating the results from our experimental approach with field scale research will further strengthen our understanding of the capabilities of low-grade weirs to reduce NO_3^- concentrations and loads in agricultural drainage ditches under an unregulated flow regime.

Table 2.1 Water volume and flow characteristics for the eight drainage ditches evaluated during the experiment at the ASU Agricultural Research Facility, Jonesboro, AR, June 2011.

Ditch	Treatment	Nutrient Inflow Rate (L/min)	Water Inflow Rate (L/min)	Total Water Volume (L)	HRT (min)
1	Non-Weir	0.37	31.26	1667.4	54
2	Non-Weir	0.39	30.01	1309	44
3	Weir	0.39	28.77	5880	198
4	Non-Weir	0.41	28.31	1203.3	41
5	Weir	0.39	29.7	8968.8	300
6	Weir	0.41	27.53	9274.95	337
7	Non-Weir	0.41	29.23	1493.45	51
8	Weir	0.39	29.53	3771.1	125

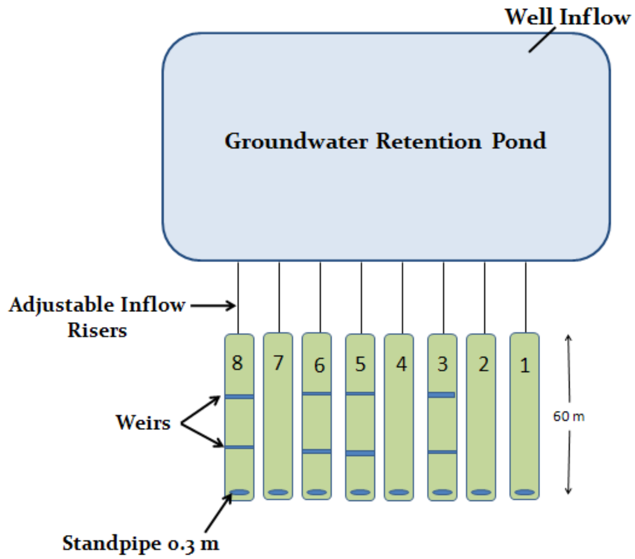

Figure 2.1 Artificial drainage system at the ASU Agricultural Research Facility.

Each drainage ditch received water from a groundwater retention pond through inflow risers fitted with adjustable ball valves. All ditches were hydro-seeded with a mixture of annual and perennial herbaceous vegetation and obligate wetland species. Ditches 3, 5, 6, and 8 were weir systems with two weirs installed in each of those ditches.

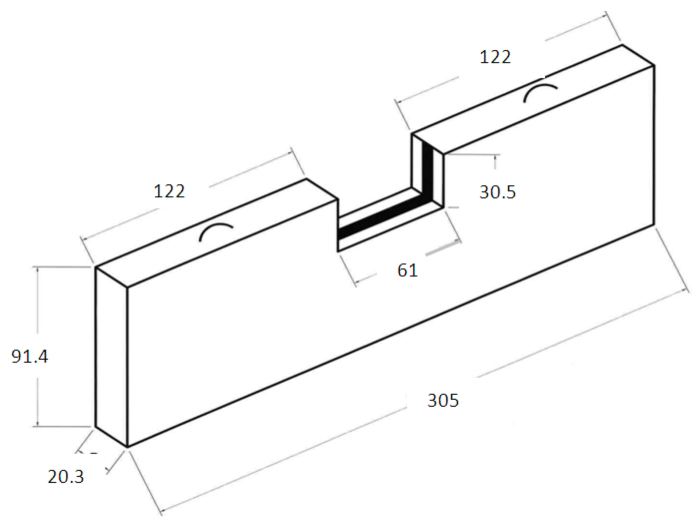

Figure 2.2 Mobile prefabricated concrete Scurlock Weir© (units are in cm) installed in ditches 3, 5, 6, and 8 at ASU Agricultural Research Facility, Jonesboro, AR.

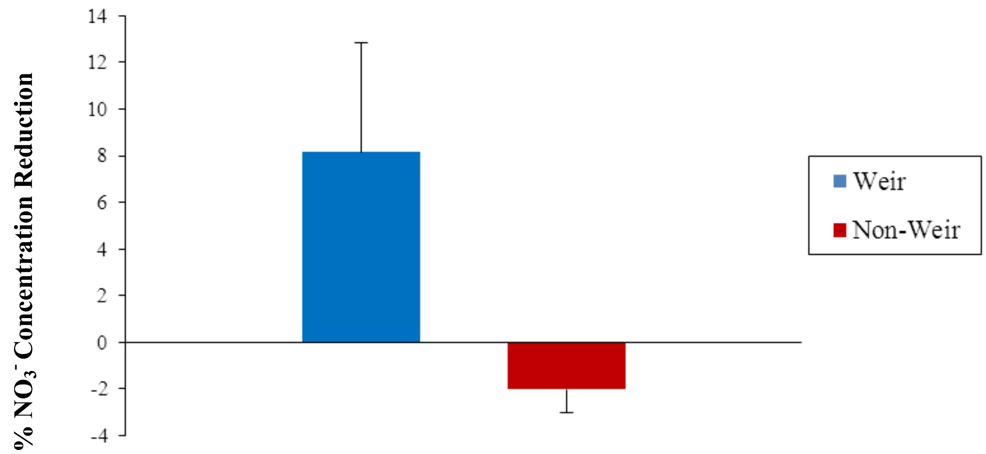

Figure 2.3 Mean NO_3^- percentage concentration reductions (± S.E.) during the ditches' biogeochemical reduction phase throughout the experiment for ditches with weirs (N=4) and non-weir ditches (N=4) at the ASU Agricultural Research Facility, Jonesboro, AR, June 2011.

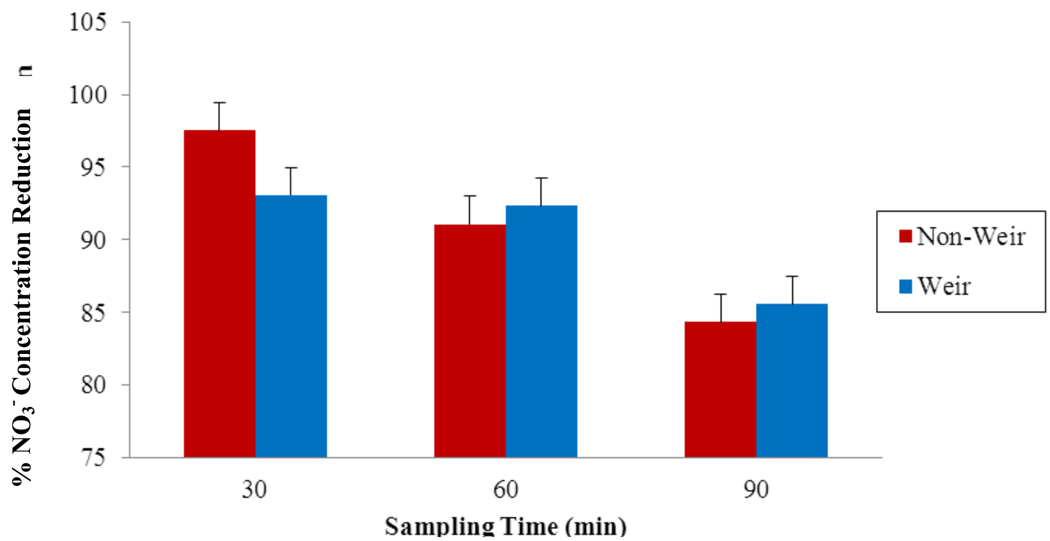

Figure 2.4 Mean NO_3^- percentage concentration reductions (± S.E.) for the first three sampling periods in each weir (N=4) and non-weir ditches (N=4) at ASU Agricultural Research Facility, Jonesboro, AR, June 2011.

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CHAPTER III

MEASURING NITRATE REDUCTASE ENZYME TO ASSESS ENHANCEMENT OF BIOLOGICAL ACTIVITY IN EXPERIMENTAL DRAINAGE DITCHES

Nutrient reduction has played a vital role in many agricultural best management practices (BMPs), and controlled drainage (CD) has received increased recognition as an additional BMP aimed at reducing nutrient concentrations and loads in drainage ditches from reaching downstream aquatic ecosystems (Kröger *et al.*, 2008a). The most common CD practice in use is the slotted board riser, which relies on the ability to control flow velocity by determining height of the riser and thus control volume of outflow and load of solutes (Skaggs *et al.*, 1994; Lalonde *et al.*, 1996; Kröger *et al.*, 2011). Because certain drainage ditches are hundreds of meters long, use of low-grade weirs installed in a stratified spatial arrangement within agricultural ditches has been proposed as an alternate CD strategy. Theoretically, this spatial arrangement would be advantageous, compared to conventional slotted board risers, as it would not only increase sediment retention by decreasing flow velocities but also increase water volumes creating multiple opportunities for decreasing nutrient concentrations within the drainage ditch. Managing these agricultural drainage ditches could prove to be valuable because they function as wetland ecosystems and could provide a suite of wetland benefits (Moore *et al.*, 2001; Kröger *et al.*, 2008a).

Agricultural drainage ditches are considered wetland ecosystems because they consist of the three main characteristics common to all wetlands: periods of inundation, hydric soils, and hydrophytic vegetation (Moore *et al.*, 2001; Kröger *et al.*, 2008b). Hydrophytic vegetation, emergent and submerged, provides vital wetland functions in agricultural drainage ditches (Moore *et al.*, 2005). These functions include decreasing nutrient concentrations by encouraging sedimentation (Johnston, 1991), nutrient adsorption to sediments (Vymazal, 2007), enhancing denitrification (Delwiche and Bryan, 1976; Vymazal, 2007) and increasing plant assimilation (Wetzel, 2001). With respect to plant assimilation, there is strong evidence of the direct and indirect effects of nitrogen (N) assimilation (Caffrey and Kemp, 1992; McJannet *et al.*, 1995).

Ammonium (NH_4^+) is often the preferred source of N for assimilation, but nitrate (NO_3^-) can move freely through the soil (Kadlec and Knight, 1996). This mobility could result in excess NO_3^- concentrations in freshwater systems, especially in areas receiving agricultural runoff (i.e., agricultural drainage ditches) (Kadlec and Knight, 1996). These excess concentrations would result in plants changing their preference from NH_4^+ to NO_3^- as a source of N for assimilation. Nitrate assimilated by plant roots is either reduced *in situ* to NH_4^+, stored in the vacuoles or transported to the shoot (Miller and Cramer, 2005).

Reduction of NO_3^- to NH_4^+ is accomplished through a series of assimilatory enzymes. Nitrate is initially reduced to nitrite (NO_2^-) via the enzyme NO_3^- reductase and further reduced to NH_4^+ via the enzyme NO_2^- reductase (Miller and Cramer, 2005). Thus, NO_3^- reductase mediates the first step in the reduction of NO_3^- to NO_2^- and to NH_4^+ for protein synthesis (Kouadio *et al.*, 2007). Determining amount of NO_3^- assimilated by a plant can be measured by determining amount of NO_3^- reductase enzyme activity occurring within the plant (Jampeetong and Brix, 2009). Hence, the primary objective of this study was to determine if low-grade weirs enhanced the assimilation of NO_3^- in drainage ditches through increased NO_3^- reductase enzyme activity. Considering this holds true, it is my prediction weirs will enhance the overall nutrient mitigation capacity of the drainage ditches through improved nutrient reduction activity.

Material and Methods

This study was conducted at the Arkansas State University (ASU) Agricultural Research Facility (35˚ 50’ 32.92” N, 90˚ 42’ 15.87” W) which is located approximately 1.5 km east of the ASU campus in Jonesboro, AR. Eight drainage ditches were constructed in 2006, hydro-seeded in 2007 and 2008, and now consist of well-established vegetative communities dominated by *Typha latifolia* (L.). Ditches have a mean width and length of 1.8 m and 58.7 m, respectively, with 0.1% slopes along their length.

Each of the eight ditches contained an independent, adjustable inflow and outflow hydraulic structure (Fig. 2.1). An electric powered groundwater well supplied a large retention pond with eight standpipes attached to ball valves acting as inflows to each ditch. Valves were used to control the inflow rate and amount of water entering each ditch system. Each ditch also contained standpipes that acted as outflow structures, which were lowered to simulate summer drainage conditions during the experiment.

Four ditches were chosen randomly to contain weirs (Fig. 2.1), with each chosen ditch containing two weirs, for a total of eight weirs. Each weir was comprised of a prefabricated constructed concrete retention structure, commonly referred to as a Scurlock Weir© (Fig. 2.2). This particular weir was designed to be a mobile unit that a manager or farmer could easily relocate to a more suitable area if needed. Once installed within the ditch, height of each weir was determined based on slope of the ditch. Ditch slopes and weir heights were determined using a Trimble Laser Theodolite Unit® (Trimble Navigation Limited, Sunnyvale, CA) with a fixed base station.

A single simulated storm runoff event was delivered to each ditch continuously for eight hours in July 2010 and May 2011. Prior to the delivery, water samples were collected in the retention pond to measure background concentrations of NO_3^- to determine overall inflow NO_3^- concentrations for each ditch. Water from the retention pond provided the source of inflow throughout the experiment and inflow rates (Table 2.1) from the retention pond were measured prior to the experiment. Inflow rates were determined in triplicate for each ditch using the bucket method, a simple technique that determines flow by timing accumulation of water to a known water volume (15 L bucket). A mixing chamber was prepared containing a NO_3^- slurry (Table 3.1) that was supplied to each ditch simultaneously through Tygon® tubing (Saint- Gobain Corp. Paris, France) by high flow model QD pumps (Fluid Metering Inc., Syosset, NY). Volume of slurry delivered from the QD pumps varied based on the inflow rates of each ditch and was calibrated individually so that the NO_3^- concentration delivered was standard across all eight ditches (Table 3.1).

Typha latifolia roots were collected due to their ability to assimilate nutrients, the plant's ability to maintain root growth under anaerobic conditions, (Jan, 2007) and abundance of the species within the ditches. In 2010, samples were taken from three ditches with weirs and three ditches without weirs. In 2011, samples were taken from two ditches, one with weirs and one without. Replicate root samples (Table 3.1) were collected for analysis prior to and 8 h post NO_3^- exposure during the experiment in 2010 and a week after NO_3^- exposure during the experiment in 2011. Each sample consisted of approximately 2.54 cm of root tissue, which was transferred to microcentrifuge tubes, frozen immediately, and transported in liquid N from the ASU facility to the USDA-ARS National Sedimentation Laboratory in Oxford, Mississippi.

The NO_3^- reductase protocol used in this experiment, including buffer and reagents is described by Scheible *et al.* (1997) and Jampeetong and Brix (2009). Approximately 50-100 mg of fresh weight material from each plant root was ground into a fine powder in a chilled mortar and pestle with liquid N and mixed with five volumes of extraction buffer. Root extract (100 µL) was mixed with 500 µL of assay buffer and incubated at room temperature for one hour. Stop reagents were then added and mixtures incubated in the dark for 15 minutes. Next, 600 µL of coloring reagent (suphanilamide/naphthyl-ethylenediamine) was added and allowed to incubate in the dark for 20 minutes. Reaction mixtures were centrifuged at 14,000 x g for 2 minutes. Nitrite concentration was determined by measuring absorbance of the supernatant at 540 nm and comparing readings to a standard curve (0-20 µM NO_2^-). Nitrate reductase activity was calculated as NO_2^- accumulation over time (µmole per gram dry weight per hour) (Scheible *et al.*, 1997; Jampeetong and Brix, 2009).

A paired t-test for means ($\alpha = 0.05$) was performed using Microsoft Excel® 2010 (Microsoft Inc., Redmond, WA) to determine if any significant difference in NO_3^- reductase activity was experienced between pre and post NO_3^- exposure. Using the same analysis, NO_3^- reductase activity also was compared between weir and non-weir ditches.

Results and Discussion

It is important to understand the physical constraints of biological N processing in drainage ditches installed with low-grade weirs because N processing near the source has the greatest chance to reduce loads before entering the downstream aquatic system (Duff *et al.*, 2008). Biological processing of N through plant assimilation is a pathway that has been quantified by determining amount of NO_3^- reductase activity within the plant tissue.

Jampeetong and Brix (2009) reported NO_3^- reductase activity in the roots of *Salvinia natans* L. placed in the following three treatments: 500 µM NO_3^-, 250 µM NH_4NO_3 and 500 µM NO_4^+. After two weeks in the treatments, the authors reported that nitrate reductase activity was significantly greater ($P \leq 0.01$) in roots than in leaves, with reductase rates being 10 times greater in NO_3^- fed plants compared to those fed NH_4^+ only. The current study found no increase in NO_3^- reductase activity in *T. latifolia* roots (Fig. 3.1) after NO_3^- exposure during the 2010 experiment. Nor were any significant differences observed between ditches with and without weirs ($P \geq 0.26$). In 2011, NO_3^- reductase activity was not detected, even at basal levels. The NO_3^- reductase enzyme assays from Jampeetong and Brix (2009) and Schieble *et al.* (1997) were followed according to the standard protocols presented in each paper. Nevertheless, due to the complexity of this analysis, any minimal disturbance during the chemical reactions also could have altered the data and lack of detectable reductase activity could be attributed to experimental errors.

Regarding to the lack of increased reductase activity following NO_3^- exposure in the 2010 experiment, NO_3^- concentrations may have not been great enough or the exposure period long enough for the plant to begin assimilation. Although the 2011 experiment supplied a greater NO_3^- concentration than the 2010 experiment and the plants collected a week later, NO_3^- exposure may need to be supplied continuously for an additional week before sampling occurs. Additional studies also have encountered problems when analyzing for reductase activity, stating that use of nitrate reductase activity as a marker of NO_3^- utilization based on an individual plant species is impossible without determining the optimal method (Munzarova *et al.*, 2006). Considering the ditches used in the current study support a diverse stand of vegetation, the method from

Zhang *et al.* (2010) may be more appropriate than the current method for this experimental setting. The method uses substrate from soil cores sampled within the experimental area and reductase activity is assessed by measuring levels of reductase enzyme within the substrate.

Based on the design of my current experiment, it would be interesting to determine if increasing NO_3^- above the concentration delivered in the 2011 experiment and continually exposing the plants to NO_3^- for at least two weeks would have any effects on the results after the final analysis. The possibility of using an alternate plant species or method that has experimentally shown to provide measurable levels of reducatse activity also would need to be considered. This research would provide critical insight into the future of BMP management because although we have an understanding of the wetland pathways that lead to nutrient reduction, we have not determined which pathways play the largest part in this particular system. Determining those particular mechanisms that play a role in reducing the nutrient concentration in these drainage ditches is vital for addressing future management strategies.

Table 3.1 Nitrate sources, slurry concentration, concentrations delivered, number of ditches sampled and number of replicates taken during each experiment at the ASU Agricultural Research Facility in Jonesboro, AR, June 2011.

Experiment Date	Source of NO_3^-	Estimated Slurry Concentration	NO3⁻ Concentration Delivered	# of Ditches Sampled	# of Replicates
2010	Calcium Nitrate [$Ca(NO_3)_2$]	348	3.74 ± .02	6	6 per ditch
2011	Potassium Nitrate (KNO_3)	1000	13.37 ± 0.36	2	6 per ditch

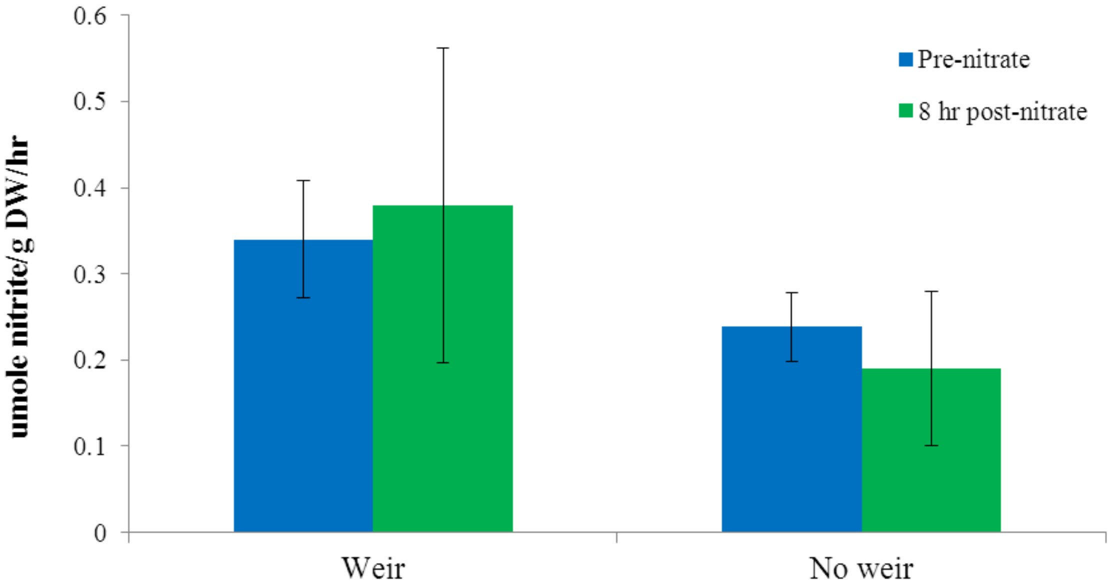

Figure 3.1 Nitrate reducatse enzyme activity in *T. latifolia* roots collected from weir and non-weir ditches prior to introduction of a known nitrate concentration and eight hours post introduction during the 2010 experiment at the ASU Agricultural Research Facility, Jonesboro, AR, June 2011.

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CHAPTER IV

NITRATE CONCENTRATION AND LOAD REDUCTION CAPABILITIES OF LOW-GRADE WEIRS IN AN AGRICULTURAL SETTING

Introduction

The global population increases by nearly three individuals each second, translating into an additional 79.4 million individuals annually who will need food and fiber to survive (Moore *et al.*, 2010). To meet this demand, agricultural food production has doubled in the last 35 years (Carvalho, 2006), leading to an almost seven-fold increase in use of nitrogen (N) fertilization (Tilman, 1999). Consequently, increased fertilizer use could result in greater loads of nutrients being delivered from agricultural soils to surface receiving waters (Donner, 2003). This could greatly increase transfer of nonpoint source (NPS) pollutants, primarily nitrate (NO_3^-), to estuaries and oceans (Vitousek *et al.*, 1997). Ultimately this can lead to a 2.5-fold increase in N driven eutrophication (Tilman *et al.*, 2001), which is now evident in locations such as the Gulf of Mexico (Mitsch *et al.*, 2001). The ubiquitous features that act as major conduits between the surface and subsurface flow of NO_3^- from the agricultural landscape to downstream aquatic ecosystems are agricultural drainage ditches (Moore *et al.*, 2005).

Adequate artificial drainage, especially in the southeastern United States, is required for agricultural field activities and to reduce the potential of surface water ponding during crop production (Thomas, 1995). Drainage ditches are truly, the forgotten links between the agricultural landscape and surface receiving waters and could serve as an additional best management practice (BMP) (Moore *et al.*, 2005a). Best management practices in agricultural landscapes usually consist of cover crops, buffer zones, crop rotation, or conservation tillage, all of which are sound land use tools for NPS mitigation (Kröger *et al.*, 2011). Constructed wetlands and retention ponds also have been suggested as another tool to add to the suite of practices used to mitigate NPS pollution. However, this practice requires land to be set aside, which removes profitable land from production. Studies have shown that managers can greatly decrease nutrient loads exiting the agricultural landscape and entering adjacent aquatic ecosystems by simply using drainage ditches through controlled drainage (CD) practices (Cooper *et al.*, 2002; Kröger *et al.*, 2008a; 2008b).

Controlled drainage practices have been used in various agricultural situations to reduce velocity and volume of outflow solutes, decrease water table depths, and increase storm water mitigation and sediment retention (Wesstrom *et al.*, 2001; Wright *et al.*, 2001; Needelman *et al.*, 2007; Kröger *et al.*, 2011). The most common CD practice in use is the slotted board riser, which uses outlets in drainage ditches to reduce erosion impacts during isolated periods of high rainfall (Skaggs *et al.*, 1994; Lalonde *et al.*, 1996; Kröger *et al.*, 2011). However, slotted board risers are only installed at ditch outlets and normally implemented during isolated temporal events when rainfall frequency and intensity are at their greatest (Kröger *et al.*, 2011). Therefore, use of a surface controlled drainage strategy such as low-grade weirs, installed in a stratified spatial arrangement within the drainage ditch, has been proposed as an innovative, alternate CD strategy.

Low-grade weirs are structures consisting of an earthen dam covered with an engineered woven filtration fabric for stabilization, which is then covered with an additional layer of rip-rap. These weirs are designed to be installed at multiple locations within the drainage ditch and should theoretically retain a certain volume of water based on the slope and cross sectional area of the given ditch (Kröger *et al.*, 2011). Low-grade weirs provide several advantages over conventional CD (i.e., slotted board riser): 1) precisely installed to avoid flooding fields and crops during large storm events, 2) decrease runoff flow velocities to increase sediment retention, 3) create multiple opportunities for decreasing nutrient concentrations by increasing water volumes within the drainage ditch; and 4) increase water depths in the adjacent landscape (Kröger *et al.*, 2008a). Increasing the water depth keeps more soil in a saturated state, producing anaerobic conditions that promoting biogeochemical processes such as nitrification, denitrification, ammonia volatilization, and plant assimilation (Gilliam *et al.*, 1979; Gilliam and Skaggs, 1986; Lalonde *et al.*, 1996; Reddy and Delaune, 2008).

Kröger et al. (2008a) found that CD increased the probability of aquatic biogeochemical processing conducive to wetland ecosystems by increasing residence times within drainage ditches, thus allowing longer periods of times for nutrient cycling and sediment retention. Results from Chapter 2 revealed that ditches with weirs had residence times that were five times longer than ditches without weirs. This could have led to the 61% reduction in outflow water volumes, the significantly greater outflow load reductions (P = 0.09) and the greater reductions during the biogeochemical reduction phase (P = 0.029) yielded by ditches with weirs during the experiment. Validating these results with field scale research will further strengthen our understanding of the capabilities of low-grade weirs to reduce NO_3^- concentrations and loads in agricultural drainage ditches. The primary objective of this study was to assess ability of low-grade weirs to reduce NO_3^- concentrations and loads in a large drainage ditch with an unregulated flow regime receiving runoff from an agricultural landscape under active crop production, as well as determine effects of low-grade weirs on depths of the surrounding groundwater table.

Materials and Methods

Study Site

A demonstration was conducted in Yazoo County, MS within the Lower Mississippi Alluvial Valley (LMAV), commonly referred to as the Mississippi Delta. Located just off US Hwy 49 South (32˚ 57' 02.63"N, 92˚ 25' 22.80" W) approximately 14 km northwest of Yazoo City (Fig. 4.1), the site contains a single drainage ditch (herein referred to as Terrace Ditch) that measures 503.6 m in length with an average width of 20.5 m, and receives runoff from approximately 970 ha under active agricultural production as well as runoff from abandoned aquaculture ponds that border its north and south banks. This demonstration site served to extrapolate results of the experiment conducted at Arkansas State University to a more realistic, larger scale study.

Terrace Ditch (Fig 4.2) was land formed during summer, 2009, to include in-stream benches and two low-grade weirs. A topographic map of Terrace Ditch (Fig 4.3) created during October 2010 displays the elevation gradient with the profile immediately above the weirs. The two low-grade weirs (Fig 4.2) were comprised of earthen banks covered with a woven filtration fabric for stabilization and an additional layer of rip-rap, impacting approximately 1300 m^2, or 33%, of the channel bed. Prior to 2009, the original ditch (Fig 4.4) was comprised of a narrow channel overgrown with upland vegetation. Figure 4.5 and Figure 4.6 show the same portion of the channel bed upstream of the lower weir one month and ten months, respectively, after construction was completed. In less than a year following construction, a diverse assemblage of naturally occurring native wetland plants could be seen in the lower weir pool (Fig 4.6).

Nitrate Sampling

Baseflow water samples and storm water samples were collected at the inflow and immediately downstream of each weir to assess the ability of low-grade weirs to reduce NO_3^- concentrations and loads. Baseflow samples were collected, using cubitainers (VWR, QC registered), every three weeks during the growing season and every six weeks during the dormant season from September 2009 to April 2011. Beyond baseflow, samples also were collected on a per storm event basis. During this time period, March to October was considered the growing season and November to February the dormant season. Storm samples were collected from March 2010 to April 2011 using three permanently staked sample containers (Fig 4.7) that were situated 200-1200 mm above sediment surface. Permanent staked samplers were located at the inflow and immediately downstream of each weir. Water samples also were collected, using cubitainers, from each of the abandoned aquaculture pond drainage pipes during base flow and storm event sampling.

Once collected, water samples were immediately placed on ice and transported to the water quality laboratory at Mississippi State University for nutrient analysis within 24 hours. Samples were stored at 4˚ C until analysis was completed. A total of 100 mL of each sample was filtered using 0.45-µm cellulose filters (Whatman®, Dassel, Germany) and NO_3^- concentrations were determined using the cadmium reduction flow injection analysis with an 8500 Quikchem Lachat (HACH®, Loveland, Colorado).

Nitrate Load Calculations

Water level changes within the drainage ditch were monitored with HOBO™ (Onset, Pocasset, MA) water level recorders. Water levels were recorded at 20 minute intervals and determined water depths by recording changes in atmospheric pressure. HOBO™ recorders were suspended just above the sediment on a permanent stake located at the inflow and directly upstream of each weir in the weir pools. An additional HOBO™ recorder was placed on the ditch's southern bank, above the water surface, to serve as a reference recorder. Data from the recorders were downloaded in the field every three or six weeks, depending on the sampling period, using a Panasonic Toughbook 31 (Panasonic©, Secaucus, NJ). Nutrient loads were calculated by inputting the water level recorder data into a Hydrologic Engineering Centers River Analysis System (HEC- RAS) 4.1.0 (U.S. Army Corps of Engineers) model.

The HEC- RAS software performed a one dimensional unsteady flow hydraulic calculation using a series of hydraulic parameters, the water depths recorded by the HOBO™ level loggers, and associated NO_3^- concentrations. Hydraulic parameters for the model were determined through survey data collected at Terrace Ditch. Survey data provided a description of the stream network, reach locations, connectivity, model cross-sections, cross-section location, and geometric data of Terrace Ditch. Manning's roughness coefficient (n) also was included in the model parameters and values were determined based on the density of the vegetation below the ditch's high water line during the growing (0.022) and dormant (0.33) seasons (Chin, 2000). Additionally, storm event sampling did not begin until March 2010; therefore loads were not calculated for events prior to this time period. Nutrient loads were only calculated for storm events from

March 2010 to March 2011 and only for those storm events that contained complete water quality data (i.e., inflow and outflow) was collected (n=7).

Groundwater Measurements

Piezometers were constructed and instrumented to measure changes in groundwater depths from August 2010 to April 2011. Prior to installation, groundwater depths were determined to be between 0.4 - 1 m using the Web Soil Survey (WSS) website, (www.websoilsurvey.nrcs.usda.gov). This site provides soil data and related information produced by the National Cooperative Soil Survey and is operated by the USDA Natural Resources Conservation Service. Two piezometers were placed on either side of the ditch on the upstream side of the upper weir. One piezometer was placed within the inner slope of the ditch and the other over the outer northern bank, 45 m from the center of the ditch. Two piezometers also were placed on either side of the ditch in the same manner downstream of the upper weir. These two piezometers served as controls as they were not under the direct hydrological influence of the weir.

Based on the data from WSS, a hand auger was used to dig a hole that was 5.1 - 7.6 cm in diameter and 1.5 m deep. Piezometers were constructed of 5.1 cm PVC pipe that was capped at the bottom. The lower section of the PVC pipe consisted of a 0.3 m section of screened interval which allowed water to move freely through the piezometer. Sand was used to back fill around the screened interval to prevent the screen from getting clogged with sediment. The hole was then filled with bentonite to seal the piezometer and prevent downward water leakage from precipitation. Soil was packed above the layer of bentonite to cover any remaining area around the PVC pipe. Level 100 TROLL (In-Situ Inc., Ft. Collins, CO) water level loggers attached to nylon twine were suspended above the bottom of the piezometer within the section of screened interval. A hole was drilled in the PVC cap at the top to hold an eye hook were the nylon twine was attached. After instrumentation and installation, water level measurements were taken at 20 minute intervals and data downloaded every six weeks using the Panasonic Toughbook 31.

Statistical Analysis

Mean inflow NO_3^- concentrations were calculated at the ditch's inflow and water samples taken from the abandoned aquaculture ponds draining into Terrace Ditch above the upper and lower weirs. Furthermore, mean NO_3^- concentrations were calculated below each weir with the samples collected immediately downstream of the weirs. Water quality changes throughout the study also were normalized by describing percentage change in concentrations between inflow and outflow. Using the mean inflow NO_3^- concentrations and mean NO_3^- concentrations below each weir, a series of NO_3^- concentration reduction percentages were calculated from the inflow to the upper weir, upper weir to the lower weir and for the entire system, inflow to lower weir. Due to the variability of inputs from adjacent aquaculture ponds and the inability to quantify water volumes leaving these systems, NO_3^- load reductions were only calculated from the inflow to the lower weir.

Depending on normality (Shapiro-Wilk) of data distributions, a paired t-test for means ($\alpha = 0.10$) or Mann-Whitney Rank Sum test was performed using Sigma Plot® 12.0 (Systat Software Inc., Chicago, IL) to determine if any significant difference was present for inflow and outflow NO_3^- concentrations and loads, individual weir concentration reductions, as well as concentration and load reductions for the entire system. Additionally, a repeated measures analysis of variance was used to determine if significant differences between seasons existed through time for NO_3^- percentage concentration reductions. In Sigma Plot® 12.0 a standard least squares model was fit using location (upper and lower weir) and seasons as effects. The repeated measures (α = 0.10) output generated differences between location, season, and location*season interactions.

Results

The inflow and outflow median NO_3^- concentrations (Figures 4.8 and 4.9) for storm samples were significantly greater ($P = 0.051$, $P = 0.02$) than baseflow samples. Median outflow NO_3^- concentrations for all baseflow (0.3 mg/L) and storm samples (2.7 mg/L) were significantly less ($P \leq 0.001$) than median inflow concentrations for baseflow (8.08 mg/L) and storm samples (13.08 mg/L). There was no significant difference (P= 0.48) detected in median overall percentage concentration reductions (i.e., inflow to the lower weir) between baseflow (53%) and storm (63%) event sampling. However, variability of multiple inputs throughout the system provided significantly different median inflow concentration values (Table 4.1) entering upper and lower weirs during baseflow ($U = 1543$, $P \leq 0.001$) and storm events ($U = 1087$, P= 0.09). Thus, understanding each weir's ability to reduce NO_3^- concentrations individually is needed.

Baseflow samples collected throughout the study yielded no significant difference ($P = 0.987$) between median inflow (0.7 mg/L) and outflow (0.9 mg/L) NO_3^- concentrations for the upper weir. However, median outflow (1.7 mg/L) NO_3^- concentration for the lower weir was significantly less ($P \leq 0.001$) than inflow concentration (4.49 mg/L) during baseflow sampling. Median concentration percentage reductions revealed that there was no significant difference ($P = 0.546$) between the upper (0%) and lower (35%) weir.

Storm event samples collected during the study yielded a significant difference ($P = 0.035$) between median NO_3^- inflow (4.2 mg/L) and outflow (1.9 mg/L) concentrations for the upper weir. Similarly for the lower weir, the median inflow (8.1 mg/L) NO_3^- concentration was significantly greater ($P \leq 0.001$) than outflow concentration (2.7 mg/L) during storm events. Median storm NO_3^- concentration percentage reductions generated statistically similar ($P = 0.594$) results for the upper (33%) and lower weir (63%).

The statistically less NO_3^- concentrations leaving the system may have possibly played a vital role in the significantly lesser ($P = 0.083$) median outflow loads (44.8 kg), generated by Terrace Ditch, compared to inflow loads (240.1 kg) (Table 4.2). This corresponded to a 65.02 ± 18.84% mean load reduction for the entire system during storm event sampling with two events generating percentage reductions greater than 97%. Seven storm events from March 2010 to March 2011 were used to determine load values and associated percentage reductions. Although NO_3^- loads seem to increase on two occasions, it is important to note that loads were only calculated using the system's inflow and outflow NO_3^- concentrations. Therefore, these two events may have yielded greater percentage reductions if concentrations from the abandoned aquaculture ponds could have been incorporated into the overall load calculations.

Due to occurrence of periodic fertilizer applications associated with crop production, seasonal variations in NO_3^- concentrations and percentage concentration reductions were accounted for. The multiple regression ($\alpha = 0.10$) output from the standard least squares model reported that season had no effect on mean inflow and outflow NO_3^- concentrations, yielding no significant difference for both baseflow ($F_{1,11} =$

1.605, $P = 0.308$) and storm ($F_{1,7} = 1.776$, $P = 0.324$) samples. However, the multiple regression output reported that season had a significant main effect on baseflow ($F_{5,17} = 8.307$, $P = 0.003$) and storm ($F_{3,9} = 6.109$, $P = 0.056$) mean NO_3^- concentration percentage reductions, with the greatest percentage concentration reductions occurring in the winter of 2010-2011 for both baseflow (68.3 ± 9.1%) and storm (67.4 ± 7.3%) samples. Considering yearly percentage concentration reductions for the entire system, median baseflow percentage reduction for the second year (82%) was statistically greater ($P \leq 0.001$) than the first year (0%). Conversely, storm samples revealed that there was no significant difference ($P = 0.313$) between the first (32.25 ± 21.7%) and second year (56.11 ± 11.7%) in terms of mean percentage concentration reduction for the entire system.

Water table depth measurements taken from piezometers (Fig. 4.10) showed a significant difference ($P \leq 0.001$) within sites on the upstream side of the weir (i.e., treatment) and within the two sites downstream of the weir (i.e., control). Analysis also revealed a significant difference ($P \leq 0.001$) comparing treatment against the control. However, location of the sites outside the ditch's northern bank and manipulation of the topography surrounding these sites have led to a skeptical interpretation of these data.

Discussion

My study sought to understand nutrient mitigation capacity of a stratified spatial arrangement of low-grade weirs in a large drainage ditch with an unregulated flow regime receiving runoff from an agricultural landscape under active crop production. Considering the experimental research often associated with low-grade weirs consist of one or two simulated storm events and associated percentage reductions in nutrient concentrations, effect of multiple storm events at a field scale was warranted. Therefore, this study sampled multiple baseflow (n=23) and storm (n=13) events to gain a better understanding of this particular arrangement's ability to reduce NO_3^- concentrations and loads through various events with different associated concentrations and to validate results from the experimental approach with field scale research.

Median storm inflow NO_3^- concentrations (13.08 mg/L) were significantly greater ($P \leq 0.001$) than baseflow (8.08 mg/L) inflow concentrations; yet median overall percentage NO_3^- concentration reductions were statistically similar between baseflow and storm events, 53 and 63%, respectively. These results are comparable to Strock *et al.* (2007), who reported N concentration reductions up to 71% in a drainage ditch following implementation of a CD structure. At low concentrations (0-0.5 mg/L) our system lacked successful percentage reductions, but greater concentrations often resulted in greater percentage reductions. Similarly, Kröger *et al.* (2011) found that at low NO_3^- concentrations (2 mg/L) systems became NO_3^- sources compared to NO_3^- sinks when greater concentrations (15 mg/L) were introduced. Positive concentration reductions may seem promising, but concentrations are only part of the picture. Nutrient loads, the product of discharge volume and related nutrient concentration, provide a better understanding of nutrient losses over time than concentrations alone (Schilling and Zhang, 2004).

Kovacic *et al.* (2000) reported constructed wetlands reduced NO_3^- loads from agricultural drainage by 34 and 44%. Authors stated that variability in the reductions, during the three year study, was due in large part to the unregulated flow traditionally experienced in agricultural landscapes. The current study, also under an unregulated flow regime, experienced a mean NO_3^- load reduction of 65% with reductions ranging from 0-

97% for the entire system. As expected, the greatest percentage reductions were associated with periods of intense precipitation and discharge. The range of percentage reductions may have generated a smaller gap or a greater average percent reduction if concentrations from the adjacent aquaculture ponds could have been included. These concentrations were not included in calculating loads because of the inability to quantify loads leaving these systems. Therefore, only concentrations collected at the inflow and outflow were incorporated. Concentrations from the abandoned ponds also led to the upper and lower weir receiving significantly different inflow concentrations (Table 4.1) during baseflow and storm events, thus understanding each weirs individual capacity to reduce nutrient concentrations was desired.

Baseflow sampling data revealed that only the lower weir significantly lessened the inflow NO_3^- concentration, whereas during storm event sampling, both weirs significantly lessened their inflow concentrations. The upper weir did not significantly decrease base flow NO_3^- concentrations, but sediment accumulation data revealed that the upper weir retained more sediment (47.2 cm) than the lower weir (30.1 cm). Interestingly enough, the upper weir may have been more efficient at sediment accumulation allowing the lower weir to effectively lower nutrient concentrations during baseflow events. Each weir's ability to effectively lower nutrient concentrations may have been affected by the lag time response that has been associated with BMPs aimed at increasing water quality.

Meals *et al.* (2010) stated that over the past four decades, most watershed projects have reported little or no improvement in water quality, even after extensive implementation of conservation measures or BMPs in the watershed. This is due in large part to lag time, amount of time between installation of BMPs on the landscape and response of water quality improvement in the target water body. This concept would explain the significantly lesser median NO_3^- concentration reductions for baseflow events seen in Year 1 (0%) compared to Year 2 (82%). Yet, percentage concentration reductions during storm events did not differ significantly, yielding 32% for Year 1 and 56% for Year 2. However, storm samples were not collected until a year post weir installation, which by then positive percentage reductions for baseflow NO_3^- concentrations had already been attained. Influence from adjacent aquaculture ponds limited the hydrological isolation of our system, which also could have played a major role in the annual and seasonal NO_3^- losses from the system.

Schilling and Zhang (2004) analyzed seasonal baseflow NO_3^- concentrations in central Iowa and found that NO_3^- losses peaked from March-June and again in late fall to early winter. Analysis of seasonal effects in the current study revealed that season yielded no effect on inflow concentrations. Yet, season did have an effect on percentage reductions, with winter, 2010-2011, experiencing the greatest concentration reductions for baseflow (66%) and storm (67%) sampling. Aquaculture effluent from adjacent ponds for this time period yielded the greatest seasonal mean inflow NO_3^- concentration (31 ± 3.74 mg/L) with concentrations ranging from 13-74 mg/L. Because the greatest percentage reductions are often associated with the greatest concentrations, this could explain the seasonal effects of my system as well as importance of understanding hydrological isolation when analyzing and reporting results.

Data from the groundwater measurements taken at Terrace Ditch are cautiously interpreted due to occurrence of pooling water within the sites located outside of ditch's northern banks. These sites were located within the banks of an abandoned aquaculture pond and although the pond's levees had been breached, the ponds were still capable of holding water. Pooling could have biased data and led to incorrect assumptions. After further consideration, an alternate location would need to be established to accurately measure and interpret effects of weirs on groundwater fluctuations. An optimal site for this analysis would be a location where a weir could be installed within a ditch that was surrounded by adjacent agricultural land with minimal slopes. This would allow the researcher to obtain multiple measurements at various distances from either side of the ditch. Data collection from such a location could lead to understanding effects on water quantity following installation of controlled drainage practices aimed at improving water quality.

Results from the field scale research at Terrace Ditch highlight the potential to establish low-grade weirs as a new innovative surface CD strategy. Validating these results with the previous experimental approach further strengthens our understanding of the capabilities of low-grade weirs to reduce NO_3^- concentrations and loads in agricultural drainage ditches under an unregulated flow regime. However, the need for long-term monitoring is necessary. Mitsch *et al.* (2012) studied two constructed wetlands that received water from the Olentangy River, a third-order stream in the agriculture-dominated Scioto River Watershed of central Ohio. After 15 years of collecting data, authors found that NO_3^- reductions decreased from 35% to 25%. They went on to state that although NO_3^- retention appeared to stabilize in years 10–15, many more years are needed for these created wetlands to develop N removal rates comparable to those of similar natural wetlands. Thus, long-term monitoring of Terrace Ditch is not only needed, but also will aid in the ability to make informed decisions regarding the future management of wetlands created in agricultural drainage ditches for nutrient mitigation.

Table 4.1 Median inflow NO_3^- concentration values (with associated quartile ranges) from September 2009- April 2011 for both the upper and lower weir during baseflow and storm sampling at Terrace Ditch, Yazoo County, MS.

Site	**Baseflow Concentration**	25th Percentile	75th Percentile	**Storm Concentration**	25th Percentile	75th Percentile
Upper Weir	**0.67 mg/L**	0.27 mg/L	10.5 mg/L	**4.18 mg/L**	1.07 mg/L	15.36 mg/L
Lower Weir	**4.49 mg/L**	0.83 mg/L	21.76 mg/L	**8.08 mg/L**	1.64 mg/L	26.2 mg/L

Table 4.2 Inflow and outflow load calculations with associated percentage decreases obtained by using NO_3^- concentrations collected during storm event from March 2010-April 2011 at Terrace Ditch, Yazoo County, MS.

Storm Event	Inflow Load (kg)*	Outflow Load (kg)	% Decrease
3/25/2010	12.62	13.53	-7.23
4/26/2010	365.81	7.51	97.95
6/30/2010	101.16	10.22	89.89
12/1/2010	214.04	23.27	89.13
1/26/2011	192.61	208.66	-8.34
2/8/2011	241.29	5.80	97.60
3/11/2011	1528.14	59.44	96.11

(*) indicates that inflow load values were determined without including concentrations collected from the aquaculture ponds flowing into the ditch.

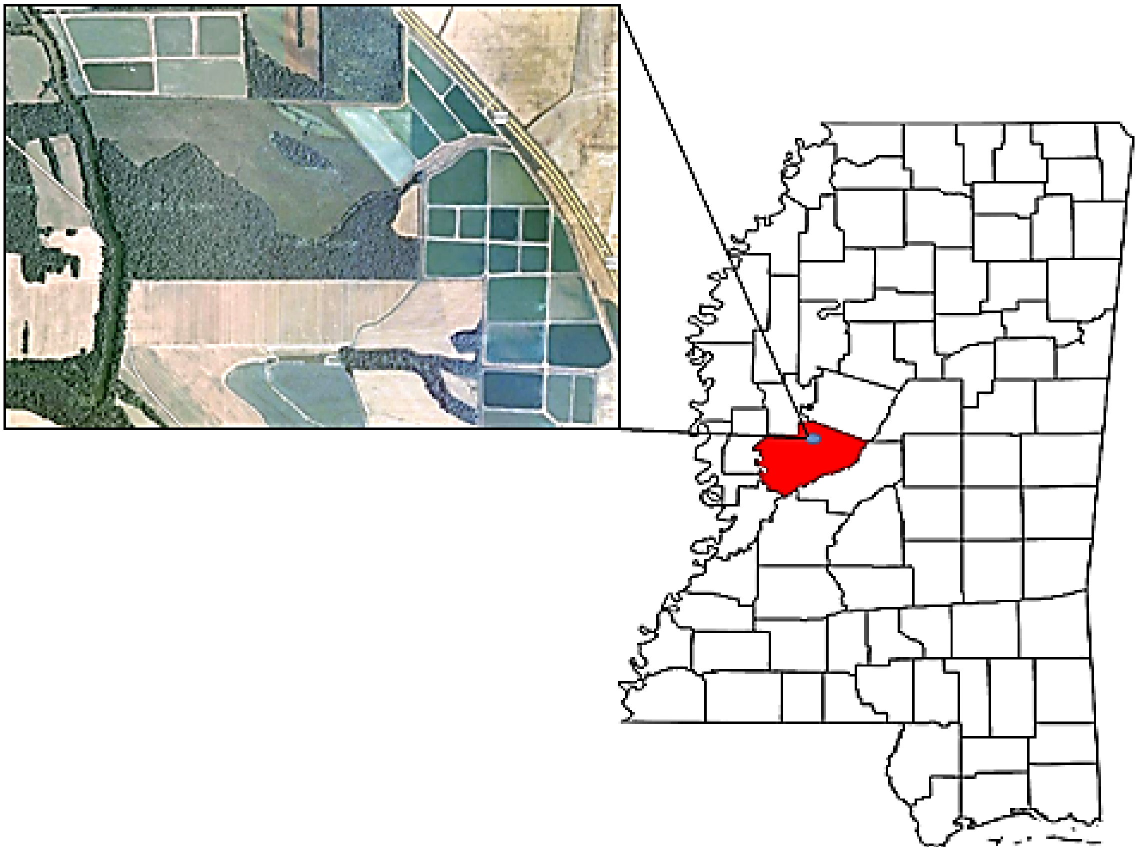

Figure 4.1	Map and location of Terrace Ditch, Yazoo County, MS.

The ditch separates two large portions of aquaculture ponds just west of U.S. Hwy 49 South and drains directly into Wolf Lake.

Figure 4.2 Terrace Ditch, Yazoo County, MS, immediately after implementation of weirs (September, 2009).

The upstream weir appears in the foreground, connected on the left to a floodplain bench and the downstream weir is visible in the background.

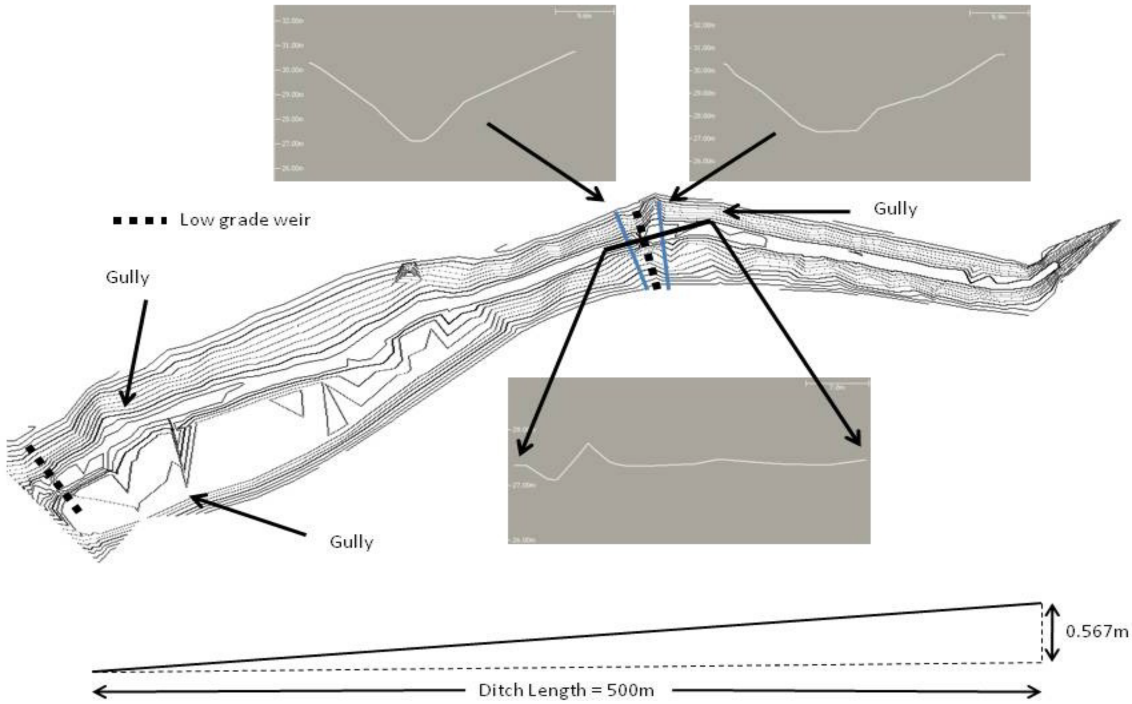

Figure 4.3 An October 2010 topographic map of Terrace Ditch Yazoo County, MS.

Water flows from right to left with low-grade weirs marked by dotted lines. Figures above the map show the downstream pool and upstream weir pool, respectively. The figure below the map shows the entire area of pooled water resulting from the upper weir. The locations of gullies draining nearby abandoned catfish ponds are also labeled.

Figure 4.4 Terrace Ditch, Yazoo County, MS, prior to construction in 2009.

The ditch consisted of a narrow and overgrown channel that resulted in severe flooding. Despite extensive vegetation, steep banks often resulted in high levels of bank erosion.

Figure 4.5 Photograph of Terrace Ditch, Yazoo County, MS, one month following construction in November 2009 and shows the upstream channel bed above the lower weir, revealing the ditch's lack of vegetation and bare soil.

Figure 4.6 Photograph shows approximately the same location as Fig. 4.5 and reveals the diverse assemblage of wetland plants immediately upstream of the lower weir following one growing season.

Revegetation occurred naturally except *Typha latifolia*, which was planted as part of the research study in June 2010 at Terrace Ditch, Yazoo County, MS.

Figure 4.7 Permanent staked samplers situated 200-1200 mm above sediment surface, located at the inflow and immediately downstream of each weir at Terrace Ditch, Yazoo County, MS.

Samplers collected water samples from March 2010-April 2011during storm events as water levels were rising. Once the sampler was filled to capacity, a ping pong ball in the sampler acted as a seal until samples were collected.

Figure 4.8 Median inflow NO_3^- concentrations for the baseflow event sampling and storm event sampling from September 2009 to April 2011 at Terrace Ditch, Yazoo County, MS.

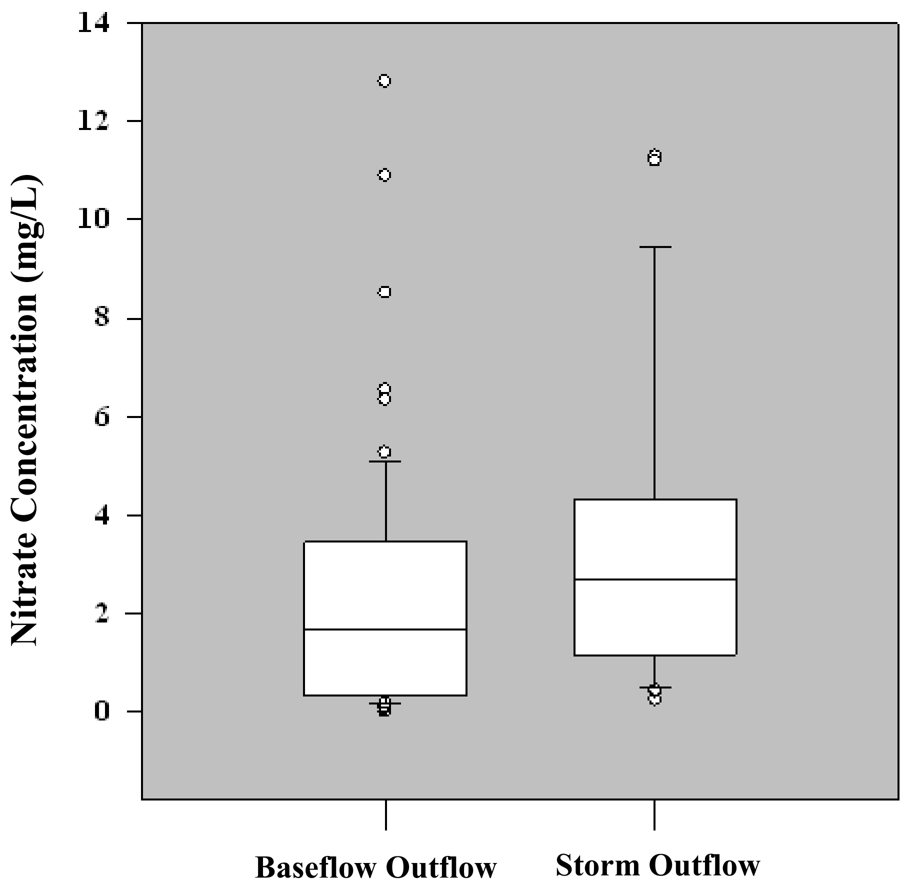

Figure 4.9 Median outflow NO_3^- concentrations for the baseflow event sampling and storm event sampling from September 2009 to April 2011 at Terrace Ditch, Yazoo County, MS.

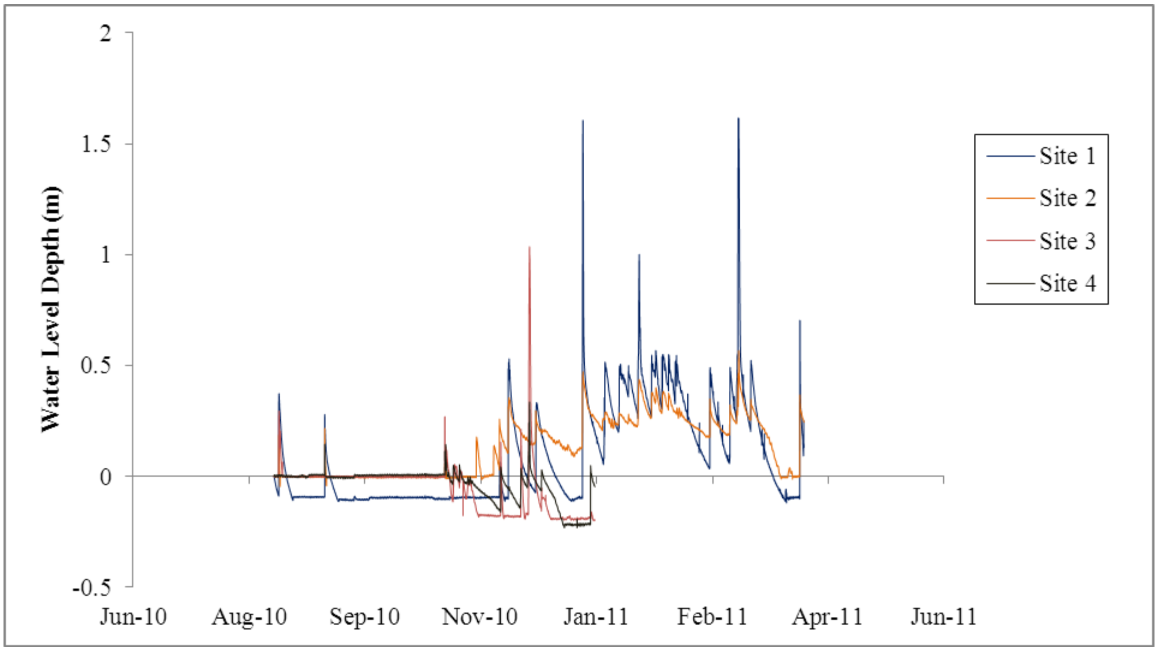

Figure 4.10 Water table depth fluctuations from August of 2010 to April of 2011 for all 4 piezometer sites at Terrace Ditch, Yazoo County, MS.

Site locations were: 1) inner bank, adjacent to lower weir pool, 2) outside bank in landscape adjacent to lower weir pool, 3) inner bank, adjacent to upper weir pool, and 4) outside bank in landscape adjacent to upper weir pool.

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CHAPTER V

MANAGEMENT IMPLICATIONS

Results from the experimental approach and field scale demonstration offer promising insight into the future of low-grade weir establishment as an additional best management practice (BMP) in agricultural landscapes. The Arkansas State University experiment revealed that weirs significantly increased hydraulic residence time (HRT) and ditch water volumes, leading to considerable reductions in outflow water volumes (61%), cumulative outflow NO_3^- load (96%), and a greater NO_3^- concentration reduction during the biogeochemical reduction phase of the experiment. Similarly, the field research from Terrace Ditch in Yazoo, MS yielded significant percentage NO_3^- concentration reductions for baseflow (53%), stormflow (63%), and load (65%). These concentration and load reductions are well within the scope of The Gulf of Mexico Alliance *Action Plan II* desired nutrient reduction criteria and long-term goals (GOMA 2009)

The Gulf of Mexico Alliance 2009 *Action Plan II* set a goal of 45% reduction in nutrient levels to mitigate the harmful effects to coastal water quality, which is intimately connected to the Gulf Coast region's sustainability. The plan stated that one of the long-term goals was to develop and implement strategies that reduce nutrient inputs and hypoxia in the Gulf of Mexico (GOMA, 2009). Although 45% reduction seems daunting, the current research highlights the ability of low-grade weirs to effectively reduce NO_3^- concentrations and loads leaving an agricultural landscape. However, it has been stated that there are limiting factors when it comes to using controlled drainage for the purpose of nutrient retention.

Nutrient mitigation by means of controlled drainage often results in a loss of productive agriculture land especially with practices such as constructed or restored wetlands. Because drainage ditches are ubiquitous features found throughout agricultural landscapes, installation of low-grade weirs requires no land to be set aside or taken out of production, yet the desired benefits are still achievable. Recent studies have found that low-grade weirs could offer benefits in the form of sediment retention and several studies have shown that controlled drainage techniques have the ability to increase water table depths. Thus, with additional research, this one management strategy could offer a suite of ecosystem services without taking profitable land out of production.

With today's ever increasing human population, a management strategy that produces several desired benefits while not taking any profitable land out of production is vitally important. Food production is expected to double in the next 50 years, requiring 18% more arable land than is in production today (Carvalho, 2006). Thus, innovative nutrient management techniques at a larger scale within the headwater systems will be needed to mitigate the effects on downstream water bodies. Ditches are those very systems from which the headwater originates, therefore understanding the spatial and temporal variation of hydrological and biological processes in the headwater system is key. Biological processing near the source has the greatest chance to reduce the effects of nutrient loads on downstream aquatic system.

Between 5-9% of the Mississippi River Basin (MRB) would need to be converted to wetland habitat to reduce N loads to Gulf of Mexico by 20-50%. There was over 370 million hectares in the U.S. in agricultural production according to the 2007 United States

Department of Agriculture census. Most of that land requires drainage ditches to adequately remove surface water off the landscape. Using these systems in each and every major watershed in the MRB could be highly beneficial, possibly reaching the recommended 5-9%. To reach and sustain the desired 45% nutrient reduction criteria set by Gulf of Mexico Alliance, incorporating a suite of management techniques would need to be considered. However, using drainage ditches with installation of low-grade weirs could possibly produce a more ecologically sound and economical sustainable landscape for future generations.

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