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A preliminary study of an alternative controlled drainage strategy in surface drainage ditches: Low-grade weirs

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ABSTRACT

This study examined hydrological characteristics of low-grade weirs, an alternative controlled drainage strategy in surface drainage ditches. Chemographs of vegetated and clear scraped (control) replicates of weir vs. non-weir treatments were compared to determine differences in time to peak (T_p) and time to base (T_b). Drainage ditches T_p and T_b were affected by both vegetation and weir presence. The order of treatment efficiency for T_p was observed to be: non-vegetated non-weir < vegetated non-weir < non-vegetated weir < vegetated weir. Furthermore, T_b for each ditch was the reverse relationship from T_p where vegetated weir > non-vegetated weir > vegetated non-weir > non-vegetated non-weir. Low-grade weirs increase chemical retention time (vegetated and clear scraped), the average time a molecule of contaminant remains in the system. Future research in water quality improvement and weir management will yield useful information for non-point source pollutant reduction.

1. Introduction

Agricultural land use requires artificial drainage for sustainability and profitable crop production. However, drainage contributes to the conveyance of non-point source pollutants such as nutrients, pesticides and sediments into surface receiving waters (Nguyen and Sukias, 2002, Zhang et al., 2004). In the Mississippi River Basin, this has profound implications downstream on aquatic ecosystem health and hypoxic zones in the Gulf of Mexico (Rabalais et al., 1996, Turner and Rabalais, 2003). Controlled drainage has been proposed as a best management practice (BMPs) primarily aimed at reducing nutrient (nitrogen and phosphorus) concentrations and loads in drainage ditches reaching receiving waters by reducing total drainage outflows (Borin et al., 2001; Evans et al., 1992; Evans et al., 1995; Gilliam and Skaggs, 1986; Gilliam et al., 1979).

Controlled drainage practices are a global phenomenon found in northeast Italy (Borin et al., 2001), southern Sweden (Wesstrom and Messing, 2007; Wesstrom et al., 2001) and North Carolina, USA (Evans et al., 1992; Evans et al., 1995). Advantages of controlled drainage include reduced outflow and outflow velocity, increased denitrification, stormwater mitigation and sedimentation, and decreased water table depths. In North Carolina, several studies have shown decreases in annual nitrogen (N), phosphorus (P) and drain outflow volumes as a result of controlled drainage (Evans et al., 1992; Evans et al., 1995). Wesstrom and Messing (2007) reported 79 and 94% reductions in drain outflows for successive years following controlled drainage implementation. These outflows corresponded to significantly reduced N, nitrate (NO_3–N) and P losses. Similarly Lalonde et al. (1996) showed drain flow and NO_3–N reductions for variable riser heights of 58–63% and 69–76%, respectively. However, as a result of decreased water table

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depths, surface runoff and the likelihood of surface N and P loss increases. Drury et al. (1996) reported consistently higher water table levels for controlled drainage as compared to tile drainage for three growing seasons from 1991 to1994. Controlled drainage also significantly decreased NO_3–N concentrations, and significantly increased surface runoff and P loss.

A commonly used practice for controlled drainage involves the use of a variable height riser in the drain or ditch outlet (Lalonde et al., 1996; Madramootoo et al., 1993; Skaggs and Gilliam, 1981). This concept relies on the ability to control drainage intensity by determining the height of the riser and thus control volume of outflow and load of solutes (Wesstrom et al., 2001). The variable height of the riser can also be used to increase groundwater levels during times of water stress and drought. For the most part, riser controlled drainage occurs seasonally when fields are fallow. Taking into consideration that certain surface drainage ditches are hundreds of meters long with variable slopes, would a temporally continuous stepwise increase of water levels improve retention and controlled drainage? An alternate controlled drainage strategy would be the use of low-grade weirs, installed in a stratified spatial arrangement within the drainage ditch. This spatial arrangement would be advantageous as it would be continuously implemented year round, while small enough to avoid large storm events flooding fields and senescing crops.

Effectiveness of controlled drainage practices is greatly influenced by their design and management. Before understanding the water quality implications of low-grade weirs, hydrological data needs to be presented to illustrate the potential of increasing water residence times within surface drainage ditches. As with subirrigation in subsurface drains, low-grade weirs aim to decrease water table depths at various spatial locations within the field and thus improve overall water and nutrient uptake for crops. The current study examined low-grade weirs as alternative water control structures in drainage ditches. The primary aim of this research was to obtain preliminary hydrological data on effectiveness of low-grade weirs in altering hydrology in vegetated and non-vegetated (control) ditch circumstances.

2. Materials and methods

2.1. *Experimental setup*

Chemical retention time experiments (CRT) were conducted at the University of Mississippi Field Station (UMFS) in June 2007.

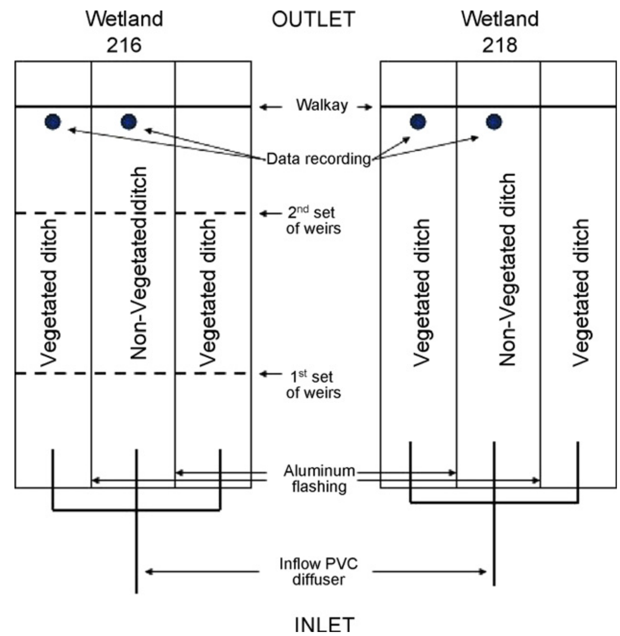


Fig. 1 – An overhead layout view illustrating the locations of experimental wetland 216 and 218, weirs, vegetated vs. non-vegetated ditches and data recording. PVC diffusers delivered a constant inflow rate for the duration of the experiment. Aluminum flashing separated individual ditches within each experimental wetland.

Experimental wetlands were specifically constructed by the US Army Corps of Engineers in conjunction with the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) to aid in constructed wetland and drainage ditch research. Two experimental wetlands (216 and 218) were utilized for the CRT experiment and divided into three artificial drainage ditches respectively ($n = 6$) (Fig. 1). Within each wetland there were two vegetated ditches and a non-vegetated control ditch. Vegetation density within each vegetated ditch was around 1200 stems/m^2, comprising for the majority (>95%) obligate emergent wetland vegetation. Dominant species within each vegetated ditch were *Leersia oryzoides* (L.)Sw., *Juncus effusus* L., and *Polygonum hydropiperoides* Michx. Drainage ditches were separated and isolated by 0.5 mm thick aluminum flashing anchored to the sediment every 2.5 m with short fence posts. Bentonite clay sealant was applied to the base of either side of the flashing to isolate and avoid any water mixing between adjacent ditches. Similar

Table 1 – Physical characteristics of ditches in wetlands 216 and 218

Ditch characteristics	Weir (216) (mean ± S.E)		Non-weir (218) (mean ± S.E)	
	Vegetated	Non-vegetated	Vegetated	Non-vegetated
Ditch width (m)	4.42 ± .04	3.37 ± .04	4.56 ± .07	3.57 ± .06
Ditch length (m)	33.5	33.5	32.2	32.2
Ditch slope	0.0076	0.0084	0.0085	0.0083
Weir height (cm)	20.7 ± 3	29.15 ± 0.95	n/a	n/a
Inflow rate (L/min)	50.69	51.15	50.69	51.15
Mean weir volume (L)	10410 ± 1930	9548 ± 978	n/a	n/a
Total ditch water volume (L)	20820	19096	8966	8769

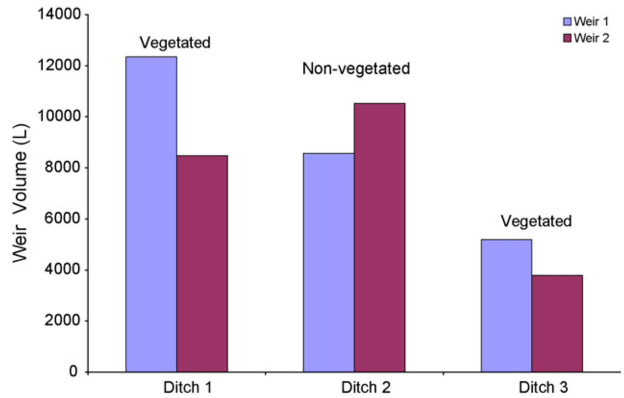


Fig. 2 – Constructed weir water volumes between the three artificial ditches within pond 216. Vegetation characteristics were similar between ditches, with the non-vegetated devoid of vegetation.

drainage ditch widths, lengths and slopes provide similar hydrological patterns for each ditch (Table 1).

2.2. *Low-grade weir construction*

Low-grade weirs were constructed within the drainage ditches of wetland 216 (Fig. 1). Two weirs were equally spaced longitudinally within each drainage ditch. Each low-grade weir was built using 3 m × 0.05 m × 0.10 m pieces of treated pine lumber. In the center of each weir, a 120° V-notch outlet was cut. Weirs were installed and sealed by inserting the lumber into the bottom sediment and surrounding with sandbags and bentonite. Weir heights were variable between ditches (Table 1). In determining weir volumes (Fig. 2), the second replicated vegetated ditch in 216 had a markedly different volume than either control or other vegetated ditch. Thus, one vegetated replicate from wetland 216 and 218 (Fig. 1) was not used in data recordings for CRT.

2.3. *Chemical retention time determination*

Chemical retention time was defined as the average length of time a compound remained in a system. A salt tracer ($NaCl^-$) was used to simulate a non-point source compound in storm runoff and determine CRT. Five CRT experiments were conducted over a weeklong period. Water flow occurred continuously at a constant rate throughout the experiments (Table 1). Each morning a pulse of $NaCl^-$ was applied to each system. Salt used in experiments was Diamond Crystal™ Water softener (22.7 kg; 99.8% $NaCl^-$). Mixing chambers for each weir experiment comprised 11.4 kg of salt mixed with 95 L of water. High salt concentrations were needed to allow for dilution from inflow and weir water volumes. For the non-weir experiments, significantly less water volumes within each ditch resulted in significantly smaller slug concentrations (2.3 kg of salt in 102 L). Volume calculations and initial conductivity measurements allowed for normalization of data between systems in order to draw comparisons. YSI™ meters in the respective ditches measured water column specific conductivity every five minutes for the study duration. These data were used to determine a time to peak (T_p) and time to base (T_b). T_p was the time it took the peak conductance to move through the ditch system. T_b was the time taken to return the system to pre-amendment levels. Specific conductivity was defined as the ability of a water solution to conduct an electrical current corrected by temperature. YSI™ data was downloaded with EcoWatch, Version 3.15. Statistical differences in CRT between each vegetated and control weir ditches in 216 and 218 were determined using paired Student *t*-tests. Differences between weir and non-weir CRT characteristics were determined using unequal variance Student *t*-tests ($\alpha = 0.05$).

3. Results and discussion

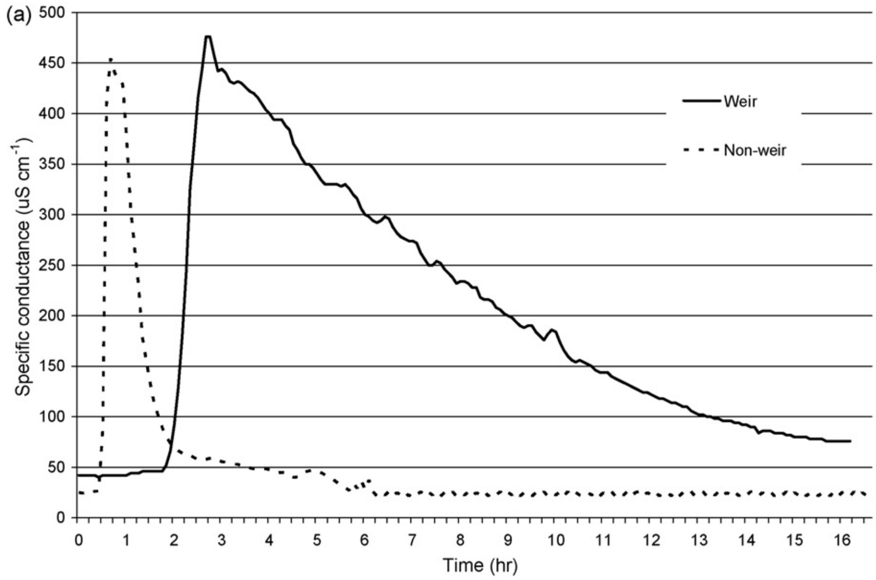
3.1. *Ditch characteristics*

Comparisons of vegetated and control ditches in wetlands 216 and 218 show similar physical characteristics (Table 1). These characteristics were similar to primary intercept drainage ditches in the field (Kröger et al., 2007), and classified primary/secondary ditches where riparian habitat consists of either bare soil and grass, and the hydroperiod has water but very little flow according to Milam et al. (2001). The order of measured slopes was: vegetated weir (216) < non-vegetated

Table 2 – Chemical retention time characteristics of drainage ditches with low-grade weirs as compared to no-weirs

CRT characteristics	Weir (216)		Non-weir (218)	
	Vegetated ($n = 5$) ($X \pm$ S.E.)	Non-vegetated ($n = 5$) ($X \pm$ S.E.)	Vegetated ($n = 2$) ($X \pm$ S.E.)	Non-vegetated ($n = 5$) ($X \pm$ S.E.)
Minimum T_p (min)	220	165	165	30
Maximum T_p (min)	390	370	330	90
Average T_p (min)	306 ± 28.08	262 ± 33	n/a[a]	60.8 ± 9.3
Minimum T_b (min)	805	750	425	165
Maximum T_b (min)	1035	1005	660	340
Average T_b (min)	890 ± 72.9	837 ± 39.3	n/a[a]	271 ± 28
Maximum conductance (μS/cm)	354	476	238.5	1045
Average peak conductance (μS/cm)	264.4 ± 24.7	378 ± 29.8	206.5 ± 32	667 ± 127

T_p: time to peak; T_b: time to base.
[a] Non-weir vegetated had only two runs that T_p and T_b could be determined from.



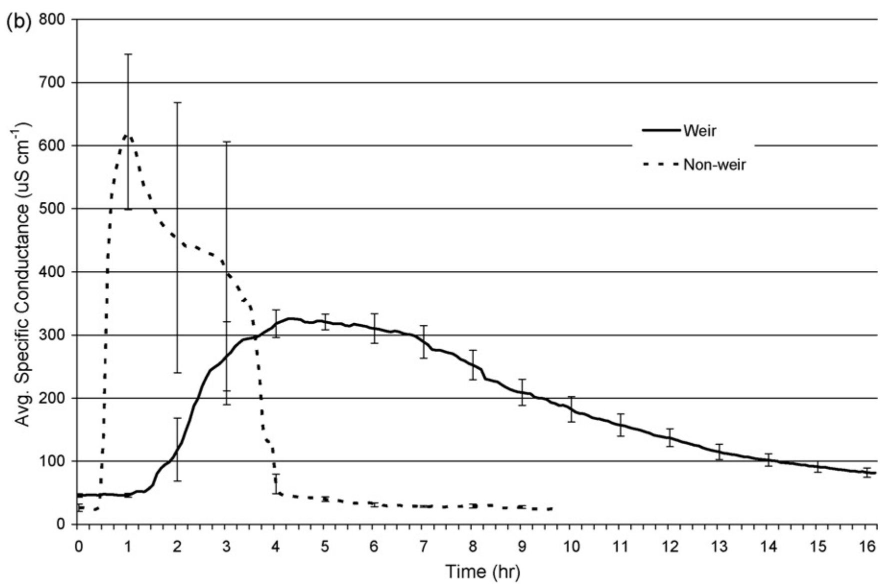


Fig. 3 – Best run specific conductance comparison (a), and mean (*n* = 5) specific conductance comparison (b) over time between non-vegetated drainage ditches with and without low-grade weirs.

non-weir (218) < non-vegetated weir (216) < vegetated non-weir (218). An increase in slope would decrease the T_p, thus decreasing CRT; however, there was no relationship between slope, CRT of respective ditches and whether ditches were weired or vegetated (Table 2).

In wetland 216 weir heights was greater within the non-vegetated ditch; however, ditch morphology (smaller width) produced an overall smaller mean weir volume (9548 ± 978 L) and total ditch volume than the adjacent vegetated ditch (Table 1). Total ditch water volumes for wetland 216 were double that in 218. Low-grade weirs within drainage ditches increases water volumes and lower flow rates, thus potentially providing an increase in niche habitat for macro-invertebrates with an increase in water depth to habitat ratios (Clare and Edwards, 1983, Eyre et al., 1990, Painter, 1999).

3.2. *Low-grade weirs increase CRT*

Chemical retention time was significantly altered by the installation of low-grade weirs (Table 2, Figs. 3 and 4). There were also differences between vegetated and non-vegetated treatments for weir vs. non-weir.

Chemical retention time chemographs for non-vegetated ditches were observed to have typical rising, peak and falling limbs of hydrographs (Fig. 3). As expected, the weir non-vegetated ditch on average increased T_p three-fold (Table 2), while T_b was decreased dramatically without weirs. Increasing T_b with weirs suggests a significant increase in water storage, shallow groundwater recharge, and water table increase. The shift in T_p allows a greater time window within the ditch for microbial transformation,

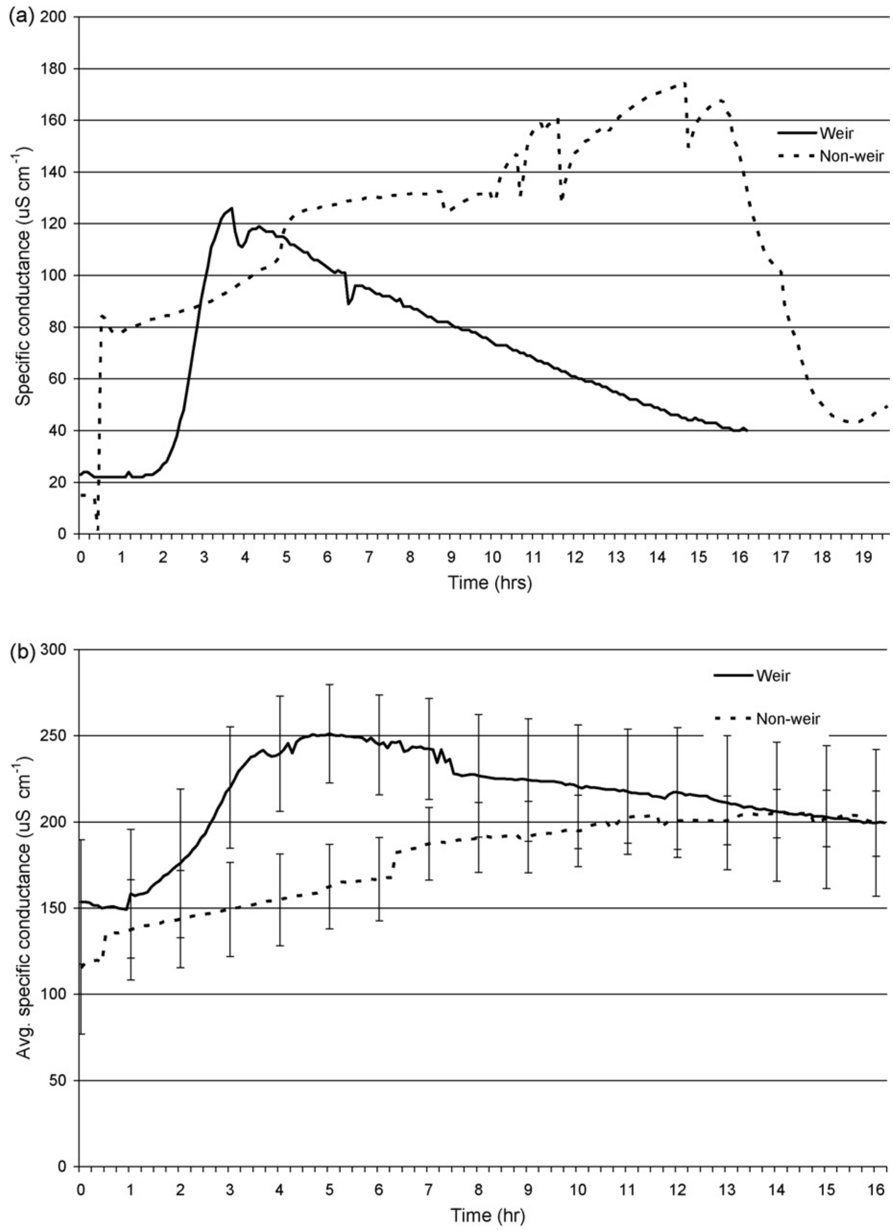


Fig. 4 – Best run specific conductance comparison (a), and mean (*n* = 5) specific conductance comparison (b) between vegetated drainage ditches with and without low-grade weirs.

plant assimilation and adsorption, and sedimentation processes.

Chemographs for weir and non-weir vegetated ditches were similar, but the results were very different from non-vegetated results (Table 2, Fig. 4). Conductivity in vegetated ditches did not peak as observed with non-vegetated ditches and did not follow the distribution common to most storm chemographs. Vegetated ditches increased T_p and T_b over non-vegetated ditches; however in most runs, the falling limb recovery of the chemograph was indistinguishable, or the run failed to peak. The difference between vegetated and non-vegetated ditches was firstly obligate emergent wetland vegetation, but also a large component of senescent decomposing organic matter above the substrate surface. Vegetation slows water flow and increases contact time for contaminant retention. This organic matter component was more than likely actively adsorbing $NaCl^-$ and slowly precipitating and desorbing throughout the course of each run and experiment, thus not allowing a defined peak to be observed (except the initial run for both vegetated treatments). Furthermore, vegetation exacts a frictional retardance to water flow, a shear stress to water hydraulics and thus would be expected to increase water CRT. Manning's *n* is a well-known roughness co-efficient which utilizes the characteristics of vegetation to determine changes in water discharge (Chin, 2000; Kröger et al., 2007).

There were no statistically significant differences in normalized maximum conductance between ditches, except for the non-weir non-vegetated ($p < 0.001$) where small ditch volumes and lack of vegetation resulted in less dilution.

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Drainage ditches T_p and T_b were affected by both vegetation and weir presence. The order of treatment efficiency for T_p was observed to be: non-vegetated non-weir < vegetated non-weir < non-vegetated weir < vegetated weir. Furthermore, T_b for each ditch was the reverse relationship from T_p where vegetated weir > non-vegetated weir > vegetated non-weir > non-vegetated non-weir. The distinct differences between T_p, T_b, and temporal conductivity measures between adjacent ditch systems clearly indicates how effective flashing and bentonite clay partitions worked at isolating each system. This isolation allowed independent measurements and analysis to be scientifically valid.

Controlled drainage has been shown to decrease water flow (i.e. increase CRT) (Borin et al., 2001; Parsons et al., 1990) and thus supports results from this study. However, these studies did not make the distinction between vegetated and non-vegetated ditches and their effects on water quantity and quality. The non-vegetated treatment is a prevalent and viable treatment, where farmers will clear-scrape ditches to improve drainage efficiency. The use of low-grade spatially positioned weirs has been demonstrated to increase mean T_p, a variable resulting in larger periods of time to support a greater mitigation efficiency for pollutants such as pesticides, nutrients and sediment. Furthermore, low-grade weirs increased T_b and water volumes resulting in the potential for greater water uptake in periods of water stress, shallow groundwater recharge and elevating surrounding water tables.

Spatial arrangement of low-grade weirs in the field has some advantages and disadvantages over conventional slotted board risers in ditch outlets. Water table depths should increase uniformly throughout the agricultural landscape rather than just around the outflow. The important first flush capture of NPS pollutants will occur at multiple entry points along the drainage ditch rather than just at the outflow increasing microbial transformations, P adsorption sites and inorganic assimilation by plants. Overall residence time of water in the ditch should increase and thus improve overall efficiency of pollutant reduction. Low-grade weirs will also be small enough that significant storm events will not result in flooded soil conditions. The major disadvantage is the set height of low-grade weirs; however, in design, a variable height weir could be installed.

This preliminary investigation laid the hydrological groundwork for future research on non-point source load mitigation with low-grade weirs. Studies have shown that controlled drainage plays a significant role in non-point nutrient reduction: NO_3^- (Lalonde et al., 1996), total N (Kalita and Kanwar, 1993) and P (Wesstrom and Messing, 2007). Further research is aimed at examining the effectiveness of weirs in nutrient and pesticide reduction, and exploring weir management (i.e. type, spatial patterning and height variation) in improving this effectiveness.

4. Conclusions

The use of low-grade weirs in drainage ditches increases CRT, and potentially will increase pollutant (i.e. nutrient and pesticide) reduction. The spatial arrangement of weirs is an alternative controlled drainage strategy to the typical single outflow riser. The spatial configuration increases water holding capacity (i.e. volume) within the drainage ditch, creates multiple stages for biological transformation and could decrease groundwater depths across a broader area of the agricultural landscape.

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