ON-FARM EVALUATION OF TREATMENT METHODS FOR EXCESS NUTRIENTS IN AGRICULTURAL SUBSURFACE TILE DRAINAGE

FINAL REPORT

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CINRAM

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Consultant's Report

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INTRODUCTION

Wetlands are widely used and promoted in watershed management for their water storage and nutrient removal benefits (Baker 1992). They have potential to store large volumes of water and are especially effective at removing sediment and nitrogen; however they have been shown to be less effective at removing phosphorus (Miller et al. 2012). Even with increasing public awareness of wetland benefits, it can be a challenge to get farm owners to enroll large areas of cropland into wetland programs. Thus, there is a strong need for smaller edge-of-field wetland systems, especially to remove nitrate from sub-surface tile flow before entering into public waters. The current study was proposed and funded by the Minnesota Department of Agriculture with coordination initiating in 2012 for the installation and monitoring design for an edge-of-field treatment wetland system.

Project goals and purpose

- To develop and test a small-scale, edge-of-field treatment wetland system compatible with an agricultural tile-drained row crop system, to serve as a research and demonstration site.
- To measure water storage and nutrient removal efficiencies in the treatment wetland for at least three years (2013-2015).
- To quantify phosphorus uptake by wetland plants.
- To test the effects of different soil and plant types on nitrogen removal using small-scale versions of the treatment wetland (mescosms) in a University of Minnesota laboratory.

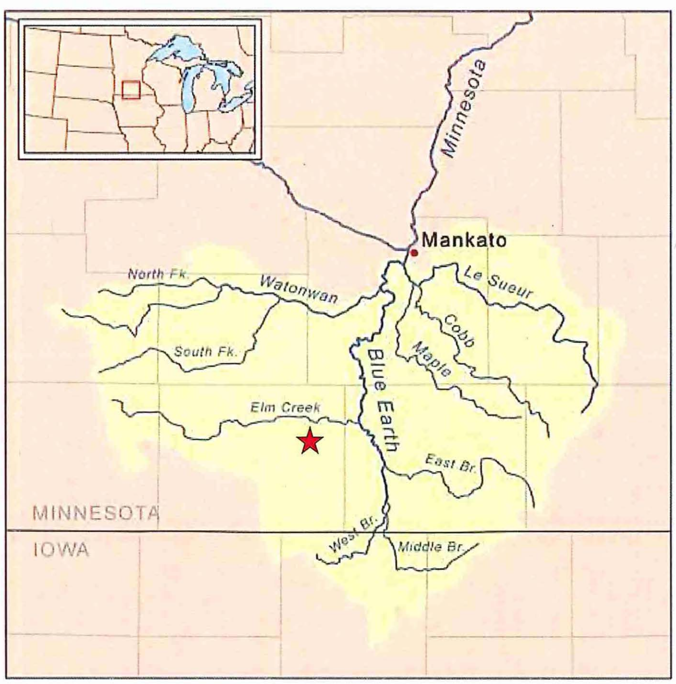


Figure 1. Project location for the constructed treatment wetland in Martin County, MN. Elm Creek is a tributary of the Blue Earth River which joins the Minnesota River near Mankato, MN

Figure 2. Treatment wetland research site located along Elm Creek in Martin County, MN

Wetland Design and Construction

The treatment wetland was constructed on a farm located near Granada, MN (coordinates 43 45' 4''N, 94 20' 51''W) (Figure 1) from January to May, 2013. The constructed wetland is located between Elm Creek and the northern edge of a row crop field. Elm Creek, which is impaired for turbidity and nutrients, meanders through the property separated from the wetland by a 68 foot strip of grass. The west and south sides of the wetland are abutted by row crops, and the east side is adjacent to a hill in native plant vegetation (Figure 2). The farmer practices rotational farming, alternating between soybeans and corn. This cropland is approximately 20.2 hectares (50.0 acres) and is divided into three drainage systems. The wetland receives sub-surface tile drainage water from approximately 10.1 hectares (25 acres) of cropland (labeled system 3 in Figure 3).

Excess water in the treatment wetland discharges into Elm Creek, a tributary to the Blue Earth River. The Blue Earth merges with the Minnesota River, draining to the Mississippi River which eventually outlets into the Gulf of Mexico (Figure 1).

The preliminary design and modeling work was conducted in 2012 (Karlheim, 2012, Appendix II). The goals of the modeling and preliminary design work was to simulate the hydrologic inputs and nitrate loading from the subsurface drainage network and to predict nitrate removal efficiency.

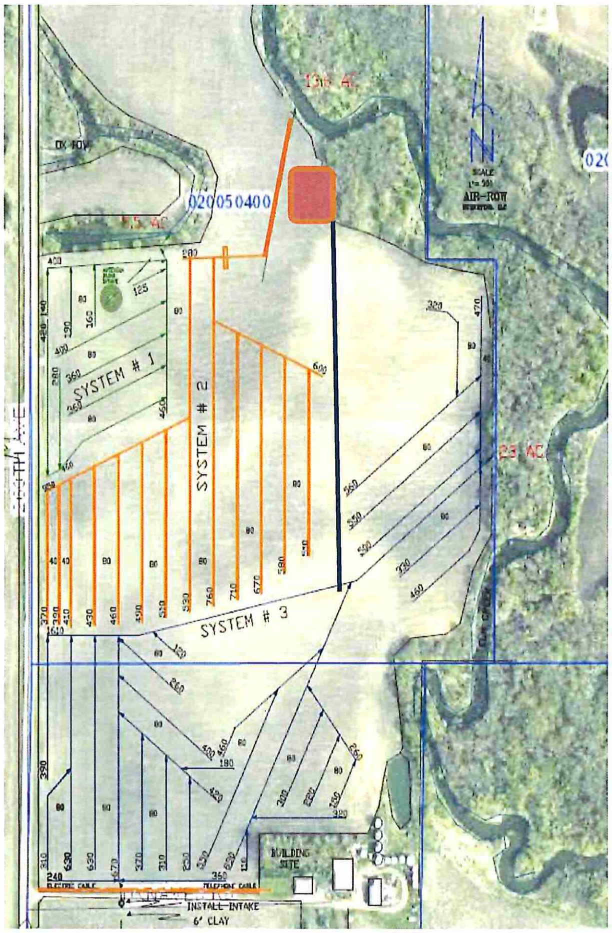


Figure 3. Sub-surface tile drainage network showing the areas draining to the treatment wetland (shown as orange block). System 3 and another system south of the driveway drain into the wetland. System 2 drains to the north bioreactor. The small, eastern portion of system 3 drains to the east bioreactor. A small portion of the wetland's drainage area drains to the east bioreactor during very large flow events.

Water from the tile drainage system is directed to a controlled inlet point which is directed into the first cell of the wetland. A water control structure is located diagonally across from the inlet in the first cell. The water control structure regulates water levels and the flow into the next cell using adjustable plastic stop logs. The surface water must be pooled above their height to pass through the Agri Drain. For this wetland the height of the plastic stop logs was set at a height of 0.6 to 1.0 feet. This same setup was repeated in cell two and cell three. Water enters each cell and then it must travel across the cell diagonally to the next control structure, rise above seven inches, and then it discharges into the next cell or the outlet (Figure 4).

Once the water has flowed across all three cells, the water enters the outlet pipe and control structure and then drain into Elm Creek. Previously, the tile drainage water from this system would outlet directly into Elm Creek. The control structures help to prevent back flow and facilitate in flow measurement.

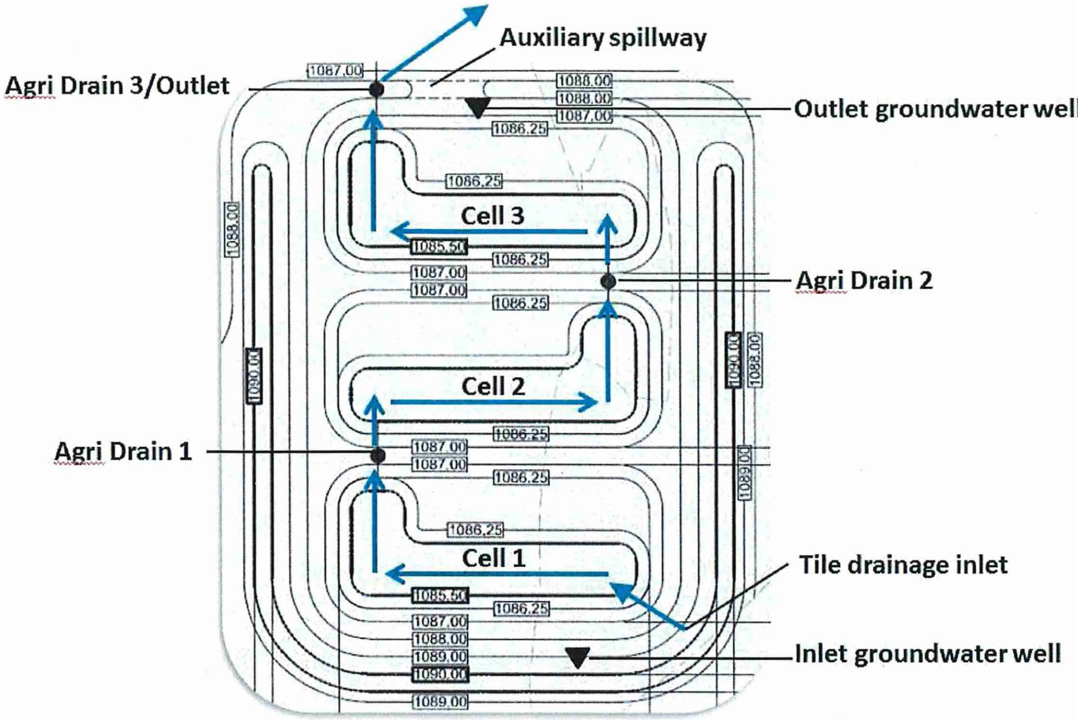


Figure 4. A depiction of the surface water flow through the constructed treatment wetland and the locations water monitoring equipment.

Methods of hydrologic analysis and nutrient removal efficiency

The flow of subsurface drainage into and through the wetland was modeled using level-pool routing and mass-balance principles with *Drainmod* for water inputs. The level-pool routing, mass balance model simulates transient flow typical of natural storm events through a wetland. The mass-balance approach assumes that total inflow is equal to the total outflow plus the change in storage.

The wetland was assumed to act as a mixed reactor since actual flow conditions were thought to fall between plug flow and completely mixed (Reed, 1995). Some other assumptions of this model included: outflow given by a unique storage-discharge relationship; storage is a non-linear function of outflow; approximately horizontal water surface; the wetland has a pool that is wide and deep compared to its length in the direction of flow; low flow velocities in the pool; outlet has a fixed discharge for a given pool elevation and there is an unmovable outlet (such as a weir) (MPCA, 2000).

The water balance of the wetland (modeled as a reactor) may be written in the following form, Equation 1:

$$Q_{in} + \underbrace{(P - ET + R - I - DP)}_{S} * A + Q_c - Q_{out} = \frac{dV}{dt}$$

Equation 1 includes the following variables:

V = volume stored in wetland (m^3)
A = surface area of wetland (m^2)
P = precipitation (m/d)
Qin = inflow (m^3/d)
Qout = outflow (m^3/d)
Qc = runoff from surrounding area (m^3/d)
ET = evaporation/transpiration (m/d)
R = irrigation addition (m/d)
I = groundwater loss or gain to wetland (m/d)
DP = Deep Percolation (m/d)
S = (P-ET+R-I)

Writing Equation 1 in difference form yields Equation 2:

$$\frac{V_2 - V_1}{\Delta t} = \frac{Q_{in2} + Q_{in1}}{2} + \frac{S_2 - S_1}{2} - \frac{Q_{out2} + Q_{out1}}{2}$$

Given storage and outflow at time level 1, we can rewrite the equation in the form of Equation 3:

$$\frac{V_2}{\Delta t} + \frac{Q_{out2}}{2} = \frac{V_1}{\Delta t} + \frac{Q_{in2} + Q_{in1}}{2} + \frac{S_2 + S_1}{2} - \frac{Q_{out1}}{2}$$

Since the right-hand-side contains all known values and there are only two unknowns (V2 and Qout2), it is possible to solve for one as a function of the other (in this case, V2 as a function of Qout2) and use a storage-discharge relationship (Figure 4) to solve for both unknowns.

$$\frac{V_2(Q_{out2})}{\Delta t} + \frac{Q_{out2}}{2} = \frac{V_1}{\Delta t} + \frac{Q_{in2} + Q_{in1}}{2} + \frac{S_2 + S_1}{2} - \frac{Q_{out1}}{2}$$

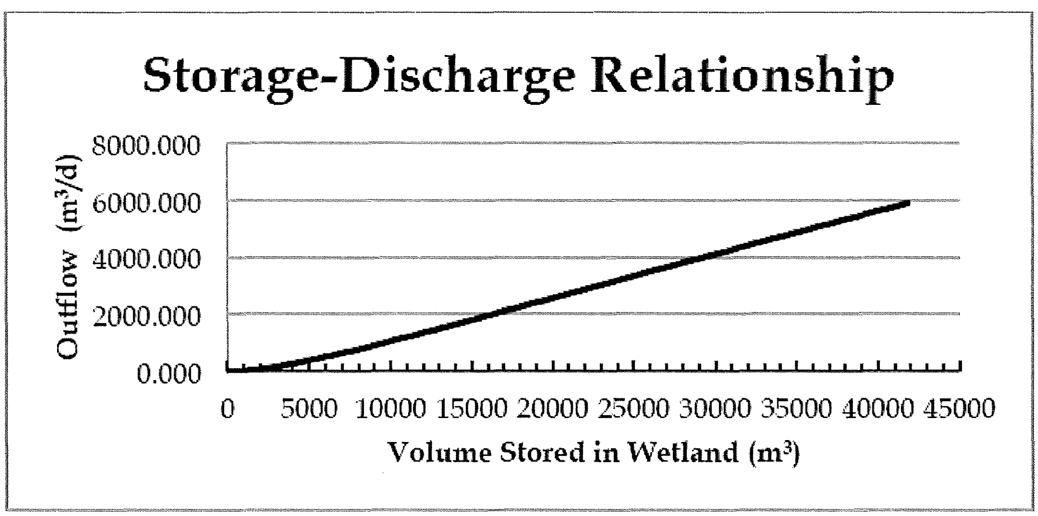


Figure 5: Volume outflow relationship for treatment wetland

Discharge from the wetland outlet is then determined by a rectangular weir equation based on the height of water above the weir, as shown below.

$$Q_o = \underbrace{C_E * W_W}_{\text{b1}}(H_o - H_W)^{1.5}$$

Qo = outflow rate (m^3/d)
CE = weir discharge coefficient (m^3/d)(m 2.5)
Ww= width of weir (m)
Ho= water surface elevation at wetland outlet (m)
Hw = weir crest elevation (m)

All of the parameters used to calculate wetland discharge from the water control structure and nutrient removal efficiency are described in Table 1.

Table 1: level-pool routing, mass balance routine input parameters and descriptors

Parameter	Symbol	Value	units
Head increment	dh	0.1	m
$Q=b1*h^{1.5}$	b1	9.95	1
Weir crest	hc	0.25	m
porosity	por	0.7	1
Time step	dt	1	days
Wetland length	L	36.6	m
Wetland width	W	9.14	m
Wetland side slopes	SS	3	1
Concentration – discharge (Q-C) relation		0.44	$mg/l/m^3/day$
Kinetic reaction	k	0.04	m/day
# cells		1	1
Total wetland area		334.45	m^2

Many of the input parameters for the Level pool routing, mass balance model were obtained through the Drainmod model (Skaggs 1994). The others are listed in Table 1. Rainfall and temperature inputs were taken from a long-term weather station located at Winnebago, Minnesota.

V = found with mass balance routine
A = treatment surface area of individual cell at each depth
P = DRAINMOD precipitation values applied to wetland cell area only
Qin = Subsurface Drainage flow from DRAINMOD
Qout = outflow in cell 1 is inflow to cell 2, outflow in cell 2 is inflow to cell 3
Qc = 0 (surface water is directed elsewhere for this application)
ET = DRAINMOD values for ET applied to wetland cell area only
R = 0 (no irrigation)
I = assuming small leakages, with unsaturated conditions beneath the wetland
DP = vertical seepage from DRAINMOD applied to wetland cell area only
*Assuming no bank loss

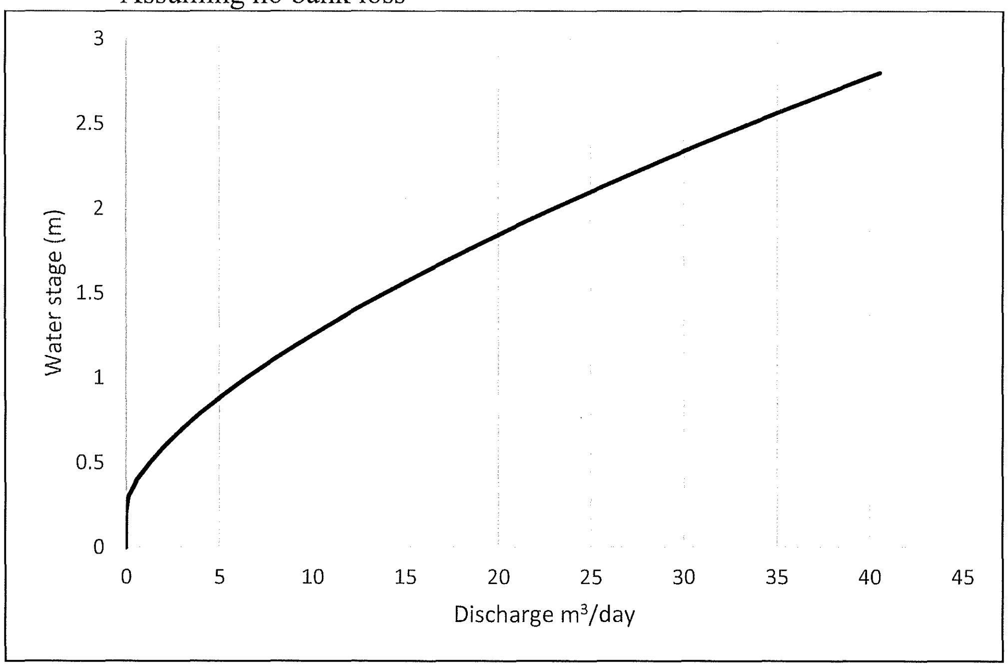


Figure 6: Predicted stage-discharge curve for the treatment wetland.
Note that the wetland's maximum stage is 1.5 meters which is set by the berm height.

Nutrient removal prediction: hydrologic model with reaction coefficients

Using the level pool routing, mass balance routine to model nitrate reduction, it is possible

to predict successive nutrient removal performance of the wetland cells. Input flow-concentrations were based on a (Q-C) relation of 0.44 mg/l/ m3/day prior to wetland monitoring. This rough estimate was found by dividing a mean nitrate concentration of 15.3 mg/l for a study done in the watershed (Lenhart 2008) by the average daily flow (~35 m3/d). The mean nitrate concentration was obtained by averaging five tile nitrate concentrations (from a nearby water quality treatment wetland) and one grab sample from the study site .

The kinetic reaction rate coefficient was set based on the median annual value determined in a compilation study by Kadlec and Wallace. This study utilized total nitrogen data from 141 wetlands. The median annual rate constant was 12.6 m/yr, making the daily rate constant ~0.04 m/d (Kadlec and Wallace, 2009).

The parameter (b1=9.95) was determined using Equation 1. The weir width was assumed to be 2.5 m for the model and the discharge coefficient was assumed to be 3.98 a typical value for a rectangular broad crested weir (http://www.engineeringcivil.com/weirs.html).

The preliminary design approach involved sizing the wetland appropriately to treat the drainage area. A wetland-watershed ratio of 1% was used based on guidance from Iowa State where numerous treatment wetlands have been built and studied for removal efficiency. This was based on the work described in Crumpton et al. 2008. A wetland area of 0.25 acres was selected based on the 25-acre drainage area feeding the site. Three cells were created to allow for experimentation with different vegetation types and to allow for water level management within each cell. Berm heights were set at 1.4 meters to allow approximately 0.5 meters of freeboard (berm height) above the highest anticipated water level.

A compact wetland design was needed to fit on the edge of the field to minimize the impact to the productive farmland and ensure compatibility with the existing operation. A sinuous flow-path through the cells was chosen to maximize retention time in the wetland to improve nutrient removal efficiency. Given the small size of the wetland, one of the primary limiting factors on nutrient removal performance is the short retention time.

Modeling results

Predicted drainage flow from the sub-surface drainage network reached a maximum in the spring between days 60 - 120 (March 1 to April 31). During the summer months of July – August the flow drops to near zero because of greater evapotranspiration (ET) as the plant growth and temperatures are at a maximum. A fall increase in tile flow was predicted as plant growth declines and ET decreases. The model predicted zero flow for 15% of the year.

A stage-discharge relationship was created for the wetland based on water volume versus outflow using a water balance approach along with level pool routing (Figure 5). Water height (stage) does not exceed 1.4 meters, which was the height of the retention berms. The maximum predicted discharge was 12.3 m^3/day assuming a low rate of infiltration and small losses to deep groundwater percolation because of the high clay content of the soil (>40% clay).

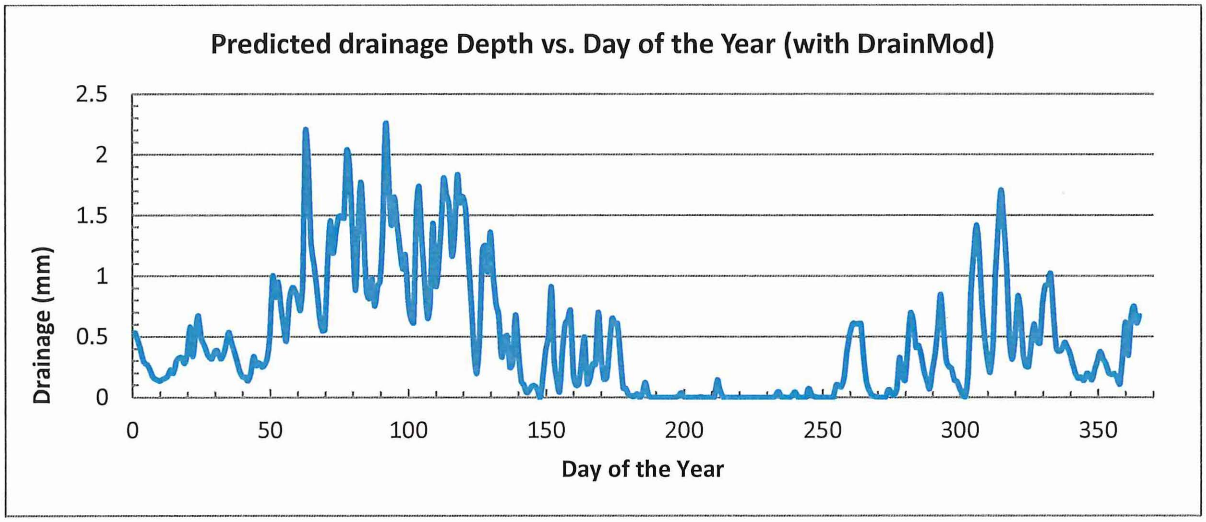


Figure 7. Predicted drainage flow from the watershed into the wetland vs. day of the year in units of mm over the watershed area.

The predicted nitrate removal efficiencies from the modeling study are shown in Table 2. A removal rate of 68% for nitrate-nitrogen was predicted, a total mass of 168 kg per year.

Table 2. Predicted nitrate inflow, outflow and removal

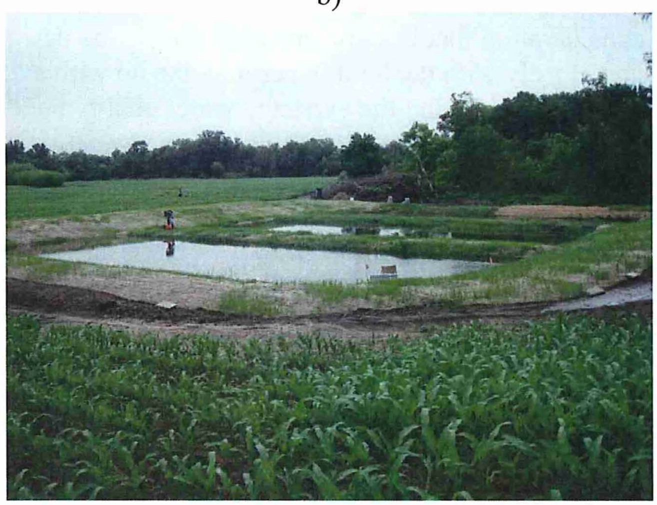
Category	Value	Units
inflow mass	248	kg
treated mass	168	kg
outflow mass	80	kg
removal efficiency	68	%
Water balance error	-0.01	%

Wetland Construction and Implementation

The treatment wetland was constructed between March and May, 2013 (Figure 8). The wetland is 41 m wide and 53 m long comprising an area of 0.22 hectares including the berms. The layout includes three separate treatment cells within the wetland; each one measuring 13.7 m by 26.7 m comprising an area of 0.0365 hectares. The area of active treatment is 0.110 hectares and includes a base and aquatic shelf in all three cell boundaries. Each cell is separated by lower berms that are 0.46m high. The entire wetland is bordered by a larger berm that is 1.37 m above the wetland base. At the outlet there is an auxiliary spillway that allows for overflow to protect the berms, structures and adjacent areas from potential flooding.

a)

b)



c)

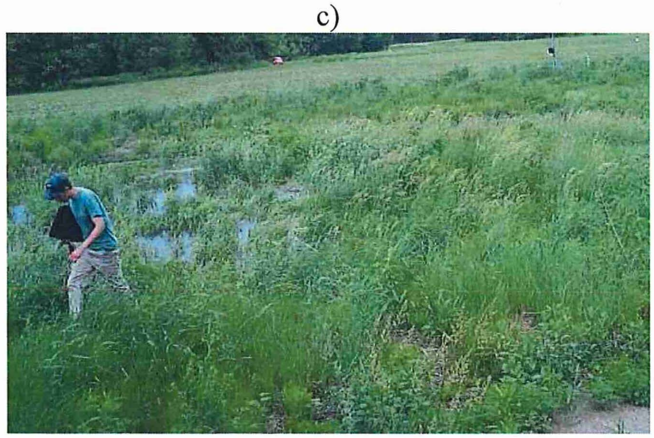


Figure 8. Photos of the treatment wetland. Photo a) - treatment wetland in early spring 2013 prior to vegetation growth. Photo b) shows the wetland in summer 2013 and photo c) shows it in summer 2015.

Construction / Implementation issues

The wetland was constructed as designed although its final location was closer to Elm Creek than University of Minnesota staff had originally anticipated. To minimize crop land area taken out of production, the treatment wetland was constructed closer to the stream, which made the basin subject to surface water flooding during overbank flood events. The wetland did provide some flood storage and additional nutrient removal, which was beneficial to Elm Creek; however, this additional storage interfered with the monitoring of sub-surface drainage flow during flooding thus reducing the total number of days with inflow data.

Other issues included vegetative management for nutrient harvest, invasive control and maintenance for walking and public field trips. The wetland was too small for an economical plant harvest operation so the plants were harvested by hand and mulched on site. Reed canary grass, an invasive aggressive, moved into the wetland in 2013 and spread each year. Finally, occasional mowing was required on the wetland berms for landowner access and to allow visitor access during the hosted field days. Future maintenance of the wetland will be dependent upon the landowner once the research project is over.

Another important consideration that became apparent during the design of the wetland was the importance of working closely with the landowner to come up with a design that fits into their management practices while achieving the expected water quality benefits. As referred to above, the wetland was moved closer to the stream as the location was negotiated with the landowner. The landowner objective was to remove the least amount of land from crop production and to ensure that the wetland did not unduly interfere with his farming operations and the movement of machinery.

WATER QUALITY STUDY

Methods

Hydrology

The following equation was used as a framework for comparing different components of the water budget in the wetland:

$$Q_{in} + P + GW_{in} + SW_{in} = Q_{out} + ET + GW_{out} + SW_{out}$$

where:
Q_{in} = subsurface tile drainage entering the wetland
P = precipitation in wetland area
GW_{in} = groundwater discharging into the wetland
SW_{in} = surface water overland flow entering the wetland
Q_{out} = water discharging from wetland tile outlet
ET = evapotranspiration
GW_{out} = groundwater recharge through infiltration leaving the wetland
SW_{out} = water leaving the wetland over the surface of the berms

Water budget components were estimated using a variety of tools. Due to the design of the wetland, SW_{out} and SW_{in} were negligible. The berms surrounding the wetland prevented any overland flow from entering the wetland over the berms. Precipitation was estimated using a HOBO rain gauge each of the three years, with an additional Davis weather station the second year, and an ISCO rain gauge the third year. The precipitation collected in these rain gauges was then multiplied by the catchment area of each treatment cell in the wetland (0.9 acres each). These rainfall amounts were also compared to data from the University of Minnesota Climatology Working Group.

Potential evapotranspiration (ET) was estimated using the Hamon and Thornthwaite potential ET equations (Lu et al. 2005, Federer 1996) from temperatures collected on an EasyLog USB temperature logger. Hamon and Thornthwaite provide an estimate of ET that These PET values were also compared to those calculated using the Jensen-Haise equation (Federer 1996) from temperatures and radiation measurements collected on the Davis weather station. In 2015, Levelogger pressure transducers were placed in shallow wells in each of the wetland cells to measure the fluctuation in water level caused by plant uptake. Using an estimate of specific yield, the amount of water available for plant uptake after the flowing water has drained off and above the wilting point, the volume of water transpired by plants during the day was calculated, providing a better estimate than the atmospheric equations.

Tile drainage into the wetland was measured using an ISCO area velocity probe and 2150 area velocity flow module each of the three years, but this was complemented by a Solinst Levelogger pressure transducer in an Agridrain control structure fixed to the end of the tile in 2015. The tile drainage flowing from the wetland was measured using an ISCO area velocity probe paired with a 4150 area velocity flow logger. A Solinst Levelogger was placed in the outlet Agridrain control structure in 2014 to complement the area velocity readings for the last two years. With Agridrain control structures determining flow between the wetland cells, Solinst Leveloggers were placed in both of the control structures dividing the cells in order to determine flow volumes between cells. Measuring the flow between cells allowed for more accurate estimates of infiltration in each cell. Groundwater recharge through infiltration was then calculated algebraically once all of the other variables in the above equation were determined.

The area velocity probes in the inlet and outlet provided readings for water level and velocity inside the tile pipe. Therefore, equations from Bengtson (2012) were used to estimate the area of the partially full pipe to multiply by the velocity measured. The Leveloggers in each agridrain provided measurements of the height of water flowing over the control structures' boards. The flow equations from Chun and Cooke (2008) were then used to calculate the volume of flow based on the height of water in the control structures. This method was more accurate than the area velocity probe in the outlet control structure due to the area velocity probe sometimes having difficulty reading velocity when the water was not turbid enough. The accuracy of measuring flow in the control structures was further improved when the top board in each structure was replaced with a v-notch weir. Measuring the height of water flowing over a smaller surface in the v-notch improved readings during low flow. The Levelogger readings of water height were then used in an equation developed by Scott Matteson (Minnesota Department of Agriculture – Mankato) to calculate the volume of flow. The equation is as follows:

$$Q = 0.9833x^{2.0801}$$

where x = stage of water in feet; Q = flow rate in cubic feet per second. The Levelogger recorded a measurement every 15 minutes. The flow rate was then converted to meters per minute and multiplied by 15 minutes to calculate the volume.

In 2014, inflow from the tile drain was not measured from March 23rd to June 5th due to a software issue in the area velocity probe. Therefore, the inflow was estimated using a tile flow equation from Greg Fransen's thesis (2011) which calculated the volume of water in subsurface tile drainage based on the precipitation in the watershed and time of year. Water volumes discharging from the wetland's outlet tile were also not measured during the period of March 23rd to June 5th due to a software issue and physical damage to the equipment. These missing measurements were estimated by calculating the percent of water which flowed from the second Agridrain control structure to the outlet during measured periods in 2013 and 2014. This percent varied during wet and dry periods, so this was also considered when estimating missing outflow values.

Nutrient Reduction

Nitrate/nitrite-N was the primary nutrient of concern in this treatment wetland. Orthophosphate and total phosphorus were also sampled throughout the study. Nutrients flowing through the wetland were analyzed through grab samples at the inlet, Agridrain 1, Agridrain 2, and the outlet. Bottles for samples were provided by and submitted to Minnesota Valley Testing Laboratory (MVTL) for all orthophosphate and total phosphorus samples. Samples were submitted to the testing laboratory to measure nitrate/nitrite-N for 2013 and 2014. In 2015, a Hach Nitratax sc, UV Nitrate sensor was used to measure nitrate/nitrite-N in the field. Other water quality parameters were measured occasionally throughout the three years of study. Conductivity was measured from the inflow 10 times, Agri Drain 1 six times, Agri Drain 2 seven times, and the outlet three times in 2013 by submitting samples to MVTL. Conductivity was measured from the inlet in 2014 and 2015 using an Onset logger. The pH was measured seven times in 2014, and TSS was measured 45 times in 2013 and 2014.

Nutrient loads into the wetland, through the Agri Drain structures, and through the outlet were calculated by multiplying the concentration of the nutrient in each grab sample by the flow volume. No relationship was observed between the concentration of each nutrient and the location of the flow on the flow duration curve. Therefore, sample concentrations were averaged by month to calculate the nutrient load by the period of the growing season. The drainage area of the wetland was 10.1 ha, so the mass of nutrients entering the wetland was divided by 10.1 ha to calculate the load.

Nutrients infiltrating into the soil were calculated by multiplying the concentration of that nutrient entering the respective cell by the volume of water estimated to be infiltrating as calculated above. Beneath the silty clay or clay surface layer, there is a sandy layer greater than 4 feet below the surface. Wells and piezometers were drilled throughout the wetland (Figure 9) in an attempt to follow the flow of water after it infiltrated into the sandy layer. The height of the potentiometric surface was measured in order to determine the direction of flow. Nutrient concentrations were measured in each well throughout the year by using a peristaltic pump to draw the sample. Stable isotopes (^{18}O and ^{2}H) were then measured in the wells and piezometers (Brooks et al. 2012). Due to the lighter isotopes evaporating before heavier isotopes, groundwater typically will have a higher ratio of heavy to light isotopes than surface water. The ratio of heavy to light isotopes was measured in Tim Griffis' lab in the Soil, Water, and Climate department at the University of Minnesota. By having two wells at known groundwater depths, other wells down gradient of where surface water was known to be infiltrating, and grab samples from the surface water, the isotope ratios were compared from these three sources to calculate the percent of surface water in the well when the nutrients were measured. The following equation was used to then calculate the contribution of groundwater to each well and piezometer sample:

$$\%GW - \text{Contribution} = (\delta_{Rmix} - \delta_{SW}/\delta_{GW} - \delta_{SW}) \times 100$$

where δ_{Rmix} is the isotope ratio of the sample where surface water and ground water are known to be mixing, δ_{SW} is the isotope ratio of the surface water sample, and δ_{GW} is the isotope ratio of the ground water. Isotope ratios of ^{2}H were used to calculate groundwater contributions in this study. Once the groundwater contribution was calculated, the following equations were used to calculate the nutrient reduction between the infiltration and the well down gradient:

Total volume flowing past wells = (SW volume infiltrating) / (%SW contribution)

GW volume flowing past wells = (Total volume flowing past) – (SW volume infiltrating)

GW nutrient load = (GW volume flowing past wells) x ([Nutrient] at GW well)

% Reduction = 100 - ([Nutrient] x Total volume flowing past) / (GW load + SW infiltration load) x 100

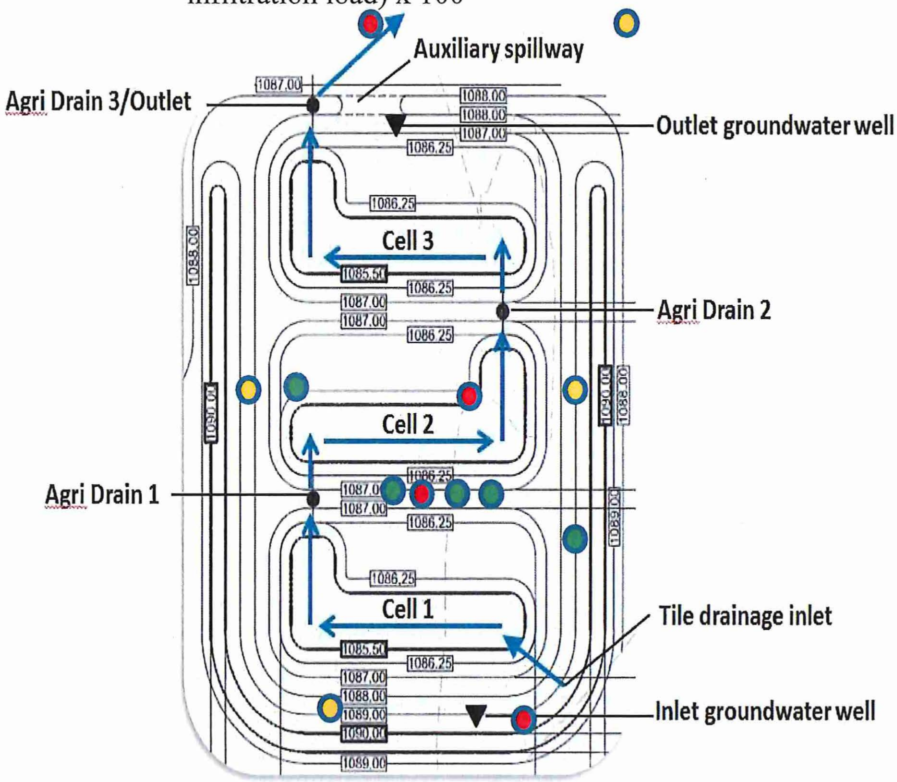


Figure 9. Groundwater monitoring network in the treatment wetland

Results and Discussion

Hydrology

This constructed treatment wetland was designed to treat agricultural subsurface tile drainage. Therefore, the greatest input of water into the wetland was tile drainage. The volume of this input varied in each of the three years, 2013 through 2015, that this wetland was studied (Table 1). Periods of flow varied each year with flow in 2013 beginning later due to the delay in construction. Flow lasted the longest in 2015. Instruments were removed when temperatures were consistently below freezing. While this coincided with flow ending in 2013 and 2014, the flow continued in small amounts even after equipment was removed in 2015, the last day of flow was likely around December 1st.

Table 3. Volume of water flowing into the wetland from tile drainage each year of the study. The flow period is also listed by start and end dates each year.

Year	Tile Drain Inflow Volume (m^3)	Starting Date of Flow	Approximate Last Date of Flow
2013*	7,240 (5,239-9,240**)	June 5	September 11
2014	12,732 (9,215-16,277**)	April 27	October 30
2015	5,666 (5,575-5669**)	April 28	December 1

*Measurements began in late May of 2013. Spring flow events are not included in this estimate.

**Range of values calculated based on instrument accuracies and uncertainty in inflow estimates when calculating from rainfall in 2014 rather than instrument measurements.

In each of the three years of the study, the wetland received average rainfall (66.7-79.6 cm for the full year) amounts for the region (climate.umn.edu). Although 2015 had the lowest tile inflow of the three years, it received the most rainfall between the dates the ground thawed in the spring and froze in the fall. The first two years received much rainfall in large events which created much flow into the wetland. The third year had more total rainfall but fewer large storm events. As a result of the events in 2013 and 2014, the wetland flooded in June both years. Elm Creek flooded the banks and some water flowed into the wetland through the outlet drain. However, flood water did not exceed the height of the berms but only flowed through the outlet drain.

Table 4. Rainfall amounts during the period from thaw in the spring to freeze in the fall each of the three years of the study. Measurements of rainfall began after the ground thawed and ended when equipment was removed and temperatures were consistently below freezing.

Year	Rainfall (cm)	Rainfall Volume into Wetland (m^3)
2013	46.65	512.1 (506.9-517.2)
2014	46.53	510.7 (505.6-515.8)
2015	60.15	660.1 (653-667)

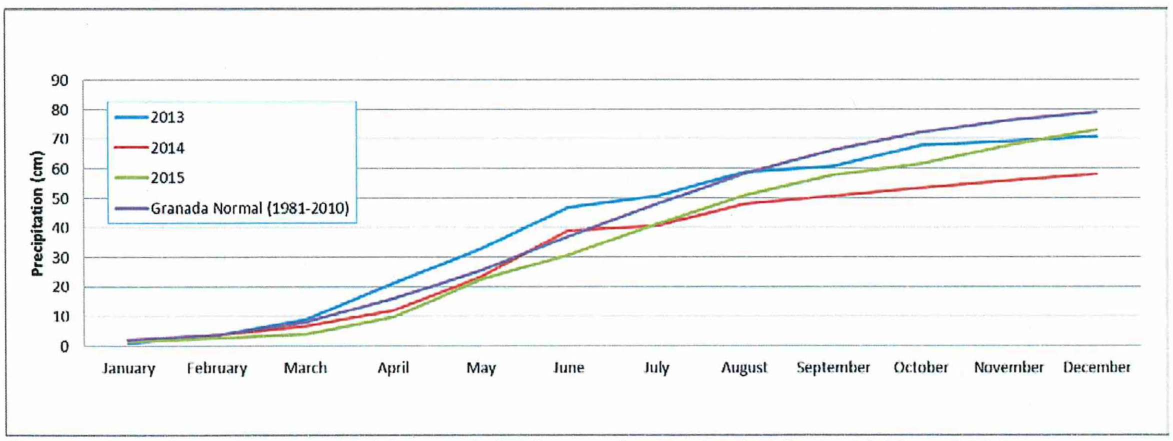


Figure 10: Cumulative monthly precipitation at the study site from 2013 to 2015.

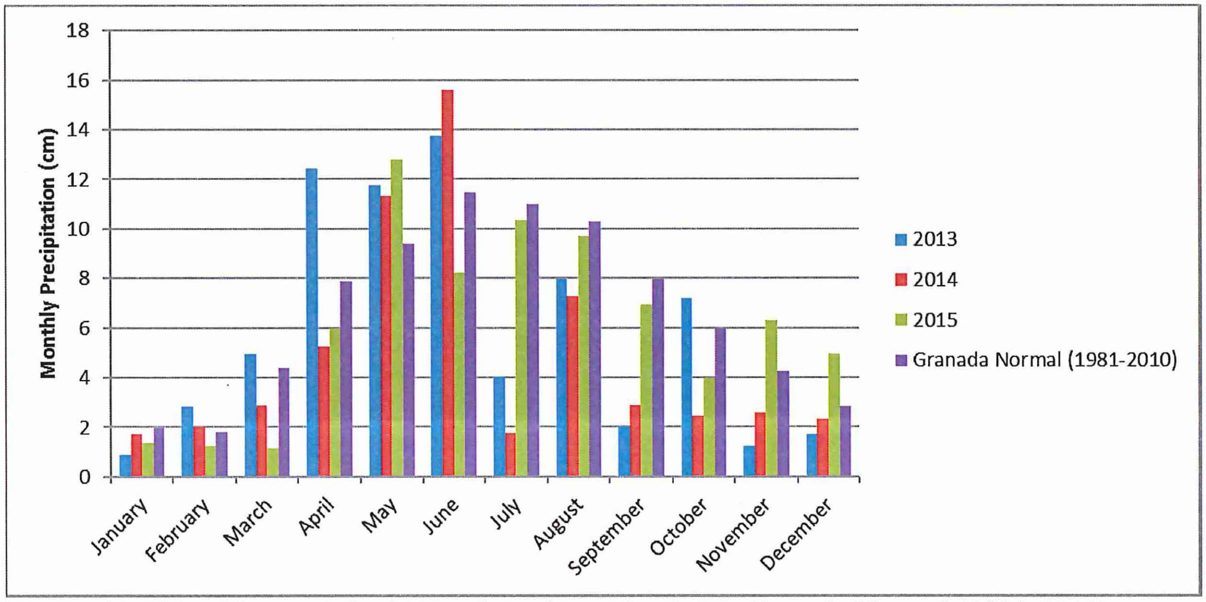


Figure 11: Monthly precipitation totals at the wetland site. Granada Normal (1981-2010) comes from the University of Minnesota Climatology Working Group.

Evapotranspiration was a small fraction of the outflow of water from the wetland. In the first year, the vegetation was not fully established, so transpiration would likely have been lower than 2014 and 2015. In 2015, the third cell was never inundated and received water from the drainage tile for only a couple hours. Therefore, evapotranspiration in the third cell played a negligible role in the removal of water entering the wetland through the tile inlet.

Table 5. Calculated potential evapotranspiration from three equations and calculated transpiration from Levelogger method. 2015 is estimated for cells 1 and 2 only due to cell 3 only receiving 6 m^3 of water from tile flow that year.

Year	**Hamon method (m^3)**	**Thornthwaite method (m^3)**	**Jensen-Haise method (m^3)**	**Levelogger method (m^3)**
2013	475	1,764	NA	No data
2014	667	2,000	1176	No data
2015	492	1,430	NA	246-685

Table 6. Average potential evapotranspiration per day.

Year	**Hamon method (mm/day)**	**Thornthwaite method (mm/day)**	**Jensen-Haise method (mm/day)**	**Levelogger method (mm/day)**
2013	2.35	8.78	NA	No data
2014	3.01	9.02	1.07	No data
2015	2.80	8.15	NA	1.4 – 3.9

The greatest volume of water in the wetland flowed out through infiltration. Approximately 77% and 69% of the water infiltrated in 2013 and 2014. An even greater portion of the water in the wetland flowed out through infiltration in 2015 due to no water reaching the outlet drain the entire 2015 season. All water in the wetland in 2015 exited through evapotranspiration or infiltration. Thus, approximately 93% of the water infiltrated in 2015.

Table 7. Calculated total annual volumes of infiltration.

Year	Infiltration Volume (m^3)
2013	5814.5
2014	9092.3
2015	5608.5

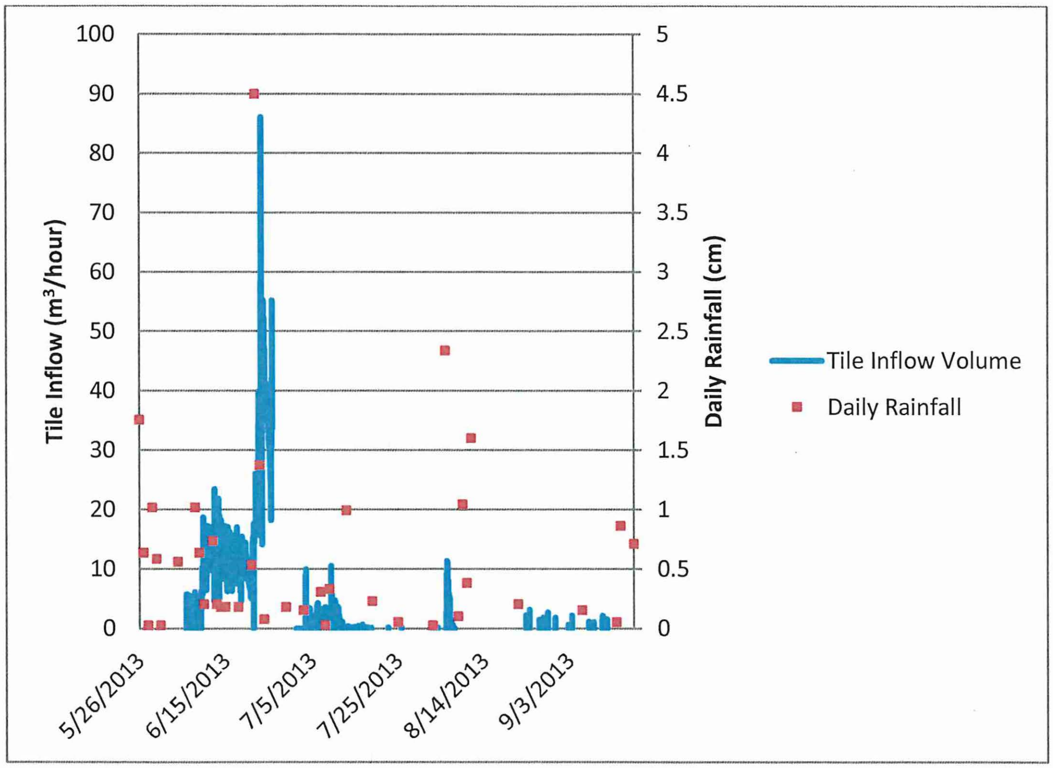


Figure 12. Hydrograph of tile inflow to the wetland in 2013. Dates of the flood, 6/24/13-7/6/13 were removed from this chart due to instruments misreading backflow.

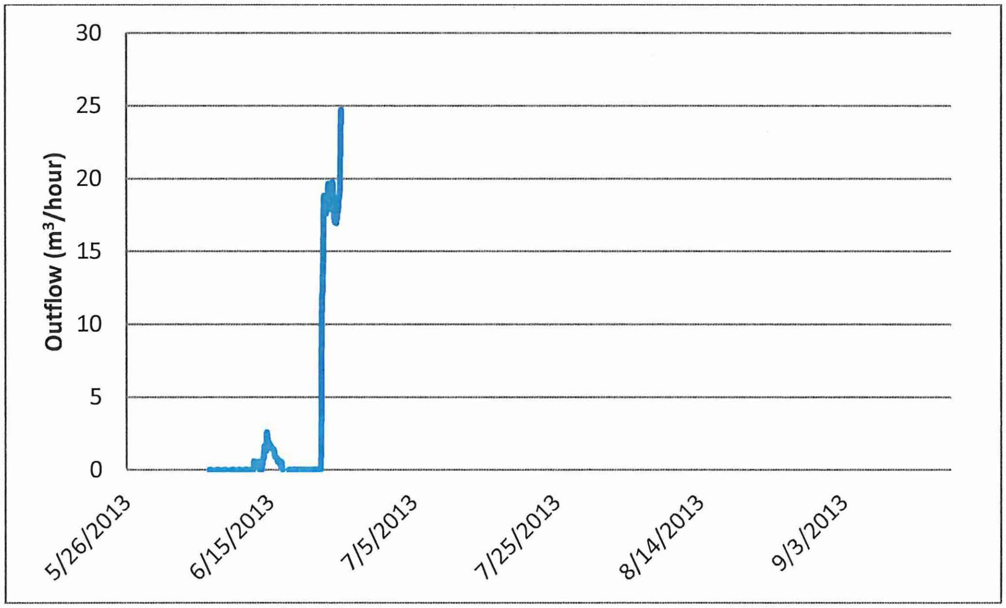


Figure 13. Hydrograph of outlet drain from the wetland in 2013. Dates of the flood, 6/24/13-7/6/13 were removed from this chart due to instruments misreading backflow.

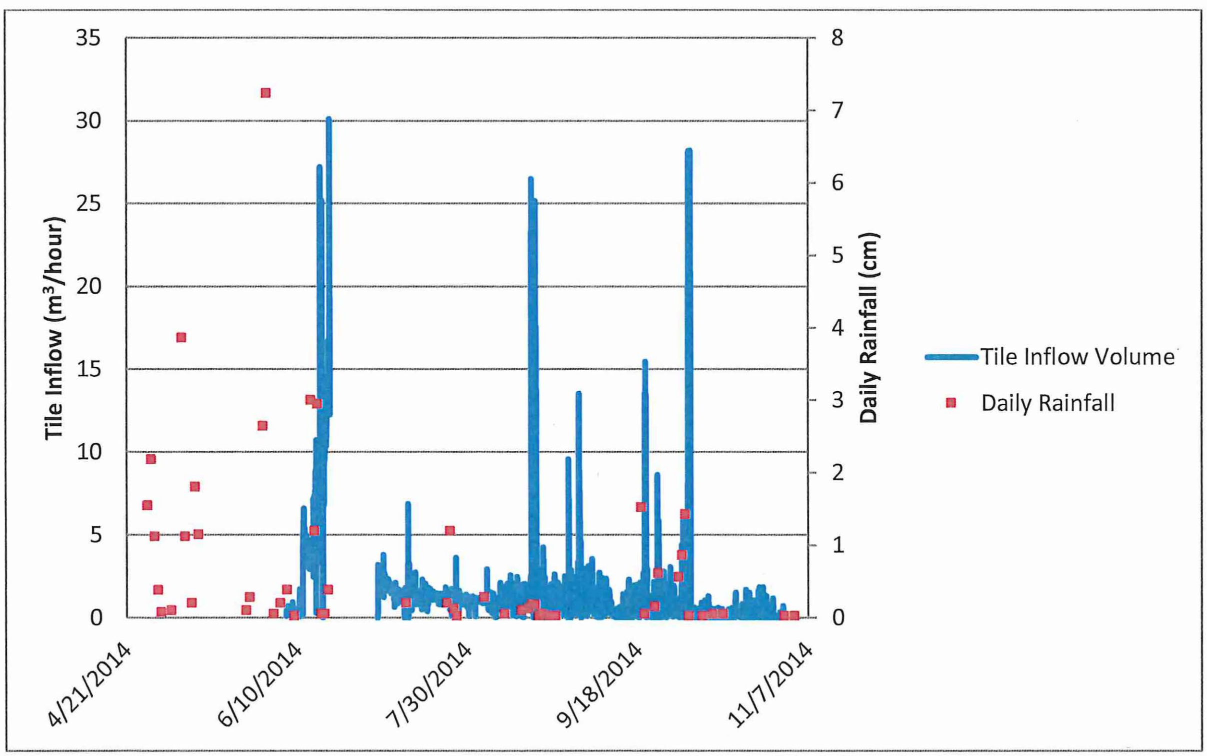


Figure 14. Hydrograph of tile inflow to the wetland in 2014. Dates of the flood, 6/19/14-7/3/14 were removed from this chart due to flow being backwards through the control structures. Flow preceding 6/6/14 is absent due to instrument malfunctions.

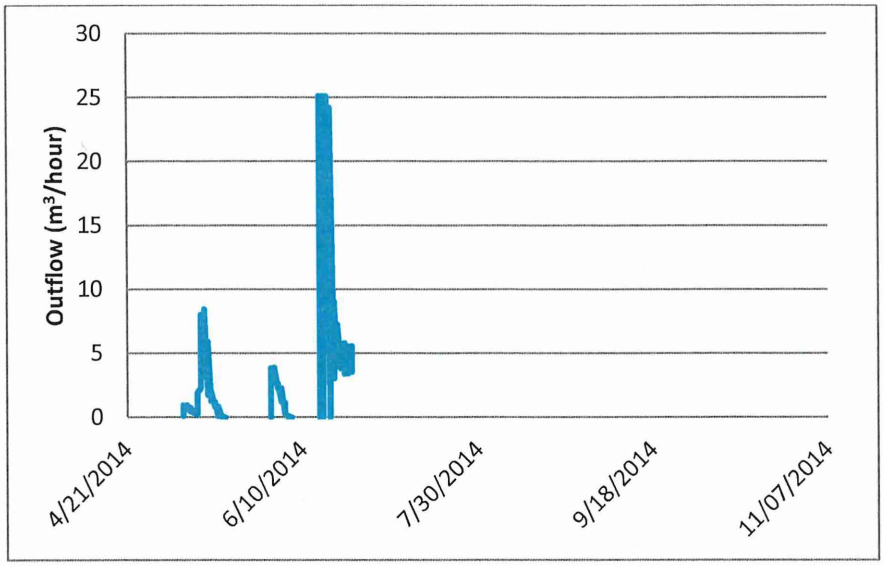


Figure 15. Hydrograph of outlet drain from the wetland in 2014. Dates of the flood, 6/19/14-7/3/14 were removed from this chart due to flow being backwards through the control structures.

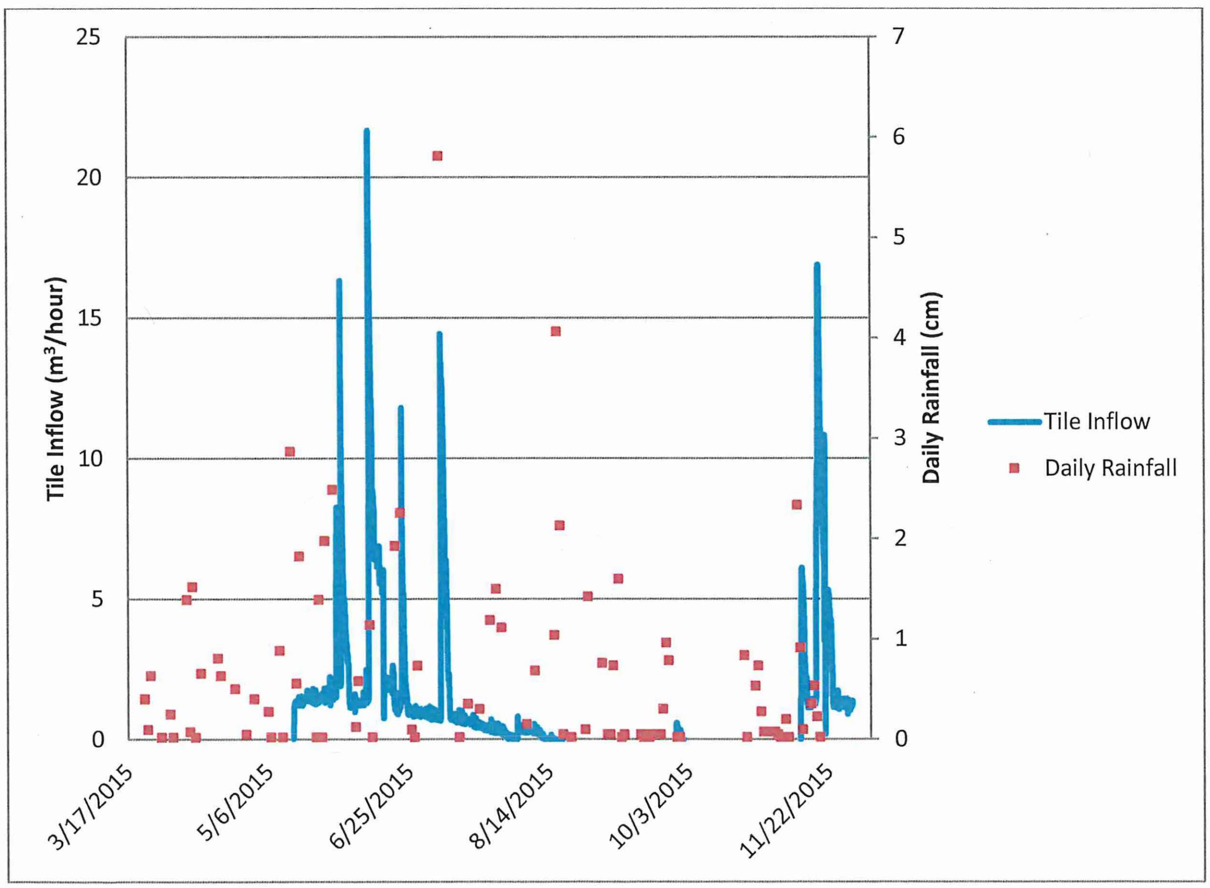


Figure 16. Hydrograph of tile inflow to the wetland in 2015. No outflow occurred through the outlet drain during this year.

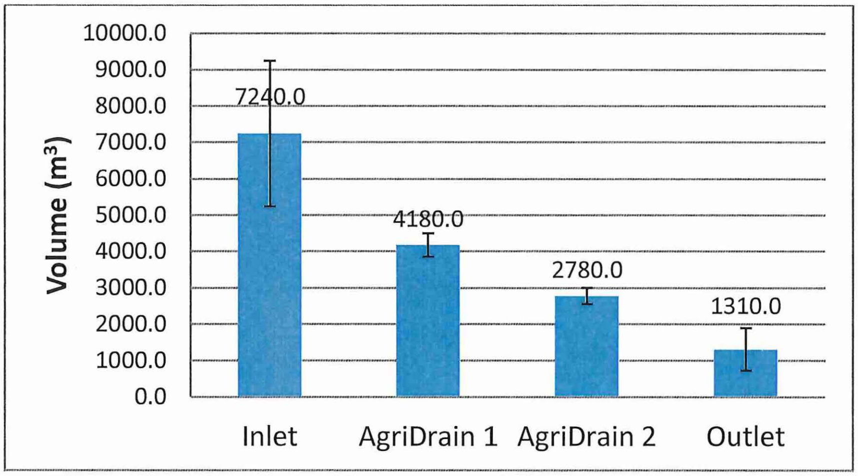


Figure 17. Water volumes flowing through the inlet, both Agri Drain structures, and the outlet in 2013.

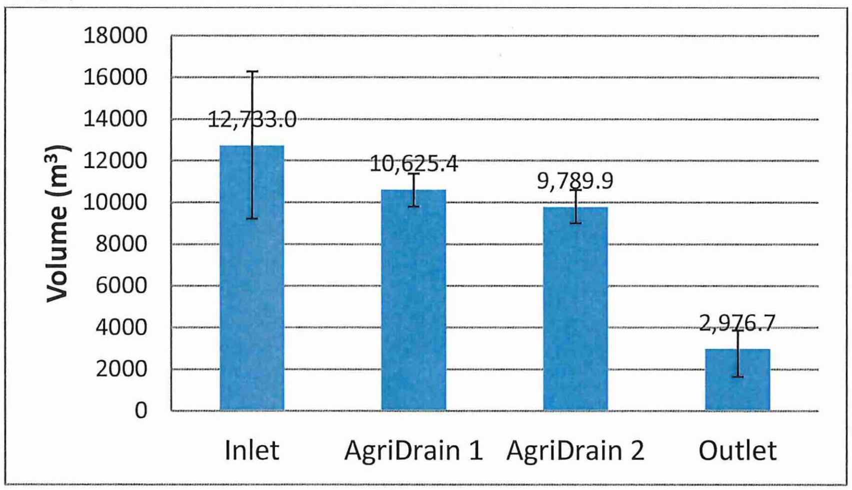


Figure 18. Water volumes flowing through the inlet, both Agri Drain structures, and the outlet in 2014.

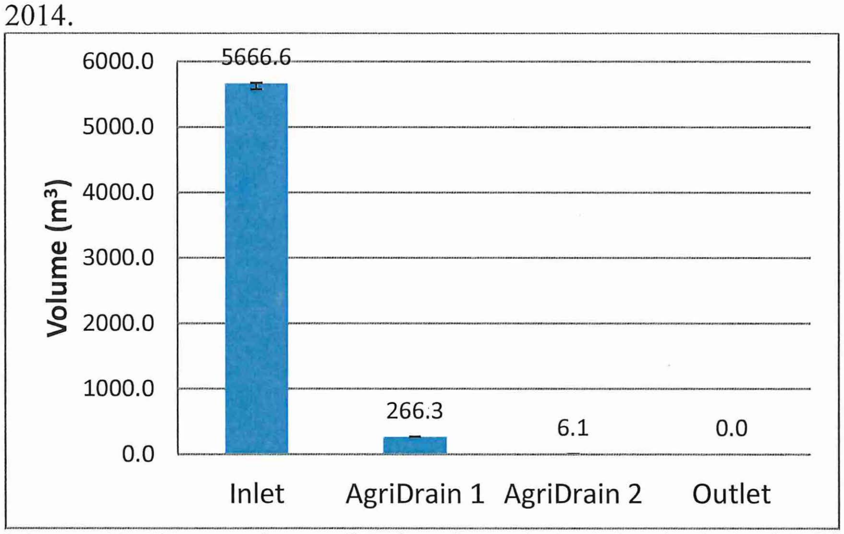


Figure 19. Water volumes flowing through the inlet, both Agri Drain structures, and the outlet in 2014.

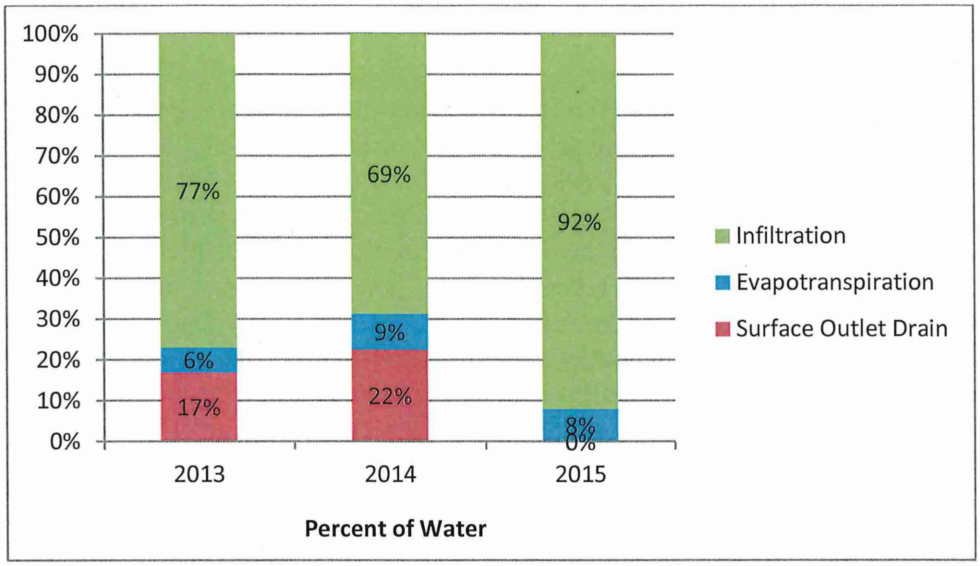


Figure 20. Outflow distribution of all water which entered the wetland each year. The total water volume includes precipitation.

Table 8. Summary of the inflow and outflow volumes in the wetland each year. The water volumes are displayed individually in the tables and charts above. The water volume ranges display high variability in some cases based on the range of the respective instrument's accuracies and sources of error from calculations.

	2013		2014		2015	
	Water Volume	**Water Volume Range**	**Water Volume**	**Water Volume Range**	**Water Volume**	**Water Volume Range**
INFLOWS (m^3)						
Tile Inflow	7,241	5,287 - 9,196	12,733	9,215 - 16,277	5,667	5,575 - 5,669
Rainfall	513	507 - 518	511	506 – 516	660	654 - 667
OUTFLOWS (m^3)						
Surface Outlet Drain	1,314	920 - 1,708	2,977	1,637 - 2,601	0	0
Evapotranspiration	475	475 - 1,764	1,175	667 – 2,000	492	492 – 1,430
Infiltration	5,815	4,345 - 7,284	9,092	6,673 - 11,528	5,609	5,521 - 5,617

Residence time

Predicted residence from the modeling study (Karlheim 2012) was in the range of 12 hours to 10 days for surface flow. Actual surface water retention time was in the range of 12 hours to 1-2 days. Below the peak outflow level most of the water infiltrated and flowed through the shallow subsurface soil, with a longer residence time of weeks.

Floodwater Retention

The wetland also provided some floodwater retention during large storm events in 2013 and 2014. These events caused Elm Creek to flood into the row crop fields surrounding the wetland. Much of the surrounding crops which were positioned in the floodplain were lost. However, the wetland did store some of the water from Elm Creek and prevented it from flooding more of the crop field. During the flood of 2014, the Leveloggers in each of the AgriDrain structures measured that the height of water was higher in the outlet than in the other structures. This indicates the water was flowing from the outlet toward the inlet. The difference in height of water between the outlet control structure and the first AgriDrain structure was then used to calculate the height of water pouring over the outlet structure's boards. The maximum height while the water was flowing backward was used to estimate the volume at this peak. This volume is approximately 40 m^3. This estimate could be low due to our not having a Levelogger closer to the inlet to determine if flood water was flowing higher than the first AgriDrain structure.

Nutrient Reduction

Although there was more rainfall during the 2015 growing season, there were much lower loads of nitrate/nitrite-N, orthophosphate, and total phosphorus that year than in 2013 or 2014. In the 25-acre watershed, the average nitrate/nitrite-N load leaving the tile drains were 16.4 kg/ha, 21.5 kg/ha, and 7.7 kg/ha for 2013, 2014, and 2015 respectively.

The outflow of nutrients from the wetland outlet to the creek also correlated with the flow volume. The second year, 2014, had the highest inflow of nutrients and the highest release of nutrients. However, 2014 had greater reductions of nitrate/nitrite-N and orthophosphorus than 2013. The third year, 2015, had the greatest reductions of nutrients from the three years due to no water flowing out of the wetland through the outlet in 2015. All water flowing into the wetland in 2015 was removed through transpiration, evaporation, or infiltration.

Table 9. Average nitrate/nitrite-N concentrations flowing from the tile drain into the wetland divided into a drainage season and evapotranspiration season (Fransen 2012).

	Nitrate/Nitrite-N (Standard Deviation; mg/L)		
	2013	**2014**	**2015**
Drainage season (April 14 - June 30)	23.0 (0.9)	16.8 (3.5)	14.5 (0.8)
Evapotranspiration season (July 1 - November 30)	NA	26.0 (NA[a])	14.0 (2.3)

[a] Only one sample was taken after July 1st in 2014.

Table 10. Average orthophosphorus concentrations flowing from the tile drain into the wetland divided into a drainage season and evapotranspiration season (Fransen 2011).

	Orthophosphorus (Standard Deviation; mg/L)		
	2013	2014	2015
Drainage season (April 14 - June 30)	0.036 (0.007)	0.097 (0.064)	0.021 (0.018)
Evapotranspiration season (July 1 - November 30)	NA[a]	NA[b]	0.035 (0.007)

[a]There was no flow in the wetlands during the July 1- Nov. 30 time period in 2013.
[b]No reliable nutrient samples were taken in the July 1-Nov. 30 time period in 2014.

Table 11. Average total phosphorus concentrations flowing from the tile drain into the wetland divided into a drainage season and evapotranspiration season (Fransen 2011).

	Total Phosphorus (Standard Deviation; mg/L)		
	2013	2014	2015
Drainage season (April 14 - June 30)	0.049 (0.008)	0.120 (0.092)	0.041 (0.013)
Evapotranspiration season (July 1 - November 30)	NA	NA	0.038 (0.006)

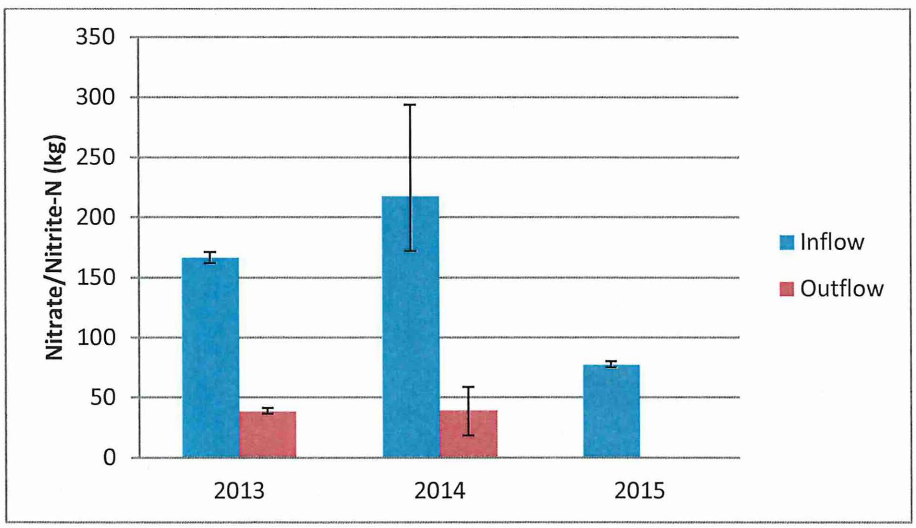


Figure 21. Nitrate/Nitrite-N loads entering the wetland through the inlet and discharging into the creek through the outlet drain each year.

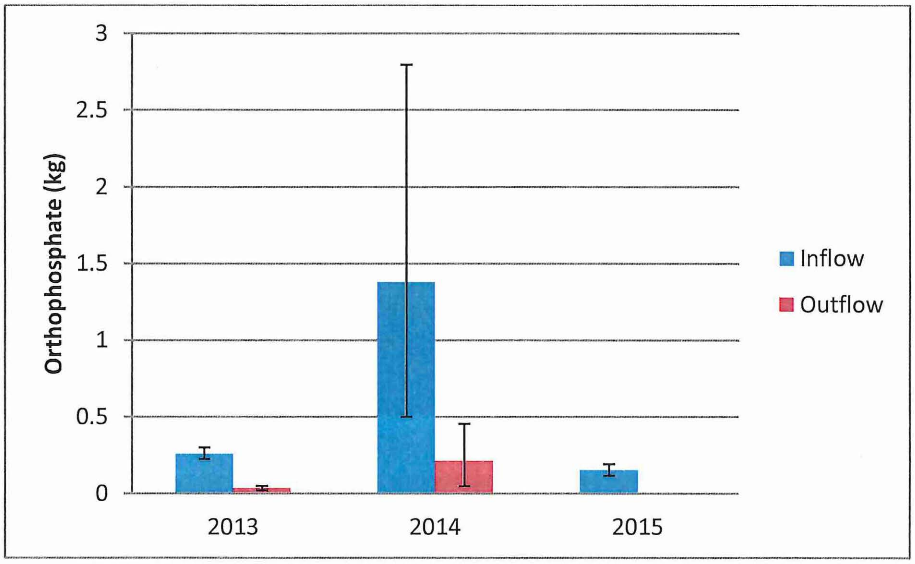


Figure 22. Orthophosphorus loads entering the wetland through the inlet and discharging into the creek through the outlet drain each year.

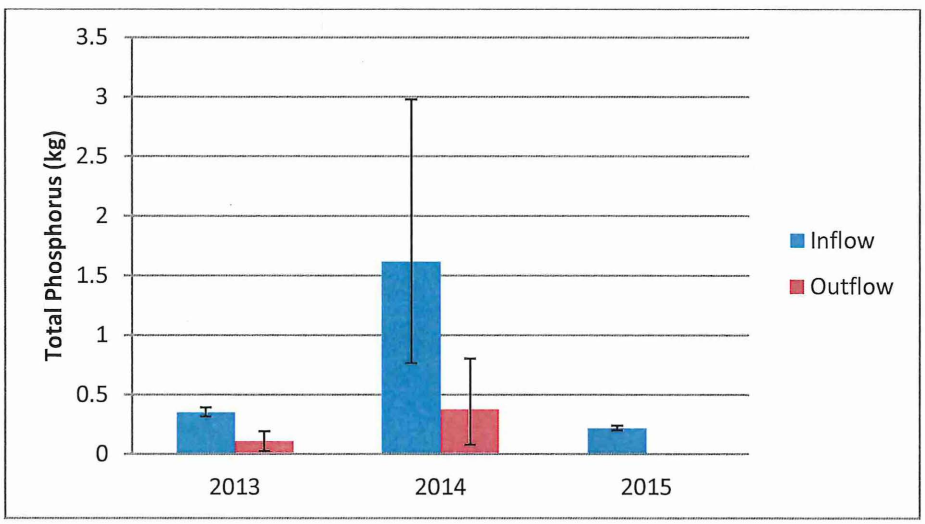


Figure 23. Total phosphorus loads entering the wetland through the inlet and discharging into the creek through the outlet drain each year.

Table 12. Load of nitrogen entering the wetland each year and calculated reduction in the wetland. The area in the denominator is from the treatment area rather than the wetland area.

Year	Nitrate/Nitrite-N Load (kg/ha)	Nitrate/Nitrite-N Reduction (accuracy range[a])
2013	16.5	60% (56-63%)
2014	21.5	68% (63-73%)
2015	7.7	93% (88-98%)

[a]accuracy range – this range is based on hydrology equipment accuracy as well as the standard deviation of nutrient sample concentrations.

Table 13. Calculated masses and distributions of nitrate/nitrite-N in the wetland each year. Estimated ranges are based on equipment accuracy and variation in sample concentrations.

	2013		2014		2015	
	Mass of Nitrate/Nitrite-N (kg)	**Estimated Range**	**Mass of Nitrate/Nitrite-N (kg)**	**Estimated Range**	**Mass of Nitrate/Nitrite-N (kg)**	**Estimated Range**
INFLOW						
Tile Inflow	166.5	161.8-171.1	217.9	171.9-293.7	77.7	75.1-80.3
OUTFLOW						
Surface Outlet Drain	38.9	36.6-41.3	39.6	18.6-58.7	0	0
Subsurface Flow to Creek	27.7	26.4-35.7	30.4	21.1-45.2	5.4	0.6-13.6
REMOVAL						
Surface and Subsurface Removal	98.8	95.4-100.9	108.7	86.0-146.9	72.3	69.8-74.7
Harvest from Vegetation	0.405	0.252-0.558[a]	1.92	1.75-2.09[a]	2.63	2.36-2.90[a]

[a]The estimated ranges of the vegetation harvest is the standard deviation.

Table 14. Summary of nitrate/nitrite-N loads each month in each of the three years.

	Nitrate/Nitrite-N Load by Month (kg)		
	2013	**2014**	**2015**
April	0.0	16.5	1.3
May	0.0	43.7	12.6
June	159.5	89.4	31.5
July	3.4	19.6	14.3
August	3.3	23.3	1.1
September	0.3	12.7	0.3
October	0.0	12.6	0.0
November	0.0	0.0	16.6

Table 15. Summary of orthophosphorus loads each month in each of the three years.

	Orthophosphorus Load by Month (kg)		
	2013	**2014**	**2015**
April	0.000	0.283	0.002
May	0.000	0.314	0.018
June	0.252	0.445	0.045
July	0.005	0.098	0.036
August	0.005	0.116	0.003
September	0.001	0.063	0.001

October	0.000	0.063	0.000
November	0.000	0.000	0.051

Table 16. Summary of total phosphorus loads each month in each of the three years.

	Total Phosphorus Load by Month (kg)		
	2013	2014	2015
April	0.000	0.337	0.003
May	0.000	0.446	0.025
June	0.337	0.473	0.097
July	0.007	0.103	0.031
August	0.007	0.123	0.002
September	0.001	0.067	0.001
October	0.000	0.067	0.000
November	0.000	0.000	0.062

Due to the high percentage of water infiltrating into the subsoil, a large portion of the soluble nutrients also likely infiltrated with that water. While the load of nutrients was much lower in the outlet than the inlet, infiltrated nutrients must be considered when calculating the effectiveness of the wetland at reducing nutrients. If measuring reduction by subtracting the outlet load of nitrate/nitrite-N from the inlet load, there would be 77%, 82%, and 100% reduction in 2013, 2014, and 2015 respectively. However, of those loads each year, up to 76%, 64%, and 99% could have infiltrated. This wetland is positioned on the edge of the floodplain, so any water infiltrating in this wetland will eventually flow to the creek. There is a clay, silty clay layer lining the wetland, but below this layer is a highly permeable sandy alluvium allowing for steady subsurface flow. Through stable isotope analysis, an estimated 78-98% of nitrate infiltrating into subsurface flow was removed as it flowed beneath the wetland in 2015. This percent range was used for 2013 and 2014 infiltration loads to estimate how much nitrate may have been reduced in subsurface flow those years as well. Total nitrate/nitrite-N removal in the wetland was 60%, 68%, and 93% for 2013, 2014, and 2015 respectively. Reductions increased each year, and 2015 was much more effective than the other years.

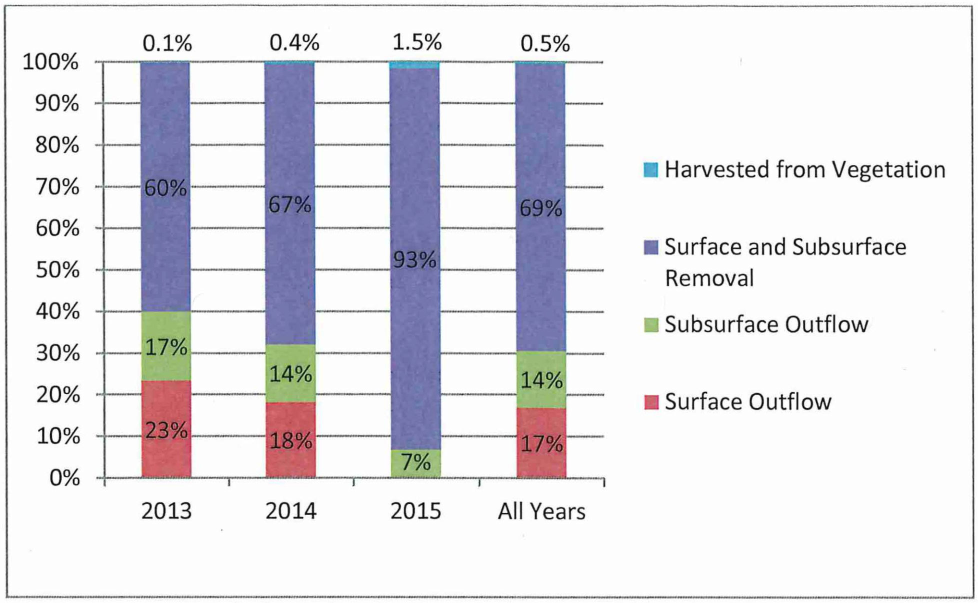


Figure 24. Fates of nitrate/nitrite-N entering the wetland each year. These percentages are the average percent of the nitrate/nitrite-N load which leaves the water through the respective fates.

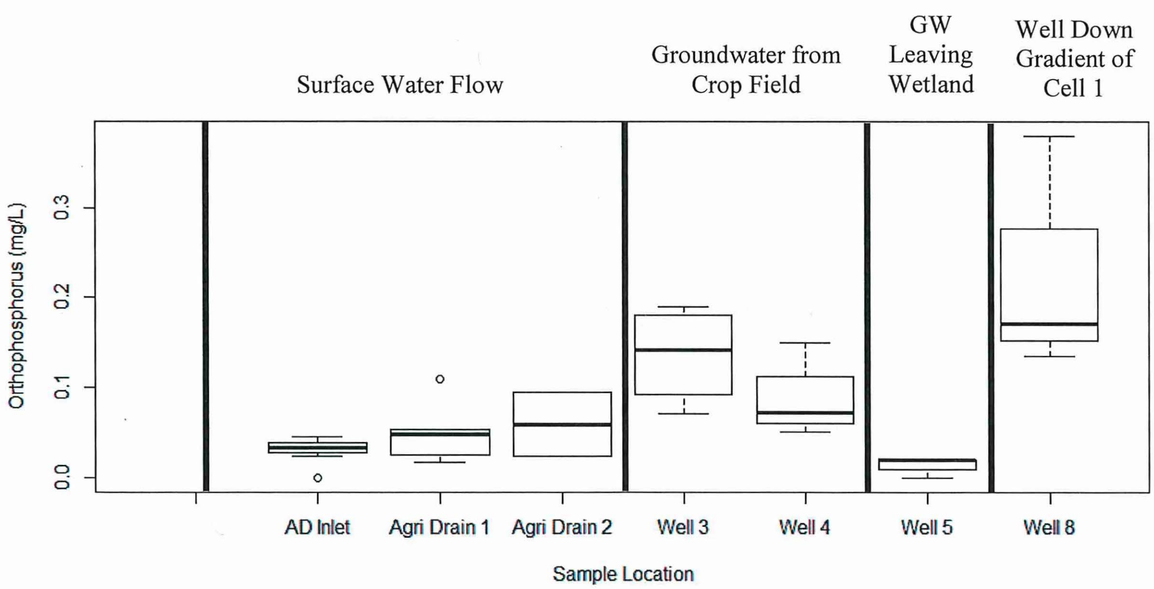


Figure 25. Orthophosphorus concentrations in surface water and subsurface flow of the wetland in 2015. AD Inlet = wetland tile inlet.

There was an overall reduction in phosphorus from the inlet to the outlet of the wetland. However, as with nitrate, much of it likely infiltrated with the large volume of water infiltrating into the subsurface flow each year. It is difficult to measure what portion of the load adsorbed to the soil, but the wells indicated a decrease in dissolved orthophosphorus as the water flowed under the wetland. In 2015, the concentration of orthophosphorus in well 8 was significantly higher than that in the surface water or groundwater from the crop field. Well 8 was positioned down gradient of cell 1 and would have captured both infiltrating surface water and subsurface flow from groundwater. Orthophosphorus concentrations were therefore increasing as the water infiltrated to the subsurface flow. However, these concentrations decreased as they flowed toward well 5 down gradient of wells 3, 4, and 8. Well 5 was positioned on the east end of cell 2, which was down gradient of both cell 1 and cell 2. There was no significant difference between the concentrations of orthophosphorus from the tile inlet and well 5. However, using the isotope analysis to estimate groundwater contribution to mixed wells estimates an approximately 73-77% reduction of orthophosphorus in subsurface flow in 2015. Reductions were likely similar in the previous two years if not higher due to more adsorption sites in the soil still available. Total phosphorus reductions in subsurface flow were not calculated due to the higher variability of reactions in the constituents in total phosphorus.

Table 17. Calculated masses and distributions of total phosphorus in surface water and orthophosphorus in subsurface flow of the wetland each year. Estimated ranges are based on equipment accuracy and variation in sample concentrations.

	2013		2014		2015	
	Mass of phosphorus ($kg\ yr^{-1}$)	**Estimated Range**	**Mass of phosphorus ($kg\ yr^{-1}$)**	**Estimated Range**	**Mass of phosphorus ($kg\ yr^{-1}$)**	**Estimated Range**
			INFLOW			
Tile Inflow	0.352	0.313-0.391	1.618	0.870-1.584	0.220	0.199-0.241
			OUTFLOW			
Surface Outlet Drain	0.109	0.025-0.192	0.375	0.079-0.805	0	0
Subsurface Flow to Creek	0.066	0.061-0.071	0.221	0.204-0.239	0.039	0.036-0.042
			REMOVAL			
Surface and Subsurface Removal	0.092 [a]	0.0160-0.169	0.538 [a]	0-0.230	0 [a]	0
Harvest from Vegetation	0.0854	0.0584-0.112 [b]	0.484	0.357-0.611 [b]	0.474	0.368-0.580 [b]

[a]The surface and subsurface removals are the difference between the inflow and the other, measured outflows and removals (tile inflow - [surface outlet drain + subsurface flow to creek + harvest from vegetation] = surface and subsurface removal). The estimated ranges of the surface and subsurface removals are the difference between the inflow range values and the outflow and vegetation harvest values.
[b]The estimated ranges of the vegetation harvest is the standard deviation.

Costs

Cost estimates were slightly lower per kilogram of nitrogen than Christianson et al. (2013) estimated for other treatment wetlands in the Midwest. However, their costs per hectare were lower than the costs for this specific constructed wetland. This wetland construction included extra hours from students and contractors due to it being a research project. Costs are likely to be lower for this design if research hours are excluded. If cost per kilogram of nitrogen is estimated using the construction costs from this project, then the costs per kilogram are slightly higher than those estimated by Christianson et al. (2013) for other wetlands around the Midwest.

Table 18. Nitrogen load reductions and costs per kilogram of nitrogen reduced over the estimated 50-year lifespan of the wetland. Standards for these calculations, equations, and the estimated lifespan of the wetland are from Christianson et al. (2013). Other best management practices and their estimated costs were also calculated by Christianson et al. (2013) for comparison. Hectares represent the treatment area rather than the wetland area.

	Annual Costs (area based)		N Load Reduction				Annual Costs (N-based)			
	Min. ($ ha^{-1} yr^{-1})	Max. ($ ha^{-1} yr^{-1})	25^{th} (%)	75^{th} (%)	Mean (%)	Median (%)	Mean (Standard Deviation, $ kg N $removed^{-1}$ yr^{-1})	Median ($ kg N $removed^{-1}$ yr^{-1})	Minimum ($ kg N $removed^{-1}$ yr^{-1})	Maximum ($ kg N $removed^{-1}$ yr^{-1})
Midwest Wetlands[a]	$31.00	$43.00	30.9	55.0	42.8	40.0	$2.90 ($0.80)	$2.80	$1.80	$4.40
Darwin Wetland with Midwest Costs[b]	$31.00	$43.00	60.0[d]	93.0[d]	73.6	68.0	$1.64 ($0.39)	$1.56	$1.06	$2.28
Darwin Wetland with Project Costs[c]	$92.00	$138.00	60.0[d]	93.0[d]	73.6[d]	68.0[d]	$5.10 ($1.38)	$4.80	$3.15	$7.32

[a] Midwest wetlands represent the wetland costs and reductions from Christianson et al. (2013).
[b] Darwin Wetland is the constructed wetland in this project. First calculations were made using the construction and maintenance cost estimates from the Midwest Wetlands but with the reductions from this research project.
[c] Darwin Wetland is the constructed wetland in this project. The second set of calculations was made using approximate costs for designing and constructed this treatment wetland ($20,000-30,000; estimates may vary depending on opinions of how much money was spent for research versus design and construction).
[d] N load reductions for Darwin Wetland have only three years of data to date. Therefore, the 25^{th} and 75^{th} percentiles were minimums and maximums for the Darwin Wetland. However, Christianson et al. (2013) used 25^{th} and 75^{th} percentiles, so those were the values available for comparison.

Conclusions

Water entering this wetland was almost entirely from tile drainage with the exception of precipitation. Each of the three years differed in volumes of water entering the wetland. The flow through the wetland was heavily impacted by few large rain events in the first two years. In the third year, the total rainfall was similar, but the rain events were all smaller and more evenly distributed. Water flowing through the surface of the wetland and then flowing through the outlet seems dependent on large rain events. This was especially evident since no water flowed through the surface outlet in the third year. However, the majority of water which entered this wetland infiltrated into the subsurface flow. This subsurface flow allowed more time for nitrate to be denitrified. While the most biologically active area is in the top layer of soil, denitrification still occurs below that surface. While this wetland was treating a smaller drainage area than many other agricultural treatment wetlands, and therefore a smaller load, it did reduce a high percentage of nitrate compared to other wetlands.

The nitrate-N load was lowest in the third year. The concentration of nitrate was highest in the first two years which may have been due to multiple factors. The year before the wetland was constructed was relatively dry, so much of the nitrogen from that year may have been released in 2013, the first year of this wetland study. The second year also had high concentrations of nitrate, but they were only over 20 mg/L for a few weeks of that growing season. The third year had consistently lower concentrations of nitrate. This final year may have been influenced by the farmer's use of a cereal rye cover crop in the spring as well as slow-release urea instead of anhydrous ammonia. The load of nitrate-N also was influenced by the lower volume of water entering the wetland in 2015. Phosphorus followed similar trends each of these years likely for similar reasons. Of these three years, removal of nutrients improved each year with 2015 having the greatest removal efficiency. This was partly due to no water leaving the surface outlet. However, vegetation biomass increased each year and likely influenced the nutrient removal. Furthermore, vegetation harvest removed more phosphorus than what entered the wetland in 2015, so vegetation was mining nutrients from the soil.

Construction and maintenance costs for this design will also likely be lower than this project's costs due to fewer research hours, so the cost per kg of nitrogen removed may be lower than most wetlands. Furthermore, it provides the potential for more efficient phosphorus removal than most wetlands because of its drier soil in the late summer and fall. Most wetlands are too wet to use equipment for vegetation harvesting, but this design would allow equipment to harvest vegetation and thus remove large portions of phosphorus in the fall each year.

VEGETATION STUDY

Introduction

The use of emergent, submerged or free floating macrophytes in constructed wetlands to remove, transform, or stabilize contaminants in agricultural runoff, known as phytoremediation, is a cost effective and environmentally sensitive method to mitigate water pollution (Dhir *et al.,* 2009; Hammer, 1989). The presence of macrophytes can result in higher treatment efficiency relative to unvegetated constructed wetlands (Vymazal, 2011). Furthermore, removing aboveground vegetative growth can enhance the nutrient removal capability and provide biomass for sustainable energy production. However, macrophyte composition in constructed wetlands greatly impacts the effectiveness of nutrient retention and thus, nutrient removal via harvest and biomass quality (Dhir *et al.,* 2009; Vymazal 2011).

Many constructed treatment wetland systems have been established around North America, yet few treatment wetlands have been built in agricultural watersheds of the upper Midwest. Wetlands restored in western Martin County for multipurpose water quality, duck habitat and recreational goals proved very effective at removing nitrate and reducing peak flow of surface runoff, but phosphorus removal was less effective (Lenhart et al. 2010, Fransen 2012). Given the current value of corn and soybeans there is strong economic pressure to find water storage and treatment approaches that fit into marginal farmland areas, such as stream valleys that are frequently flooded. Stream valleys in agricultural regions of Minnesota have distinct soil, topography and hydrology that will determine their effectiveness or lack of effectiveness at removing sediment and nutrients. For example the presence of clay soils would limit the infiltration capacity of drainage water in the treatment wetland, while sandier, alluvial soils would more quickly infiltrate drainage water.

Restored and reconstructed wetlands in areas with high phosphorus content in the soils tend to release phosphorus (stored as residual P in the soils) to water in wetlands that may be discharged into streams. Perennial crops that are adapted to wet soil conditions, or along the fringe of wetlands, have the capacity to aid in removing excess phosphorus from wetlands and thus provide an opportunity for addressing phosphorus in drainage water and wetlands used to treat those waters.

Our objectives were to assess the effectiveness of vegetative systems of varying diversity within the treatment wetland, and to assess the potential of wetland vegetation to serve as a bioenergy feedstock.

Deliverables:

1. Dry matter productivity of vegetative treatments will be estimated for each treatment in each year. This information will be used to determine the potential of these systems for dedicated bioenergy feedstock production.

2. Aboveground plant tissue nutrient concentrations will be estimated for each treatment in each year. This data will be used to calculate plant nutrient uptake and compare potential nutrient removal in biomass harvests for each vegetative treatment in each year.

3. Plant nutrient uptake data will be synthesized with water sampling data to determine overall treatment effectiveness of each vegetative treatment as well as to assess the relative effectiveness of plant nutrient uptake from tile effluent water relative to other wetland removal processes.

Methods

In early May 2013, three vegetative treatments were seeded in the wetland along with an oat cover crop. Vegetative treatments included a low diversity wet prairie mix (12 species; Table III1), a medium diversity wet prairie mix (20 species; Table III2), and a high diversity wet prairie mix (32 species; Table III-3), which were seeded into Cells 1, 2, and 3, respectively. Following wetland construction, a firm seed bed was prepared in each wetland cell and seed mixes were broadcast by hand and raked lightly into the soil. Heavy precipitation from June 21 through June 23, 2013 resulted in flash flooding, which at its peak rose above the interior berms. The flooding washed much of the seed out of the first wetland cell. Cell 1 was reseeded in early August with a 23 species native mixture (Table III-4).

On September 10, 2014, spot spraying of reed canary grass was conducted with a.i. glyphosate [2-[(phosphonomethyl)amino]acetic acid]. On June 19 and again on September 19, 2015 spot spraying of reed canary grass was conducted with a tank mix of 18% a.i. glyphosate [2-[(phosphonomethyl)amino]acetic acid] and 0.73% a.i. diquat dobromide [1,1'-Ethylene-2,2'-bipyridyldiylium dibromide].

In fall 2013 and spring 2014, counts of plant populations and visual estimates of ground cover were conducted to assess stand establishment and stand vigor. Percent vegetative cover by functional group was visually estimated using six cover classes in two randomly selected 0.25-m^2 quadrats in each plot. The cover class midpoints of each observation were then averaged.

Biomass yield was determined each year by harvesting and weighing a two representative 1 m×1 m area to a 1.5-cm stubble height within each plot in early November each year following a killing frost (− 2 °C). Samples were weighed wet in the field following harvest. The samples were then dried in a 60-°C oven to a constant weight and weighed again to obtain biomass dry matter yield (hereafter referred to as "biomass yield") and moisture content. Randomly collected sub- samples were ground with a Wiley mill (Thomas-Wiley Mill Co., Philadelphia, PA, USA) to pass a 1-mm screen and then reground with a cyclone mill. Biomass P concentrations were determined with inductively coupled plasma (ICP) mass spectroscopy following digestion with HNO3 and H2O2 , while biomass N concentration was determined via dry combustion and a Perkin-Elmer 2400CHNS Analyzer (Perkin-Elmer Inc.,Waltham, MA, USA) at a commercial laboratory (Brookside Laboratories, New Bremen, OH or Agvise Laboratories, Benson, MN). Each subsample was also analyzed for cell wall polysaccharides using a combination of wet chemistry (Theander and Aman 1995) and near-infrared reflectance spectroscopy (NIRS) (Vogel et al. 2010). Equations for NIRS were developed using the software program Calibrate (NIRS 3 version 4.0, Infrasoft International, Port Matilda, PA) with the modified partial least squares regression option (Shenk and Westerhaus 1991). Ethanol potential was calculated based on biomass 5- and 6-carbon sugar concentrations with the following equation (Jungers et al. 2015b):

Theoretical ethanol yield L Mg^{-1}

((% Arabinose + % Xylose) x 737.55 + (% Glucose + % Galactose + % Mannose) x 720.66)

Land ethanol yield was calculated by multiplying ethanol potential by biomass yield. Nutrient export was calculated by multiplying biomass nutrient concentrations by biomass yield.

Results & Discussion

Vegetation establishment

By early June 2013, oat cover crop emergence was evident (10.8 plants m^{-2}), though no other seeded species were observed. Heavy precipitation from June 21 through June 23, 2013 resulted in flash flooding, which at its peak rose above the interior berms. The vegetation was submerged for 6 – 10 days, with the duration decreasing from cell 1 to cell 3. The flooding resulted in high mortality of the oat cover crop and washed much of the seed out of the first wetland cell. Cell 1 was reseeded in early August with a 23 species native mixture.

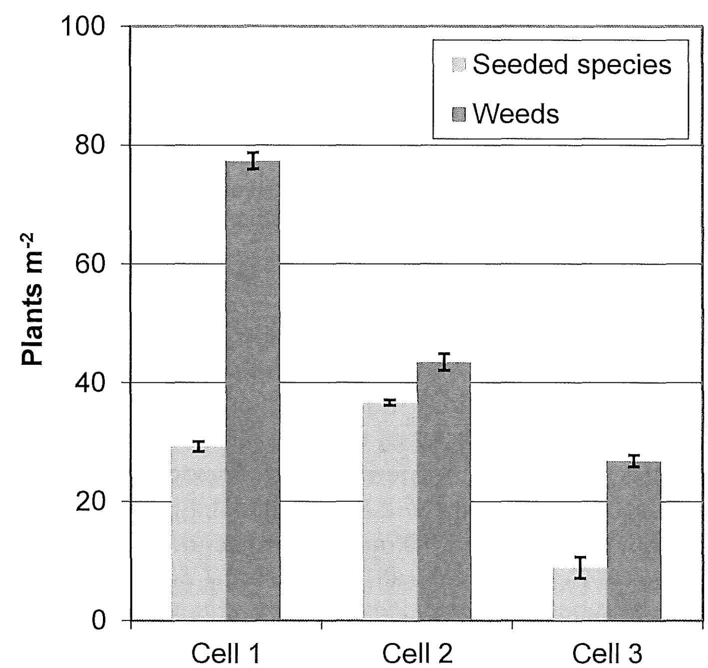


Figure 26: Treatment wetland plant counts by cell on October 7, 2013 following the establishment year. Error bars represent one standard error of the mean.

By October 2013, native species seedling emergence ranged from 14.0 to 38.0 seedlings m^{-2}, and was lowest in Cell 3 (**Figure 26**). Emergence was similar in Cells 1 and 2. Weed emergence ranged from 26.9 to 77.4 weeds m^{-2}, and was greatest in Cell 1 and lowest in Cell 3. Native species establishment index was similar in Cells 1 ($\mu = 0.020$) and 2 ($\mu = 0.020$), but lower in Cell 3 ($\mu = 0.009$; **Table 19**). The establishment indices observed in this study are substantially lower than indices reported for similar native perennials established in the area. Gamble et al.

(2014) found establishment indices ranging from 0.18 to 0.21 for an 11 species native polyculture grown in agroforestry. However, Mangan et al (2011) found an average establishment index of 0.05 for a similar native polyculture that was broadcast seeded at eight Minnesota sites, which is only slightly higher than indices observed in the treatment wetland. Native plants can be challenging to establish in the upper Midwest because of occasionally poor seedling vigor and significant competition with annual and perennial weeds. This challenge is even greater in a treatment wetland setting where water levels in spring are variable and unpredictable. This highlights the value of fall seeding such plantings to improve the likelihood of establishment success on the first try

Table 19 : Seeding rate, emergence, and establishment index for treatment wetland vegetation following the establishment year. Means are presented followed by standard errors in parenthesis.

	Seeding rate (PLS m^{-2})	Emergence (seedlings m^{-2})	Establishment Index
Cell 1	1672	32.7 (7.5)	0.020 (0.004)
Cell 2	1664	38.0 (5.3)	0.023 (0.003)
Cell 3	1631	14.0 (5.4)	0.009 (0.003)

Botanical survey of the wetland in fall 2013 revealed that, across wetland cells, *Verbena hastata* was the most commonly observed seeded species, followed by *Panicum virgatum*, *Carex* spp., *Asclepias incarnata* and *Spartina pectinata* (**Table 20**). The only other seeded species observed was *Desmodium canadense*, though only a single individual was observed in Cell 1. The most commonly observed identifiable weed species were *Amaranthus* spp., *Populus deltoides*, and *Phalaris arundinacea*, though many species of weeds were unidentifiable at this time. Grass weeds were the most commonly observed plants in the treatment wetland following the first growing season.

Table 20: Most frequently occurring seeded and weed species across wetland cells in the treatment wetland on October 7, 2013

		Plants m^{-2}	
	Species or category	**Mean**	**SEM**
Seeded species	*Verbena hastata*	10.3	2.7
	Panicum virgatum	8.0	2.6
	Carex spp.	3.4	2.5
	Asclepias incarnata	3.4	0.8
	Spartina pectinata	1.9	1.3
Weeds	*Amaranthus* spp.	5.3	1.7
	Populus deltoides	1.9	0.8
	Phalaris arundinacea	1.5	1.0
	Other broadleaves	9.1	2.5
	Other grasses	39.2	8.6

Ground cover, stand vigor, and weed management

In fall 2013, ground cover was predominated by weed species in each wetland cell, with up to 69% cover in Cell 1 (**Figure 27**). Forbs also provided substantial ground cover in Cells 1 and 2, while reed canary grass cover was nearly 30% in Cell 3. In fall 2014, cover of desired (seeded) species increased relative to 2013, but reed canary grass (*Phalaris arundinacea* L.) also became more prominent in Cells 1 and 2. Reed canary grass cover in Cell 3 was similar in 2013 and 2014. Cover of all other weed species declined in each cell from 2013 to 2014. Forb cover in Cell 1 increased substantially from 2013 to 2014, but declined substantially in Cell 2. Forb cover in Cell 3 was similar from 2013 to 2014. Warm season (C_4) grass cover increased substantially in each cell from 2013 to 2014. On September 10, 2014, spot spraying of reed canary grass was conducted with a.i. glyphosate [2-[(phosphonomethyl)amino]acetic acid].

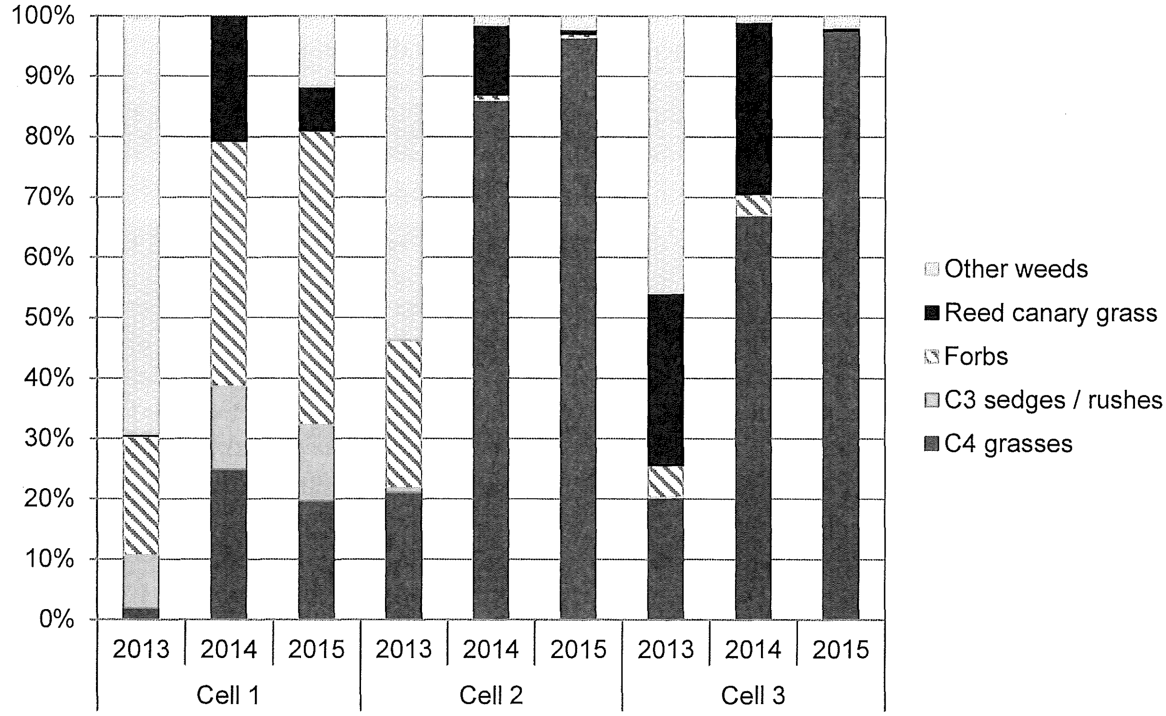


Figure 27: Botanical composition of treatment wetland cells by year.

In spring 2015, plant emergence revealed that fall 2014 chemical treatment was effective in controlling reed canary grass (*Phalaris arundinacea* L.) in Cells 2 and 3 of the treatment wetland. Visual observations were that reed canary grass populations were much reduced in these cells relative to fall 2014, while populations of desired (seeded) species were increasing. However, reed canary grass populations were increased in Cell 1 and on wetland berms relative to fall 2014. On June 19, 2015 spot spraying of reed canary grass was conducted with a tank mix of 18% a.i. glyphosate [2-[(phosphonomethyl)amino]acetic acid] and 0.73% a.i. diquat dobromide [1,1'-Ethylene-2,2'-bipyridyldiylium dibromide]. Visual observations were that reed canary grass mortality was extensive following the June 19 chemical application. However, some live reed canary grass was still present. On September 19, 2015 spot spraying of reed canary grass was conducted with a tank mix of 18% a.i. glyphosate [2-

[(phosphonomethyl)amino]acetic acid] and 0.73% a.i. diquat dobromide [1,1'-Ethylene-2,2'-bipyridyldiylium dibromide].

By November 2015, the predominant ground cover in Cell 1 was forbs. Weeds comprised less than 20% of ground cover in this cell, while cover of C_4 grasses and C_3 sedges and rushes was about 20% and 13%, respectively. By 2015, ground cover in both Cells 2 and 3 was over 90% C_4 grasses (Switchgrass and prairie cordgrass). Weed cover declined in these cells from 2014 to 2015. Over time, the proportion of seeded species increased in each cell, while the proportion of weeds decreased. However, Cells 2 and 3 have low species diversity, with very little forb or sedge and rush cover.

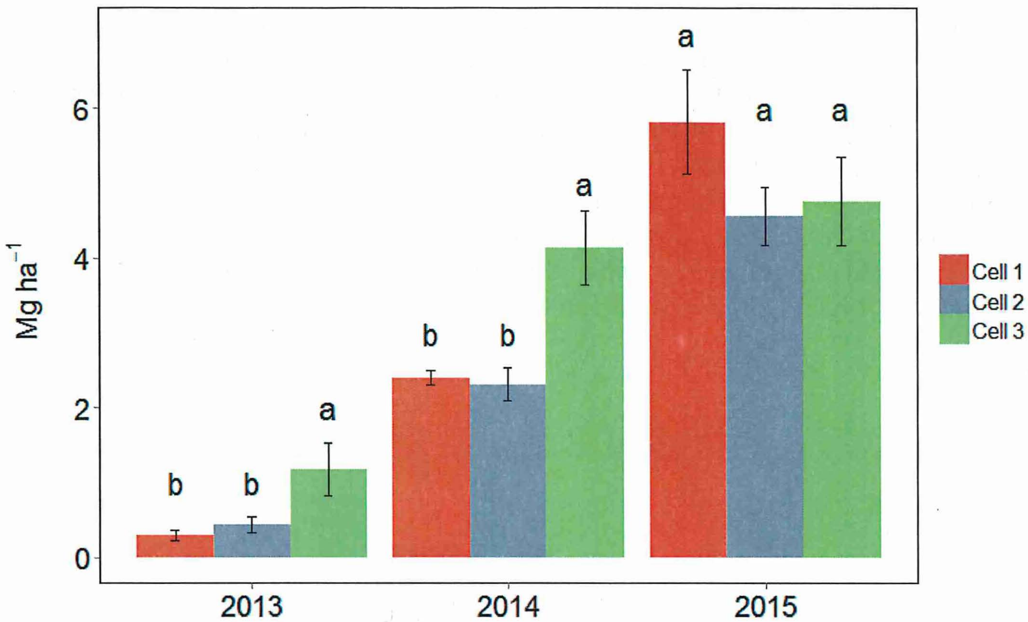


Figure 28: Treatment wetland biomass yield by cell and year. Error bars represent one standard error of the mean. Within years, bars with the same letter are not different (Tukey HSD, α = 0.05)

Biomass, ethanol yields, and nutrient export

Total biomass yield of all vegetation in the treatment wetland ranged from 0.2 to 9.8 Mg ha^{-1} and varied by Cell and year. In 2013 and 2014, yield was greatest in Cell 3 and similar in Cells 1 and 2 (**Figure 28**). In 2015, yield was similar among cells. Within Cells 1 and 2, yield was lowest in 2013 and increased each year to 2015. In Cell 3, yield was lowest in 2013 and similar in 2014 and 2015. When averaged across cells, biomass yield increased from 2013 to 2014, and again from 2014 to 2015.

Biomass yields in this study were similar to reports of yields of other low-input perennial herbaceous crops in the region, but were lower, in general, than yields of fertilized herbaceous perennial biomass crops. For example, (Boe et al. 2009; Johnson et al. 2013),reported yields of mature prairie cordgrass of up to 14.9 Mg ha^{-1} yr^{-1} in fertilized monocultures. reported yields of mature native polyculture bioenergy crops in Minnesota. Reported yields of low-input polycultures, which are typically unfertilized, vary widely from 0.5 to 7.6 Mg ha^{-1} yr^{-1} depending on site characteristics and species composition (Mangan et al. 2011; Gillitzer et al. 2012; Jungers et al. 2013; Johnson et al. 2013; Jungers et al. 2015a). By 2015, average biomass yield for the entire wetland was 5.0 Mg ha^{-1}, which is within the range reported above for low-input native polycultures. Biomass yields in emergent wetlands are often higher than yields in the present study. For instance, Cicek et al. (2006) reported an annual yield of 9.1 Mg ha^{-1} for emergent vegetation in a natural marsh associated with Lake Winnipeg and Dubbe et al. (1988) reported that yields of *Typha* spp. can range up to 22 Mg ha^{-1} yr^{-1}. Sizing treatment wetlands to increase water retention time may allow for use of more productive species, such as *Typha,* which would increase biomass yields.

Theoretical ethanol yield (TEY) of wetland biomass varied by Cell in 2015. Biomass in Cell 1had a TEY = 414 L Mg^{-1}, which was lower than Cells 2 and 3 (500 and 491 L Mg^{-1}, respectively). This was likely due to the high proportion switchgrass and prairie cordgrass in Cells 2 and 3. Cover of C4 grasses is often positively correlated to TEY (Jungers et al. 2013). Despite differences in TEY, Land Ethanol Yield (LEY) was similar among wetland Cells, averaging 2.389 L ha^{-1}. While not statistically significant, arithmetic mean biomass yields were higher in Cell 1 than other Cells, which explains why LEY was similar among Cells despite lower TEY in Cell 1. Land ethanol yield found in this study is similar to other low-input grasslands in Minnesota, which typically yield 1,600 – 2,200 L ha^{-1} (Jungers et al. 2015b).

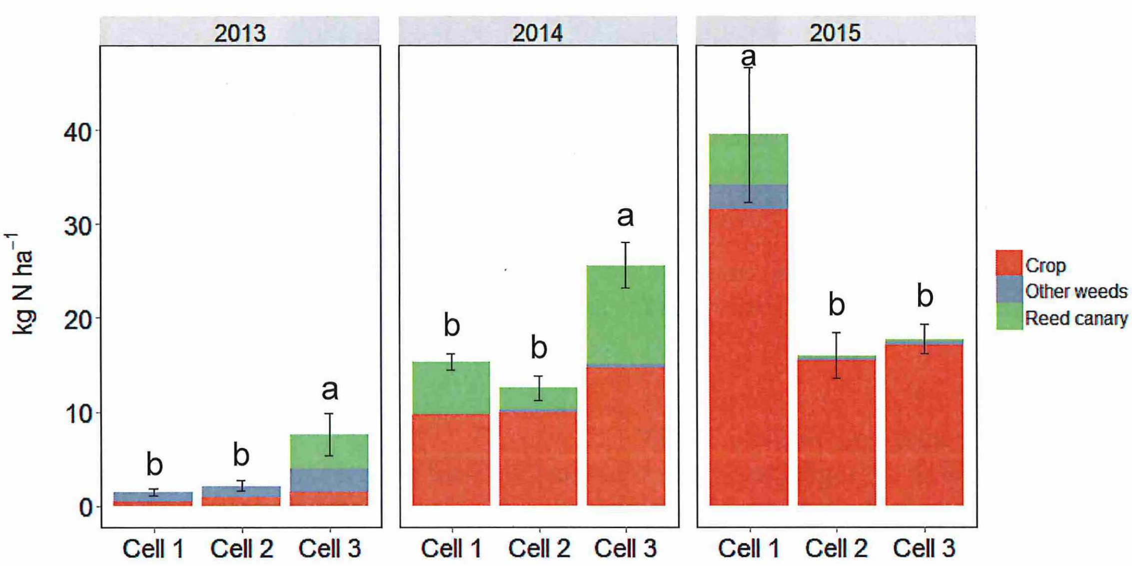


Figure 29: Nitrogen export by cell and vegetation type from 2013 to 2015. Error bars represent one standard error of the mean for the sum of N export for all vegetation types. Within years, bars with the same letter are not different (Tukey HSD, $\alpha = 0.05$)

Nitrogen export in harvested biomass ranged from 0.8 to 80.5 kg N ha^{-1} and varied by wetland cell within each year. In 2013, N export was greatest in Cell 3, and a larger fraction of N was exported in weeds than in crop (seeded species) biomass (**Figure 29**). In 2014, N export was greatest in Cell 3, and larger fraction of N was exported in crop than reed canary grass or other weed biomass. In 2015, N export was greatest in Cell 1 and the largest fraction of N was exported in crop biomass. When averaged across cells, N exported in weed biomass increased from 2013 to 2014, then decreased from 2014 to 2015. In contrast, the amount of N exported in crop biomass increased each year of the study. Total N export in harvested (weed + crop) biomass was 3.7 kg ha^{-1} in 2013, 17.8 kg ha^{-1} in 2014, and 24.4 kg ha^{-1} in 2015.

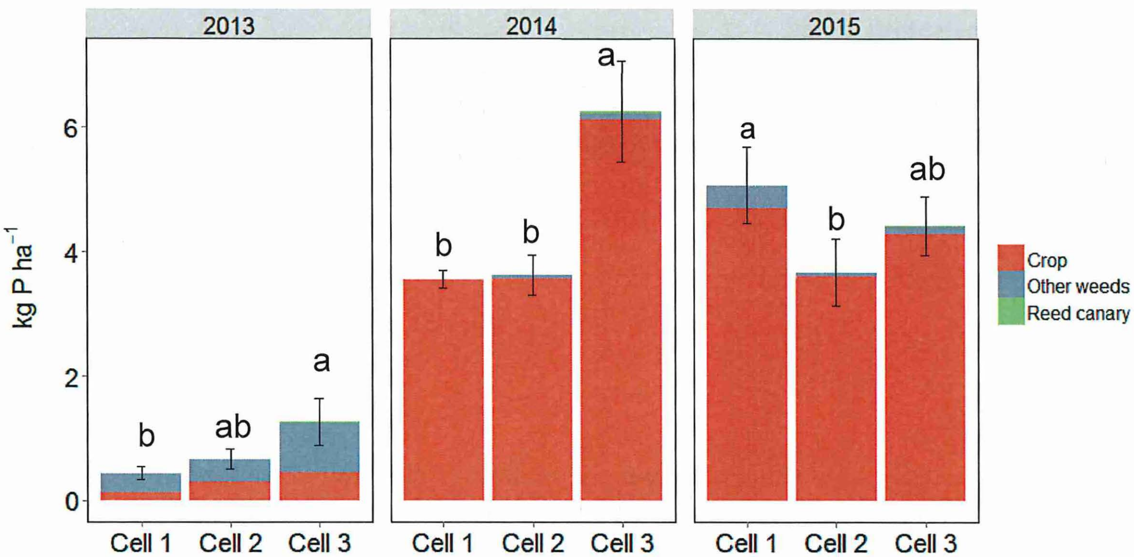


Figure 30: Phosphorus export by cell and vegetation type from 2013 to 2015. Error bars represent one standard error of the mean for the sum of P export for all vegetation types. Within years, bars with the same letter are not different (Tukey HSD, $\alpha = 0.05$)

Phosphorus export ranged from 0.2 to 11.5 kg P ha^{-1} and varied by wetland cell within each year. In 2013, P export was greater in Cell 3 than Cell 1, and a larger fraction of N was exported in weeds than in crop biomass in each Cell (**Figure 30**). In 2014, P export was greatest in Cell 3, and larger fraction of P was exported in crop than reed canary grass or other weed biomass. In 2015, P export was greater in Cell 1 than Cell 2, and the largest fraction of P was exported in crop biomass. When averaged across cells, P exported in weed biomass decreased from 2013 to 2014, then increased slightly from 2014 to 2015. In contrast, the amount of P exported in crop biomass increased from 2013 to 2014, then remained similar from 2014 to 2015. Total P export in harvested (weed + crop) biomass was 0.8 kg ha^{-1} in 2013, 4.5 kg ha^{-1} in 2014, and 4.4 kg ha^{-1} in 2015.

To calculate the contribution of vegetation harvest to total N and P load reduction, area based estimates of nutrient export were multiplied by the total surface area of each wetland cell (0.036 ha) and summed. In 2013, vegetation harvest removed a total of 0.4 kg N and 0.09 kg P, representing < 1% and 24% of the total N and P loads (**Table 21**). In 2014, vegetation harvest removed a total of 1.92 kg N and 0.48 kg P, representing < 1% and 41% of the total N and P loads. In 2015, vegetation harvest removed a total of 2.63 kg N and 0.47 kg P, representing

3.4% and 215% of the total N and P loads. Over the study period, vegetation harvest resulted in removal of 4.95 kg N and 1.03 kg P, representing 1% and 60% of the total N and P loads from 2013 to 2015. This reduction in P loads is larger than other reports for harvested wetland vegetation. For example, Cicek et al. (2006) reported than annual harvest of marsh vegetation resulted in total P removal rates equal to 3.8 – 4.7% of total P loading to a natural marsh near with Lake Winnipeg. However, total P loading in the present study was quite low relative to that in the study by Cicek et al. (2006).

Table 21: Contribution of vegetation harvest to N and P load reduction in the treatment wetland over the study period.

	2013		2014		2015		Sum	
	kg $year^{-1}$	Load reduction	kg $year^{-1}$	Load reduction	kg $year^{-1}$	Load reduction	kg $year^{-1}$	Load reduction
N	0.40	< 1%	1.92	< 1%	2.63	3.4%	4.96	1%
P	0.09	24%	0.48	41%	0.47	215%	1.04	60%

Conclusions

Over the first three years following establishment, biomass yields from a wetland designed for treatment of tile drainage water were generally lower than fertilized monocultures of herbaceous bioenergy crops, but similar to yield of low-input perennial grasslands managed for bioenergy. Export of N from vegetation harvest was low compared to other removal pathways, but biomass harvest resulted in export of 60% of the inlet P load over the study period. These results suggest that vegetation harvest can have a substantial impact on the P treatment efficiency of similar wetlands, and that biomass harvest from such wetlands could contribute to bioenergy production as part of a larger, landscape-scale approach to biomass feedstock production.

MESOCOSM STUDY

Introduction

This portion of the project aimed to understand some of the roles of soil and vegetation on nitrate removal in newly constructed treatment wetlands. The mesocosm study had multiple phases performed by graduate and undergraduate students at the University of Minnesota in the Bioproducts and Biosystems Engineering department. The first phase was conducted by Ross (2014) as part of an M.S. thesis on how different soil types from the surrounding agricultural land would impact denitrification if used in the constructed wetland. She also studied how two plant species and one mixture of species planted in these soils would further impact nitrate removal in this system.

The second and third phases of the study researched how three wetland soils compared in nitrate removal and how *Phalaris arundinacea* (reed canary grass; RCG) compared to *Carex crinita* (fringed sedge) in removing nitrate. In the second phase it was found that the remnant wetland soil had significantly hire denitrification rates than the control (bare sand) and soils obtained from the treatment wetland area. The third phase was conducted by Brad Gordon, a PhD candidate in water resources science. One aspect of the wetlands that needs more research is the impact of invasive species cover and microbial populations in treatment wetlands. When constructing treatment wetlands, native vegetation is recommended but invasive species such as reed canary grass (RCG, *Phalaris arundinacea* L.) often dominate. It is recommended in *The Agricultural BMP Handbook for Minnesota* that invasive species should be eliminated prior to the construction of wetlands for biodiversity reasons, but this recommendation is not greatly stressed nor supported with reasons besides biodiversity improvement (Miller *et al.* 2012, MPCA 2014b). More needs to be understood of how these plants impact the effectiveness of treatment wetlands and other BMPs used to treat nitrate runoff, including a better understanding of how well denitrifying bacteria populations establish in new wetlands with and without invasive species.

As RCG invades an area, it degrades the native plant community and often creates a dense monoculture as it replaces the native vegetation (Morrison and Molofsky 1998, Green and Galatowitsch 2001 & 2002, Maurer and Zedler 2002, Kercher and Zedler 2004). Thus, RCG reduces biodiversity in many wetland and riparian plant communities even though it may increase overall productivity. RCG's aggressiveness is and will continue to be a concern in any constructed wetland or ditch developed to treat nutrients from agricultural drainage (Crumpton *et al.* 2012). These systems are often disturbed areas prone to RCG invasion before the native seed establishes. Even following establishment, these systems will likely need managed to prevent RCG dominance due to high concentrations of nitrates tending to select for RCG and the difficulty of removing RCG once it establishes (Teale 1982, Mack 1985, Barrett 1989, Morrison and Molofsky 1998, Galatowitsch *et al.* 1999, Green and Galatowitsch 2001 & 2002, Perry and Galatowitsch 2002, Iannone III and Galatowitsch 2008, Stiles *et al.* 2008). If RCG is invading and potentially converting many BMPs to monocultures over time rather than maintaining a native wetland plant community, the following question is raised: how does RCG compare to a native plant community at removing nitrate in treatment wetlands?

Some previous studies have attempted to address this question. David *et al.* (1997) looked at the effect of carbon availability and temperature on nitrate removal in bare soil and RCG mesocosms. They concluded that denitrification was likely the dominant mechanism for nitrate removal in the treatment wetland while temperatures enhanced the removal. However, they also concluded that the vegetation, RCG, did not play a significant role because the soil containing RCG removed slightly less nitrate in June than bare soil. There seemed to be a better removal in vegetation during April, but most of the flow in our treatment wetland has occurred in June. In another study, Herr-Turoff and Zedler (2005) compared the nutrient uptake of RCG-invaded wetland plant communities to that of a native wet prairie mix due to the presumptions that RCG retains a high level of nitrogen from wetland soil and water. However, they concluded that RCG invasion did not increase nitrogen accumulation in plants, had little effect on soil nitrogen, and did not decrease nitrates in discharged water.

Studies addressing both the uptake of nitrogen by RCG alongside the plant's interaction with denitrifying bacteria are limited. Studies have looked at the plant's nitrogen uptake and partial role in the nutrient cycle, but they seem to be lacking a more intensive look at the plant uptake alongside the denitrifying bacteria populations. An ecological approach to understand the bacteria in the soil relating to the plants rooted in the same soil is necessary. Hoagland *et al.* (2001) mention that approximately 90% of nitrogen removal is by denitrification (Xue *et al.* 1999). As mentioned above, David *et al.* (1997) also concluded that denitrification likely plays a larger role in nitrate removal than plant uptake. The rate of denitrification could also be related to denitrifying bacteria abundance (O'Conner *et al.* 2006, Baxter *et al.* 2012). Thus, if denitrifying bacteria abundance is lower among RCG, denitrification rates may also be lower. Furthermore, if denitrifying bacteria are less abundant in the constructed treatment wetland than other, older wetland soils, then inoculations or carbon provisions may need to be considered to improve denitrification in the early years of the wetland.

Methods

Eleven 100-gallon mesocosms were arranged randomly based on two variables: vegetation type and soil source. The mesocosms were dispersed in the workshop of the Biosystems and Ag Engineering Building on the University of Minnesota St. Paul campus. This space has lighting on a timer, a large door open daily for air flow, and easy access to watering. Nitrate retention has been and will continue to be studied in RCG monocultures and fringed sedge monocultures under 8 mg/l nitrate concentration input. The 100-gallon mesocosms are black high-density structural resin stock tanks measuring 53" x 31" x 25" on the outside. The bottom 11 inches of each mesocosm were filled with crushed sandstone. This was then covered with 6 inches of wetland topsoil from three wetlands (Kittleson->10 years old; Sarita-remnant wetland; and Darwin's-2 years old). Both RCG and the sedge were transplanted from other wetlands or mesocosms. They were rinsed before planting in order to remove soil from their original wetlands. These mesocosms were weeded multiple times throughout the growing season and watered every 3 to 4 days.

Figure 31. Wetland mesocosm located at the University of Minnesota, BBE Department lab.

Treatments were made to mimic the hydrologic regime and nitrate load of row crop tile drainage discharging into a treatment wetland (Crumpton *et al.* 2006). This regime has included intermittent flooding early in the growing season and limited flow later in the season. Before a treatment begins, each mesocosm was rinsed with clean (tap) water for four hours at a rate of 121 Liters/hour (32 gallons/hour). Water was discharged out of the mesocosm through an outlet tube one inch from the rim of the tank thus covering the soil with 6 inches of water each time the mesocosms were filled. After rinsing, the water remained stagnant for a period of 48 hours.

Nitrate treatment began with each mesocosm containing standing water with a nitrate concentration below 4.0 mg/L. Nitrate water was mixed using sodium nitrate to concentrations between 8.0 and 9.0 mg/L NO_3-N. The first two years of this experiment used concentrations of 24.0 mg/L NO_3-N, but others with mesocosm experiments advised that this high of a concentration overwhelms 100-gallon mesocosms. The 8.0 mg/L treatment concentration is a low representation of those often found in a study of Midwestern tile drainage by Kovacic *et al.* (1996), Crumpton *et al.* (2006), Carlson *et al.* (2013), and personal observations in southern Minnesota. Each treatment concentration was pumped into all the mesocosms (3 with RCG, 3 with fringed sedge, and 3 bare soils with one of each in one of the 3 soil types) at 5 gallons/hour for twenty four hours to simulate tile drainage from a rain event. The inflow pipe was placed on the surface at the opposite end of the mesocosm from the outlet tube.

Nitrates were measured immediately before treatment, immediately after the start of the treatment, 4 hours after, and then every 24 hours at the same time the treatment started for ten consecutive days. The rates of outflow and nitrate concentrations were measured from the outflow in order to record the nitrogen load entering and leaving the wetland. The Hach Nitratax sc, UV Nitrate sensor, was placed near the outlet tube for each measurement to maintain consistency. Dissolved oxygen, oxidation reduction potential, pH, and temperature were measured at the outlet at the same time nitrate was measured using a YSI Professional Plus Multiparameter Instrument. The mesocosms were then rinsed with clean (tap) water at the end of 10 days at 32 gallons/hour for four hours with at least 10 measurements of nitrates taken from the outflow to observe what would be discharged in the following rain event.

Following the establishment of vegetation and after the first test in the summer of 2014, 5 soil samples were taken from each of the above mesocosms. Approximately 500 mg of soil (wet weight) was extracted from these samples for DNA analysis. DNA was extracted using the FastDNA SPIN Kit for Soil (MP Biomedicals, LLC) according to the manufacturer's instructions. PCR was used to generate 16S rRNA genes and fragments of the denitrifying primers (16S rRNA and *nosZ*) (Rosch *et al.* 2002). Standard curves were generated using known quantities of template DNA. qPCR was then used to quantify the cell abundance per gram of soil of each of the genes (Rosch *et al.* 2002, Rich *et al.* 2003, Baxter *et al.* 2012). These steps were performed with the LaPara Research Group in the University of Minnesota Department of Civil Engineering. The *nosZ* gene is a key gene in denitrification for nitrous oxide reductase and is the gene most commonly used as a marker in the past to quantify the denitrifying bacteria in soil samples (Rosch *et al.* 2002, Rich *et al.* 2003, Baxter *et al.* 2012).

Studies are planned to continue to examine more of the species used in the treatment wetland seed mix. These will include comparisons of RCG to switch grass (*Panicum virgatum*), sneezeweed (*Helenium autumnale*), swamp milkweed (*Asclepias incarnate*), and other wet prairie species.

Statistical analysis

The first two hypotheses (nitrate released from RCG mesocosms is not significantly different than that from native sedge mesocosms and nitrate reductions in the three soil types do not differ) were analyzed with two-way ANOVA. Tukey's honestly significant difference were used to assess which treatment means differ when ANOVA yielded a significant difference. The third and fourth hypotheses (populations of denitrifying bacteria are less abundant in RCG dominated soils than native sedge vegetated soils and do not differ among soil sources) were analyzed similarly to the first hypothesis.

Results & Discussion

The Sarita wetland is a remnant wetland located on the University of Minnesota St. Paul campus. It treats much of the runoff from the campus. The vegetation surrounding the wetland consists mostly of cattails and floodplain tree species. The soil collected for this experiment came from a section with trees along the perimeter. This soil had a high organic matter, total organic carbon, and ammonium content (**Table 22**).

The Kittleson wetland is a 70-acre restored wetland located in southern Minnesota with a watershed approximately 1,000 acres. It was constructed approximately 15 years prior to this study. This watershed contains row-crop acreage, pastureland, and farmsteads. In a previous study by Lenhart (2008), this wetland removed >85% of its nitrate/nitrite load. Its perimeter consists mostly of cattails, reed canary grass, and river bulrush. The soil collected for this experiment came from an edge with mostly reed canary grass dominating the perimeter. It was much lower in organic matter, ammonium, and organic carbon than the Sarita wetland soil. It also had the highest sand content of any of the three soils (**Table 22**).

Darwin's wetland is the treatment wetland described above as the primary wetland of focus for this study. Similarly to the Kittleson wetland, it had low organic matter and organic carbon percentages. It did have a higher ammonium concentration, but it had a lower total nitrogen percent. It also had the highest clay content (**Table 22**).

Table 22. Difference in properties and nutrients among three wetland soils.

Sample	**NO_3-N***	**NH_4-N***	**LOI OM**	**Sand**	**Silt**	**Clay**
ID	**(ppm)**	**(ppm)**	**(%)**	**(%)**	**(%)**	**(%)**
Sarita Wetland	0.31	23.61	15.5 / 14.6	18.8 / 17.5	36.2 / 37.5	45.0 / 45.0
Darwin's Wetland	< 0.05	16.83	4.4	25.0	28.8	46.3
Kittleson Wetland	0.16 / 0.51	2.45 / 1.74	4.3	50.0	17.5	32.5
	Bray P	**Olsen P**	**Water**	**TOC**	**Total N**	**C/N Ratio**
	(ppm)	**(ppm)**	**pH**	**(% C)**	**(% N)**	
Sarita Wetland	31 / 29	27 / 27	6.9 / 6.8	8.86	0.569	15.58
Darwin's Wetland	7	6	7.5	2.07	0.150	13.77
Kittleson Wetland	2	18	7.5	2.68 / 2.59	0.228 / 0.211	11.74 / 12.26

There was a significant difference in the population of denitrifying bacteria in each soil. Darwin's wetland had the lowest density of all bacteria (16s RNA, **Figure 32**) and denitrifying bacteria (nosZ1, **Figure 33**; and nosZ2, **Figure 34**). It also had a significantly lower population of all bacteria than Kittleson ($p = 0.017$), but it did not differ significantly from Sarita ($p = 0.118$). However, Darwin's soil had a significantly lower population of denitrifying bacteria than both Kittleson and Sarita ($p < 0.001$). The soils containing reed canary grass, cattail, fringed sedge, and no vegetation did not differ significantly in bacteria populations (**Figure 35**, **Figure 36**, and **Figure 37**). There was also a significant difference in the reduction of nitrate among the three soils (**Figure 38**). Darwin's wetland soil had lower nitrate reductions than both Kittleson and Sarita ($p = 0.088$ and 0.019 respectively), but Kittleson and Sarita did not differ. The mesocosms containing reed canary grass also had higher reductions of nitrate than the mesocosms with no vegetation and those with fringed sedge ($p = 0.024$ and 0.0064 respectively). There were no significant differences between the mesocosms with no vegetation and those with fringed sedge.

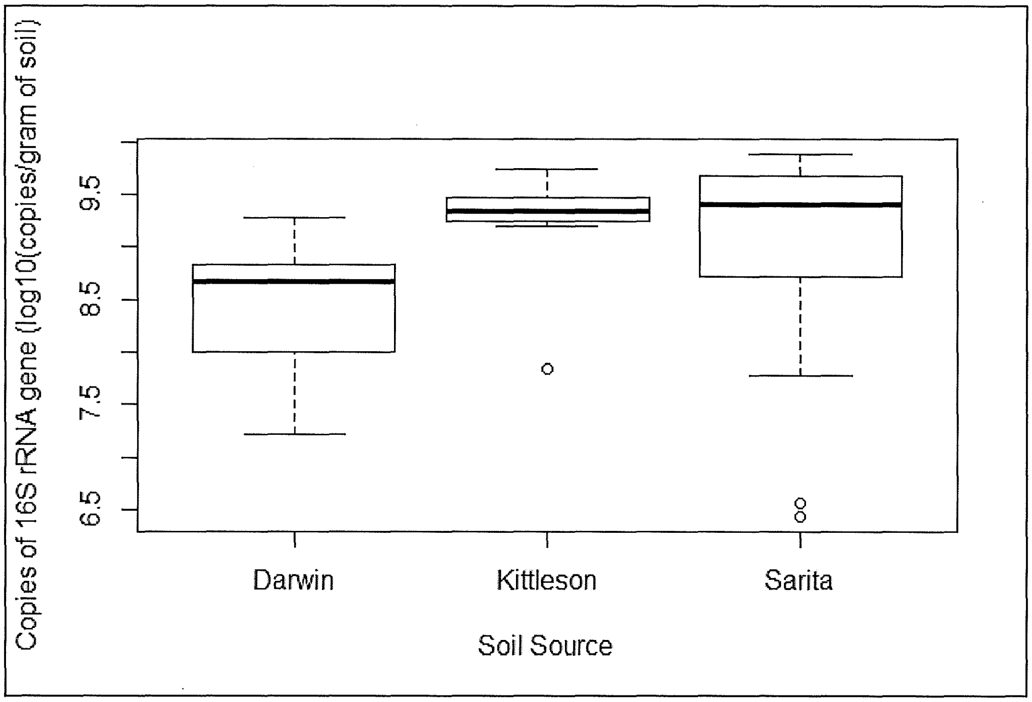


Figure 32. Copies of 16S rDNA gene from all of the mesocosms containing the respective soils.

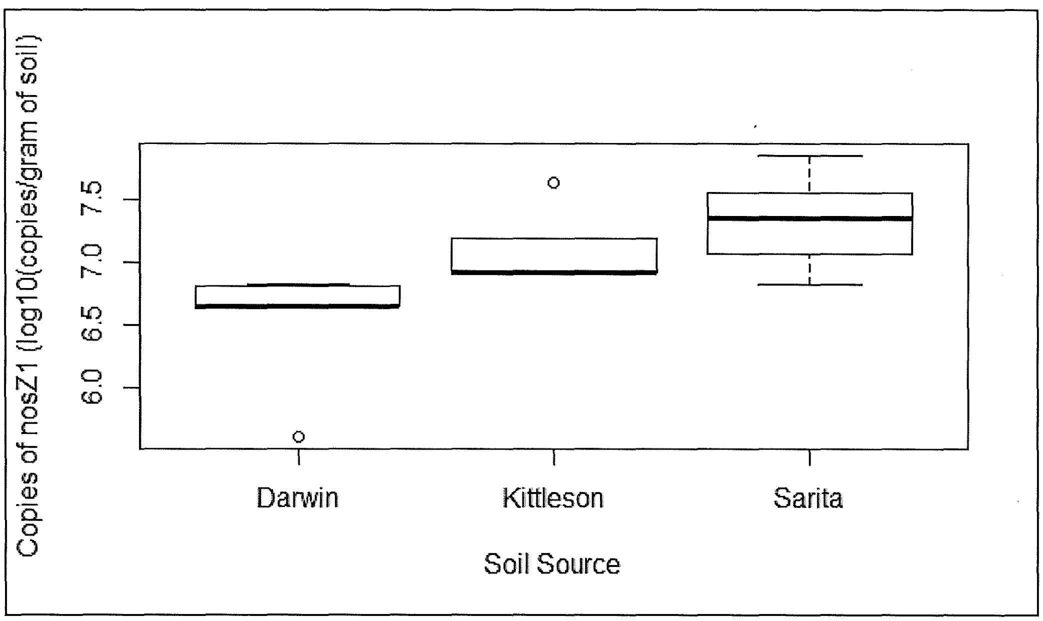


Figure 33. Copies of nosZ1 gene from all of the mesocosms containing the respective soils.

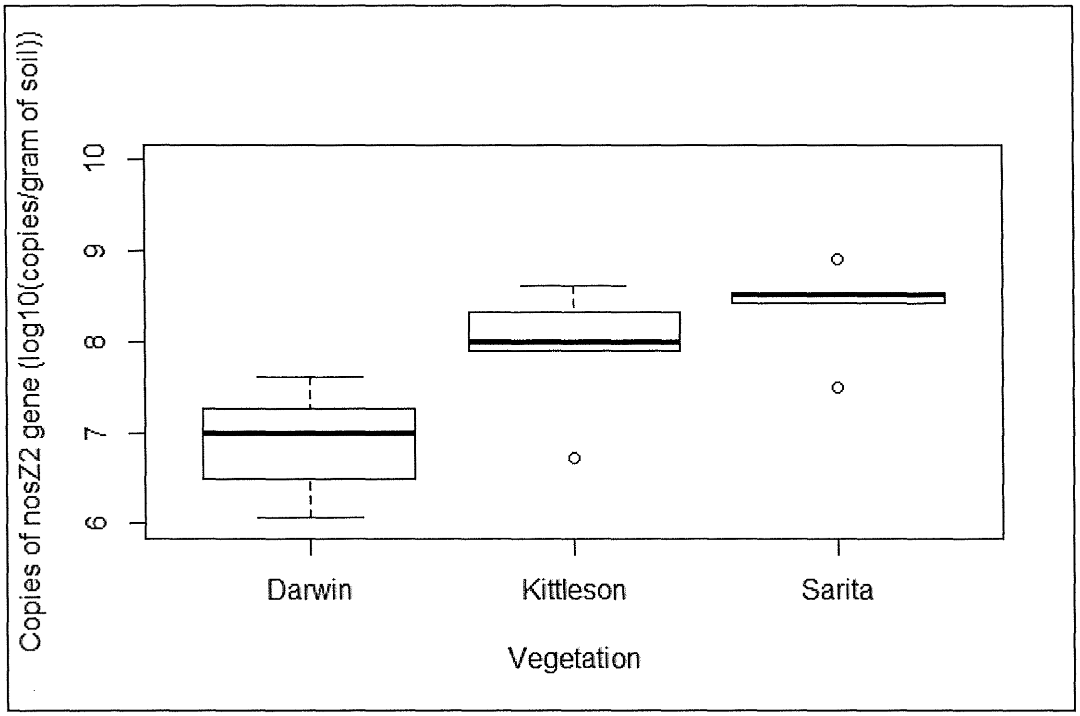


Figure 34. Copies of nosZ2 gene from all of the mesocosms containing the respective soils.

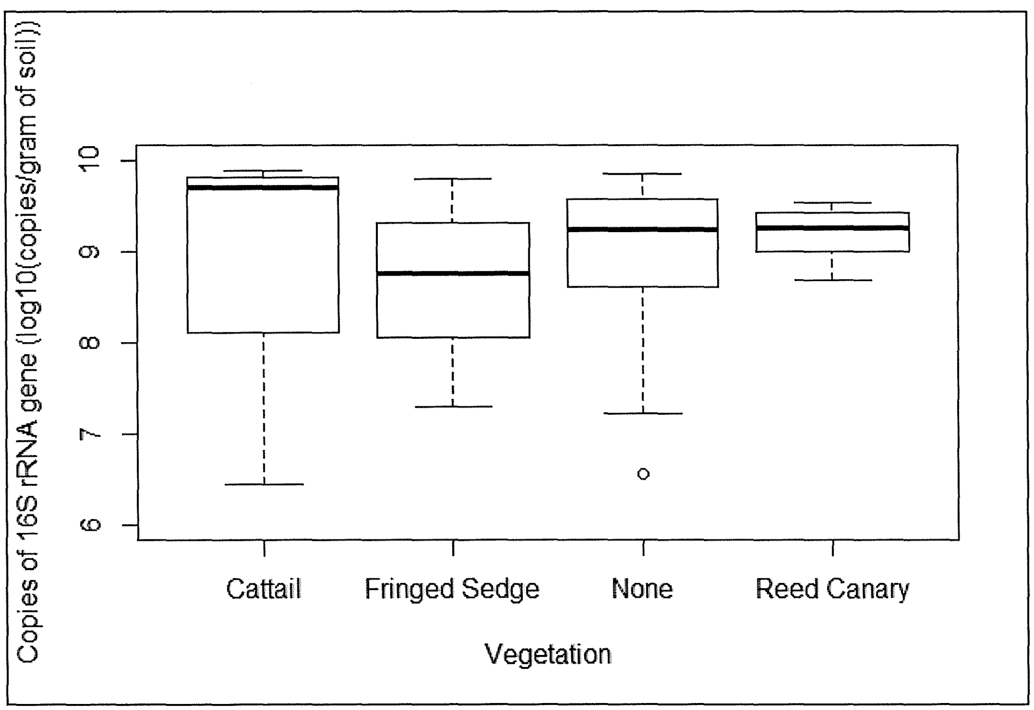


Figure 35. Copies of 16S rDNA gene from all of the mesocosms containing the respective vegetation.

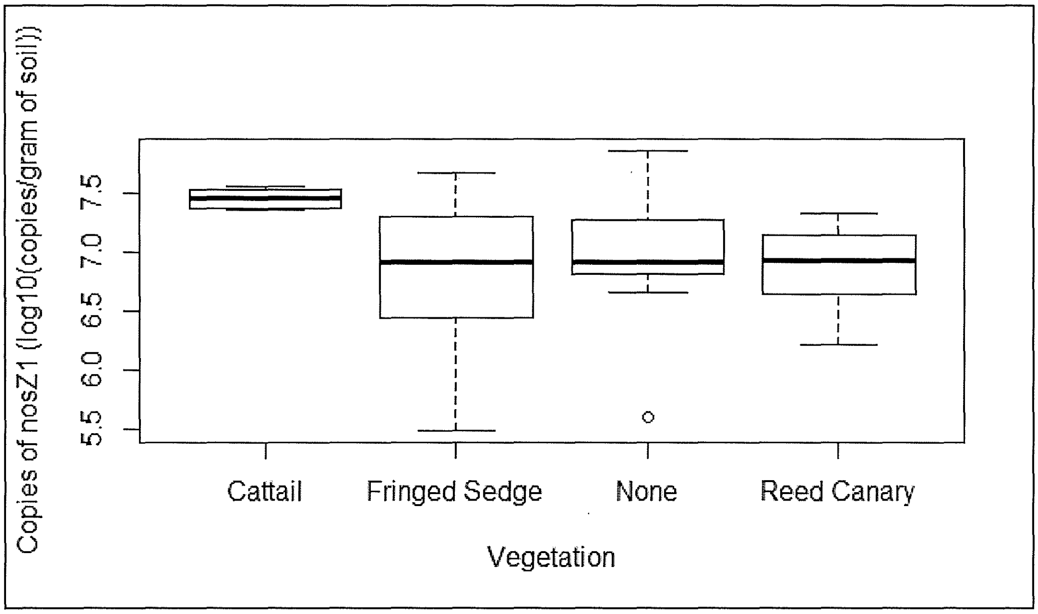


Figure 36. Copies of nosZ1 gene from all of the mesocosms containing the respective vegetation.

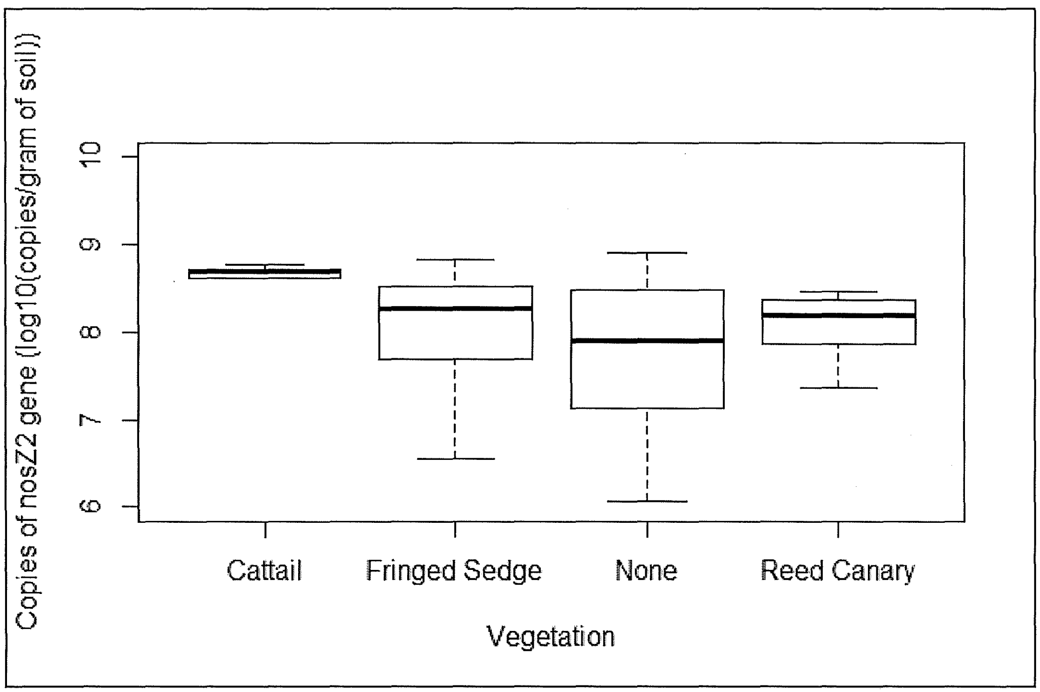


Figure 37. Copies of nosZ2 gene from all of the mesocosms containing the respective vegetation.

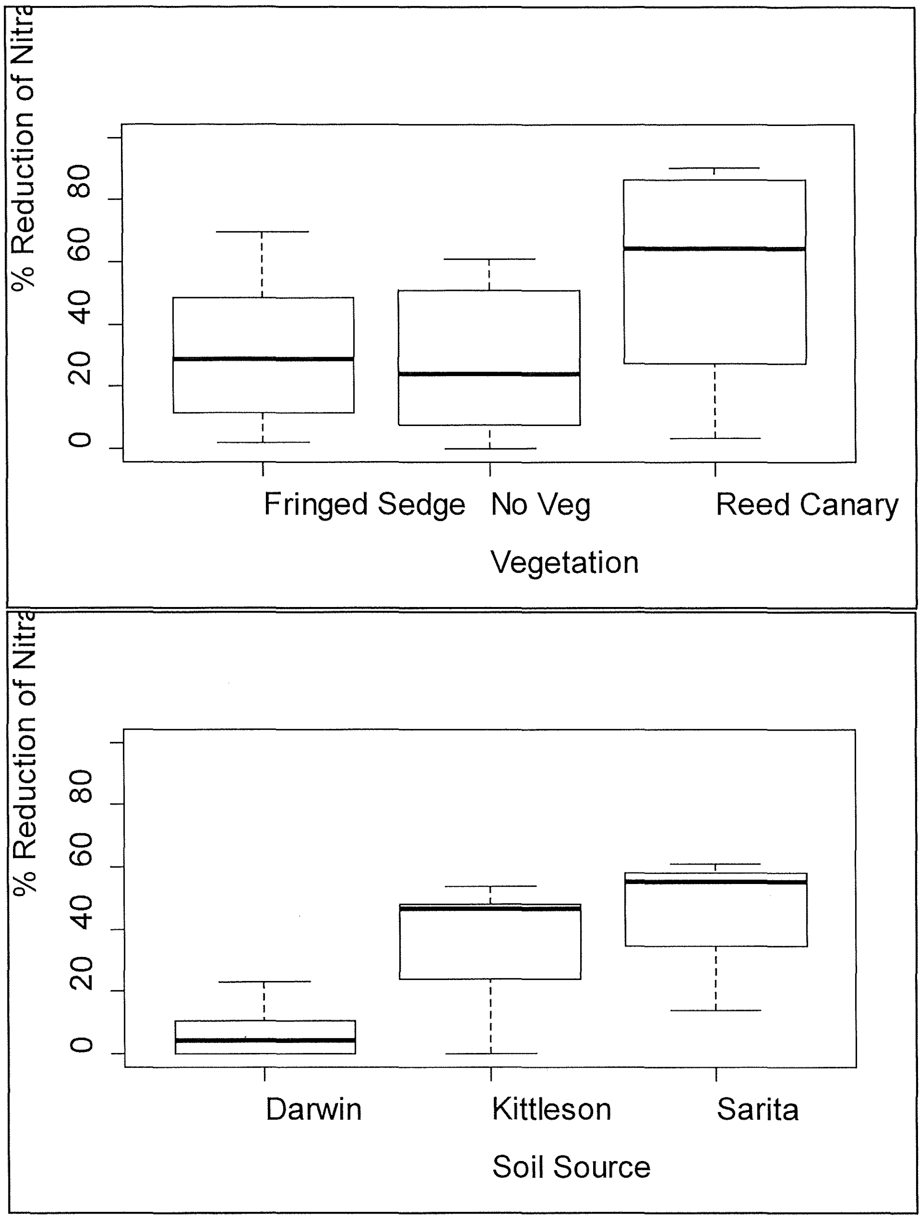


Figure 38. Reduction of nitrate from the seven wetland mesocosms after three tests.

Conclusions

Although the treatment wetland in this study has a lower denitrifying bacteria density than the other wetland soils, these population densities are comparable to other studies quantifying the nosZ gene in wetland soils ((Henry et al. 2006; Ma et al. 2008; Wang et al. 2013; Chen et al. 2014). However, the nitrate reduction rates were also significantly lower in this soil than other soils. Therefore, the issue in nitrate reduction does not seem to be the lack of denitrifying bacteria. The wetland could use improvements in the first two years to increase nitrate removal, but inoculation of bacteria does not seem to be a solution due to the already abundant population of bacteria. If the bacteria are not removing high rates of nitrate, there may be another limiting element in this newly constructed wetland soil. Carbon was lower in this wetland than the other two wetlands although only slightly lower than the Kittleson wetland's soil. Therefore, adding available carbon to the soil before the vegetation starts replenishing the soil in the first couple years of a new wetland could improve denitrification. In wetlands like the one in this study, soil may often come from a row crop field which will likely be depleted of carbon. Adding carbon to the soil may be helpful for future treatment wetland construction.

GENERAL DISCUSSION

The treatment wetland proved very effective at reducing nitrate in water flowing from the agricultural tile drain. One of the objectives was to determine the effectiveness of a constructed treatment wetland of this size (0.1 ha of inundation) and placed on the edge of the row-crop field. It was effective each of the three years of this study and improved each year. With each year reducing approximately 60%, 68%, and 93% of the nitrate/nitrite-N entering the wetland, it compares well to other treatment wetlands in the Midwest. Christianson et al. (2013) listed wetland studies from around the Midwest. In these wetland studies, the mean reduction of nitrogen was 42.8%, 25^{th} percentile was 30.9%, and 75^{th} percentile was 55.0%. Thus, the treatment wetland in this study is much more effective than most other wetlands in the Midwest based on the percentage, in terms of concentration reduction.

Various aspects of the hydrology, nutrient load, and weather should be considered, however, in assessing the effectiveness of this wetland relative to others. Firstly, this wetland was treating only tile drain water, so nitrate was the nitrogen form of primary concern. These nitrogen reduction values therefore do not consider organic nitrogen or ammonium, two other forms sometimes studied in other treatment wetland projects, but these other forms play a minor role in other studies. The wetland also was treating a smaller drainage area (10 ha) than is typically designed for water quality wetlands.

The volume of water varied each year, but 2014 was a significantly higher volume entering the wetland than in 2013 and 2015. While rainfall totals were less in the 2013 and 2014, the first two years had much more rain in each event than 2015. This was evident in the floods of 2013 and 2014 and having no flood in 2015. There was also a cover crop of cereal rye in the spring of 2015, so the drainage area had a much shorter window of time with no cover. Thus, much of the precipitation in the spring of 2015 was likely transpired before it could reach the drainage tile and enter the wetland.

The location of this wetland likely played a large role in the volume of water which infiltrated into the subsurface flow. The silty clay/clay soil on the surface typically should retain most of the water on the surface. However, there were likely some macropores in the soil causing preferential flow paths into the subsurface layer where sand and gravel provided a permeable layer for water to flow beneath the wetland. The macropores may have been created during construction if the soil was not packed well. There also may have been tree roots which penetrated the soil from the east edge of the wetland or undecomposed roots mixed into the soil used as the liner. The root growth is less likely due to the soil being mixed well and the infiltration being high in the first year when root growth would not likely have reached the wetland yet.

This subsurface flow and high infiltration rate allowed for a second pathway for denitrification in the wetland. Most nitrate removal occurs near the surface of the soil due to the carbon available, but denitrification can continue in the subsoil (MPCA 2013). In this specific wetland, there were two flow paths for denitrification, the surface and the subsurface. This allowed for greater volumes of water to be treated at the same time. Rather than water flowing out of the outlet drain when the wetland was inundated, much of the water infiltrated where it could receive more treatment while the wetland continued to fill. This subsurface flow also moved at a slower rate than surface flow, so water had even more time to be treated while in the subsurface. Residence time for the subsurface flow was in the range of weeks versus hours for surface flow.

This study may also differ from others by the variation in the nitrogen load. June was the month with the highest nitrogen load each year. Furthermore, 2014 had the highest load of any of the three years. These loads correlated with the water volume entering the wetland. However, 2013 had the highest average concentration of nitrate/nitrite-N in the grab samples and 2015 had the lowest. The first year was likely the highest due to 2012 being a drought year, and the nitrogen in the crop field was not wash away until 2013. This would have included fertilizer added in 2013 in addition to the remnant nitrogen from 2012. The third year, 2015, likely had the lowest concentrations due to the cover crop in the spring and a change from anhydrous ammonia to slow-release urea in 2015. Due to this wetland having a smaller watershed than most at 10.12 ha, the nitrogen load is likely to vary more than other wetlands. Furthermore, the steady flow in 2015, rather than having large rain events, provides a higher reduction than most years will likely have due to increased residence time and no water flowing out the outlet drain.

Applications to management

One major concern with small drainage area wetland is that they will not be saturated long enough during the summer to provide anaerobic conditions consistently to support denitrification and vegetation types typical of treatment wetlands. With a smaller watershed, the fields are likely to drain quickly. While water did infiltrate fairly readily, there was enough water entering the wetland to keep the soil saturated for at least 14 consecutive days in the first cell each year. Cells 2 and 3 did not receive enough water to be saturated on the surface for 14 days each year. However, the seed mixes worked well by having switch grass thrive in cells 2 and 3 and having a diverse mix of wet prairie species thrive in cell 1. Furthermore, the dryer conditions in late summer and fall may allow for easier vegetation harvesting in these smaller wetlands.

If the cost per hectare for design and construction of these small wetlands matches that of other wetlands in the Midwest (Christianson et al. 2013), this design is more cost effective than that of other wetlands. However, if each wetland of this size costs $20,000-30,000, then this would not be as cost effective for each kg of nitrogen removed. The benefit of this design is the total cost and potential for better landowner acceptance. Since this design will remove a negligible amount of cropland from production, revenue will not be impacted like it would be from a larger wetland. If landowner acceptance is better for this design, then the nitrogen reductions could accumulate with each wetland built. Larger wetlands will still remove more nitrogen in each wetland, but they may be more challenging to build due to landowner acceptance.

Phosphorus concentrations coming from the field drainage tile were fairly low throughout the three years of study. This may be due to the farmer's on-field practices which would limit preferential flow paths for dissolved orthophosphate. Particle-bound phosphorus was also unlikely to enter the wetland due to tile drain water being relatively clear of particulates. However, vegetation harvest removed a large portion of the input phosphorus each year. In 2015, vegetation harvest removed more phosphorus than what entered the wetland through the tile drain. Vegetation harvest had little impact on nitrogen removal, but it has a major contribution to phosphorus removal. Because this wetland has been dry during the harvest of crops, it would be fairly easy to harvest the vegetation each year.

The mesocosm study revealed a lack of denitrifying bacteria in the constructed wetland compared to two other wetlands. This is helpful knowing that adding carbon or inoculating the soil with microbes and carbon could improve denitrification in the first few years of a newly constructed wetland. Row-crop soil may be depleted of denitrifying microbes, so if soil from a nearby field is used to construct a wetland, it should receive these treatments. The mesocosm study also indicated reed canary grass works well as a vegetative cover and carbon source for denitrifying microbes in treatment wetlands. More comparisons need to be made to other species from this type of constructed treatment wetland, but biodiversity will need to be a goal in the construction of a wetland in order to prevent the invasion of reed canary grass. If treatment of nitrate is the only goal of a constructed wetland, then removing reed canary grass may not be necessary. In other words the initial goals of the project dictate the management that is needed.

Predicted vs. observed nutrient removal rates

The modeling study simulated 67% nitrate removal on average over the 20-year simulation period. The measured nitrate removal ranged from 60 – 93% for annual average over the 2013-2015 monitoring period. Cumulatively the removal was 69%. The model assumed most of the denitrification was occurring in surface water flow, however most of the nitrate removal observed in the wetland occurred via a subsurface treatment process as the water slowly drained out the soil.

Observations from the treatment wetland showed that the efficiency of nitrate removal in surface flow was very low as during periods of high rates of surface flow through the wetlands there was very little reduction in nitrate concentration. When surface flow was occurring across the wetland, residence time was very short, in the range of hours. This apparently was too rapid for nutrient removal to occur through denitrification processes.

General applications for wetland design in the region

Compared to other wetlands the nutrient removal effectiveness was fairly typical for nitrate (Crumpton et al. 2008; Miller et al. 2012). The removal rate was slightly higher than the average removal rates observed in the Iowa wetlands (Crumpton et al. 2008). In terms of cost effectiveness small edge-of-field treatment wetlands have both advantages and disadvantages relatively to larger restored wetlands. They cost more per unit area to construct due to their small size. However because land easement or purchase costs are avoided, tens to hundreds of thousands of dollars are saved. In addition they likely have higher landowner adoption rates since they are compatible with existing agricultural production systems.

Compared to other edge-of-field BMPs such as riparian buffers, construction costs are slightly higher, (>$10,000 total) compared to vegetative practices which don't require as much engineering design and grading work. The major benefit of small wetlands is that they temporarily store and retain water providing greater benefit to downstream water quality through total load reduction (Lewandowski et al. 2015).

The role of edge-of-field treatment wetlands in larger, watershed-scale nutrient reduction strategies is particularly important in the intensively drained tile drained landscape of southern Minnesota, Iowa and other parts of the Midwestern U.S. In these settings edge-of-field wetlands are more likely to fit in with existing land-uses. Based on the experience of this study, wetlands with small drainage areas, less than 50 or 100 ha may likely be more effective as sub-surface treatment systems to promote longer residence time. Wetlands that have larger drainage areas, in the range of 100s to 1000s of ha are better planned as surface water treatment wetlands for example the ones described for nitrate removal in Iowa (Crumpton et al. 2008).

Wetlands projects have generally focused on nitrate removal but phosphorus removal is also very important for aquatic ecosystem health in Minnesota lakes and rivers. Although phosphorus is not as effectively removed as nitrate through wetlands, certain management practices can improve phosphorus removal. Vegetative uptake followed by plant harvest can increase phosphorus removal from wetlands since plant uptake is the dominant form of phosphorus removal in wetlands, unlike nitrogen. Wet prairie vegetation with associated water depth and duration of flooding enables vegetation harvest during the late summer and fall. This is not possible in the emergent marshes typical of treatment wetland design. Shallower depth facilitates more cost-effective phosphorus removal as people can walk through the wetland and/or lightweight machinery may be used in larger basins.

Cost-effectiveness could by improved by using a single-cell layout to reduce design and construction. The multiple cell design does promote greater residence time of surface water flow through the wetlands, however. It also allows for use of different vegetative management and water level practices in each cell. In any case, a standardized design would promote greater assurance of the wetland's effectiveness.

Future research needs:
There is much known about the performance of individual BMPs including treatment wetlands (although not in this specific region and landscape setting). More data is needed on combination of agricultural BMPs in series to maximize their performance and lifespan. There is little data on the effectiveness of such treatment train practices. For example the use of cover crops uphill from treatment wetlands can reduce nutrient and sediment loading greatly increasing their performance and lifespan.

At the larger scale there is a need to develop a treatment wetland strategy for southern Minnesota that incorporates lessons learned from this study and others like it. Scaling up the use of wetlands will be needed to store and treat agricultural drainage water to meet state nutrient reduction goals.

PROJECT ACCOMPLISHMENTS

The project established a novel edge-of-field wetland treatment system that now serves as a demonstration site for the southern Minnesota region. The site was the host of three field trips hosted by the UMN Extension, Rural Advantage, MDA, Darwin Roberts (landowner) and other partners since 2013. It will continue to be a research and demonstration site in upcoming years.

This project had synergistic benefits as it partially supported the establishment of a wetland mesocosm lab in the basement of BAE Hall with University of Minnesota funding. The lab supported studies by 5 undergraduate and 2 graduate students at the University of Minnesota between the years 2013 – 2015.

Numerous conference and meeting presentations were made as listed below:

Oral presentations:

- Gordon, B. et al. Treatment wetland presentation. America Society of Agronomy (ASA), Crop Science Society of America (CSSA) Soil Science Society of America (SSSA), Minneapolis Nov. 2015
- Gordon, B. et al. Treatment wetland presentation. Water Resources Center conference, St. Paul, October 2015
- Gamble, J. Vegetation harvest in treatment wetlands. Minnesota Association of Watershed Districts (MAWD) conference Fall 2014
- Gordon, B. et al. Treatment wetlands. MAWD conference Fall 2014
- Lenhart et al., Lessons learned from field and lab studies of wetlands, WRC meeting, October 2014
- Lenhart et al. Minnesota Wetland Professionals, Bloomington, MN, March 2014

Poster presentations

- Gamble et al. 2015. Soil and Water Conservation District (SWCD) conference in Bloomington, Minnesota
- Gordon et al. Society for Ecological Restoration-Midwest, Great Lakes-Midwest (SER-MWGL) conference, Chicago, IL April 2015
- Gordon et al. Bioproducts and Biosystems Engineering (BBE) annual conference, St. Paul, MN October 2014
- Ross et al. SER-MWGL conference, St. Paul, MN April 2014
- Ross et al. BBE annual conference, St. Paul, MN October 2013
- Zebrowski, Undergraduate Research Opportunities (UROP) poster uploaded to UMN Digital Conservancy, spring 2014

Student theses

Ross, N. B. (2014). Constructed Wetland Used to Treat Nitrate Pollution Generated from Agricultural Tile Drainage Waters in Southern Minnesota. M.S. thesis, University of Minnesota.

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APPENDIX I: Hydrology Data

Table 23. Daily inflow measurements from the tile drain each of the three years. Values estimated in the spring of 2014 were not included due to their being calculated by rainfall instead of measured. Values in during the June floods of 2013 and 2014 were also excluded. The spring calculations of 2013 were excluded due to the tile not being fully installed until late May.

Date	Volume (m^3)	Date	Volume (m^3)	Date	Volume (m^3)
04/02/2013		04/02/2014		04/02/2015	0.00
04/03/2013		04/03/2014		04/03/2015	0.00
04/04/2013		04/04/2014		04/04/2015	0.00
04/05/2013		04/05/2014		04/05/2015	0.00
04/06/2013		04/06/2014		04/06/2015	0.00
04/07/2013		04/07/2014		04/07/2015	0.00
04/08/2013		04/08/2014		04/08/2015	0.00
04/09/2013		04/09/2014		04/09/2015	0.00
04/10/2013		04/10/2014		04/10/2015	0.00
04/11/2013		04/11/2014		04/11/2015	0.00
04/12/2013		04/12/2014		04/12/2015	0.00
04/13/2013		04/13/2014		04/13/2015	0.00
04/14/2013		04/14/2014		04/14/2015	0.00
04/15/2013		04/15/2014		04/15/2015	0.00
04/16/2013		04/16/2014		04/16/2015	0.00
04/17/2013		04/17/2014		04/17/2015	0.00
04/18/2013		04/18/2014		04/18/2015	0.00
04/19/2013		04/19/2014		04/19/2015	0.00
04/20/2013		04/20/2014		04/20/2015	0.00

04/21/2013		04/21/2014		04/21/2015	0.00
04/22/2013		04/22/2014		04/22/2015	0.00
04/23/2013		04/23/2014		04/23/2015	0.00
04/24/2013		04/24/2014		04/24/2015	0.00
04/25/2013		04/25/2014		04/25/2015	0.00
04/26/2013		04/26/2014		04/26/2015	0.00
04/27/2013		04/27/2014		04/27/2015	0.91
04/28/2013		04/28/2014		04/28/2015	34.90
04/29/2013		04/29/2014		04/29/2015	30.87
04/30/2013		04/30/2014		04/30/2015	22.06
05/01/2013		05/01/2014		05/01/2015	10.27
05/02/2013		05/02/2014		05/02/2015	0.83
05/03/2013		05/03/2014		05/03/2015	1.54
05/04/2013		05/04/2014		05/04/2015	0.00
05/05/2013		05/05/2014		05/05/2015	0.00
05/06/2013		05/06/2014		05/06/2015	0.00
05/07/2013		05/07/2014		05/07/2015	0.00
05/08/2013		05/08/2014		05/08/2015	0.00
05/09/2013		05/09/2014		05/09/2015	0.00
05/10/2013		05/10/2014		05/10/2015	0.00
05/11/2013		05/11/2014		05/11/2015	0.00
05/12/2013		05/12/2014		05/12/2015	0.00
05/13/2013		05/13/2014		05/13/2015	0.00
05/14/2013		05/14/2014		05/14/2015	2.80
05/15/2013		05/15/2014		05/15/2015	30.77
05/16/2013		05/16/2014		05/16/2015	32.84
05/17/2013		05/17/2014		05/17/2015	33.23
05/18/2013	0.00	05/18/2014		05/18/2015	33.84
05/19/2013	0.00	05/19/2014		05/19/2015	36.91
05/20/2013	0.00	05/20/2014		05/20/2015	35.76
05/21/2013	0.00	05/21/2014		05/21/2015	36.61
05/22/2013	0.00	05/22/2014		05/22/2015	35.52
05/23/2013	0.00	05/23/2014		05/23/2015	35.07
05/24/2013	0.00	05/24/2014		05/24/2015	37.45
05/25/2013	0.00	05/25/2014		05/25/2015	37.70
05/26/2013	0.00	05/26/2014		05/26/2015	38.02
05/27/2013	0.00	05/27/2014		05/27/2015	41.23
05/28/2013	0.00	05/28/2014		05/28/2015	38.18
05/29/2013	0.00	05/29/2014		05/29/2015	44.36
05/30/2013	0.00	05/30/2014		05/30/2015	154.59
05/31/2013	0.00	05/31/2014		05/31/2015	145.57

06/01/2013	0.00	06/01/2014		06/01/2015	140.60
06/02/2013	0.00	06/02/2014		06/02/2015	87.22
06/03/2013	0.00	06/03/2014		06/03/2015	46.73
06/04/2013	0.00	06/04/2014		06/04/2015	31.80
06/05/2013	12.76	06/05/2014		06/05/2015	31.93
06/06/2013	89.22	06/06/2014	3.40	06/06/2015	31.66
06/07/2013	35.98	06/07/2014	9.19	06/07/2015	31.39
06/08/2013	21.98	06/08/2014	11.31	06/08/2015	34.25
06/09/2013	168.86	06/09/2014	9.23	06/09/2015	40.32
06/10/2013	302.23	06/10/2014	12.96	06/10/2015	203.05
06/11/2013	341.62	06/11/2014	21.82	06/11/2015	294.35
06/12/2013	344.54	06/12/2014	105.51	06/12/2015	181.24
06/13/2013	379.35	06/13/2014	93.19	06/13/2015	156.79
06/14/2013	343.86	06/14/2014	106.23	06/14/2015	146.12
06/15/2013	337.21	06/15/2014	163.61	06/15/2015	115.55
06/16/2013	329.36	06/16/2014	248.06	06/16/2015	49.07
06/17/2013	328.99	06/17/2014	218.36	06/17/2015	48.75
06/18/2013	292.71	06/18/2014	294.64	06/18/2015	48.03
06/19/2013	270.75	06/19/2014	251.19	06/19/2015	42.71
06/20/2013	218.93	06/20/2014	797.74	06/20/2015	27.69
06/21/2013	325.08	06/21/2015	797.74	06/21/2015	29.05
06/22/2013	657.16	06/22/2016	797.73	06/22/2015	120.17
06/23/2013	1181.22			06/23/2015	61.83
06/24/2013	931.09			06/24/2015	26.76
06/25/2013	23.68			06/25/2015	23.95
06/26/2013				06/26/2015	23.49
06/27/2013				06/27/2015	24.46
06/28/2013				06/28/2015	23.26
06/29/2013				06/29/2015	23.17
06/30/2013				06/30/2015	22.30
07/01/2013				07/01/2015	23.11
07/02/2013				07/02/2015	22.66
07/03/2013		07/03/2014	25.48	07/03/2015	22.10
07/04/2013		07/04/2014	55.94	07/04/2015	20.68
07/05/2013		07/05/2014	54.63	07/05/2015	19.65
07/06/2013	25.71	07/06/2014	49.27	07/06/2015	238.71
07/07/2013	21.53	07/07/2014	43.06	07/07/2015	194.57
07/08/2013	11.01	07/08/2014	37.32	07/08/2015	100.10
07/09/2013	24.82	07/09/2014	33.78	07/09/2015	30.62
07/10/2013	46.09	07/10/2014	32.70	07/10/2015	19.95
07/11/2013	13.58	07/11/2014	28.47	07/11/2015	18.15

07/12/2013	0.00	07/12/2014	42.31	07/12/2015	18.55
07/13/2013	1.26	07/13/2014	35.39	07/13/2015	17.32
07/14/2013	0.32	07/14/2014	36.61	07/14/2015	16.80
07/15/2013	0.95	07/15/2014	33.52	07/15/2015	15.52
07/16/2013	0.84	07/16/2014	33.43	07/16/2015	15.21
07/17/2013	0.50	07/17/2014	34.27	07/17/2015	15.65
07/18/2013	0.16	07/18/2014	31.18	07/18/2015	13.89
07/19/2013	0.00	07/19/2014	33.62	07/19/2015	13.52
07/20/2013	0.00	07/20/2014	33.06	07/20/2015	11.63
07/21/2013	0.00	07/21/2014	30.97	07/21/2015	11.57
07/22/2013	0.20	07/22/2014	29.51	07/22/2015	10.39
07/23/2013	0.00	07/23/2014	29.21	07/23/2015	10.45
07/24/2013	0.00	07/24/2014	29.01	07/24/2015	9.80
07/25/2013	0.55	07/25/2014	26.41	07/25/2015	7.99
07/26/2013	0.00	07/26/2014	32.93	07/26/2015	8.46
07/27/2013	0.00	07/27/2014	30.78	07/27/2015	7.49
07/28/2013	0.00	07/28/2014	25.94	07/28/2015	7.34
07/29/2013	0.00	07/29/2014	28.09	07/29/2015	4.17
07/30/2013	0.00	07/30/2014	25.59	07/30/2015	1.36
07/31/2013	0.00	07/31/2014	24.94	07/31/2015	0.97
08/01/2013	0.00	08/01/2014	26.15	08/01/2015	1.06
08/02/2013	0.00	08/02/2014	26.64	08/02/2015	5.34
08/03/2013	0.21	08/03/2014	26.05	08/03/2015	8.26
08/04/2013	0.00	08/04/2014	26.15	08/04/2015	8.04
08/05/2013	121.04	08/05/2014	20.71	08/05/2015	8.01
08/06/2013	6.45	08/06/2014	16.55	08/06/2015	8.66
08/07/2013	0.00	08/07/2014	10.54	08/07/2015	8.81
08/08/2013	0.00	08/08/2014	24.13	08/08/2015	8.30
08/09/2013	0.00	08/09/2014	25.36	08/09/2015	7.16
08/10/2013	0.00	08/10/2014	27.09	08/10/2015	5.26
08/11/2013	0.00	08/11/2014	22.11	08/11/2015	2.18
08/12/2013	0.00	08/12/2014	17.21	08/12/2015	0.50
08/13/2013	0.00	08/13/2014	19.79	08/13/2015	0.01
08/14/2013	0.00	08/14/2014	21.25	08/14/2015	0.63
08/15/2013	0.00	08/15/2014	20.88	08/15/2015	0.13
08/16/2013	0.00	08/16/2014	26.57	08/16/2015	0.00
08/17/2013	0.00	08/17/2014	107.84	08/17/2015	0.00
08/18/2013	0.00	08/18/2014	238.21	08/18/2015	0.01
08/19/2013	0.00	08/19/2014	141.44	08/19/2015	0.00
08/20/2013	0.00	08/20/2014	25.26	08/20/2015	0.00
08/21/2013	0.00	08/21/2014	27.28	08/21/2015	0.00

08/22/2013	0.00	08/22/2014	19.56	08/22/2015	0.00
08/23/2013	4.17	08/23/2014	15.03	08/23/2015	0.00
08/24/2013	3.14	08/24/2014	36.31	08/24/2015	0.00
08/25/2013	0.00	08/25/2014	20.41	08/25/2015	0.00
08/26/2013	1.50	08/26/2014	14.28	08/26/2015	0.00
08/27/2013	1.84	08/27/2014	19.72	08/27/2015	0.00
08/28/2013	2.73	08/28/2014	44.85	08/28/2015	0.00
08/29/2013	0.00	08/29/2014	21.82	08/29/2015	0.00
08/30/2013	1.79	08/30/2014	25.95	08/30/2015	0.00
08/31/2013	0.00	08/31/2014	61.14	08/31/2015	0.00
09/01/2013	0.00	09/01/2014	45.87	09/01/2015	0.00
09/02/2013	0.65	09/02/2014	18.83	09/02/2015	0.00
09/03/2013	2.18	09/03/2014	26.08	09/03/2015	0.00
09/04/2013	0.00	09/04/2014	35.57	09/04/2015	0.00
09/05/2013	0.00	09/05/2014	10.92	09/05/2015	0.00
09/06/2013	0.00	09/06/2014	14.45	09/06/2015	0.00
09/07/2013	1.18	09/07/2014	13.56	09/07/2015	0.00
09/08/2013	1.05	09/08/2014	17.95	09/08/2015	0.00
09/09/2013	0.00	09/09/2014	21.67	09/09/2015	0.00
09/10/2013	3.80	09/10/2014	9.29	09/10/2015	0.00
09/11/2013	5.16	09/11/2014	4.20	09/11/2015	0.00
09/12/2013	0.00	09/12/2014	3.22	09/12/2015	0.00
09/13/2013	0.00	09/13/2014	7.49	09/13/2015	0.00
09/14/2013	0.00	09/14/2014	8.63	09/14/2015	0.00
09/15/2013	0.00	09/15/2014	12.29	09/15/2015	0.00
09/16/2013	0.00	09/16/2014	9.64	09/16/2015	0.00
09/17/2013	0.00	09/17/2014	14.84	09/17/2015	0.00
09/18/2013	0.00	09/18/2014	13.14	09/18/2015	0.00
09/19/2013	0.00	09/19/2014	29.79	09/19/2015	0.00
09/20/2013	0.00	09/20/2014	133.31	09/20/2015	0.00
09/21/2013	0.00	09/21/2014	8.85	09/21/2015	0.00
09/22/2013	0.00	09/22/2014	10.03	09/22/2015	0.00
09/23/2013	0.00	09/23/2014	20.71	09/23/2015	0.00
09/24/2013	0.00	09/24/2014	41.77	09/24/2015	0.00
09/25/2013	0.00	09/25/2014	20.43	09/25/2015	0.00
09/26/2013	0.00	09/26/2014	17.11	09/26/2015	0.00
09/27/2013	0.00	09/27/2014	23.09	09/27/2015	0.00
09/28/2013	0.00	09/28/2014	17.02	09/28/2015	7.18
09/29/2013	0.00	09/29/2014	11.79	09/29/2015	8.11
09/30/2013	0.00	09/30/2014	20.11	09/30/2015	1.63
10/01/2013	0.00	10/01/2014	47.65	10/01/2015	0.01

10/02/2013	0.00	10/02/2014	157.34	10/02/2015	0.00
10/03/2013	0.00	10/03/2014	316.66	10/03/2015	0.00
10/04/2013	0.00	10/04/2014	1.53	10/04/2015	0.00
10/05/2013	0.00	10/05/2014	2.65	10/05/2015	0.00
10/06/2013	0.00	10/06/2014	4.03	10/06/2015	0.00
10/07/2013	0.00	10/07/2014	5.47	10/07/2015	0.00
10/08/2013	0.00	10/08/2014	6.01	10/08/2015	0.00
10/09/2013	0.00	10/09/2014	2.55	10/09/2015	0.00
10/10/2013	0.00	10/10/2014	1.88	10/10/2015	0.00
10/11/2013	0.00	10/11/2014	2.00	10/11/2015	0.00
10/12/2013	0.00	10/12/2014	2.06	10/12/2015	0.00
10/13/2013	0.00	10/13/2014	0.25	10/13/2015	0.00
10/14/2013	0.00	10/14/2014	0.99	10/14/2015	0.00
10/15/2013	0.00	10/15/2014	1.50	10/15/2015	0.00
10/16/2013	0.00	10/16/2014	8.99	10/16/2015	0.00
10/17/2013	0.00	10/17/2014	3.68	10/17/2015	0.00
10/18/2013	0.00	10/18/2014	3.00	10/18/2015	0.00
10/19/2013	0.00	10/19/2014	8.23	10/19/2015	0.00
10/20/2013	0.00	10/20/2014	6.77	10/20/2015	0.00
10/21/2013	0.00	10/21/2014	4.45	10/21/2015	0.00
10/22/2013	0.00	10/22/2014	6.57	10/22/2015	0.00
10/23/2013	0.00	10/23/2014	11.69	10/23/2015	0.00
10/24/2013	0.00	10/24/2014	9.48	10/24/2015	0.00
10/25/2013	0.00	10/25/2014	6.60	10/25/2015	0.00
10/26/2013	0.00	10/26/2014	3.86	10/26/2015	0.00
10/27/2013	0.00	10/27/2014	5.76	10/27/2015	0.00
10/28/2013	0.00	10/28/2014	0.69	10/28/2015	0.00
10/29/2013	0.00	10/29/2014	1.00	10/29/2015	0.00
10/30/2013	0.00	10/30/2014	2.82	10/30/2015	0.00
10/31/2013	0.00	10/31/2014	0.00	10/31/2015	0.00
11/01/2013	0.00			11/01/2015	0.00
11/02/2013	0.00			11/02/2015	0.00
11/03/2013	0.00			11/03/2015	0.00
11/04/2013	0.00			11/04/2015	0.00
11/05/2013	0.00			11/05/2015	0.00
11/06/2013	0.00			11/06/2015	0.00
11/07/2013	0.00			11/07/2015	0.00
				11/08/2015	0.00
				11/09/2015	0.00
				11/10/2015	0.00
				11/11/2015	1.72

				11/12/2015	108.57
				11/13/2015	76.80
				11/14/2015	35.86
				11/15/2015	30.96
				11/16/2015	33.26
				11/17/2015	112.60
				11/18/2015	336.39
				11/19/2015	217.03
				11/20/2015	115.00
				11/21/2015	112.73
				11/22/2015	103.79
				11/23/2015	41.86
				11/24/2015	33.70
				11/25/2015	32.89
				11/26/2015	31.64
				11/27/2015	31.78
				11/28/2015	31.03
				11/29/2015	27.97
				11/30/2015	13.75

Table 24. Daily outflow measurements from the outlet drain each of the three years. Values estimated in the spring of 2014 were not included due to their being calculated rather than measured. Values in during the June floods of 2013 and 2014 were also excluded. The spring calculations of 2013 were excluded due to the tile not being fully installed until late May.

Date	Volume (m^3)	Date	Volume (m^3)	Date	Volume (m^3)
04/02/2013		04/02/2014		04/02/2015	0.00
04/03/2013		04/03/2014		04/03/2015	0.00
04/04/2013		04/04/2014		04/04/2015	0.00
04/05/2013		04/05/2014		04/05/2015	0.00
04/06/2013		04/06/2014		04/06/2015	0.00
04/07/2013		04/07/2014		04/07/2015	0.00
04/08/2013		04/08/2014		04/08/2015	0.00
04/09/2013		04/09/2014		04/09/2015	0.00
04/10/2013		04/10/2014		04/10/2015	0.00
04/11/2013		04/11/2014		04/11/2015	0.00
04/12/2013		04/12/2014		04/12/2015	0.00
04/13/2013		04/13/2014		04/13/2015	0.00
04/14/2013		04/14/2014		04/14/2015	0.00
04/15/2013		04/15/2014		04/15/2015	0.00
04/16/2013		04/16/2014		04/16/2015	0.00
04/17/2013		04/17/2014		04/17/2015	0.00

04/18/2013		04/18/2014		04/18/2015	0.00
04/19/2013		04/19/2014		04/19/2015	0.00
04/20/2013		04/20/2014		04/20/2015	0.00
04/21/2013		04/21/2014		04/21/2015	0.00
04/22/2013		04/22/2014		04/22/2015	0.00
04/23/2013		04/23/2014		04/23/2015	0.00
04/24/2013		04/24/2014		04/24/2015	0.00
04/25/2013		04/25/2014		04/25/2015	0.00
04/26/2013		04/26/2014		04/26/2015	0.00
04/27/2013		04/27/2014		04/27/2015	0.00
04/28/2013		04/28/2014		04/28/2015	0.00
04/29/2013		04/29/2014		04/29/2015	0.00
04/30/2013		04/30/2014		04/30/2015	0.00
05/01/2013		05/01/2014		05/01/2015	0.00
05/02/2013		05/02/2014		05/02/2015	0.00
05/03/2013		05/03/2014		05/03/2015	0.00
05/04/2013		05/04/2014		05/04/2015	0.00
05/05/2013		05/05/2014		05/05/2015	0.00
05/06/2013		05/06/2014		05/06/2015	0.00
05/07/2013		05/07/2014		05/07/2015	0.00
05/08/2013		05/08/2014		05/08/2015	0.00
05/09/2013		05/09/2014		05/09/2015	0.00
05/10/2013		05/10/2014		05/10/2015	0.00
05/11/2013		05/11/2014		05/11/2015	0.00
05/12/2013		05/12/2014		05/12/2015	0.00
05/13/2013		05/13/2014		05/13/2015	0.00
05/14/2013		05/14/2014		05/14/2015	0.00
05/15/2013		05/15/2014		05/15/2015	0.00
05/16/2013		05/16/2014		05/16/2015	0.00
05/17/2013		05/17/2014		05/17/2015	0.00
05/18/2013	0.00	05/18/2014		05/18/2015	0.00
05/19/2013	0.00	05/19/2014		05/19/2015	0.00
05/20/2013	0.00	05/20/2014		05/20/2015	0.00
05/21/2013	0.00	05/21/2014		05/21/2015	0.00
05/22/2013	0.00	05/22/2014		05/22/2015	0.00
05/23/2013	0.00	05/23/2014		05/23/2015	0.00
05/24/2013	0.00	05/24/2014		05/24/2015	0.00
05/25/2013	0.00	05/25/2014		05/25/2015	0.00
05/26/2013	0.00	05/26/2014		05/26/2015	0.00
05/27/2013	0.00	05/27/2014		05/27/2015	0.00
05/28/2013	0.00	05/28/2014		05/28/2015	0.00

05/29/2013	0.00	05/29/2014		05/29/2015	0.00
05/30/2013	0.00	05/30/2014		05/30/2015	0.00
05/31/2013	0.00	05/31/2014		05/31/2015	0.00
06/01/2013	0.00	06/01/2014		06/01/2015	0.00
06/02/2013	0.00	06/02/2014		06/02/2015	0.00
06/03/2013	0.00	06/03/2014		06/03/2015	0.00
06/04/2013	0.00	06/04/2014		06/04/2015	0.00
06/05/2013	0.00	06/05/2014		06/05/2015	0.00
06/06/2013	0.00	06/06/2014		06/06/2015	0.00
06/07/2013	0.00	06/07/2014		06/07/2015	0.00
06/08/2013	0.00	06/08/2014		06/08/2015	0.00
06/09/2013	0.00	06/09/2014		06/09/2015	0.00
06/10/2013	0.04	06/10/2014		06/10/2015	0.00
06/11/2013	0.14	06/11/2014	64.18	06/11/2015	0.00
06/12/2013	3.73	06/12/2014	0.00	06/12/2015	0.00
06/13/2013	7.97	06/13/2014	0.00	06/13/2015	0.00
06/14/2013	39.82	06/14/2014	0.00	06/14/2015	0.00
06/15/2013	30.56	06/15/2014	245.39	06/15/2015	0.00
06/16/2013	8.26	06/16/2014	465.11	06/16/2015	0.00
06/17/2013	0.02	06/17/2014	193.11	06/17/2015	0.00
06/18/2013	0.00	06/18/2014	539.53	06/18/2015	0.00
06/19/2013	0.00	06/19/2014	219.97	06/19/2015	0.00
06/20/2013	0.00	06/20/2014	168.46	06/20/2015	0.00
06/21/2013	0.43	06/21/2014	104.57	06/21/2015	0.00
06/22/2013	304.93	06/22/2014	104.77	06/22/2015	0.00
06/23/2013	449.76	06/23/2014	93.51	06/23/2015	0.00
06/24/2013	450.33	06/24/2014	94.69	06/24/2015	0.00
06/25/2013	17.65	06/25/2014	101.10	06/25/2015	0.00
06/26/2013		06/26/2014	118.56	06/26/2015	0.00
06/27/2013		06/27/2014	92.74	06/27/2015	0.00
06/28/2013		06/28/2014	88.82	06/28/2015	0.00
06/29/2013		06/29/2014	111.10	06/29/2015	0.00
06/30/2013		06/30/2014	202.41	06/30/2015	0.00
07/01/2013		07/01/2014	393.29	07/01/2015	0.00
07/02/2013		07/02/2014	257.85	07/02/2015	0.00
07/03/2013		07/03/2014	1.82	07/03/2015	0.00
07/04/2013		07/04/2014	0.00	07/04/2015	0.00
07/05/2013		07/05/2014	0.00	07/05/2015	0.00
07/06/2013	0.00	07/06/2014	0.00	07/06/2015	0.00
07/07/2013	0.00	07/07/2014	0.00	07/07/2015	0.00
07/08/2013	0.00	07/08/2014	0.00	07/08/2015	0.00

07/09/2013	0.00	07/09/2014	0.00	07/09/2015	0.00
07/10/2013	0.00	07/10/2014	0.00	07/10/2015	0.00
07/11/2013	0.00	07/11/2014	0.00	07/11/2015	0.00
07/12/2013	0.00	07/12/2014	0.00	07/12/2015	0.00
07/13/2013	0.00	07/13/2014	0.00	07/13/2015	0.00
07/14/2013	0.00	07/14/2014	0.00	07/14/2015	0.00
07/15/2013	0.00	07/15/2014	0.00	07/15/2015	0.00
07/16/2013	0.00	07/16/2014	0.00	07/16/2015	0.00
07/17/2013	0.00	07/17/2014	0.00	07/17/2015	0.00
07/18/2013	0.00	07/18/2014	0.00	07/18/2015	0.00
07/19/2013	0.00	07/19/2014	0.00	07/19/2015	0.00
07/20/2013	0.00	07/20/2014	0.00	07/20/2015	0.00
07/21/2013	0.00	07/21/2014	0.00	07/21/2015	0.00
07/22/2013	0.00	07/22/2014	0.00	07/22/2015	0.00
07/23/2013	0.00	07/23/2014	0.00	07/23/2015	0.00
07/24/2013	0.00	07/24/2014	0.00	07/24/2015	0.00
07/25/2013	0.00	07/25/2014	0.00	07/25/2015	0.00
07/26/2013	0.00	07/26/2014	0.00	07/26/2015	0.00
07/27/2013	0.00	07/27/2014	0.00	07/27/2015	0.00
07/28/2013	0.00	07/28/2014	0.00	07/28/2015	0.00
07/29/2013	0.00	07/29/2014	0.00	07/29/2015	0.00
07/30/2013	0.00	07/30/2014	0.00	07/30/2015	0.00
07/31/2013	0.00	07/31/2014	0.00	07/31/2015	0.00
08/01/2013	0.00	08/01/2014	0.00	08/01/2015	0.00
08/02/2013	0.00	08/02/2014	0.00	08/02/2015	0.00
08/03/2013	0.00	08/03/2014	0.00	08/03/2015	0.00
08/04/2013	0.00	08/04/2014	0.00	08/04/2015	0.00
08/05/2013	0.00	08/05/2014	0.00	08/05/2015	0.00
08/06/2013	0.00	08/06/2014	0.00	08/06/2015	0.00
08/07/2013	0.00	08/07/2014	0.00	08/07/2015	0.00
08/08/2013	0.00	08/08/2014	0.00	08/08/2015	0.00
08/09/2013	0.00	08/09/2014	0.00	08/09/2015	0.00
08/10/2013	0.00	08/10/2014	0.00	08/10/2015	0.00
08/11/2013	0.00	08/11/2014	0.00	08/11/2015	0.00
08/12/2013	0.00	08/12/2014	0.00	08/12/2015	0.00
08/13/2013	0.00	08/13/2014	0.00	08/13/2015	0.00
08/14/2013	0.00	08/14/2014	0.00	08/14/2015	0.00
08/15/2013	0.00	08/15/2014	0.00	08/15/2015	0.00
08/16/2013	0.00	08/16/2014	0.00	08/16/2015	0.00
08/17/2013	0.00	08/17/2014	0.00	08/17/2015	0.00
08/18/2013	0.00	08/18/2014	0.00	08/18/2015	0.00

08/19/2013	0.00	08/19/2014	0.00	08/19/2015	0.00
08/20/2013	0.00	08/20/2014	0.00	08/20/2015	0.00
08/21/2013	0.00	08/21/2014	0.00	08/21/2015	0.00
08/22/2013	0.00	08/22/2014	0.00	08/22/2015	0.00
08/23/2013	0.00	08/23/2014	0.00	08/23/2015	0.00
08/24/2013	0.00	08/24/2014	0.00	08/24/2015	0.00
08/25/2013	0.00	08/25/2014	0.00	08/25/2015	0.00
08/26/2013	0.00	08/26/2014	0.00	08/26/2015	0.00
08/27/2013	0.00	08/27/2014	0.00	08/27/2015	0.00
08/28/2013	0.00	08/28/2014	0.00	08/28/2015	0.00
08/29/2013	0.00	08/29/2014	0.00	08/29/2015	0.00
08/30/2013	0.00	08/30/2014	0.00	08/30/2015	0.00
08/31/2013	0.00	08/31/2014	0.00	08/31/2015	0.00
09/01/2013	0.00	09/01/2014	0.00	09/01/2015	0.00
09/02/2013	0.00	09/02/2014	0.00	09/02/2015	0.00
09/03/2013	0.00	09/03/2014	0.00	09/03/2015	0.00
09/04/2013	0.00	09/04/2014	0.00	09/04/2015	0.00
09/05/2013	0.00	09/05/2014	0.00	09/05/2015	0.00
09/06/2013	0.00	09/06/2014	0.00	09/06/2015	0.00
09/07/2013	0.00	09/07/2014	0.00	09/07/2015	0.00
09/08/2013	0.00	09/08/2014	0.00	09/08/2015	0.00
09/09/2013	0.00	09/09/2014	0.00	09/09/2015	0.00
09/10/2013	0.00	09/10/2014	0.00	09/10/2015	0.00
09/11/2013	0.00	09/11/2014	0.00	09/11/2015	0.00
09/12/2013	0.00	09/12/2014	0.00	09/12/2015	0.00
09/13/2013	0.00	09/13/2014	0.00	09/13/2015	0.00
09/14/2013	0.00	09/14/2014	0.00	09/14/2015	0.00
09/15/2013	0.00	09/15/2014	0.00	09/15/2015	0.00
09/16/2013	0.00	09/16/2014	0.00	09/16/2015	0.00
09/17/2013	0.00	09/17/2014	0.00	09/17/2015	0.00
09/18/2013	0.00	09/18/2014	0.00	09/18/2015	0.00
09/19/2013	0.00	09/19/2014	0.00	09/19/2015	0.00
09/20/2013	0.00	09/20/2014	0.00	09/20/2015	0.00
09/21/2013	0.00	09/21/2014	0.00	09/21/2015	0.00
09/22/2013	0.00	09/22/2014	0.00	09/22/2015	0.00
09/23/2013	0.00	09/23/2014	0.00	09/23/2015	0.00
09/24/2013	0.00	09/24/2014	0.00	09/24/2015	0.00
09/25/2013	0.00	09/25/2014	0.00	09/25/2015	0.00
09/26/2013	0.00	09/26/2014	0.00	09/26/2015	0.00
09/27/2013	0.00	09/27/2014	0.00	09/27/2015	0.00
09/28/2013	0.00	09/28/2014	0.00	09/28/2015	0.00

09/29/2013	0.00	09/29/2014	0.00	09/29/2015	0.00
09/30/2013	0.00	09/30/2014	0.00	09/30/2015	0.00
10/01/2013	0.00	10/01/2014	0.00	10/01/2015	0.00
10/02/2013	0.00	10/02/2014	0.00	10/02/2015	0.00
10/03/2013	0.00	10/03/2014	0.00	10/03/2015	0.00
10/04/2013	0.00	10/04/2014	0.00	10/04/2015	0.00
10/05/2013	0.00	10/05/2014	0.00	10/05/2015	0.00
10/06/2013	0.00	10/06/2014	0.00	10/06/2015	0.00
10/07/2013	0.00	10/07/2014	0.00	10/07/2015	0.00
10/08/2013	0.00	10/08/2014	0.00	10/08/2015	0.00
10/09/2013	0.00	10/09/2014	0.00	10/09/2015	0.00
10/10/2013	0.00	10/10/2014	0.00	10/10/2015	0.00
10/11/2013	0.00	10/11/2014	0.00	10/11/2015	0.00
10/12/2013	0.00	10/12/2014	0.00	10/12/2015	0.00
10/13/2013	0.00	10/13/2014	0.00	10/13/2015	0.00
10/14/2013	0.00	10/14/2014	0.00	10/14/2015	0.00
10/15/2013	0.00	10/15/2014	0.00	10/15/2015	0.00
10/16/2013	0.00	10/16/2014	0.00	10/16/2015	0.00
10/17/2013	0.00	10/17/2014	0.00	10/17/2015	0.00
10/18/2013	0.00	10/18/2014	0.00	10/18/2015	0.00
10/19/2013	0.00	10/19/2014	0.00	10/19/2015	0.00
10/20/2013	0.00	10/20/2014	0.00	10/20/2015	0.00
10/21/2013	0.00	10/21/2014	0.00	10/21/2015	0.00
10/22/2013	0.00	10/22/2014	0.00	10/22/2015	0.00
10/23/2013	0.00	10/23/2014	0.00	10/23/2015	0.00
10/24/2013	0.00	10/24/2014	0.00	10/24/2015	0.00
10/25/2013	0.00	10/25/2014	0.00	10/25/2015	0.00
10/26/2013	0.00	10/26/2014	0.00	10/26/2015	0.00
10/27/2013	0.00	10/27/2014	0.00	10/27/2015	0.00
10/28/2013	0.00	10/28/2014	0.00	10/28/2015	0.00
10/29/2013	0.00	10/29/2014	0.00	10/29/2015	0.00
10/30/2013	0.00	10/30/2014	0.00	10/30/2015	0.00
10/31/2013	0.00			10/31/2015	0.00
11/01/2013	0.00			11/01/2015	0.00
11/02/2013	0.00			11/02/2015	0.00
11/03/2013	0.00			11/03/2015	0.00
11/04/2013	0.00			11/04/2015	0.00
11/05/2013	0.00			11/05/2015	0.00
11/06/2013	0.00			11/06/2015	0.00
11/07/2013	0.00			11/07/2015	0.00
				11/08/2015	0.00

				11/09/2015	0.00
				11/10/2015	0.00
				11/11/2015	0.00
				11/12/2015	0.00
				11/13/2015	0.00
				11/14/2015	0.00
				11/15/2015	0.00
				11/16/2015	0.00
				11/17/2015	0.00
				11/18/2015	0.00
				11/19/2015	0.00
				11/20/2015	0.00
				11/21/2015	0.00
				11/22/2015	0.00
				11/23/2015	0.00
				11/24/2015	0.00
				11/25/2015	0.00
				11/26/2015	0.00
				11/27/2015	0.00
				11/28/2015	0.00
				11/29/2015	0.00
				11/30/2015	0.00

APPENDIX II: Water Quality Constituents.

Table 25. Inflow measurements of Orthophosphorus and Total Phosphorus concentrations from grab samples each of the three years.

Sample Date	Soluble Ortho Phosphorus (mg/L)	Total Phosphorus (mg/L)
6/6/2013	0.043	0.058
6/10/2013	0.035	0.046
6/10/2013	0.040	0.049
6/12/2013	0.028	0.042
6/14/2013	0.031	0.043
6/14/2013	0.034	0.044
6/17/2013	0.03	0.044
6/24/2013	0.05	0.063
4/30/2014	0.187	0.223
5/4/2014	0.18	0.217
5/9/2014		0.144
5/10/2014		0.148
5/10/2014		0.151
5/12/2014	0.062	0.087
5/12/2014	0.062	0.087
5/13/2014	0.084	0.123
5/15/2014	0.091	0.134
6/2/2014	0.247	0.404
6/4/2014	0.071	0.089
6/6/2014		0.064
6/11/2014		0.066
6/12/2014		0.067
6/12/2014		0.067
6/13/2014	0.073	0.075
6/16/2014	0.055	0.056
6/18/2014	0.048	0.057
5/27/2015		0.029
6/8/2015	0.028	0.049
6/19/2015	0	0.03
6/22/2015	0.035	0.055
7/1/2015	0.04	0.038
7/7/2015	0.031	0.032
7/8/2015	0.046	0.029
11/12/2015	0.039	0.045

11/13/2015	0.036	0.039
11/17/2015	0.039	0.046
11/18/2015	0.029	0.037
11/18/2015	0.032	0.042
11/19/2015	0.024	0.034

Table 26. Inflow measurements of Nitrate/Nitrite-N concentrations from grab samples each of the three years.

Sample Date	Nitrate/Nitrite (mg/L as N)
6/6/2013	22.4
6/10/2013	22.6
6/10/2013	24.4
6/12/2013	21.8
6/14/2013	22.3
6/14/2013	22.8
6/17/2013	23.4
6/24/2013	24.2
4/30/2014	10.9
5/4/2014	10.9
5/9/2014	13.1
5/10/2014	13.5
5/10/2014	13.6
5/12/2014	12.8
5/12/2014	12.8
5/13/2014	14.1
5/15/2014	16.1
6/2/2014	8.74
6/4/2014	19.2
6/6/2014	21.7
6/11/2014	20.9
6/11/2014	19.7
6/12/2014	19.9
6/12/2014	19.4
6/13/2014	19.9
6/16/2014	19.2
6/18/2014	18.6
7/11/2014	26
5/27/2015	14.6
5/29/2015	14.6
5/29/2015	14.6

6/5/2015	15.3
6/5/2015	15.1
6/8/2015	15.5
6/12/2015	13.6
6/12/2015	13.8
6/12/2015	13.2
6/12/2015	13.2
6/12/2015	13.2
6/19/2015	14.6
6/19/2015	14.6
6/19/2015	14.7
6/19/2015	14.8
6/19/2015	14.7
6/19/2015	14.6
6/19/2015	14.6
6/19/2015	14.5
6/19/2015	14.6
6/19/2015	14.6
6/22/2015	17
7/1/2015	13.4
7/7/2015	15.7
7/7/2015	15.6
7/7/2015	15.6
7/7/2015	15.7
7/7/2015	15.7
7/7/2015	15.6
7/7/2015	15.7
7/7/2015	15.7
7/7/2015	15.7
7/7/2015	15.7
7/7/2015	15.7
7/8/2015	14.3
11/12/2015	11
11/13/2015	11.9
11/17/2015	9
11/18/2015	10.6
11/18/2015	11
11/19/2015	11.7

Table 27. Measurements of Orthophosphorus, Nitrate/Nitrite-N, and Total Phosphorus concentrations from grab samples in AgriDrain 1 between cells 1 and 2 each of the three years.

Sample Date	Soluble Ortho Phosphorus (mg/L)	Nitrate/Nitrite-N (mg/L)	Total Phosphorus (mg/L)
6/10/2013	0.032	24.4	0.044
6/10/2013	0.033	24.1	0.044
6/12/2013	0.023	23.8	0.042
6/14/2013	0.024	23.2	0.038
6/14/2013	0.024	21.5	0.035
6/17/2013	0.017	23.4	0.038
6/24/2013	0.049	23.1	0.062
5/9/2014		12.8	0.166
5/10/2014		13.1	0.143
5/12/2014	0.078	12	0.134
5/12/2014	0.078	12	0.134
5/15/2014	0.078	15.7	0.125
6/4/2014	0.053	17.3	0.085
6/16/2014	0.009	17.1	0.028
6/12/2015		13.2	
6/12/2015		13.2	
6/12/2015		13.1	
6/12/2015		13.1	
6/12/2015	0.11	13.1	
7/7/2015		15.4	
7/7/2015		15.5	
7/7/2015		15.4	
7/7/2015		15.4	
7/8/2015	0.018	13.6	0.035
11/18/2015	0.054	9.69	0.073
11/19/2015	0.048	10.6	0.074

Table 28. Measurements of Orthophosphorus, Nitrate/Nitrite-N, and Total Phosphorus concentrations from grab samples in AgriDrain 2 between cells 2 and 3 each of the three years.

Sample Date	Soluble Ortho Phosphorus (mg/L)	Nitrate/Nitrite-N (mg/L)	Total Phosphorus (mg/L)
6/10/2013	0.035	23.9	0.053

6/10/2013	0.035	23.7	0.049
6/12/2013	0.017	21.7	0.131
6/14/2013	0.019	22	0.041
6/14/2013	0.016	21.5	0.051
6/17/2013	0.008	24	0.047
6/24/2013	0.051	23.1	0.065
5/9/2014		12.3	0.166
5/10/2014		12.6	0.143
5/12/2014	0.102	11	0.191
5/12/2014	0.102	11	0.191
5/15/2014	0.061	15	0.108
6/4/2014	0.057	15.3	0.093
6/16/2014	0.008	18.7	0.032
7/7/2015		13	
7/7/2015		13.1	
7/7/2015		13.6	
7/7/2015	0.024	13.5	0.042
7/8/2015	0.095	10.3	1.51

Table 29. Measurements of Orthophosphorus, Nitrate/Nitrite-N, and Total Phosphorus concentrations from grab samples at the wetland outlet each of the three years.

Sample Date	Soluble Ortho Phosphorus (mg/L)	Nitrate/Nitrite-N (mg/L)	Total Phosphorus (mg/L)
6/14/2013	0.006	21.9	0.044
6/14/2013	0.006	24.2	0.034
6/24/2013	0.053	22.3	0.113
5/9/2014		12	0.173
5/10/2014		12.2	0.164
5/10/2014		12.1	0.195
5/12/2014	0.125	9.94	0.226
5/12/2014	0.125	9.94	0.226
5/13/2014	0.1	12.6	0.1
5/15/2014	0.043	14.8	0.069
6/2/2014	0.13	11.3	0.243
6/4/2014	0.075	13.4	0.122
6/16/2014	0.02	16.3	0.03
6/18/2014	0.045	13.3	0.077

Table 30. Total Suspended Sediment concentrations measured from grab samples throughout the wetland, snow melt in the wetland in 2014, and Elm Creek.

Sample Location	Sample Date	TSS (mg/L)
Inlet	6/6/2013	5
Snow Melt	3/21/2014	6
Snow Melt	3/21/2014	16
Inlet	4/30/2014	3
Inlet	5/4/2014	< 2
AgriDrain 1	5/9/2014	17
AgriDrain 2	5/9/2014	10
Inlet	5/9/2014	< 2
Outlet	5/9/2014	8
AgriDrain 1	5/10/2014	< 2
AgriDrain 2	5/10/2014	8
Inlet	5/10/2014	< 2
Inlet	5/10/2014	< 2
Outlet	5/10/2014	25
Outlet	5/10/2014	43
AgriDrain 1	5/12/2014	12
AgriDrain 1	5/12/2014	12
AgriDrain 2	5/12/2014	24
AgriDrain 2	5/12/2014	24
Inlet	5/12/2014	5
Inlet	5/12/2014	5
Outlet	5/12/2014	19
Outlet	5/12/2014	19
Inlet	5/13/2014	5
Outlet	5/13/2014	< 2
AgriDrain 1	5/15/2014	6
AgriDrain 2	5/15/2014	5
Inlet	5/15/2014	2
Outlet	5/15/2014	6
Inlet	6/2/2014	52
Outlet	6/2/2014	17
AgriDrain 1	6/4/2014	< 2
AgriDrain 2	6/4/2014	2
Inlet	6/4/2014	4
Outlet	6/4/2014	12
Inlet	6/6/2014	< 2

Inlet	6/11/2014	4
Inlet	6/12/2014	2
Inlet	6/12/2014	<2
Inlet	6/13/2014	<2
Inlet	6/16/2014	<2
Outlet	6/16/2014	2
Inlet	6/18/2014	4
Outlet	6/18/2014	8
Elm Creek	3/30/2015	14

Table 31. Conductivity measured from grab samples throughout the wetland and from snow melt in the wetland in 2014.

Sample Location	Sample Date	Specified Conductance (µs/cm)
Inlet	6/6/2013	754.0
AgriDrain 1	6/10/2013	770.0
AgriDrain 1	6/10/2013	772.0
AgriDrain 2	6/10/2013	747.0
AgriDrain 2	6/10/2013	753.0
Inlet	6/10/2013	777.0
Inlet	6/10/2013	780.0
AgriDrain 1	6/12/2013	739.0
AgriDrain 2	6/12/2013	729.0
Inlet	6/12/2013	752.0
AgriDrain 1	6/14/2013	771.0
AgriDrain 1	6/14/2013	785.0
AgriDrain 2	6/14/2013	774.0
AgriDrain 2	6/14/2013	783.0
Inlet	6/14/2013	782.0
Inlet	6/14/2013	793.0
Outlet	6/14/2013	753.0
Outlet	6/14/2013	759.0
AgriDrain 1	6/17/2013	783.0
AgriDrain 2	6/17/2013	791.0
Inlet	6/17/2013	790.0
AgriDrain 1	6/24/2013	783
AgriDrain 2	6/24/2013	779
Inlet	6/24/2013	785
Outlet	6/24/2013	771
Snow Melt	3/21/2014	326
Snow Melt	3/21/2014	327
Inlet	4/30/2014	642

Inlet	5/4/2014	640

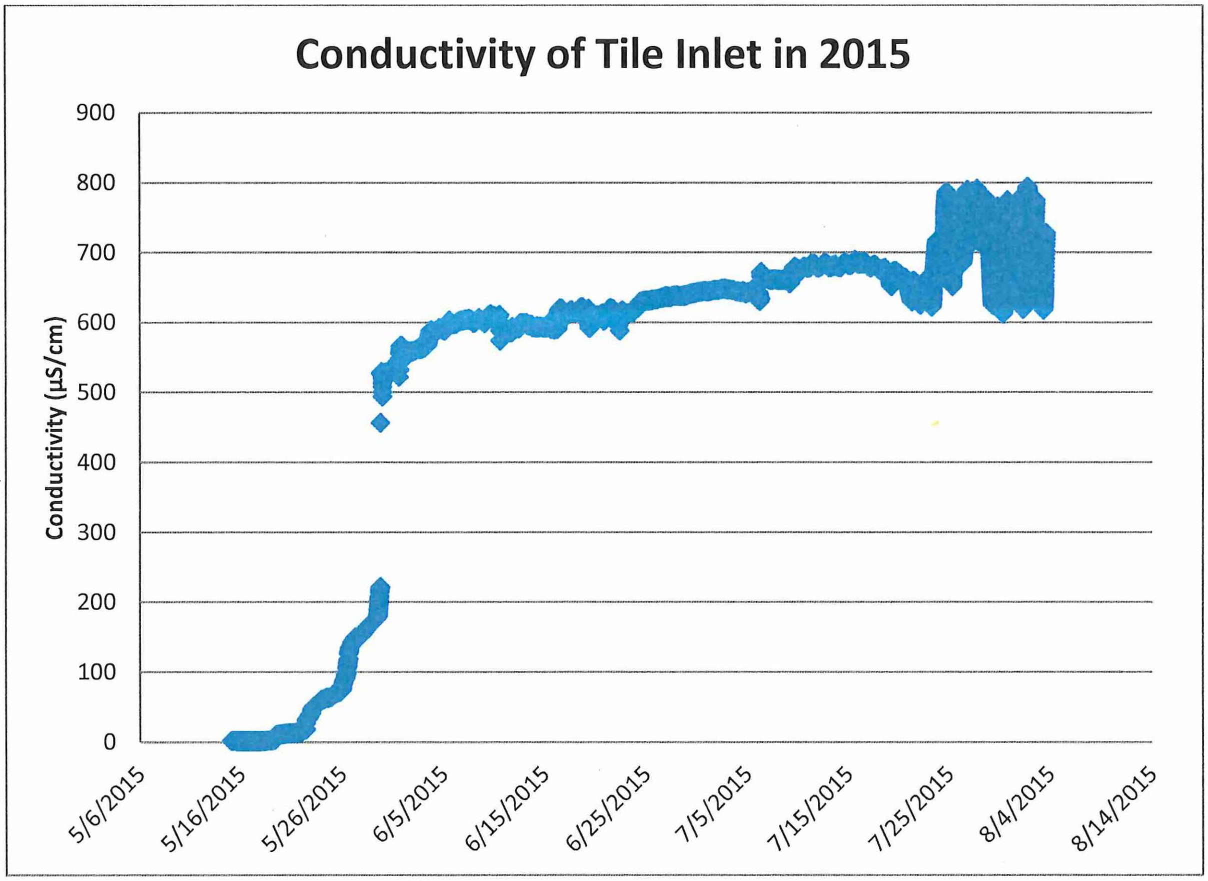

Figure 39: Conductivity of tile inlet water in 2015

Table 32. Readings of pH from grab samples throughout the wetland and from snow melt in the wetland in the spring of 2014.

Sample Location	Sample Date	pH
Snow Melt	3/21/2014	7.3
Snow Melt	3/21/2014	7.4
Inlet	5/4/2014	7.6
AgriDrain 1	6/16/2014	7.8
AgriDrain 2	6/16/2014	7.8
Inlet	6/16/2014	7.3
Outlet	6/16/2014	7.8

APPENDIX III : Wetland seed mix descriptions

Table 33: Low diversity wet prairie mix seeded in treatment wetland cell 1 (original seeding) Feder's Nursery, Blue Earth, MN

Scientific name	Common name	Functional group	% of Mix (by weight)	Seeds/ft^2	Rate/Acre (PLS lb)
Elymus canadensis	Canada Wild Rye	Grass	70.50%	6.21	4.03
Panicum virgatum	Switchgrass	Grass	101.83%	8.97	1.73
Poa palustris	Fowl Bluegrass	Grass	250.65%	22.08	0.46
Carex vulpinoidea	Brown Fox Sedge	Sedge	96.61%	8.51	0.23
Scirpus atrovirens	Green Bulrush	Rush	441.25%	38.87	0.23
Scirpus cyperinus	Woolgrass	Rush	488.25%	43.01	0.07
Asclepias incarnata	Swamp Milkweed	Forb	2.61%	0.23	0.18
Aster puniceus	Swamp Aster	Forb	62.66%	5.52	0.18
Desmodium canadense	Showy Tick Trefoil	Legume	26.11%	2.30	1.15
Eupatorium maculatum	Joe Pye Weed	Forb	36.55%	3.22	0.09
Helianthus grosseserratus	Sawtooth Sunflower	Forb	7.83%	0.69	0.12
Verbena hastata	Blue Vervain	Forb	133.16%	11.73	0.35
Avena sativa	Oats	Cover crop		2.7	6.2

Table 34: Medium diversity wet prairie mix seeded in treatment wetland cell 2

Scientific name	Common name	Functional group	% of Mix (by weight)	Seeds/ft ^{2}	Rate/Acre (PLS lb)
Andropogon gerardii	Big Bluestem	Grass	17.73%	6.5	1.75
Elymus canadensis	Canada Wild Rye	Grass	31.03%	4.7	3.06
Glyceria grandis	Reed Manna Grass		2.66%	6.8	0.26
Panicum virgatum	Switchgrass	Grass	13.30%	6.8	1.31
Poa palustris	Fowl Bluegrass	Grass	3.55%	16.8	0.35
Spartina pectinata	Prairie Cord Grass	Grass	8.87%	2.1	0.88
Carex pellita	Broad-leaved Woolly Sedge	Sedge	0.89%	0.9	0.09
Carex vulpinoidea	Brown Fox Sedge	Sedge	1.77%	6.5	0.18
Scirpus atrovirens	Green Bulrush	Rush	1.77%	29.6	0.18
Scirpus cyperinus	Woolgrass	Rush	0.53%	32.7	0.05
Asclepias incarnata	Swamp Milkweed	Forb	1.42%	0.2	0.14
Aster puniceus	Swamp Aster	Forb	1.42%	4.2	0.14
Desmodium canadense	Showy Tick Trefoil	Legume	8.87%	1.8	0.88
Eupatorium maculatum	Joe Pye Weed	Forb	0.71%	2.5	0.07
Helenium autumnale	Sneezeweed	Forb	0.89%	4.2	0.09
Helianthus grosseserratus	Sawtooth Sunflower	Forb	0.89%	0.5	0.09
Liatris pycnostachya	Prairie Blazingstar	Forb	0.35%	0.2	0.04
Mimulus ringens	Monkey Flower	Forb	0.18%	14.7	0.02
Verbena hastata	Blue Vervain	Forb	2.66%	8.9	0.26
Vernonia fasciculata	Common Ironweed	Forb	0.53%	0.5	0.0525
Avena sativa	Oats	Cover crop		2.7	6.2

Table 35: High diversity wet prairie mix seeded in treatment wetland cell 3

Scientific name	Common name	Functional group	% of Mix (by weight)	Seeds/ft^2	Rate/Acre (PLS lb)
Andropogon gerardii	Big Bluestem	Grass	12.08%	4.6	1.25
Bromus ciliatus	Fringed Brome	Grass	18.12%	6.9	1.88
Calamagrostis canadensis	Blue Joint Grass	Grass	0.48%	5.1	0.05
Elymus canadensis	Canada Wild Rye	Grass	21.14%	3.4	2.19
Glyceria grandis	Reed Manna Grass	Grass	1.81%	4.9	0.19
Glyceria striata	Fowl Manna Grass	Grass	1.33%	4.5	0.14
Panicum virgatum	Switchgrass	Grass	9.06%	4.9	0.94
Poa palustris	Fowl Bluegrass	Grass	2.42%	12.0	0.25
Sorghastrum nutans	Indiangrass	Grass	6.04%	2.8	0.63
Spartina pectinata	Prairie Cord Grass	Grass	6.04%	1.5	0.63
Carex pellita	Broad-leaved Woolly Sedge	Sedge	0.60%	0.6	0.06
Carex stricta	Tussock Sedge	Sedge	0.24%	0.5	0.03
Carex vulpinoidea	Brown Fox Sedge	Sedge	1.21%	4.6	0.13
Scirpus atrovirens	Green Bulrush	Rush	1.21%	21.1	0.13
Scirpus cyperinus	Woolgrass	Rush	0.36%	23.4	0.04
Anemone canadensis	Canada Anemone	Forb	0.36%	0.1	0.04
Asclepias incarnata	Swamp Milkweed	Forb	0.97%	0.1	0.10
Aster puniceus	Swamp Aster	Forb	0.97%	3.0	0.10
Aster umbellatus	Flat-topped Aster	Forb	0.60%	1.5	0.06
Desmodium canadense	Showy Tick Trefoil	Legume	6.04%	1.3	0.63
Eupatorium maculatum	Joe Pye Weed	Forb	0.48%	1.8	0.05
Eupatorium perfoliatum	Boneset	Forb	0.36%	2.3	0.04
Helenium autumnale	Sneezeweed	Forb	0.60%	3.0	0.06
Helianthus grosseserratus	Sawtooth Sunflower	Forb	0.60%	0.4	0.06
Liatris pycnostachya	Prairie Blazingstar	Forb	0.24%	0.1	0.03
Lobelia siphilitica	Great Blue Lobelia	Forb	0.12%	2.3	0.01
Mimulus ringens	Monkey Flower	Forb	0.12%	10.5	0.01
Pycnanthemum virginianum	Mountain Mint	Forb	0.97%	8.1	0.10
Verbena hastata	Blue Vervain	Forb	1.81%	6.4	0.19
Vernonia fasciculata	Common Ironweed	Forb	0.36%	0.4	0.04
Veronicastrum virginicum	Culver's Root	Forb	0.24%	7.4	0.03
Zizia aurea	Golden Alexanders	Forb	3.02%	1.3	0.31
Avena sativa	Oats	Cover crop		2.7	6.2

Table 36: Native storm water wet prairie mix seeded in treatment wetland cell 1 (reseeding)

Scientific name	Common name	Functional group	% of Mix (by weight)	Seeds/ft^2	Rate/Acre (PLS lb)
Agropyron trachycaulum	Slender Wheatgrass	Grass	2.86%	2.5	1
Andropogon gerardii	Big Bluestem	Grass	5.71%	7.3	2
Bromus ciliatus	Fringed Brome	Grass	5.71%	7.3	2
Calamagrostis canadensis	Blue Joint Grass	Grass	0.17%	6.2	0.06
Elymus canadensis	Canada Wild Rye	Grass	4.29%	2.3	1.5
Panicum virgatum	Switchgrass	Grass	1.09%	2	0.38
Poa palustris	Fowl Bluegrass	Grass	3.03%	50.6	1.06
Sorghastrum nutans	Indiangrass	Grass	0.34%	0.5	0.12
Spartina pectinata	Prairie Cord Grass	Grass	1.09%	0.9	0.38
Carex stipata	Fox Sedge	Sedge	0.71%	3.1	0.25
Scirpus atrovirens	Green Bulrush	Rush	0.54%	32.1	0.19
Scirpus cyperinus	Woolgrass	Rush	0.17%	37.5	0.06
Anemone canadensis	Canada Anemone	Forb	0.20%	0.2	0.07
Asclepias incarnata	Swamp Milkweed	Forb	0.31%	0.2	0.11
Aster novae-angliae	New England Aster	Forb	0.20%	1.7	0.07
Aster umbellatus	Flat-topped Aster	Forb	0.17%	1.5	0.06
Bidens frondosa	Beggar's Tick	Forb	0.31%	0.2	0.11
Eupatorium maculatum	Joe Pye Weed	Forb	0.17%	2.1	0.06
Helenium autumnale	Sneezeweed	Forb	0.37%	6.2	0.13
Physostegia virginiana	Obedient Plant	Forb	0.20%	0.3	0.07
Rudbeckia laciniata	Wild Golden Glow	Forb	0.20%	0.4	0.07
Verbena hastata	Blue Vervain	Forb	0.14%	1.7	0.05
Zizia aurea	Golden Alexanders	Forb	0.57%	0.8	0.2