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Mitigating Aquaculture Effluent through Use of Low-Grade Weirs

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Mitigating aquaculture effluent through use of low-grade weirs

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Water management practices to reduce mass discharge are a major point of concern for aquaculture producers. This study assessed effects of consecutive low-grade weirs on chemical retention and settling of aquaculture pond effluent in a single drainage ditch. Two control and nine treatment discharges were conducted September - October 2012. Control discharge dissolved inorganic phosphorus (DIP) load increased 154%, whereas total inorganic phosphorus (TIP), ammonia, and nitrate loads decreased (47%, 43%, and 63%, respectively). Treatment discharge nutrient loads decreased across all analytes (80% DIP, 86% TIP, 89% ammonia, 89% nitrate). However, control and treatment discharges concentrations of DIP and nitrate increased, whereas TIP and ammonia concentrations decreased. All discharges reduced total and volatile suspended solid loads 72% - 94%, with removal rates of 0.02 ± 0.01 mg/L/min total and 0.02 ± 0.001 mg/L/min volatile suspended solids. Results indicate ditches fit with low-grade weirs may be an innovative management practice.

DEDICATION

I dedicate this thesis to my family and friends, whose love and support was there when I needed it. Especially to Philip, who put life in perspective each time I reached the end of my rope.

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CHAPTER I

INTRODUCTION

The Mississippi River Basin (MRB) discharges an average of 580 km^3 of fresh water into the northern Gulf of Mexico annually (Rabalais et al. 2007). Increased fluxes of nitrogen and phosphorus from the MRB have been linked to a seasonal hypoxic zone in the northern Gulf of Mexico (Alexander et al. 2008). Due to the increasing size and frequency of the hypoxic zone, a management goal has been established to reduce point and non-point source inputs to streams in the MRB by at least 45% in total nitrogen and total phosphorus (EPA 2007). The Mississippi River Basin drains more than 40% of the continental United States including the Mississippi Alluvial Valley, regionally known as the “Delta” (Milliman and Meade 1983). Commercial aquaculture production of channel catfish (*Ictalurus punctatus*) in the Delta covers 16,000 ha. Current production levels rank Mississippi as the leader in catfish production in the United States (USDA/NASS 2013). Most channel catfish facilities in the Delta are embankment ponds, which inevitably will discharge water, either by intentional discharge or overflow.

Overflow is the most common effluent type in commercial aquaculture, occurring during periods of high rainfall (Boyd et al. 2000, Boyd and Gross 2000, Boyd 2003). Overflow is difficult to treat because volumes can vary from insignificant to large (Tucker and Hargreaves 2003). Best management practices (BMPs) have been developed to reduce water discharges from ponds as well as reducing nutrient and sediment loading to downstream receiving waters. Aquaculture facility BMPs include in-pond and post-discharge approaches.

In-pond BMPs reduce erosion, limit discharge, and promote nutrient reduction through in-pond processes. Possible in-pond BMPs include “no drain” and drop-fill schemes. No drain schemes promote multiple-batch continuous fish production with several age classes in a single pond. Continuous production is possible because biogeochemical processes continually remove nutrients and organic matter from pond water (Tucker et al. 1996). Drop-fill schemes recommend a certain storage level in ponds allowing water levels to rise during storm events without overflowing. Discharge volumes are especially low in embankment ponds operating with water levels 7.5 to 10 cm below overflow intake structures (Boyd and Gross 2000, Boyd et al. 2008). However, Boyd et al. (2008) found embankment ponds at Auburn, AL operated with water levels 7.5 cm below overflow intakes will still discharge water during years with average rainfall.

Currently, post-discharge BMPs include constructed wetlands and settling basins. Constructed wetlands and settling basins have been shown to reduce nutrients and suspended solids from aquaculture effluent (Schwartz and Boyd 1995, Kadlec and Knight 1996, Boyd and Queiroz 2001, Lin et al. 2002, Engle and Valderrama 2003, Schulz et al. 2004). However, use of these post-discharge BMPs is often not economically feasible for many facilities due to amount of land taken out of production (Boyd 2003). For instance, a retention pond of 1.53 ha would be needed to retain water from a 1-ha embankment pond after a 25-year rainfall event (Boyd and Queiroz 2001). Loss of land for production negatively affects farms financially, emphasizing the need for more economic management practices. The key to more economic effluent management practices may be in use of ubiquitous features of the aquaculture landscape.

Vegetated ditches are necessary components of the aquaculture landscape. These systems are a primary intercept between pond and receiving waters with the potential to act as long settling basins (Shireman and Cichra 1994, Tucker and Hargreaves 2003). Vegetated ditches possess hydric soils, hydrophytes, and fluctuating hydroperiods that are characteristic of wetland ecosystems (Kröger 2008), and have been shown to remove nutrients from agricultural landscapes (Cooper et al. 2004, Kröger et al. 2008a, Moore et al. 2010, Kröger et al. 2012). Introducing a controlled drainage practice to these systems may further improve water quality by decreasing flow velocities within the system.

Low-grade weirs are controlled drainage structures which increase hydraulic residence time (HRT), reduce flow and promote sedimentation (Kröger et al. 2008b, Kröger et al. 2012). Individual weirs are installed spatially according to ditch slope and independent of one another's function, which optimizes biogeochemical processes occurring behind each weir (Kröger 2008). Introduction of low-grade weirs into ditch systems may serve as an innovative alternative to reduce nutrients and organic material entering receiving waters. The aim of this study is to test efficiency of a vegetated ditch system fitted with low-grade weirs in mitigating aquaculture effluent by reducing nutrient and suspended material load reaching receiving waters. This study assessed effects of multiple low-grade weirs on chemical and suspended load retention to mitigate aquaculture pond effluent in a drainage ditch system. Efficiencies of individual and consecutive low-grade weirs were assessed within the system. Objectives included:

Objective 1: Assess effects of multiple low-grade weirs on nutrient retention to mitigate aquaculture pond effluent in a drainage ditch system

H_o: Consecutive low-grade weirs will have no effect on nitrogen and phosphorus retention of aquaculture effluent before it enters downstream receiving waters

Objective 2: Assess effects of multiple low-grade weirs on suspended load removal rates to mitigate aquaculture pond effluent in a drainage ditch system

H_o: Consecutive low-grade weirs will have no effect on suspended load removal rates of aquaculture effluent

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CHAPTER II

LOW-GRADE WEIRS: AN INNOVATIVE BMP FOR AQUACULTURE EFFLUENT NUTRIENT MITIGATION

2.1 Introduction

Increased fluxes of nitrogen and phosphorus in aquatic systems have been linked to ecological impairments, such as the seasonal hypoxia zone in the Gulf of Mexico (Alexander et al. 2008). Catfish aquaculture encompasses 16,000 ha in the Mississippi Alluvial Valley where water eventually discharges into the Gulf of Mexico (USDA/NASS 2013). In the past aquaculture ponds, like embankment ponds that dominate catfish culture in Mississippi, have been targeted as nutrient inputs. As part of the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) classifies concentrated aquatic animal production as a point source and establishes pollutant monitoring and reporting requirements (EPA 2013). Currently, however, due to facility size or frequency of discharge catfish production facilities are exempt from NPDES permitting. Even with permit exemptions, best management practices (BMPs) aim to minimize or treat effluent from embankment ponds. Effluent-treatment BMPs, including settling basins and constructed wetlands, take land out of production, warranting consideration for innovative BMPs in primary waterways (e.g., ditches) where effluent drainage already occurs.

Vegetated ditches are a ubiquitous feature on the aquaculture landscape. This feature serves as a primary intercept between ponds and receiving waters. Vegetated ditches possess hydric soils, hydrophytes, and fluctuating hydroperiods that are characteristic of wetland ecosystems (Kröger 2008), and have been shown to remove nutrients from agricultural landscapes (Cooper et al. 2004, Kröger et al. 2008a, Moore et al. 2010, Kröger et al. 2012). Kröger et al. (2007, 2008a) reported vegetated agricultural ditches were able to decrease 57% of dissolved inorganic nitrogen and decreased 45% of total inorganic phosphorus (TIP) in farm-field effluent loads. Moore et al. (2010) reported that drainage ditch vegetation can decrease dissolved inorganic phosphorus (DIP) concentration up to 52%. Introducing a controlled drainage practice to these systems may further improve water quality by decreasing flow velocities within the system.

Low-grade weirs are controlled drainage structures which increase hydraulic residence time (HRT) by reducing velocities throughout the system (Kröger et al. 2008b, Kröger et al. 2012). Multiple stages are created for biological transformation, potentially lowering nutrient loads before effluent reaches downstream receiving waters. Kröger et al. (2008b, 2011) found that chemical retention time was altered significantly by installation of low-grade weirs, and further concluded weirs reduced significantly outflow loads and concentrations of nitrate (NO_3^--N), DIP, and TIP. The objective of this chapter was to assess effects of multiple low-grade weirs on nutrient load and concentration to mitigate aquaculture pond effluent in drainage ditch systems. It was hypothesized that weirs installed in aquaculture drainage ditches would increase nutrient reduction. The null hypothesis tested was that low-grade weirs have no effect on nitrogen and phosphorus retention of aquaculture effluent before it enters downstream receiving waters.

2.2 Materials & Methods

In September and October 2012, 11 experimental embankment ponds (0.05 ha) were intentionally discharged at the Mississippi State University South Farm Aquaculture Facility (Mississippi State, MS) into a 292-m vegetated ditch fitted with three pre-cast concrete low-grade weirs (Figure 2.1). Randomly assigned ponds were unstocked (n=2) or stocked with either freshwater prawns (*Macrobrachium rosenbergii*) (n=7) or channel catfish (*Ictalurus punctatus*) fry (n=2). Ditch channel width averaged 3 m and volunteer vegetation primarily consisted of cutgrass (*Leersia sp*.) and cattails (*Typha sp*.). Weirs were constructed with removable riser boards to manipulate flow. To allow the system to act as a conventional ditch, riser boards were removed from all weirs and two control discharges were conducted. Weir height without riser boards in place was 0.17 m, 0.15 m, and 0.34 m, respectively. Nine treatment discharges were conducted with riser boards installed, allowing assessment of weir function. With boards installed, weir height was 0.35 m, 0.24 m, and 0.55 m, respectively. Order of discharges was randomly assigned. Prior to discharge events, initial water samples were collected from the pond (n=2) and each ditch sample site (n=4). Distance from initial effluent to weir 1 was measured and initial ditch volume was calculated. Volumes of each reach of the ditch were calculated as ditch area above each weir by water depth at the corresponding weir, and summed for the in-ditch volume.

Ponds were drained using a hydraulic PTO tractor pump (custom fabrication, Starkville, MS) to simulate overflow. Nutrient load entering and leaving the system was calculated for one control discharge and four treatment discharges (concentration x flow rate). All loads were normalized by dividing load by the wetted ditch area. Change in depth of pond was monitored using a rugged troll level logger (InSitu, Inc., Ft. Collins, CO) mounted at the deepest point of each pond. Rate of flow entering the system was calculated as the change in pond depth over time. Rate of flow leaving the system was determined by taking a three-sample average of the time it took to fill a 21-L bucket behind the last weir at each hourly water sampling event throughout each drainage event.

To calculate HRT, one control and two treatment discharges were randomly selected to which a salt slug was introduced to the system when pumping began and when pumping ended. The salt solution was created in a mixing chamber using 18.14 kg of 99% pure NaCl, Diamond Crystal® pool salt (Cargill, Inc., Wayzata, MN), dissolved in 125 L of pond water. Specific conductivity (µS) was measured above each weir using a Hydrolab Minisonde 5 Multiprobe SE (Hach, Loveland, CO) to monitor the salt slug movement through the system. At maximum weir capacity, volume of the ditch was additionally measured to calculate difference in water volume from initial ditch volume.

2.2.1 Water Sampling and Analysis

Water samples were collected from pond initial effluent and below each weir at 30 min intervals until pumping ended. Water samples were then collected below each weir every 60 min until the discharge event was sampled for six hours. After the 6 h sample, water samples were taken above each weir at 12 h, 24 h, 30 h, and 42 h. Snap-seal 237-mL plastic containers (Corning, Corning, NY) were used for sample collection. Samples were collected 0.1 m below the water surface and kept on ice until transported to the Mississippi State University Water Quality Lab for analysis.

Water samples were analyzed for TIP, DIP, ammonia (NH_3-N), nitrite-nitrogen (NO_2^--N), and NO_3^--N. Within 24 h of collection, TIP was analyzed using colorimetric reaction methods described by Murphy and Riley (1962) on digested unfiltered samples using a DR5000 spectrophotometer (Hach, Loveland, CO). Samples were then filtered through a 0.45 µm nitrate-cellulose membrane for analysis of DIP, NH_3-N, NO_2^--N, and NO_3^--N. Dissolved inorganic phosphorus, NH_3-N, and NO_2^--N were analyzed using colorimetric reaction methods and NO_3^--N was analyzed using the cadmium reduction method on a LaChat Quikchem 8500 (Loveland, CO).

2.2.2 Statistical Analysis

Serial autocorrelation was used to verify independence in events. Homogeneity of variance was verified using Levene's test for equality of variance. Normality and goodness of fit in the data sets was determined with a Shapiro-Wilk W test. For each discharge, differences in nutrient concentrations between pond and initial effluent as well as differences in nutrient concentrations between initial and 48-hr ditch samples were analyzed with a student *t*-test. Percentage load leaving the system was calculated for all events where pond volume was available (n=5). Weir efficiency was calculated as the difference between weir peak concentration and individual sample concentration divided by peak concentration. Nutrient concentration reduction differences were compared using a repeated measure mixed model analysis of variance (ANOVA) for a split-plot design with discharge as the whole plot, weir as the subplot, and time as replication. All effects except the interaction of discharge x time were considered to be fixed. In treatments where significant nutrient reduction was observed for weirs, a post-hoc Tukey-Kramer test and a least square means pairwise comparison was conducted by weir. Furthermore, the repeated measure mixed model ANOVA for a split-plot design was expanded to include additional fixed effects of distance, number of discharges, initial effluent concentration, and flow rate to determine significant effects on changes in nutrient concentrations. If a significant effect was observed, a post-hoc Tukey-Kramer test and a least square means pairwise comparison of the interaction between weir and significant factor was performed. An alpha level of 0.05 was used for all statistical analyses. Statistical analysis was performed using SAS software, Version 9.3 of the SAS system for Windows (SAS 2009).

2.3 Results

Initial ditch volume ranged from 37 m^3 to 120 m^3. Increases in ditch volume of 21 m^3 to 103 m^3 were observed from initial volume to maximum weir capacity. Average hydraulic residence time increased from 98 min in control discharges to 129 min in treatment discharges. Initial effluent nutrient concentrations were similar to pond water and the vegetated ditch system returned to baseline values within 48 hr of each event ($P > 0.20$ for each nutrient at all sites).

Nutrient loads ($mg/m^2/d$) exhibited greater reduction in treatment discharges compared to the control discharge. Nutrient loads in the control discharge increased across the system for DIP (Table 2.1 and Figure 2.2). Alternatively, TIP, NH_3-N, and NO_3^--N control discharge loads decreased (Table 2.1, Figure 2.2, and Figure 2.3). Nitrite was not detected in control discharge samples. Treatment discharge nutrient loads decreased in all analytes (Table 2.2, Figure 2.2, and Figure 2.3). Nitrite was present in treatment discharges with load reduction ranging from 5 $mg/m^2/d$ (100%) to 567 $mg/m^2/d$ (84%) (Figure 2.3).

Nutrient concentration reduction (mg/L) was variable between control discharges and treatment discharges. In control discharges, TIP and NH_3-N concentrations were reduced significantly by the system (TIP: F=4.59, P=0.02; NH_3-N: F=6.70, P<0.001) (Figure 2.4). However, overall changes in concentrations of DIP and NO_3^--N were not significant (DIP: F=0.11, P=0.90; NO_3^--N: F=0.95, P=0.40). Within the system, TIP concentration reduction at weir 3 was significantly greater than previous weirs (t = -2.78, P=0.01 weir 1; t = -2.48, P=0.02 weir 2). Also, in control discharges, NH_3-N concentration reduction at weir 2 was significantly less than the rest of the ditch system (t = 3.40, P<0.001 weir 1; t = -2.80, P=0.01 weir 3). Increasing nutrient concentrations at individual weirs allowed for significant concentration reduction differences among weirs during control discharges.

Treatment discharges reduced overall concentrations of TIP, NO_2^--N, and NO_3^--N, while increasing overall concentrations of DIP (Figure 2.4, Figure 2.5, and Figure 2.6). Total inorganic P, NO_2^--N, and NO_3^--N concentrations were reduced significantly (F=4.95, P=0.01; F=2.91, P=0.06; F=5.18, P=0.01, respectively). Conversely, DIP concentrations increased significantly (F=12.60, P<0.001). Overall, NH_3-N concentrations were not reduced significantly (F=2.39; P=0.10). Within the system, TIP and NO_3^--N concentrations in treatment discharges decreased significantly at weir 1 (t = 2.97, P<0.001; t = 2.54, P=0.01) and weir 3 (t = -2.25, P=0.03; t = -2.91, P<0.001). Weir 3 was the only site at which DIP concentrations increased significantly (t = -5.16, P<0.001).

Of the fixed effects analyzed, initial effluent concentration was the only factor affecting nutrient reduction significantly. Initial effluent concentration of individual discharges significantly affected TIP ($F = 4.28$, $P < 0.001$) and NO_3^--N ($F = 2.41$, $P = 0.02$) concentration reductions. The treatment discharges with the three greatest concentrations of TIP (treatment discharges 5, 9, and 8) had significant reductions in concentration ($t = 2.88$, $P < 0.001$; $t = 5.66$, $P < 0.001$; $t = 3.49$, $P < 0.001$). Concentrations of TIP in the three discharges were greater than 1.00 mg/L, whereas concentrations in all other discharge events were below 0.65 mg/L. Even though overall concentrations of NO_3^--N increased in treatment discharges, the three discharges with the greatest initial effluent concentration of NO_3^--N (treatment discharges 5, 9, and 7) had significant reductions in concentrations ($t = 1.98$, $P = 0.05$; $t = 2.50$, $P = 0.01$; $t = 3.69$, $P < 0.001$, respectively).

Mean percent overall reduction efficiency was analyzed across the system and at individual weirs (Table 2.3). In control discharges, TIP was the only nutrient with positive efficiency across the system (13% ± 61), whereas DIP and NO_3^--N had negative efficiency (-543% ± 218 and -116% ± 94). Dissolved inorganic phosphorus reduction efficiency had no distinct trend; however, NO_3^--N had greater reduction efficiency as effluent progressed through the system. Ammonia also had greater reduction efficiency as effluent progressed through the system; despite NH_3-N increasing efficiency among weirs, total reduction efficiency across the system was 0%. Treatment discharges had decreasing reduction efficiency across the system for phosphorus species (-23% ± 21 TIP, -79% ± 42 DIP). However, nitrogen species had overall increasing reduction efficiency (87% ± 15 NH_3-N, 53% ± 12 NO_2^--N, and 22% ± 20 NO_3^--N). As in control discharges, NH_3-N reduction efficiency increased as effluent progressed through the system in treatment discharges (Table 2.3); yet, DIP reduction efficiency decreased.

Reduction efficiencies of all other analytes varied from weir to weir with no distinct trend.

2.4 Discussion

Research has been done on ability of current BMPs to mitigate nutrients from aquaculture effluent. Schwartz and Boyd (1995) analyzed constructed wetlands for effluent treatment and found concentrations reductions ranging from 1% - 81% in NH_3-N, 43% - 98% in NO_2^--N, 51% - 75% in NO_3^--N, and 59% - 84% in total phosphorus. However, they noted for proper HRT to achieve this reduction during a pond drainage event, 70% of pond area was needed. Schulz et al. (2004) found constructed wetlands reduced concentrations of total phosphorus 41%, NO_3^--N 19%, and ammonia-nitrogen 41%. Lefrançois et al. (2010) reported a sediment retention system having a mean removal rate of 12.4 g P/d of total phosphorus. All of these systems, however, take land out of production or are limited in nutrient species treated. Little research has been done on ability of vegetated ditches already in the aquaculture landscape to mitigate nutrients in effluent.

Tucker and Hargreaves (2003) noted vegetated ditches have the potential to act as long settling ponds, removing phosphorus through sedimentation. Boyd et al. (1998) found that 75% of total phosphorus removal in catfish pond effluent may be explained by sedimentation. Results of the current study indicate vegetated ditches fit with low-grade weirs reduce TIP load 53% to 81%. Phosphorus concentrations are reduced in wetland systems through sedimentation and adsorption. Reddy and D'Angelo (1997) noted precipitation of phosphorus may be especially notable when pH of floodwaters is diurnally altered by photosynthetic processes of algae, which is prevalent in aquaculture effluent. Despite the TIP reduction in the current study, DIP increased significantly across the system. It is possible that through multiple flood pulses, iron in the soil became reduced, thus leaching phosphorus into the overlying water column.

Shireman and Cichra (1994) found total nitrogen was not reduced from baitfish pond effluent when passed through a vegetated ditch. In the current study, NO_2^--N, NO_3^--N, and NH_3-N load and concentrations were reduced. This may indicate that modification of aquaculture ditch systems through installation of low-grade weirs reshapes the biogeochemistry of the ditch system, satisfying needs of nitrification, denitrification, volatilization, and plant or microbial uptake. Conditions for denitrification include NO_3^--N availability, reduced oxygen concentrations, and available electron donors (Seitzinger et al. 2006). Satisfaction of denitrification needs may be more evident in rate of reduction for nitrogen analytes in this study. Above-weir water depth increased through the system, as did rate of reduction in NO_2^--N and NO_3^--N. Fostering anaerobic soils, the flooded state of the ditch system could allow nitrate to diffuse into soils and be removed by reduction to gaseous nitrogen (Reddy et al. 1984). Vegetation may also play a significant role in nitrogen removal through assimilation into plant tissue and increased rhizosphere for nitrification-denitrification processes to occur (Reddy and D'Angelo 1997).

Schwartz and Boyd (1995) reported effluent outflow percentage reductions in concentrations of total phosphorus from 23% to 43%, NO_2^--N from 0% to 95%, and NO_3^--N from -3% to 60% when passed through constructed wetlands under a 1-d HRT. Lin et al. (2002) reported average removal efficiencies for nutrients in catfish effluent in constructed wetlands of 86% to 98% for NH_4-N, >99% for NO_2^--N, and 82% to 99% for NO_3^--N under a 4-h HRT. Results from the current study indicate vegetated ditches fit with low-grade weirs act similarly to constructed wetlands in reducing nutrients from aquaculture effluent; however, reductions in the current study were achieved under a 2-h HRT and did not remove land from production. Furthermore, reductions reported by Lin et al. (2002) were through surface and subsurface flow, whereas all reductions in the current study were through surface flow.

Best management practices aim to increase environmental responsibility in aquaculture, while considering social and economic sustainability (Bosma and Verdegem 2011). A vegetated ditch fitted with consecutive low-grade weirs shows potential to meet these considerations. Vegetated ditches with low-grade weirs do not require removal of large amounts of land from production, which is a disadvantage of settling basins and constructed wetlands. During this study a vegetated ditch fit with low-grade weirs was a tool to reduce of nutrient concentrations and load entering receiving waters. Boyd et al. (2000) noted settling basins and constructed wetlands were the most promising effluent treatment procedures for catfish effluent; however, they failed to acknowledge the use of land to undergo treatment. Results of this study indicate vegetated ditches with low-grade weirs have the potential to be added as another promising effluent mitigation strategy. Along with overflow reduction strategies, which greatly reduce overflow volumes (Tucker et al. 1996, Boyd and Gross 2000, Boyd et al. 2008), use of vegetated ditches fit with low-grade weirs in aquaculture facilities can improve environmental sustainability.

Table 2.1 Control discharge nutrient discharge load reductions and load differences.

Control		
Nutrient	Load reduction ($mg/m^2/d$)	Load difference (%)
TIP	2,825	47
DIP	-194	154
NH_3-N	819	43
NO_2^--N	0	0
NO_3^--N	602	63

Control discharge (n=1) load reduction and load difference (%) for total inorganic phosphorus (TIP), dissolved inorganic phosphorus (DIP), ammonia (NH_3-N), nitrite-nitrogen (NO_2^--N), and nitrate-nitrogen (NO_3^--N). Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Load increase indicated by (-). The control discharge was run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system.

Table 2.2 Treatment discharge nutrient discharge ranges, mean load reductions, and mean load changes.

Treatment			
Nutrient	Range in load reduction ($mg/m^2/d$)	Mean load reduction ± SE	Mean load change ± SE (%)
TIP	4,587 – 84,228	32,240 ± 18,093	86 ± 4
DIP	365 – 1,468	725 ± 259	80 ± 6
NH_3-N	700 – 2,807	2,058 ± 487	89 ± 8
NO_2^--N	5 – 567	173 ± 133	94 ± 4
NO_3^--N	4,732 – 25,701	11,616 ± 4,764	89 ± 4

Treatment discharge (n=4) range, mean ± SE load reduction, and mean ± SE load change (%) for total inorganic phosphorus (TIP), dissolved inorganic phosphorus (DIP), ammonia (NH_3-N), nitrite-nitrogen (NO_2^--N), and nitrate-nitrogen (NO_3^--N). Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. The control discharge was run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system.

Table 2.3 Mean reduction efficiency of a vegetated ditch system fitted with three consecutive low-grade weirs.

	Reduction efficiency (% ± SE)				
Location	TIP	DIP	NH_3-N	NO_2^--N	NO_3^--N
Control					
Weir 1	8±13	-116±43	-43±19	0±0	-79±36
Weir 2	28±17	-227±79	5±12	0±0	-32±35
Weir 3	-23±31	-199±95	39±8	0±0	-4±23
Total	13±61	-543±218	0±39	0±0	-116±94
Treatment					
Weir 1	-42±14	-4±6	16±4	21±3	16±5
Weir 2	19±17	-26±15	26±7	14±6	-3±8
Weir 3	-1±5	-49±21	45±4	17±3	9±6
Total	-23±21	-79±42	87±15	53±12	22±20

Mean ± SE reduction efficiency (%) of a vegetated ditch system fitted with three consecutive low-grade weirs at individual weir (weir 1, weir 2, weir 3) and total for the ditch system. Reduction efficiencies for total inorganic phosphorus (TIP), dissolved inorganic phosphorus (DIP), ammonia (NH_3-N), nitrite-nitrogen (NO_2^--N), and nitrate-nitrogen (NO_3^--N) are presented. Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Control discharges were run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system.

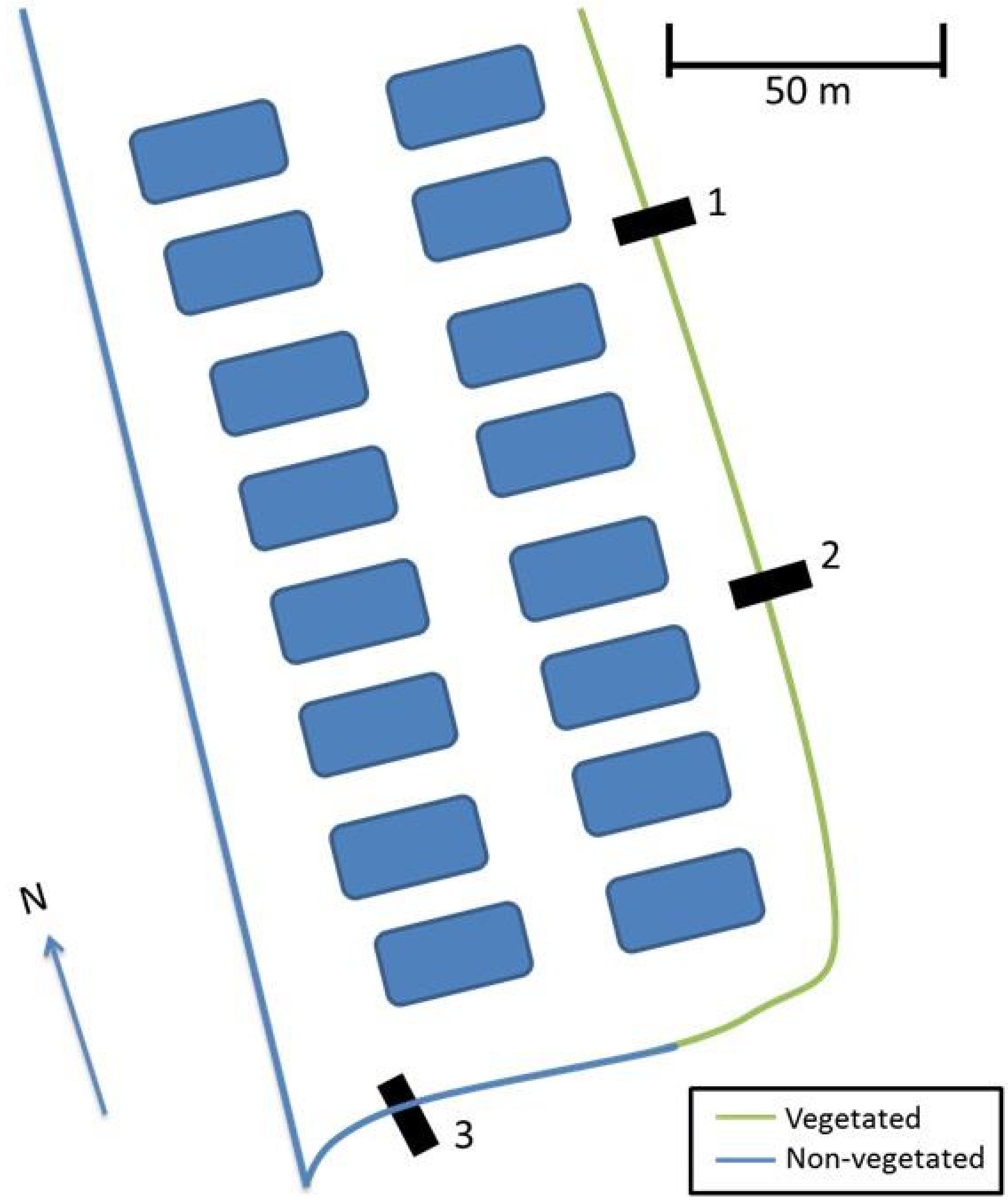


Figure 2.1 Experimental site – South Farm Aquaculture Facilities on the campus of Mississippi State University, Starkville, MS.

The 292 m treatment ditch is fit with 3 low-grade weirs in step fashion. Sample sites are referred to by weir number within the ditch.

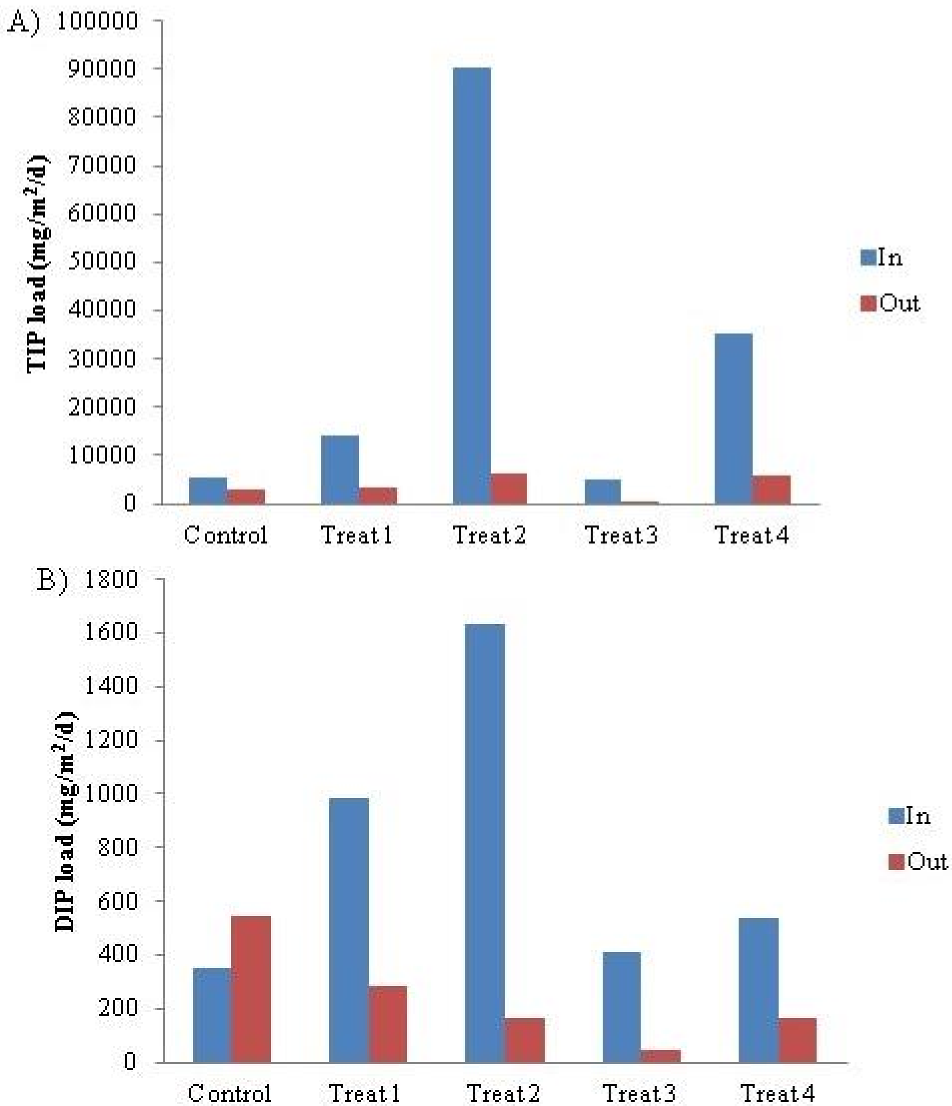


Figure 2.2 Aquaculture pond effluent phosphorus loads in and out of the vegetated ditch system.

Control discharge (n=1) and treatment (Treat) discharges (n=4) of A) total inorganic phosphorus (TIP) and B) dissolved inorganic phosphorus (DIP) aquaculture pond load (mg/m^2/day) in and out of a vegetated ditch system fit with three consecutive low-grade weirs. Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Control discharges were run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system.

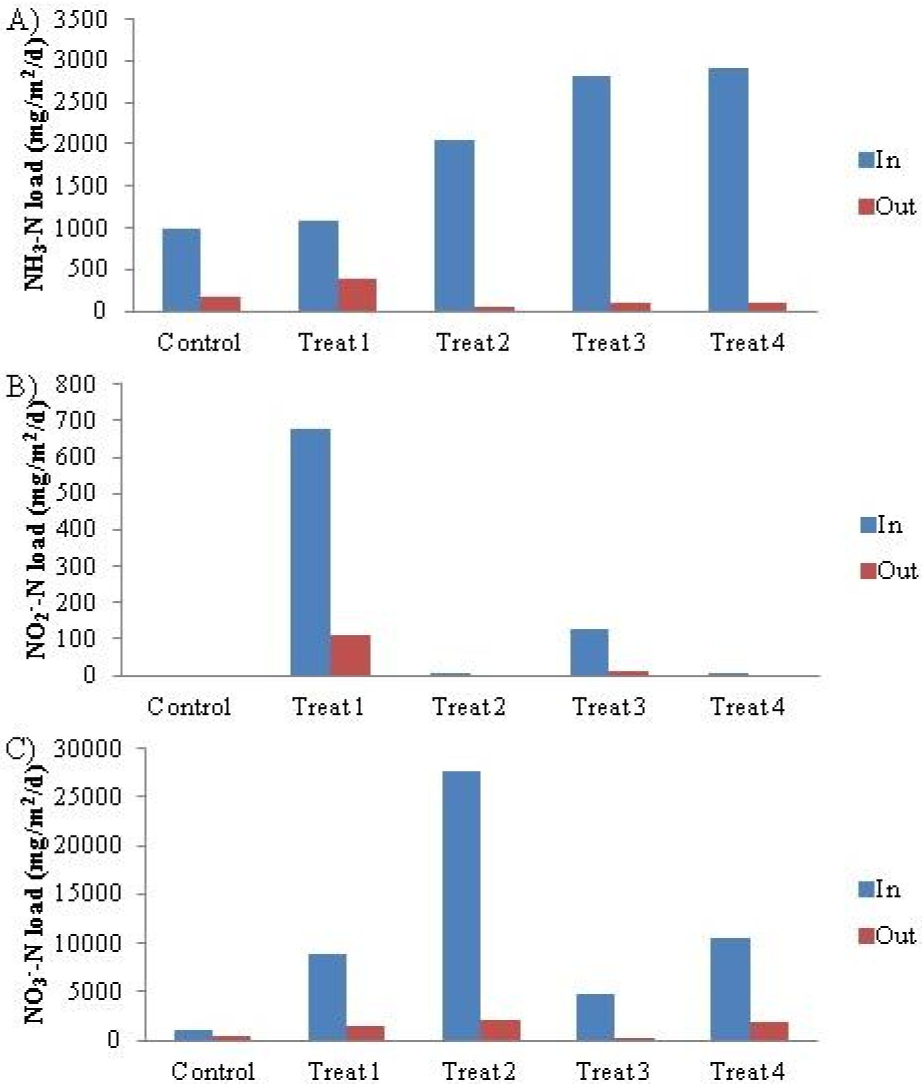


Figure 2.3 Aquaculture pond effluent nitrogen loads in and out of the vegetated ditch system.

Control discharge (n=1) and treatment (Treat) discharges (n=4) of A) ammonia (NH_3-N), B) nitrite-nitrogen (NO_2^--N), and C) nitrate-nitrogen (NO_3^--N) aquaculture pond load ($mg/m^2/day$) in and out of the vegetated ditch system fitted with three consecutive low-grade weirs. Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Control discharges were run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system.

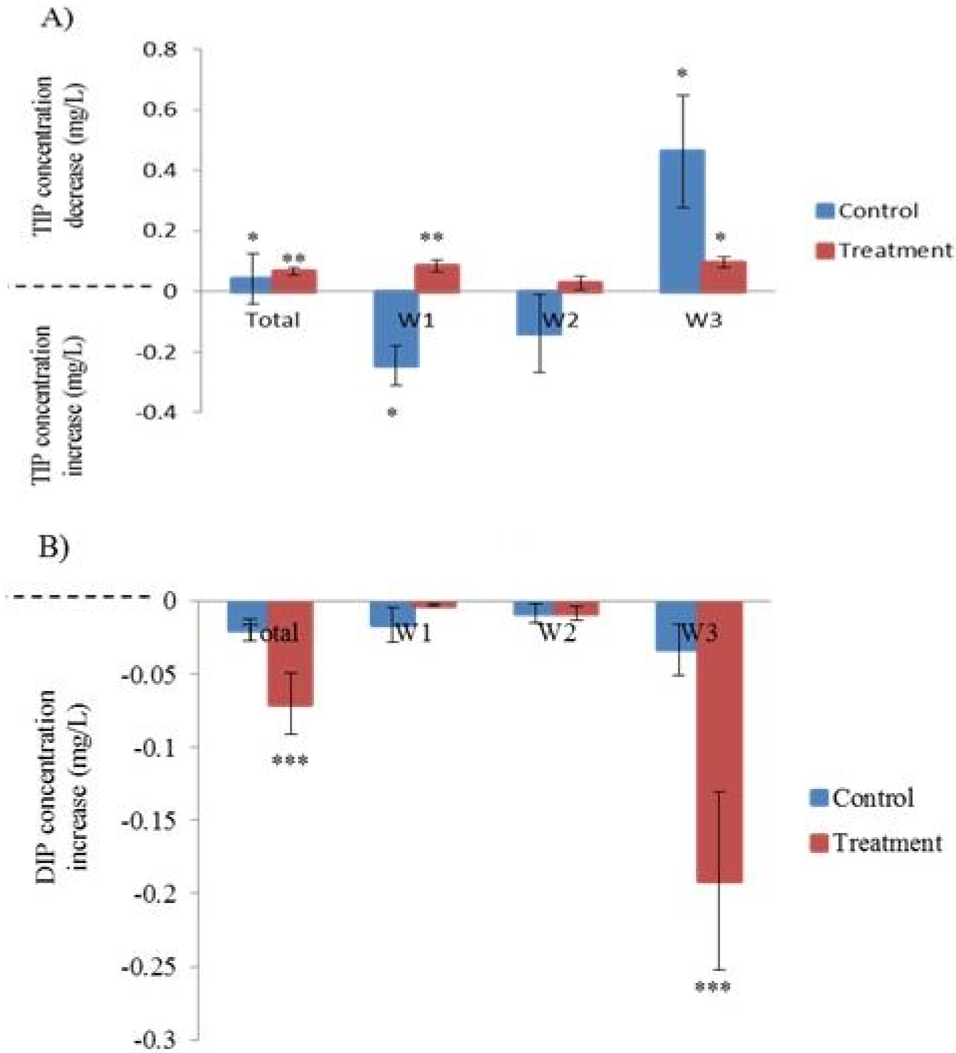
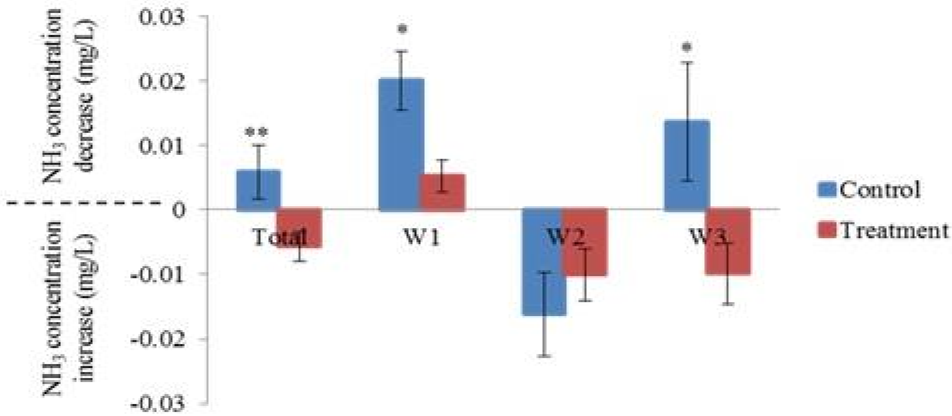


Figure 2.4 Mean phosphorus concentration reduction of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs.

Control and treatment mean concentration reduction (mg/L) of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs of A) total inorganic phosphorus (TIP) and B) dissolved inorganic phosphorus (DIP). Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Data was analyzed over the total ditch system (total) and at individual weir (weir 1-W1, weir 2- W2, and weir 3- W3) sampling sites. Control discharges were run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system. Error bars indicate standard error. Statistical significance is indicated by asterisks with *, **, and *** denoting p-values of less than 0.01, 0.001, and 0.0001, respectively.

A)



B)

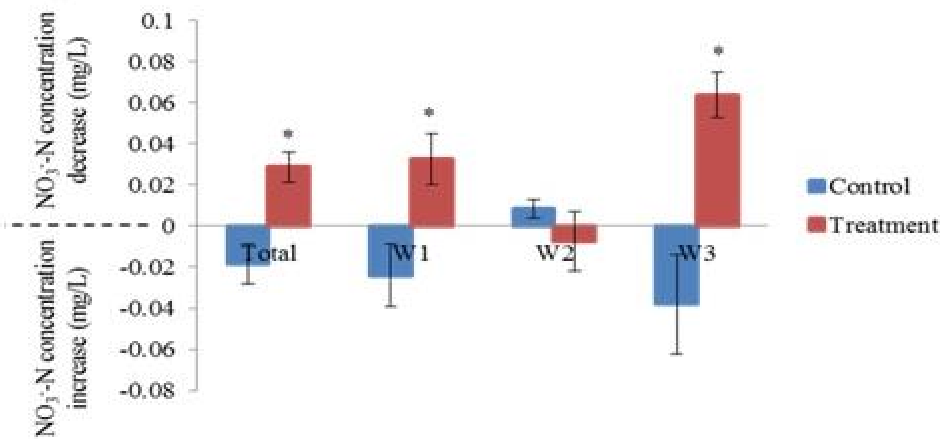


Figure 2.5 Mean nitrogen concentration reduction of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs.

Control and treatment mean concentration reduction (mg/L) of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs of A) ammonia (NH_3-N) and B) nitrate-nitrogen (NO_3^--N). Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Data was analyzed over the total ditch system (total) and at individual weir (weir 1-W1, weir 2- W2, and weir 3-W3) sampling sites. Control discharges were run through the vegetated ditch system with no boards in the weirs, to act as a conventional ditch system. Error bars indicate standard error. Statistical significance is indicated by asterisks with * and ** denoting p-values of less than 0.01 and 0.001.

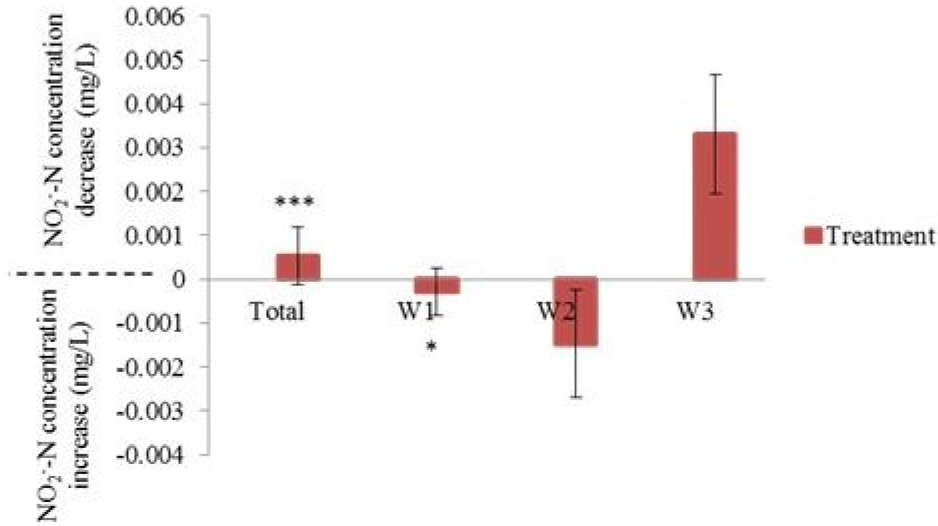


Figure 2.6 Mean nitrite concentration reduction of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs.

Treatment mean concentration reduction (mg/L) of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs of nitrite-nitrogen (NO_2^--N). Experiment was conducted in fall 2012 at Mississippi State University South Farm Aquaculture Facility. Data was analyzed over the total ditch system (total) and at individual weir (weir 1-W1, weir 2- W2, and weir 3- W3) sampling sites. Error bars indicate standard error. Statistical significance is indicated by asterisks with * and *** denoting p-values of less than 0.01 and 0.0001.

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CHAPTER III

ASSESSMENT OF LOW-GRADE WEIRS FOR SUSPENDED SEDIMENT MITIGATION IN AQUACULTURE DRAINAGE DITCHES

3.1 Introduction

Total suspended solids (TSS) are a priority pollutant regulated under the Clean Water Act as they have been shown to degrade downstream water quality and carry nutrients that adversely affect aquatic life (Ritchie 1972). The Mississippi River discharges an average of 172 million T/year of sediment into the northern Gulf of Mexico (Meade and Moody 2010). Aquaculture facilities have been targeted in the past for TSS reduction in pond effluent. Catfish aquaculture encompasses 16,000 ha in the Mississippi Alluvial Valley (MAV), and is dominated by embankment pond culture which discharges effluent during harvest and heavy rain events (USDA/NASS 2013). Current TSS removal best management practices (BMPs), such as settling basins and constructed wetlands, take land out of production and therefore are not economically sustainable. Environmentally and economically sustainable production practices emphasize a need for development of innovative BMPs. Using ubiquitous features on the aquaculture landscape, such as ditch systems to which effluent is already discharged, may serve in innovative BMP development.

Schwartz and Boyd (1994) reported for every ton of catfish produced, 530 kg of settleable solids were discharged. To prevent and reduce solids entering receiving waters, BMPs have been developed for aquaculture facilities. Some BMPs, when adopted, prevent erosion including: proper slope and compaction of embankments, vegetation above slope, thoughtful placement of aeration, properly maintained embankments, and discharge structures in ditches designed to prevent scouring (Boyd 2003). Other BMPs have been developed to reduce discharge volumes. Tucker at al. (1996) developed a model for managing water levels in ponds which has been shown to greatly reduce overflow volumes compared to ponds managed without storage levels (Boyd and Gross 2000, Boyd et al. 2008). Current post-discharge BMPs include settling basins and constructed wetlands. Boyd and Queiroz (2001) calculated that for every one ha of production pond, 1.53 ha of retention pond would be needed after a 25-year rainfall event in Alabama. Schwartz and Boyd (1995) determined that during pond drainage a minimum wetland area of 70 % of drained pond area is needed.

Wetlands have been used to purify water around the world since the 1950s (Verhoeven and Meuleman 1999). Vegetated ditches possess hydric soils, hydrophytes, and a fluctuating hydroperiod characteristic of wetland ecosystems (Kröger 2008), and have been shown to remove suspended solids (Moore et al. 2010, Kröger et al. 2012). Wetland vegetation increases friction and roughness in a channel, thus decreasing water velocity, increasing sedimentation, and decreasing suspended sediments from the overlying water column (Dieter 1990, Abt et al. 1994, Braskerud 2002, Schoonover et al. 2006). Vegetated ditches are a primary intercept between pond and receiving waters capable of suspended solid reduction from aquaculture effluent (Shireman and Cichra 1994, Tucker and Hargreaves 2003). Introduction of controlled drainage structures to the ditch system may further impede flow, increasing overall sedimentation.

Low-grade weirs are controlled drainage structures which increase hydraulic residence time (HRT), reduce flow and promote sedimentation (Kröger et al. 2008, Kröger et al. 2012). Individual weirs are installed spatially according to ditch slope and independent of one another's function which optimizes biogeochemical processes occurring behind each weir (Kröger 2008). Introduction of low-grade weirs may serve as an innovative alternative for suspended solids reduction in aquaculture pond effluent prior to entering receiving waters. The objective of this chapter was to assess effects of multiple low-grade weirs on rate of removal for suspended solids removal in aquaculture pond effluent. It was hypothesized that weirs installed in aquaculture-drainage ditches would increase removal rates of suspended solids. The null hypothesis tested was that consecutive low-grade weirs have no effect on suspended load removal rates of aquaculture effluent.

3.2 Materials & Methods

In September and October 2012, 11 experimental embankment ponds (0.05 ha) were intentionally discharged at the Mississippi State University South Farm Aquaculture Facility (Mississippi State, MS) into a 292-m vegetated ditch fitted with three pre-cast concrete low-grade weirs (Figure 3.1). Randomly assigned ponds were unstocked (n=2) or stocked with either freshwater prawns (*Macrobrachium rosenbergii*) (n=7) or channel catfish (*Ictalurus punctatus*) fry (n=2). Ditch channel width averaged 3 m and volunteer vegetation mainly consisted of cutgrass (*Leersia sp.*) and cattails (*Typha sp.*). Weirs were constructed with removable riser boards to manipulate flow. Weir height without riser boards in place was 0.17 m at weir 1, 0.15 m at weir 2, and 0.34 m at weir 3. With boards installed, weir height was 0.35 m at weir 1, 0.24 m at weir 2, and 0.55 m at weir 3. To allow the system to act as a conventional ditch, riser boards were removed from all weirs and two control discharges were conducted. Nine treatment discharges were conducted with riser boards installed, allowing assessment of weir function. Order of discharges was randomly assigned. Prior to discharge events, initial water samples were collected from the pond (n=2) and each ditch sample site (n=4). Distance from initial effluent to weir 1 was measured and initial ditch volume was calculated. Volumes of each reach of the ditch were calculated as ditch area above each weir by water depth at the corresponding weir, and summed for the in-ditch volume.

Ponds were drained using a hydraulic PTO tractor pump (custom fabrication, Starkville, MS) to simulate overflow. Nutrient load entering and leaving the system was calculated for one control discharge and four treatment discharges (concentration x flow rate). All loads were normalized by dividing load by the wetted ditch area. Change in depth of the pond was monitored using a rugged troll level logger (InSitu, Inc., Ft. Collins, CO) mounted at the deepest point of each pond. Rate of flow entering the system was calculated as change in pond depth over time. Rate of flow leaving the system was determined by taking a three-sample average of the time it took to fill a 21-L bucket behind the last weir at each hourly water sampling event throughout each drainage event.

3.2.1 Water Sampling and Analysis

Water samples were collected from pond initial effluent and below each weir at 30 min intervals until pumping ended. Water samples were then collected below each weir every 60 min until the discharge event was sampled for six hours. After the 6 h sample, water samples were taken above each weir at 12 h, 24 h, 30 h, and 42 h. Snap-seal 237-mL plastic containers (Corning, Corning, NY) were used for sample collection.

Samples were collected 0.1 m below the water surface and kept on ice until transported to the Mississippi State University Water Quality Lab for analysis.

In the lab, individual water samples were analyzed for TSS and volatile suspended solids (VSS) by filtering 100 - 200 mL of sample through a pre-ashed, pre-weighed 0.45 µm glass fiber filter (APHA 1998). Filters were dried at 105 °C for 24 h and then weighed to the nearest mg using a SA210 scale (Scientech Inc., Boulder, CO). Total suspended solids were calculated as change in mass between dried samples and initial filter weight. Once weighed for TSS, filters were ignited in a muffle furnace at 550 °C for 20 min intervals to constant mass. Volatile suspended solids were calculated as change in mass between ignited filter and TSS weight prior to ignition. Total suspended solids and VSS concentrations were used to calculate concentration reduction and removal rates for the ditch system. Individual parcels of water were followed through the system using HRT to monitor reduction and calculate reduction rates throughout the system.

3.2.2 Statistical Analysis

Serial autocorrelation was used to verify independence in events. Homogeneity of variance was verified using Levene's test for equality of variance. Normality and goodness of fit in the data sets was determined with a Shapiro-Wilk W test. For each discharge, differences in suspended solid concentrations between pond and initial effluent as well as differences in suspended solid concentrations between initial and 48-hr ditch samples were analyzed with a student *t*-test. Percentage load leaving the system was calculated for all events where pond volume was available (n=5). Differences in suspended sediment reduction and removal rates were compared using a repeated measure mixed model analysis of variance (ANOVA) for a split-plot design with discharge as the whole plot, weir as the subplot, and time as replication. All effects except interaction of discharge x time were considered to be fixed. In treatments where significant suspended sediment reduction or removal rate was observed for weir class, a post-hoc Tukey-Kramer test and a least square means pairwise comparison was conducted by weir. Furthermore, suspended sediment reduction or removal rate were analyzed by expanding the repeated measure mixed model ANOVA for split-plot design to include fixed effects of distance, number of discharges, initial effluent concentration, and flow rate. If a significant effect was observed, a post-hoc Tukey-Kramer test was performed and a least square means a pairwise comparison of the interaction between weir and significant factor was performed to determine significance among individual treatments. An alpha level of 0.05 was used for all statistical analyses. Statistical analysis was performed using Version 9.3 of the SAS system for Windows (SAS 2009).

3.3 Results

Initial effluent suspended solid concentrations were similar to pond water and the vegetated ditch system returned to baseline values within 48 hr of each event ($P > 0.55$ for all sites). Suspended solid loads decreased across the system in all drainage events for TSS and VSS (Figure 3.2). In control discharge, TSS load was reduced 94%, releasing 5 $mg/m^2/day$, and VSS load was reduced 92%, releasing 1 $mg/m^2/day$. Treatment discharges similarly reduced TSS and VSS loads across the system. Total suspended solids load reduced 80% - 94%, releasing on average 9 $mg/m^2/day$, and VSS loads reduced 72% - 91%, releasing on average 2 $mg/m^2/day$.

Total suspended solid removal rates for the system as a whole were 0.02 ± 0.01 mg/L/min in control and treatment discharges (Figure 3.3). Overall removal rate was significant for control discharges ($F = 6.12$, $P < 0.001$) and treatment discharges ($F = 16.02$, $P < 0.001$). Control discharge removal rate was -0.04 ± 0.02 mg/L/min at weir 1, increasing TSS in the first reach of the system. However, this rate of increase was not significant ($t = -0.84$, $P = 0.40$). Through the remainder of the ditch system, control discharge TSS removal rates were significant ($t = 2.19$, $P = 0.04$ weir 2; $t = 3.69$, $P < 0.001$ weir 3), reducing TSS across the subsequent reaches. Conversely, treatment discharge removal rates reduced significantly TSS at weir 1 at a rate of 0.05 ± 0.01 mg/L/min ($t = 4.81$, $P< 0.001$); although, treatment discharge removal rates were not significant for the rest of ditch system ($t = -1.31$, $P = 0.19$ weir 2; $t = -0.56$, $P = 0.57$ weir 3). Of the fixed effects analyzed, total suspended solid removal rate was reduced significantly due to flow rate ($F = 3.85$, $P < 0.001$). Flow rates ranged from 146 L/min - 5,946 L/min. The five greatest flow rates in treatment discharges had significantly lesser rates of TSS reduction (median: -2.98 mg/L) than treatment discharges with slower flow rates (median: 2.66 mg/L).

Volatile suspended solids comprised 2% - 80% of the TSS in effluent. Overall, VSS removal rate was 0.002 ± 0.001 mg/L/min for control and treatment discharges (Figure 3.3). Removal rates were significant for control discharges ($F = 10.46$, $P < 0.001$) and treatment discharges ($F = 6.28$, $P < 0.001$). Control discharges removal rate at weir 1 was -0.008 ± 0.002 mg/L/min, increasing VSS significantly ($t = 6.76$, $P < 0.001$). Conversely, treatment discharges removal rate at weir 1 was 0.006 ± 0.002 mg/L/min, decreasing VSS significantly ($t = 2.94$, $P < 0.001$). Treatment discharges removal rates were not significant for the remainder of the ditch system (*t* = -0.94, P = 0.35 weir 2; *t* = -0.21, P = 0.84 weir 3). However, control discharges removal rate at weir 3 of 0.008 ± 0.001 mg/L/min VSS was significant (*t* = 4.28, P < 0.001). Of the fixed effects analyzed, volatile suspended solid reduction rate was affected significantly by initial concentrations in discharge events (F = 4.11, P < 0.001); however, no trend was detected.

3.4 Discussion

The current study accepted the null hypothesis, as there were no significant differences between the weired and conventional ditch systems. Findings contrasted those of Frimpong et al. (2004) and were similar to TSS reductions reported by Shireman and Cichra (1994) and Hargreaves et al. (2005), the only known studies investigating potential of vegetated drainage ditches for effluent suspended solid mitigation within the aquaculture landscape. Frimpong et al. (2004) reported no significant changes in TSS or VSS across the system even though ditches were of adequate length for substantial solids reduction as noted by Hargreaves et al. (2005). In the current study a 292-m vegetated ditch system reduced TSS 79% in controlled discharges. Shireman and Cichra (1994) found a 92% reduction in TSS concentrations after flowing through a 93-m vegetated ditch; whereas, Hargreaves et al. (2005) found a 93% reduction in TSS concentrations after passing through a 221-m vegetated ditch. Furthermore, in the current study, treatment discharges through the system reduced TSS load by 71%. Due to a lack in control replication, load differences between control and treatment discharges could not be compared directly. Total suspended solids load reductions were similar to reductions reported for constructed wetlands and settling basins where suspended solids retention varied from 67% - 91% (Schwartz and Boyd 1995, Boyd et al. 1998, Schulz et al. 2004).

Reductions of suspended solids in the current study are similar to previous studies and current BMPs for sediment removal. However, the current study achieved similar reductions under a 2-hr HRT which is markedly less than the 4-hr to 1-d HRT current BMPs require for equivalent reduction. Wong and Piedrahita (2000) calculated sedimentation basins needed to be designed with overflow rates below 0.5 cm/s to capture 80% of settleable solids. These settleable solids may also be a reason in which the current study has similar reductions for control and treatment discharges as well as similar reductions to previous studies. With consideration for HRT and settleable solids, any ditch system under a certain HRT would have comparable reduction. In systems where the HRT was low, the installation of low-grade weirs would modify the HRT to achieve these reduction levels.

The current study found a marked increase in HRT and ditch capacity at initial ditch volume when weirs' riser boards were in place. Low-grade weirs increasing HRT and ditch capacity is consistent with findings reported by Kröger et al. (2008). With an increase in HRT, it is expected there would be an increase in sedimentation across the system. However, overall removal rates were equivalent in control and treatment discharges; yet, there were significant differences in removal rates at individual weirs between control and treatment discharges. These individual weir differences are most likely due to suspended solids initially increasing during control discharges, which is consistent with findings of Hargreaves et al. (2005). It is likely the ditch sediments being resuspended during control discharges consisted of greater density solids which settled out during previous discharge events. These greater density solids which added to the TSS load prior to weir 1 likely settled out of the water column before reaching receiving waters, thus allowing control discharges to have significant concentration reduction rates at subsequent weirs whereas treatment discharges did not have significant reduction rates past weir 1. Treatment discharge did not add to initial concentrations as reduction rates were significant at weir 1, reducing TSS where control discharges increase TSS.

Because phytoplankton and phytoplankton-derived detritus constitute most catfish pond solids (Tucker and Hargreaves 2003) and phytoplankton is a portion of the VSS portion of TSS, the VSS removal rate may have an overall greater effect on solids removal. This is especially relevant because VSS has a lesser density than TSS, making VSS less likely to settle out of the system (Samocha et al. 2004). Control and treatment solid removal rates were consistent with removal rates of constructed wetlands and settling basins (Boyd et al. 1998, Lin et al. 2002, Lin et al. 2005). Greater initial TSS and VSS concentrations in effluent should constitute greater concentration reductions before effluent reaches receiving waters. Removal rates and concentration reductions are keys to an effective BMP for suspended solids because effluent regulations often place limits on potential pollutant concentrations discharged rather than load (Tucker and Hargreaves 2003).

The goal of aquaculture BMPs are to make production environmentally responsible, while also considering economic sustainability (Bosma and Verdegem 2011). Sustainability is the ability of a system to function into the indefinite future without being forced into decline (Frankic and Hershner 2003). Therefore, BMPs should be related back to farm economic performance (Boyd 2003). Using of wetlands and settling basins is often not economically feasible for many farmers (Kouka and Engle 1996, Boyd 2003). Catfish farmers have a high level of fixed costs which requires them to maximize yields and spread costs over greater production levels (Engle 2003). Along with overflow reduction strategies and erosion prevention, use of vegetated ditches with low-grade weirs as part of the suspended sediment management plan of aquaculture landscape can improve environmental sustainability while minimizing cost of treating effluent. Further research needs to be conducted on impacts consecutive low-grade weirs may have in aquaculture ditch systems, especially in truncated systems where initial effluent is closer to outflow.

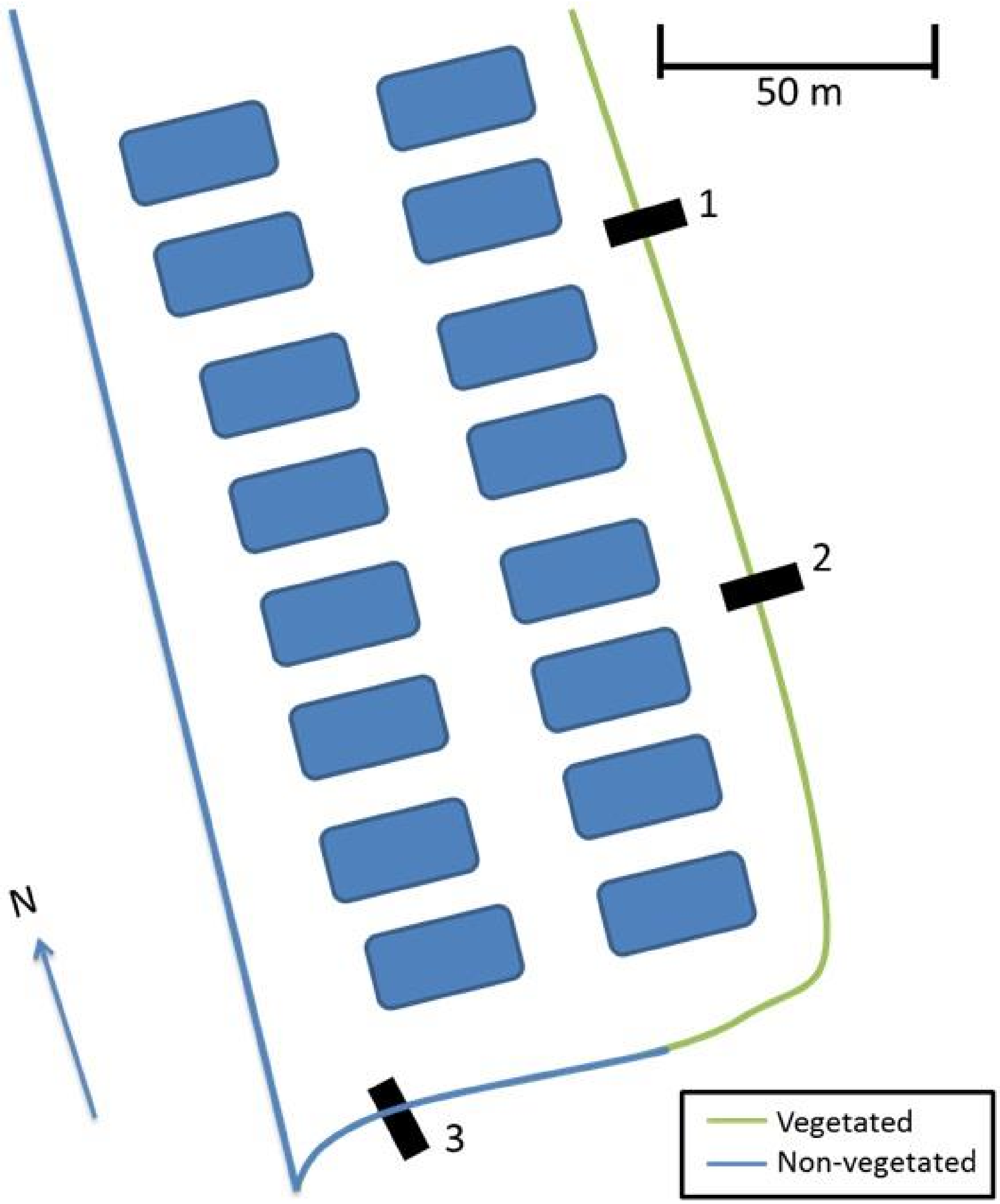

Figure 3.1 Experimental site – South Farm Aquaculture Facilities on the campus of Mississippi State University, Starkville, MS.

The 292 m experimental ditch is fit with 3 low-grade weirs in step fashion. The ditch was sampled September – October 2012 with initial effluent being pumped by PTO tractor pump from 11 adjacent ponds. Sample sites are referred to by weir number within the ditch.

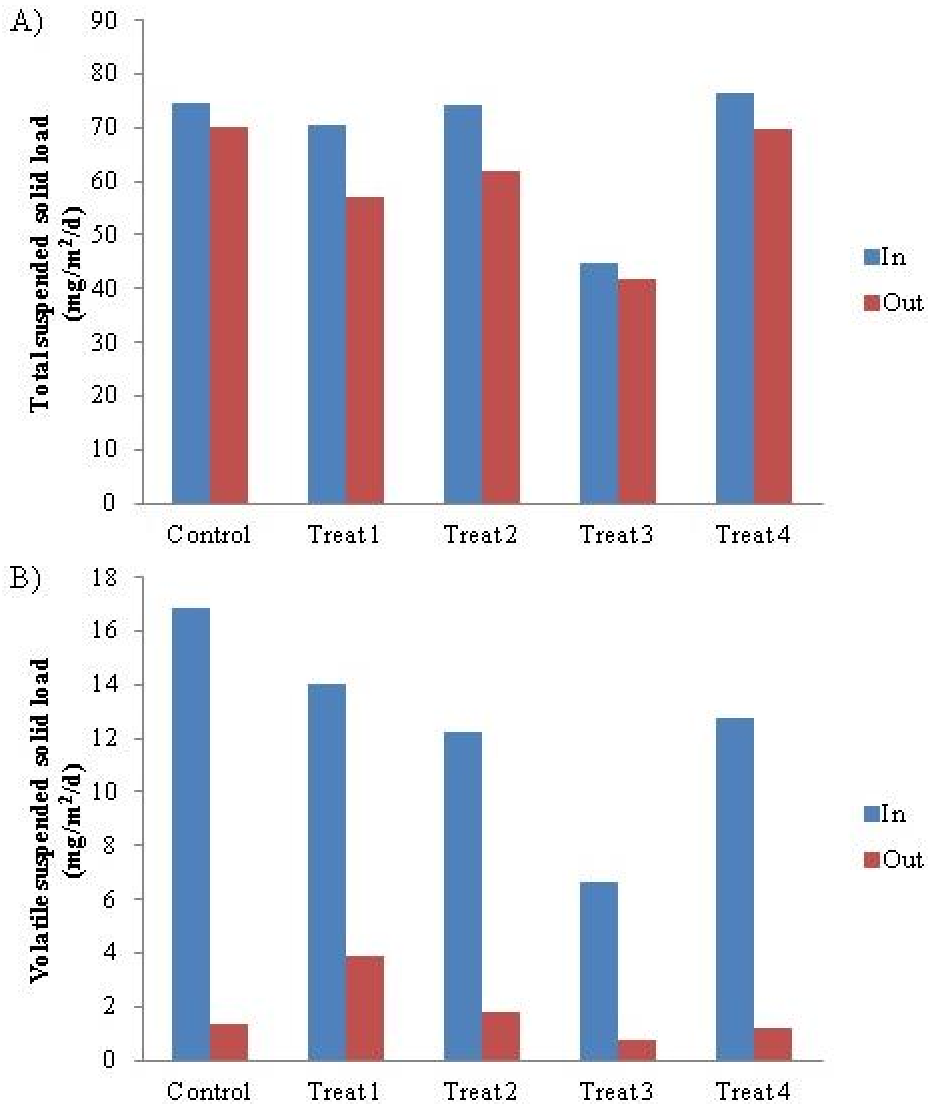

Figure 3.2 Aquaculture pond effluent suspended solids load in and effluent load out of a vegetated ditch system fit with three consecutive low-grade weirs.

Control discharge (n=1) and treatment discharges (n=4) of A) total suspended solids and B) volatile suspended solids aquaculture pond effluent load ($mg/m^2/day$) in and effluent load out of a vegetated ditch system fit with three consecutive low-grade weirs. Control discharges were run through the system with no boards in the weirs to act as a conventional ditch system. The experiment was conducted September – October, 2012 at the South Farm Aquaculture Facilities on the campus of Mississippi State University, Starkville, MS.

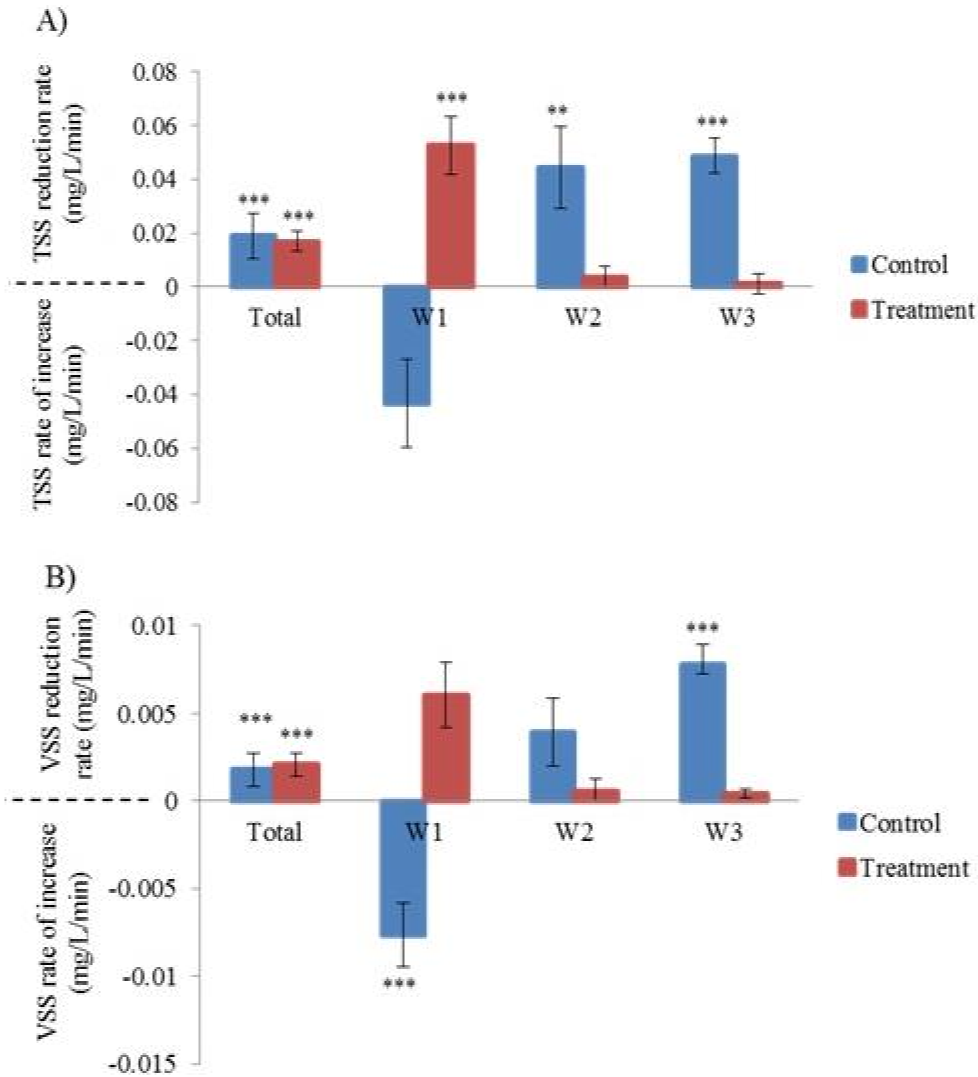

Figure 3.3 Mean suspended solids reduction rates of aquaculture pond effluent in a vegetated ditch system fit with three consecutive low-grade weirs.

Control (n=2) and treatment (n=9) mean removal rate of A) total suspended solids (TSS) and B) volatile suspended solids (VSS) from aquaculture pond effluent discharged into a vegetated ditch system fit with three consecutive low-grade weirs. Mean concentrations were analyzed across the system (Total) and at individual weirs (weir 1: W1, weir 2: W2, and weir 3: W3). Control discharges were run through the system with no boards in the weirs to act as a conventional ditch system. The experiment was conducted September – October, 2012 at the South Farm Aquaculture Facilities on the campus of Mississippi State University, Starkville, MS. Error bars indicate standard error. Statistical significance is indicated by asterisks with ** and *** denoting p-values of less than 0.001 and 0.0001, respectively.

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CHAPTER IV

SYNTHESIS

Sustainability is the ability of an ecosystem, society, or any such system to continue functioning into the indefinite future without being forced into decline through exhaustion or overloading of key resources on which the system depends (Frankic and Hershner 2003). Thus sustainability in respect to embankment pond aquaculture should be assessed across criteria for social, economic, and environmental sustainability. Economic implications need to be at the forefront of aquaculture sustainability because a large amount of freshwater embankment pond production takes place in rural communities where some producers can be characterized as "resource poor" (Bosma and Verdegem 2011). Introduction of sustainable production system certifications gives incentive to farmers to introduce new best management practices (BMPs) to their production facilities, increasing possible markets and revenue (Bosma and Verdegem 2011, Boyd 2003). Several organizations are developing standards for ecolabeled products as large-scale seafood buyers are seeking products produced responsibly to satisfy increasing consumer environmental consciousness (Seafood Choices Alliance 2003, Boyd and Banzhaf 2007, Bosma and Verdegem 2011). Production certifications programs set standards for environmental, social, and food safety by requiring BMP adoptions (Boyd et al. 2007). As part of these standards, facilities will need to adopt effluent treatment BMPs. Vegetated ditches fit with low-grade weirs would satisfy this need for an alternative, innovative, and sustainable effluent treatment BMP for farmers.

Effluent treatment BMPs are designed to prevent negative impacts on receiving waters and achieve aquaculture effluent standards. Nutrient regulations typically specify concentration limits; however, standards sometimes place restrictions on volume and specify maximum daily loads (Boyd 2003). Load takes into consideration nutrient or suspended sediments concentrations and volume of water being discharged from a facility. Tucker and Hargreaves (2003) noted effluent concentration effects tend to be localized, whereas load effects tend to affect a larger temporal and spatial scale. With that in mind, it may be more sound to regulate aquaculture facilities based on load and results from this current study agree with this assessment. During treatment discharge events of the current study, concentrations of some nutrients did increase across the system, yet loads of these nutrients decreased in all treatment events before reaching receiving waters. This illustrates how concentration and load regulations would have different impacts on effluent quality standards in the aquaculture industry. However, nutrient and suspended solids concentrations must still be monitored as a significant relationship was noted in the current study between initial concentrations and reductions across the system.

The current study is the lone study of its type, using low-grade weirs to alter hydrology of an aquaculture ditch system to treat effluent. Nutrient reductions in this study were comparable to reductions in current effluent treatment BMPs (Schwartz and Boyd 1995, Boyd and Queiroz 2001, Lin et al. 2002, Schulz et al. 2004, Lefrançois et al. 2010); yet, vegetated ditches are ubiquitous systems on the aquaculture landscape, requiring no land to be removed from production and therefore not increasing production costs. Additionally, suspended sediment reductions in the current study were equivalent to previous studies of aquaculture ditch systems (Shireman and Cichra 1994, Hargreaves et al. 2005). However, all of these ditches were of adequate length for substantial suspended solids removal. Use of low-grade weirs could still be an innovative BMP for suspended sediment mediation in aquaculture facilities with truncated ditch systems. To fully understand the relationships of effluent nutrient and suspended solid dynamics and effects of altering system hydrology, further research of aquaculture ditches fitted with low-grade weirs should be conducted.

The current study indicated concentrations and flow rates have significant effects on nutrient and suspended solids reductions. To further evaluate effects of initial concentrations, ponds with varying initial nutrient concentrations should be selected prior to experimentation and discharged into a low-grade weir ditch system. Total suspended solid reduction in the current study related directly to discharge flow rate; yet, a maximum flow rate for reduction could not be established during the current study due to a gap in flow rates. The full scope of distance effecting sedimentation is also unknown. Tucker and Hargreaves (2003) found a ditch of an average width of 1-m and 95 to 126-m length is sufficient for suspended solids removal; however, this system did not include weirs. It is logical to assume installation of low-grade weirs into the system would decrease the necessary ditch length for sufficient removal. With further analysis of low-grade weir systems in the aquaculture landscape and establishment of concentration effects, maximum flow rate, and minimum ditch distance for nutrient and suspended solids reduction, individual facilities can tailor their drainage ditch systems to suit their needs. Installation of low-grade weirs to maintain flow rates and maximize nutrient and suspended solids reduction could be calculated for individual landscapes. Additionally, intentional discharge events could then be monitored to regulate discharge below the maximum flow rate for an additional level of farm management.

Furthermore, research needs to be expanded to multiple drainage ditches and multiple aquaculture facilities. Multiple ditches would allow for a cross comparison of systems as ditch sediment and initial in-ditch water quality parameters may affect reduction across and among systems. The current research is limited to one ditch system being compared over multiple drainage events. Even though individual discharges can be compared within the system (because initial levels of all analytes were taken prior to each event and discharge events were independent), only one system was evaluated. Differences in sediment, microbial communities, and vegetation among ditches are only a few possible parameters that may affect nutrient and suspended solids reduction in individual systems, and require more investigation. Additionally, differences among in-pond BMPs across facilities may impact effectiveness of low-grade weir systems. Broadening this study to a farm level would also allow for a more in-depth analysis on the sustainability of low-grade weirs as a BMP for aquaculture facilities.

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