Monitoring the Hydrologic and Water Quality Performance of a Subsurface Gravel Wetland

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MONITORING THE HYDROLOGIC AND WATER QUALITY PERFORMANCE OF A SUBSURFACE GRAVEL WETLAND

by

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ABSTRACT

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Managing stormwater is a crucial task for many communities that are required to mitigate the harmful effects of pollution from urban runoff. Subsurface gravel wetlands are an emerging type of green infrastructure that can be used to manage stormwater through the capture and slow release of runoff. These wetland systems are unique to other types of green infrastructure in that they have a distinct fully saturated gravel layer below an occasionally saturated soil layer. While there is substantial literature on the performance of different types of green infrastructure, such as bioretention, bioswales, and permeable pavements, there is a lack of monitoring studies on the performance of subsurface gravel wetlands. To fill this gap, the flow and water quality in a subsurface gravel wetland in Oshkosh, Wisconsin were monitored. To do so, the influent and effluent flow rates were captured, and water quality samples were collected at the influent, effluent, and an observation well and tested for total suspended solids, total nitrogen, total phosphorus, chloride, and *E. coli*. Nine storm events were captured over the summer of 2021 and results indicated that the wetland had a median volume reduction of 73.7% and a median peak flow reduction of 89%. The average and median total suspended solids concentration reduced by the wetland was 49% and 37.5%. Total nitrogen and total phosphorus concentrations increased on average by 20.8% and 0.22%, respectively. However, these results were influenced by several influent concentrations that were below the concentration levels that are generally irreducible by green infrastructure. In cases where influent concentrations were above irreducible levels, total phosphorus reduction was 45.3% (influent $\geq$ 0.25 mg/L) and total nitrogen reduction was 38% (influent $\geq$ 2.5 mg/L). Results for *E. coli* were inconclusive due to minimal quantifiable results. Chloride concentrations in the inlet and outlet decreased over time, indicating the salt from winter was flushed from the system in late spring and early summer. Overall, this study shows that the subsurface gravel wetland generally performed similarly to other types of green infrastructure and could be a good management practice to mitigate the harmful effects of stormwater runoff.

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1. INTRODUCTION

1.1 Motivation for Work

Managing stormwater runoff to mitigate its harmful impact on urban and natural systems is a challenge for many communities. Doing so requires integrated infrastructure solutions that can reduce runoff peaks, volumes, and pollutants to downstream water bodies. Green infrastructure is an infrastructure type that captures, treats, and infiltrates water at the source and can be applied throughout a watershed as a part of a stormwater management plan to reduce downstream flooding and water quality impacts (Environmental Protection Agency, 2021c). One type of green infrastructure is wetlands, which are typically planted systems with a regularly saturated soil layer (Environmental Protection Agency, 2021b). An emerging type of wetland designed for use as an urban stormwater practice is subsurface gravel wetlands, sometimes referred to as gravel wetlands or prairie treatment systems.

Subsurface gravel wetlands function similarly to bioretention or bioswale systems in that they capture stormwater runoff through a vegetative depression, filter water through subsurface media, and discharge excess runoff through an underdrain. Unique to subsurface gravel wetlands is a designed wetted region that serves to provide anaerobic conditions to further remove pollutants through biological processes. This is accomplished through two specific zones: a saturated gravel layer that sits below an unsaturated soil layer, which may only be saturated during rain events (J. Houle et al., 2012). While there is a wealth of studies on bioretention performance, monitoring studies on the performance of subsurface gravel wetlands are lacking. This is an important gap as monitoring studies on the performance of subsurface gravel wetlands can help to verify their hypothesized performance and shed light on their value over other types of green infrastructure.

To that end, this thesis seeks to fill this gap by monitoring the hydrologic and water quality performance of a subsurface gravel wetland. The wetland is located near the new headquarter facilities of the Oshkosh Corporation in Oshkosh, WI, which includes a new road and business park area. With an increased focus on stormwater management for construction projects by the City of Oshkosh (Brown and Caldwell, 2021), this site had several stormwater management practices incorporated into the development design, including a subsurface gravel wetland. This wetland was installed along the new street to provide peak flow and stormwater pollution control (Brown and Caldwell, 2021). Therefore, this wetland provided an opportunity to monitor and evaluate this type of stormwater management practice in order to better understand its hydrologic performance and pollutant reduction efficiency.

1.2 Study Objectives

The goal of this study was to evaluate the hydrologic and water quality performance of a field-scale subsurface gravel wetland in Wisconsin. The specific objectives to meet this goal were (1) continuously monitor the influent and effluent flows from the wetland, (2) collect flow-weighted grab samples during runoff events, (3) test grab samples for pollutant concentrations (total suspended solids, total nitrogen, total phosphorus, chloride, and *Escherichia coli*), and (4) use the data to evaluate the hydrologic performances (volume and peak flow reduction) and water quality performance. In focusing on commonly regulated pollutants and hydrologic indicators, this study strives to provide valuable data and information to inform future designs and uses of subsurface gravel wetlands in Wisconsin and elsewhere.

2. LITERATURE REVIEW

2.1 Introduction

Managing urban stormwater runoff can be a challenge for communities due to a need to reduce runoff peaks, volumes, and pollutants. Green infrastructure is one solution to this challenge by providing a way to treat and mitigate the runoff near the source (Environmental Protection Agency, 2021c). Wetlands are a type of green infrastructure that captures, filters, and slowly releases runoff. In doing so, wetlands promote processes that can remove pollutants from the runoff (Environmental Protection Agency, 2021d). Subsurface gravel wetlands are a type of wetland that have emerged as a best management practice for treating stormwater runoff by capturing and filtering water through a subsurface gravel media. This design is gaining in popularity due to easy placement within the footprint of stormwater ponds, small hydraulic head requirement, and water quality mitigation potential due to filtration through media and a saturated zone.

Despite its growing use, there are limited monitoring studies that have verified the efficiency of treatment processes in subsurface gravel wetlands, especially in colder climates. The following literature review will outline the current knowledge of subsurface gravel wetlands from previous monitoring studies. Specifically, this review will summarize the outcomes of monitoring studies that captured pollutant reduction including Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), Chloride (Cl^-), and *Escherichia coli* (*E. coli*), as well as the hydrologic performance including peak flow and volume reductions. This review will also discuss various designs of subsurface gravel wetlands and how they relate to bioretention green infrastructure, which is similar in design and more broadly studied.

2.2 Subsurface Gravel Wetlands

Subsurface gravel wetlands are a type of green infrastructure that has been gaining popularity due to their treatment of contaminants in stormwater runoff. Subsurface gravel wetlands can vary in size, with literature describing surface areas between 0.65 ft^2 and 4,456 ft^2, which affects their retention time and volumetric treatment capacity (Amado et al., 2012; Kabenge et al., 2018). Subsurface gravel wetlands treat runoff through a layered media that generally contains plants as the top layer followed by a soil layer and a gravel layer. The gravel layer is designed to remain saturated, which makes this type of green infrastructure unique (J. Houle et al., 2012). In order to maintain a saturated zone, subsurface gravel wetlands tend to either be placed in areas with clay soils or have a liner installed below the gravel layer that allows for an anaerobic wet zone within the wetland, which is different from standard wetlands for the treatment of pollutants. The unique design of this wetland allows water to flow from an aerobic region into an anaerobic region (J. Houle et al., 2012), which has implications for pollutant reduction. For example, in the process of reducing nitrogen, aerobic conditions are required to convert nitrogen forms to nitrate through nitrification and the anaerobic conditions are required to convert nitrate to nitrogen through denitrification (J. Houle et al., 2012).

There is established literature of nitrifications and denitrification in wetlands. Nitrification and denitrification are completed by microbes under different conditions within wetlands (LeFevre et al., 2015). The aerobic conditions required for the nitrification process means access to oxygen while the anaerobic conditions required for the denitrification means no oxygen in the system (Lee et al., 2009). Within the aerobic region, microbes can utilize oxygen to convert ammonia to nitrite and then using oxygen to convert nitrite to nitrate (LeFevre et al., 2015). In the anaerobic region, the microbes covert the nitrate to nitrogen gas since there is a lack of oxygen other microbes can develop which perform this conversion by using nitrate as an energy source (Lee et al., 2009).

2.3 Design Descriptions

The construction of subsurface gravel wetlands can vary significantly, depending on the stormwater management goals and the location. In many pilot-scale studies, subsurface gravel wetlands are constructed tubs that are small in size (0.06 – 6 m^2 surface area) and are fed by smaller volumes of water (Huett et al., 2005; Sacco et al., 2021; Wu et al., 2011). The constructed tub designs tend to have rigid edges with controlled inlet flow. These tub designs are also used in lab-scale studies to test the reduction efficiencies of wetlands (Wu et al., 2011).

At the full-scale field size, subsurface gravel wetlands are generally much larger in size (450 ft^2 – 4500 ft^2) (Amado et al., 2012; Billore et al., 1999). These full-scale constructions tend to have slanted edges for natural water flow into the system (Neralla et al., 2000). The full-scale constructions can also contain either an artificial or clay soil liner to prevent infiltration and ensure a saturated zone (J. Houle et al., 2012). The full-scale systems appear similar to other “classic” wetlands in that on the surface they contain a soil and plant layer that contain typical wetland plants that have an important role in the nutrient removal processes (Wu et al., 2011).

Both types of construction (constructed tubs and full-scale) contain an aggregate layer made up of either gravel or another small stone-like material. In some unique cases, the aggregate layer has been augmented with a light expanded clay aggregate (LECA); however, these have not been shown to result in improvement in water quality over traditional gravel aggregate (Amado et al., 2012). Subsurface gravel wetlands can be applied to treat different sources of water including both wastewater and stormwater (Billore et al., 1999; Bixler et al., 2019; Huett et al., 2005; Neralla et al., 2000), and have even been applied to treat polluted river water (Wu et al., 2011).

In addition to the diversity in the designs, the way in which past studies have monitored subsurface gravel wetlands varies as well. The monitoring approaches are largely a function of the goals of the study, with some evaluating the performance over monthly averages (Billore et al., 1999; Neralla et al., 2000), while other more controlled systems were monitored on a more frequent basis (every 2 days) (Kabenge et al., 2018; Wu et al., 2011). The latter tended to use more frequent data to evaluate how the retention time affects the performance of the wetlands, and also tended to be on a lab scale where the wetlands were small (< 1.4 ft^2) (Kabenge et al., 2018; Wu et al., 2011). In one of the more frequently sampled studies, the samples were tested at different times: the influent samples were tested when added to the tubs and then the effluent samples were tested after time in the system (Kabenge et al., 2018). For the monthly sampled cases, the samples were collected and tested at the same time (Neralla et al., 2000).

2.4 Similar Green Infrastructure Practices

There are two green infrastructure practices that operate similarly to subsurface gravel wetlands but are more widely studied: bioretention and classic wetlands. Therefore, to gain a better understanding of the processes that lead to pollutant removal in subsurface gravel wetlands, the following review outlines the factors that influence hydrologic and pollutant removal processes in bioretention and classic wetland systems.

Bioretention is similar to subsurface gravel wetlands in that they are small, vegetated depressions that collect stormwater runoff, filter it through a subsurface media, and discharge the effluent through an underdrain into a stormwater network. However, they differ in that bioretention promotes infiltration, whereas subsurface gravel wetlands do not in order to ensure a continual saturated zone. Bioretention can also have both aerobic and anaerobic zones, but the difference is that subsurface gravel wetlands are less permeable, so the stormwater spends more time in the anaerobic zone compared to bioretention (J. Houle et al., 2012; Wu et al., 2011). For bioretention, the reduction efficiencies for TSS, nitrogen, and bacteria are 77%, 24%, and 99%, respectively (Clary et al., 2020). Total phosphorus was found to have either an insignificant change or significant increase in concentration for bioretention with a median reduction of -26% (Clary et al., 2020). These values are a summary on many studies and do not account for the differences in design and methodology. Comparatively, the limited literature has found subsurface gravel wetlands generally performed better than bioretention for nitrogen and phosphorus concentration reduction, with 20%-73% reduction of nitrogen and 25%-85% reduction of phosphorus (Amado et al., 2012; Huett et al., 2005; Kabenge et al., 2018). Previous studies of subsurface gravel wetlands found similar reduction to bioretention for TSS and bacteria, with TSS reduction of 58%-81% and 90% reduction of coliforms (Amado et al., 2012; Neralla et al., 2000).

Another comparable type of green infrastructure to subsurface gravel wetlands is classic wetlands. Wetlands are natural systems that usually do not contain an engineered impermeable liner and also tend to be larger in overall size than subsurface gravel wetlands (Neralla et al., 2000; Wadzuk et al., 2010). One classic wetland was 43,056 ft^2 (Wadzuk et al., 2010) while subsurface gravel wetlands range from 0.65 ft^2 to 4,456 ft^2 (Amado et al., 2012; Neralla et al., 2000). Wetlands also tend to have a large volume of standing water and longer duration of saturation than subsurface gravel wetlands, which, while designed to maintain a saturated gravel section in the subsurface layer, also have a layer of engineered soil and plants designed to fully drain after a runoff event. The reduction efficiencies of wetlands for TSS, P, and bacteria are 60%, 28%, and 95%, respectively (Clary et al., 2020). Total nitrogen did not have a significant change in concentration for "classic" wetlands with a median reduction of 4% (Clary et al., 2020). These values are a summary on many studies and do not account for the differences in design and methodology. Comparatively, the subsurface gravel wetlands in the literature perform better in all categories except for bacteria reduction.

2.5 Water Quality

The reduction of pollutants from stormwater runoff is important for protecting the health of downstream rivers and lakes. This thesis focuses on pollutants of concern, as identified in discussions with regional stakeholders who served in an advisory role on the project (Wisconsin Department of Natural Resources, City of Oshkosh, WI, and Milwaukee Metropolitan Sewerage District), including TSS, TN, TP, Cl^-, and *E. coli*. The following sections outline the hypothesized processes of reduction in subsurface gravel wetlands based upon other monitoring studies, as well as bioretention and classic wetlands described in the International Stormwater BMP database (Clary et al., 2020).

2.5.1 Total Suspended Solids

Total suspended solids in water can lead to higher temperatures and less sunlight penetration of the water, which harms aquatic life and leads to higher levels of other contaminants (Murphy, 2007). Removal mechanisms of TSS in subsurface gravel wetlands include filtration and settling. A high retention time and slow flow rate through the wetland allow for the suspended solids to settle out into the bottom of the wetland. In the literature, the reduction of TSS has been shown to vary. Two subsurface gravel wetlands with similar surface areas that treated wastewater had similar TSS reduction of 78% (450 ft^2) (Billore et al., 1999) and 81% (242-407 ft^2) (Neralla et al., 2000). However, a subsurface gravel wetland that treated both stormwater and wastewater had a TSS reduction of 58% (Amado et al., 2012). The difference in reduction could be due to the lower concentration of TSS in stormwater compared to wastewater; wastewater influent TSS concentration was 700 mg/L (Billore et al., 1999), and the stormwater influent TSS concentration ranged from 8-298 mg/L (Amado et al., 2012).

2.5.2 Nitrogen

Nitrogen is a problem for water bodies because various species nitrogen like nitrate can have severe health effects on people and animals (USGS, 2018). The transport and removal of nitrogen in stormwater management practices are complex due to the diversity of nitrogen species and different treatment mechanisms. Nitrogen solids such as leaf litter can be removed through sedimentation and filtration. Aerobic conditions at the surface of the wetland allow for nitrification followed by the anaerobic conditions in the subsurface gravel zone that allow for denitrification (J. Houle et al., 2012), where nitrate, ammonia, and nitrite are converted into nitrogen gas. Several studies suggest that at least a part of the reduction of total nitrogen is due to the uptake of nutrients through the plants (Billore et al., 1999; Huett et al., 2005; Wu et al., 2011). One study found that nutrient reduction decreased from 67-60% reduction in planted units to 39% for unplanted units (Wu et al., 2011).

The reduction of total nitrogen varies among different configurations of the subsurface gravel wetland, size of wetland, and influent concentrations of pollutant. Around 60% reduction of total nitrogen was found in several studies with varying type of influent: polluted river water (Wu et al., 2011), plant nursery runoff (Huett et al., 2005), and wastewater (Billore et al., 1999). However, another study where the wetland was fed by wastewater and stormwater found only 20% reduction of total nitrogen (Amado et al., 2012).

2.5.3 Phosphorus

Increased phosphorus levels in water bodies can also lead to eutrophication that can be harmful for people and animals (Environmental Protection Agency, 2021a). Phosphorus reduction could be due to a number of mechanisms including the adsorption of phosphorus species (Bixler et al., 2019; Huett et al., 2005). Phosphorus can also be removed in wetlands through sedimentation because the solids in runoff can contain phosphorus (Clary et al., 2020). Microbial processes can also be a method for phosphorus reduction in wetlands (Clary et al., 2020).

The reduction of phosphorus in subsurface gravel wetland studies is highly variable (25-84% reduction) (Amado et al., 2012; Huett et al., 2005). Several studies have shown the reduction of phosphorus to be around 60% with, variable influent including polluted river water (Wu et al., 2011), wastewater (Billore et al., 1999), and urban stormwater (Bixler et al., 2019). The range in pollutant reduction for the various studies could be due to the differences in construction, size, or inlet concentration. Maintenance of these wetlands through pruning/harvesting the plants has been shown to be a key factor in increasing plant nutrient uptake (Huett et al., 2005). Because the plants uptake nutrients, operators often prune the plants so the nutrients are not redistributed into the system (Huett et al., 2005).

2.5.4 E. coli

E. coli serves as an indicator of potential pathogens that can cause illness in people and animals. *E. coli* itself can also cause stomach issues including vomiting and diarrhea (Centers for

Disease Control and Prevention, 2021). Some ways that E coli and other bacteria can be removed by wetlands are natural inactivation, predation and sedimentation. Natural inactivation is simply the deterioration of bacteria over time for many reasons, while predation is the destruction of bacteria by other microorganisms (Clary et al., 2020). Filtration and sedimentation are also ways the *E. coli* can be removed. Longer retention times and slower flowrates through the wetlands allow the bacteria to filter and settle out or inactivate over time (Clary et al., 2020). Only one study of subsurface gravel wetlands that evaluated bacteria was found and it reduced 90% of coliforms from wastewater (Neralla et al., 2000).

2.5.5 Irreducible Concentration of Pollutants

It has been proposed that there is an irreducible concentration of pollutants that can be treated by wetlands (Schueler, 2000). Low influent concentrations of pollutants lead to wetlands not being able to further reduce the pollutants. This has been evaluated for multiple pollutants and different sources of influent like stormwater and wastewater (Schueler, 2000). The suggested irreducible concentration in stormwater for TSS, TN, and TP are 40 mg/L, 1.9 mg/L, and 0.2 mg/L, respectively (Schueler, 2000). If the influent pollutant concentrations are below these limits, wetlands will not be able to further reduce the concentration of these pollutants.

2.6 Volume and peak flow reduction

Subsurface gravel wetlands can also improve stormwater management through the reduction of peak flows and volume of runoff. Few studies have studied their hydrologic performance due to a hypothesized minimal infiltration of these systems based on their saturated zone. However, it has been shown that the retention time of these wetlands affects water quality performance. Increasing the hydraulic residence time (HRT) from 2 days up to 8 days in a subsurface gravel wetland that collects stormwater runoff from a parking lot increased the reduction of TSS from 21.9% to 49.7%, TN from 10% to 72.5%, and TP from 5.1% to 63.5% (Kabenge et al., 2018). In one case, 17 out of 23 data points showed less than 50% volume reduction in the subsurface gravel wetland (J. J. Houle & Ballestero, 2020). Another subsurface gravel wetland also showed consistent peak flow reduction. A subsurface gravel wetland fed by parking lot runoff was reported to have an annual K_p (peak reduction coefficient) of 0.13; a peak reduction coefficient less than one indicates peak flow reduction (Wildey et al., 2009). While these provide limited examples of the hydrologic performance of subsurface gravel wetlands, their hydrologic effects are under reported.

2.7 Summary of research objectives and hypothesized performance

The central goal of this study was to identify the pollutant reduction (nitrogen, phosphorus, TSS, chloride, and bacteria) and hydrologic mitigation of a subsurface gravel wetland that collects stormwater runoff. The objectives to meet this goal were to: (1) continuously monitor the influent and effluent flows from the wetland, (2) collect flow-weighted grab samples during runoff events, (3) test grab samples for pollutant concentrations (Total Suspended Solids, Total Nitrogen, Total Phosphorus, Chloride, and *Escherichia coli*), and (4) apply the data to evaluate the hydrologic performances (volume and peak flow reduction) and water quality performance. It was hypothesized that the subsurface gravel wetland would reduce the measured pollutant concentrations from the inlet to the outlet, further reduce pollutant loading through volume reduction, and significantly reduce the peak flow rates.

3. MATERIALS AND METHODS

3.1 Site Description

The subsurface gravel wetland is located in Oshkosh, Wisconsin and collects stormwater runoff from a street in a newly constructed business park (Figure 1). The surface area of the subsurface gravel wetland is 135-by-35 feet and treats a watershed area of about 1.9 acres that includes the street, sidewalk, and landscaped areas. Stormwater enters the wetland through a 24-inch pipe that collects runoff from four grates in the road. This inlet pipe discharges into a pretreatment sediment bay (10' x 10') where it then infiltrates through large stone aggregate into the wetland system. The wetland slopes away from the sediment bay into the larger wetland area that is planted with grasses and native vegetation. Below this vegetation is a layer of soil followed by a layer of stone and an impermeable liner to maintain a saturated zone. Within the stone layer is a perforated PVC underdrain that runs the length of the wetland and transports runoff from the wetland to the outlet structure. In addition, three PVC pipes are placed throughout the length of the wetland as observations wells.

Figure 1. An image of the subsurface gravel wetland in summer facing west (left); An image of the wetland in early spring facing east (right)

Within the outlet structure, water is discharged from the underdrain through a vertical pipe that contains a 2.25-inch hole at the elevation of the outlet pipe, and a 6-inch overflow two feet above. This allows for the slow release of water from the wetland system. The outlet structure itself is a four-foot by four-foot concrete structure with an overflow grate on top. The water exits the structure through a 19-by-30-inch elliptical pipe that is connected to the storm sewer system. The pipe is 8.7-inches off the bottom to allow water to accumulate and solids to settle in the structure.

Figure 2. An image of the vertical pipe in the outlet structure and the outlet pipe to the storm sewer

3.2 Monitoring Equipment and Methods

Numerous factors were monitored to understand the hydrologic and water quality effects including flow rates, rain volume, and concentration of Total Suspended Solids, Total Nitrogen, Total Phosphorus, Chloride, and *Escherichia coli*. To monitor the wetland, a variety of equipment was used to determine the flow rate and water quality concentrations in the influent and effluent of the subsurface gravel wetland. This included precipitation to validate the influent flow rates, which was collected from a Texas Electronics 6” tipping bucket rain gauge with an Onset HOBO pendant data logger. When the rain gauge data was not available, data was acquired from the NOAA rain gauge at the Wittman Regional Airport about 5 miles south. The following sections outline the additional flow and water quality monitoring equipment.

3.2.1 Flow Monitoring

The flow rate in the outlet pipe was monitored using 90-degree V-notch weir and level sensor. The outlet pipe had redundant level sensors including a Global Water WL16 vented water level logger, as well as an ISCO 730 bubbler. The Global Water WL16 water level sensor has an accuracy of ±0.2% over various temperatures (Xylem, 2022). Water level was used to compute flow rates using the following equation for a 90-degree v-notch weir (Washington State University, 2021):

$$Q = 2.49H^{2.48} \quad \text{[Equation 1]}$$

where Q is the volumetric flow rate in cubic feet per second and H is the height over the weir of the water in feet.

In the outlet structure, the invert of the pipe exiting the structure was roughly 10 inches from the bottom of the structure. A v-notch weir was placed at the face of the outlet pipe and two level sensors were placed in the outlet structure to estimate the water level within the structure and computed the flow exiting the system. In addition, there was a level sensor placed in the middle observation well to track the water level within the wetland.

Figure 3. Inlet pipe with weir and forebay shown (left); Outlet structure and outlet pipe with weir (right)

During the monitoring, backwater effects were observed at the inlet pipe, which affected the data at the v-notch weir installed at the end of the inlet pipe (Figure 3). Therefore, flow rate for the inlet was estimated using the rain gauge at the site. The rational method was applied to estimate input volumes from rainfall data collected by the rain gauge using the following equation:

$$Q = ciA \qquad \text{[Equation 2]}$$

where Q is the flow rate in ft^3/s, c is the runoff coefficient derived from land cover, i is the rainfall intensity, and A is the area in acres. The runoff coefficient, 0.8, was selected for concrete since the street and sidewalk which contribute the majority of the runoff were concrete (Wisconsin Department of Transportation, 1997).

3.2.2 Water Quality Monitoring

To observe the changes in the water quality due to the treatment processes in the wetland, water samples were taken at several locations and tested for pollutants including Total Suspended Solids, Total Phosphorus, Total Nitrogen, Chloride, and *Escherichia coli*. In the inlet and outlet pipes, flow-weighted samples were taken using ISCO Avalanche refrigerated autosamplers and triggered using water level from the ISCO 730 bubble (effluent) and the ISCO 720 pressure sensor (influent). Each of the autosamplers has a carriage of 14 bottles, which can each hold 950 mL of water. The sampling volumes were iteratively selected based upon observed data to optimize volume capture, with the inlet finally set to collect a 50 mL sample every 5000 gal of water passing the sensor, while the outlet was set to collect a 100 mL sample every 50 gal of water passing the sensor.

In some cases, there was not enough flow rate to trigger a sample, especially in the effluent pipe. Therefore, in addition to the autosamplers, two Thermo Scientific Nalgene stormwater sampling bottles were used to collect additional samples. The first bottle was placed in the outlet structure just below the invert elevation of the pipe exiting the structure to allow for a sample of the initial effluent leaving the system. An additional sampling bottle was placed in the observation well furthest from the inlet and outlet of the wetland to collect water as it flows through the wetland.

Figure 4. ISCO Avalanche Autosampler at the site

3.3 Water Quality Testing

Water samples were collected from the site and transported in coolers to the Water Quality Center at Marquette University, where they were tested for Total Suspended Solids, Total Nitrogen, Total Phosphorus, Chloride, and E coli. Total suspended solids was tested using the standard methods: vacuum filtration of a known sample volume (Cole-Parmer, 2021). The total nitrogen was tested using the Hach Method 10071 Test'N'Tube using persulfate digestion (HACH, 2015). The total phosphorus was tested using the Hach low range total phosphorus test (HACH, 2021). The chloride was performed using Hach TNTplus Chloride test using the Iron(III)-thiocyanate method (HACH, 2018). Spectrophotometer readings were complete in triplicate for all HACH test sample. The *E. coli* test was performed in triplicate by the standard EPA method 1603 using membrane filtration (USEPA, 2002). This method was completed using Difco M-Endo Broth to culture the E coli.

3.4 Data Analysis

Inflow and outflow volumes across the entire storm events were approximated using the flow rate data derived from water level and rain gauge data. To obtain the volumes, the trapezoid integration approximation method was applied.

$$V_T = \sum_n (t_n - t_{n-1}) \left(\frac{q(t_{n-1}) + q(t_n)}{2}\right) \qquad \text{[Equation 3]}$$

where V_T is the total volume, n is the number of flowrate measurement, t is the time of the measurement, and q is the flowrate at that time.

The pollutant load allows for another perspective on the water quality performance of the wetlands. Load was determined by multiplying the volume of a storm with the concentration of each pollutant.

$$L = VC \qquad \text{[Equation 4]}$$

where L is the load, V is the total volume, and C is the concentration of the contaminant.

To analyze and observe changes in the data, the following ratios of outflow to inflow were used for all the major water flow and water quality metrics across each storm event.

$$R_{volume} = \frac{V_{out}}{V_{in}} \quad \text{[Equation 5]}$$

$$R_{peak} = \frac{q_{peak-out}}{q_{peak-in}} \quad \text{[Equation 6]}$$

$$R_{concentration} = \frac{C_{out}}{C_{in}} \quad \text{[Equation 7]}$$

$$R_{load} = \frac{L_{out}}{L_{in}} \quad \text{[Equation 8]}$$

where R_{volume} is the ratio of the total outlet volume (V_{out}) and total inlet volume (V_{in}), R_{peak} is the ratio of peak outlet flow rate ($q_{peak-out}$) and the peak inlet flow rate ($q_{peak-in}$), $R_{concentration}$ is the ratio of outlet concentration (C_{out}) for each contaminant and the inlet concentration (C_{in}) for each contaminant, and R_{load} is the ratio of outlet load (L_{out}) for each contaminant and the inlet load (L_{in}) for each contaminant.

In addition, these ratios were used to express the performance as a percent reduction using the equation as follows:

$$Parameter\ Reduction = (1 - R) \times 100\% \quad \text{[Equation 9]}$$

where R is a ratio of volume, peak, concentration, or load and the parameter reduction is expressed as a percentage. In addition, due to the non-normal distribution of the data, the Wilcoxon signed-rank test was used to statistically compare the influent and effluent data. For these tests the statistical significance level was set to 0.05.

4. RESULTS

There were 13 recorded storm events that were large enough to produce flow rate in both the inlet and the outlet that could be sampled. Due to limitations of the autosamplers, in only 9 of those storms were samples collected in either the inlet or outlet: 5 events produced both outlet and inlet samples, 1 event with just outlet samples, and 3 events with just inlet samples. The events with just influent or effluent samples were due to issues with the autosamplers not collecting samples. TSS, TN, TP, and Cl^- tests were performed on all samples; however, three of the samples tested for phosphorus came in under the testable range. The chloride tests were conducted with round vials instead of the recommended square vials. While it is possible this could introduce uncertainty in the data, the trends may still be valid since the testing was consistent among all samples. Two of the *E. coli* results were considered too few to count and five of the samples were not tested due to a lack of testing material availability at the time of the storms.

4.1 Hydrologic Performance

The subsurface gravel wetland captured and removed 11% of the runoff on average, with a median of 74%, totaling about 311,600 gallons of water across 13 events (Table 1). This was further illustrated in Figure 5a, which plotted the influent and effluent volume and demonstrated that the wetland captured and infiltrated volumes across all storms. The average precipitation recorded was 1.94 inches with an average storm length of 3.9 hours. The subsurface gravel wetland appeared to have a short hydraulic residence time with the average delay between the first flow over the inlet weir and the first flow over the outlet weir during a storm event of 3.47 hours. In addition to volume reductions, the magnitude of peak flows was also reduced by 73% (average) and 89% (median), with a clear increase in effluent peak flows for larger influent peaks (Table 1 and Figure 5b). Figure 6 also illustrated the volume reduction for each runoff event as a function of the rainfall depth. As illustrated, besides a low outlier at the lowest rainfall depth, the volume reduction in the wetland appeared to decrease as the rainfall depth increases.

Table 1. Hydrologic performance summaries of the subsurface gravel wetland

	Average	Median
Volume Ratio (Effluent: Influent)	0.89	0.26
Volume Captured (gallons)	24,000	22,300
Volume Captured	11%	74%
Peak Flow Ratio (Effluent: Influent)	0.27	0.11
Peak Flow Reduction	73%	89%

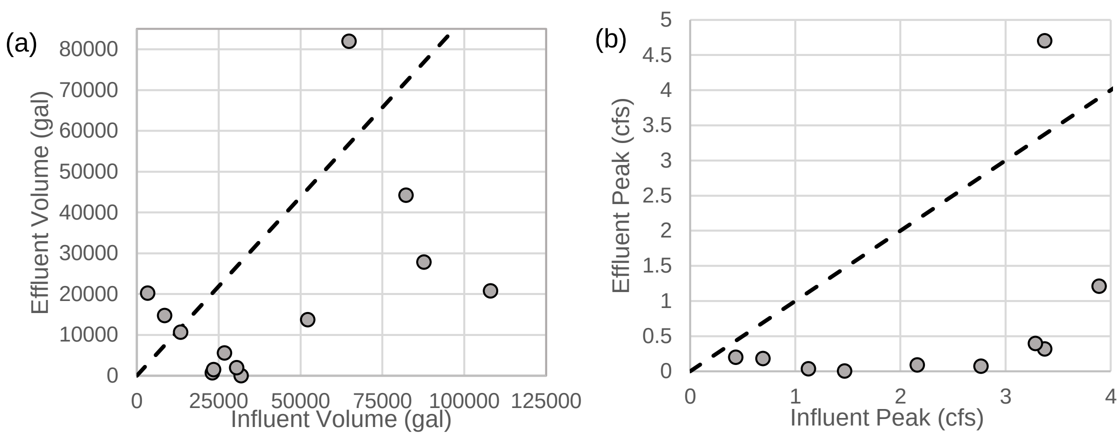


Figure 5. Comparison of the influent and effluent volume (a) and peak flows (b), with the dashed line representing a 1:1 relationship.

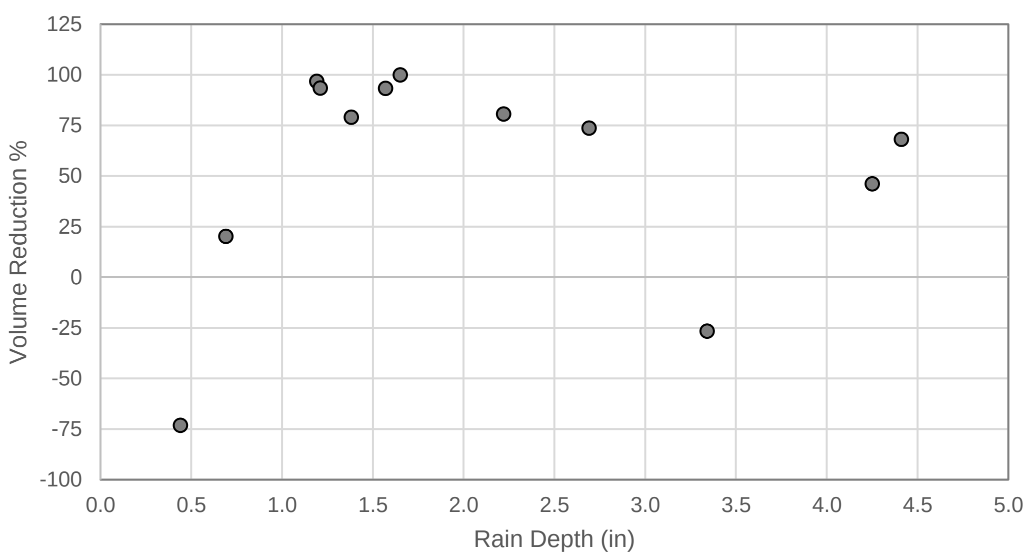
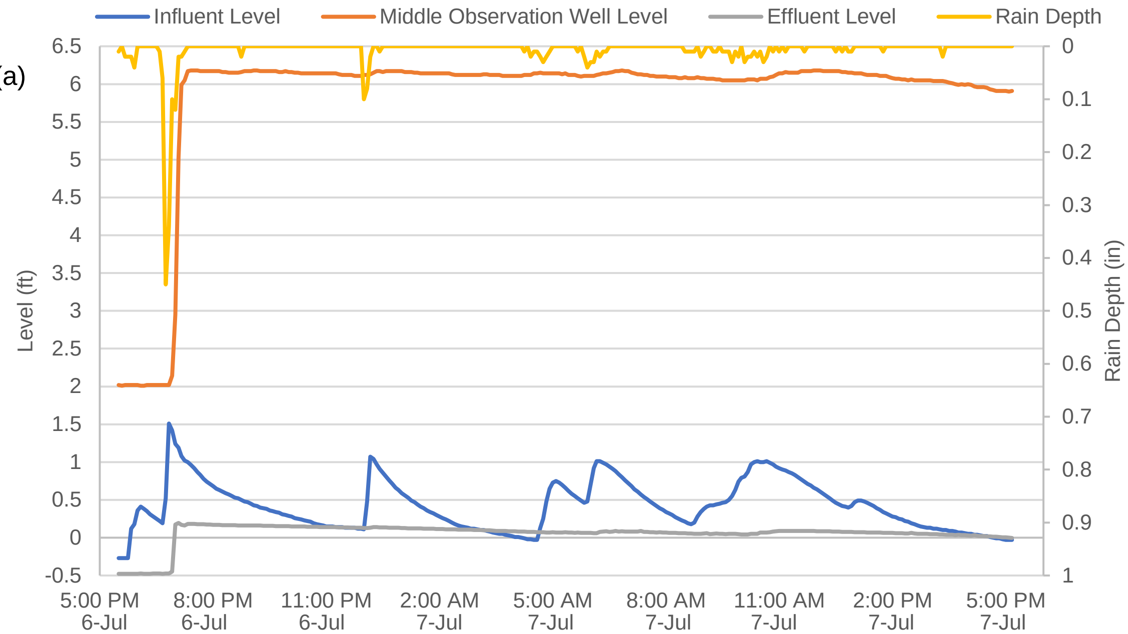


Figure 6. The percent volume reduction over different rainfall depths. Not illustrated is the low outlier at 0.17 inches that had a negative volume reduction.

In Figure 7a, the water level in the influent pipe, effluent pipe, and observation well were illustrated as a function of time, highlighting how the water level functioned in the wetland during a runoff event. The influent and effluent pipe levels were adjusted to reflect the water level over the weir. As illustrated, the water level in the influent increased quickly in response to rainfall, which then subsequently caused the water in the subsurface gravel wetland to rise as illustrated by the level in the observation well. Both the observation well and the effluent levels gradually decreased over time as the wetland released the captured runoff. This was further illustrated in Figure 7b, which showed the water level in the wetland slowly receding over time until it got back down to base levels after a week.

(a)



(b)

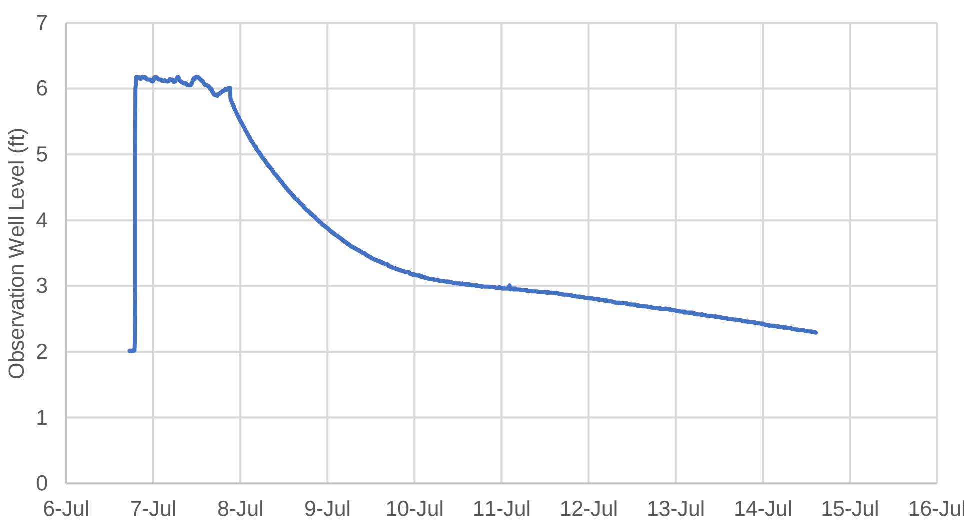


Figure 7. The level of influent, effluent, and middle observation well and the rain depth are shown over 24 hours (a), and the level of the middle observation well is shown over 10 days (b). They both show the same storm event.

4.2 Water Quality Performance

The influent and effluent concentration data was shown in Figure 9 for each contaminant: TSS, TN, TP, Cl^-, and *E. coli*. Each graph has a diagonal dashed line showing the point where the influent and effluent would be equal – points below the line indicated a reduction in concentration, while points above the line indicated an increase in concentration. Additionally, the TSS, TN, and TP graphs had a vertical dashed line showing the irreducible concentration in stormwater. Points with influent concentrations below this line may not be reduced by wetlands. The TSS average reduction was 49% with a median reduction of 37% with some reduction in all samples. For TN, the average and median reductions were -21% and -12%, respectively, indicating an increase in the concentration from the influent to the effluent. However, for those with an influent concentration above 2.5 mg/L the average reduction was 38%. The TP average reduction was -0.22% with a median reduction was 38%. The singular event with a TP concentration increased between influent and effluent had a small influent concentration (<0.25 mg/L). In addition, similar to TN, for those events with an influent concentration above 0.25 mg/L, the average reduction increased to 45%. Cl^- reduction was -480% on average, and the median reduction of Cl^- was -200%. The average *E. coli* reduction was -1640%, and the median was 66%.

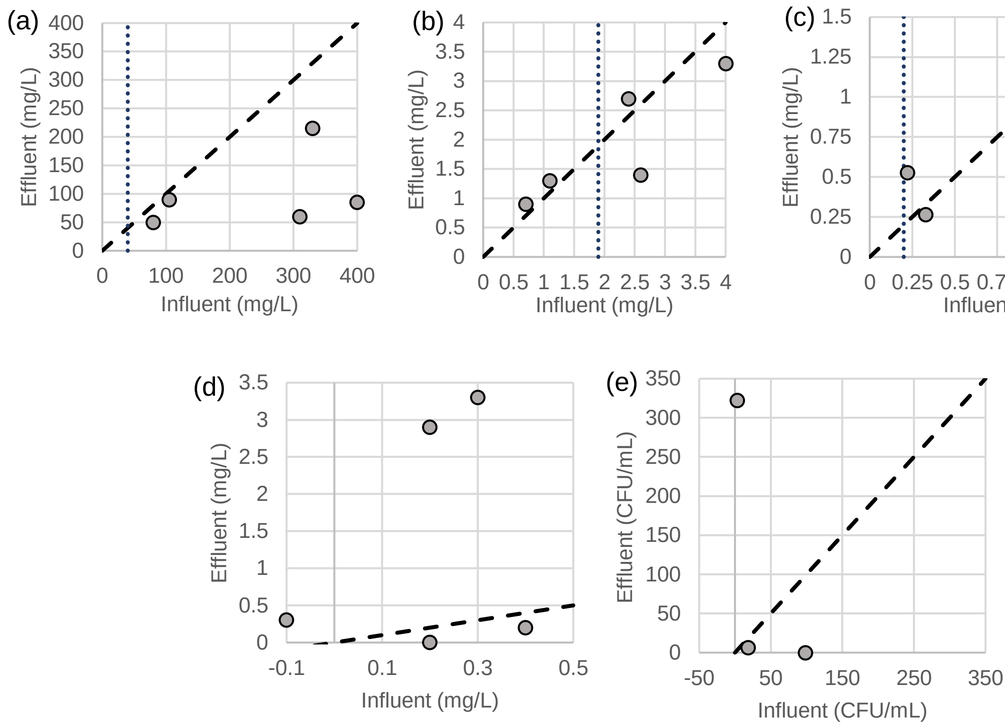


Figure 8. Influent and effluent concentrations in the wetland for TSS (a), TN (b), TP, (c), Cl^- (d) and E coli (e) with the dashed line representing a 1:1 relationship. TSS (a), TN (b), and TP (c) plots include vertical lines representing the irreducible concentration.

In Figure 9, the distributions of the influent and effluent concentrations for all the contaminants were shown. Events that had only outlet or inlet samples were also included in this figure. The distributions in Figure 9 show that for TSS, TN, and TP, the influent samples had higher variation in concentration than the effluent samples. In addition, on average the influent samples for the TSS, TN, TP are higher than the effluent. Most of the Cl^- points are actually in a close range for the influent (< 0.6 mg/L). Figure 10 shows the Cl^- concentration over time for the influent and effluent. This figure highlights the flushing effect of salts from the system during the summer months. The inlet had a high concentration in the spring when salts on the roads may have still been present, followed by a steady decrease in the inlet concentrations for the summer months. Similarly, the effluent had higher concentrations in the beginning of the summer, which slowly decreased to match inlet concentrations in mid-July.

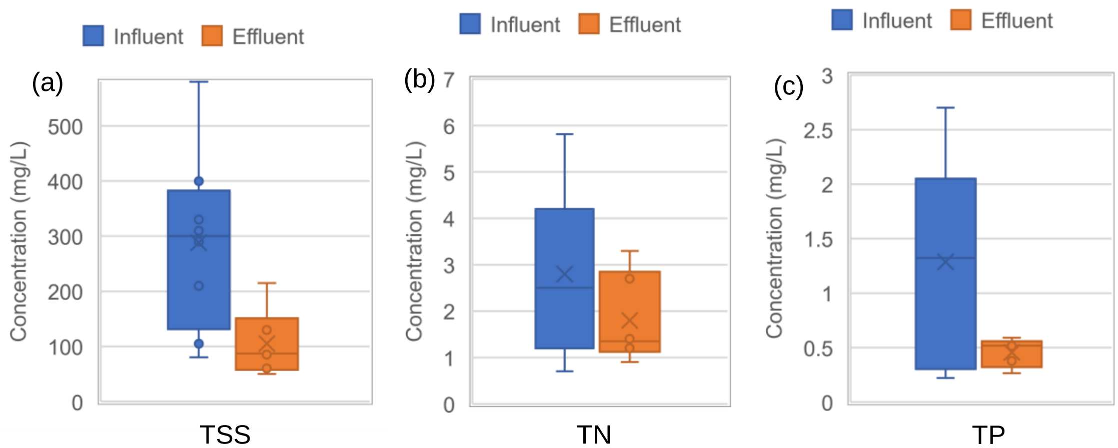


Figure 9. Distribution of the influent and effluent concentrations in the influent and effluent samples for TSS (a), TN (b), and TP (c).

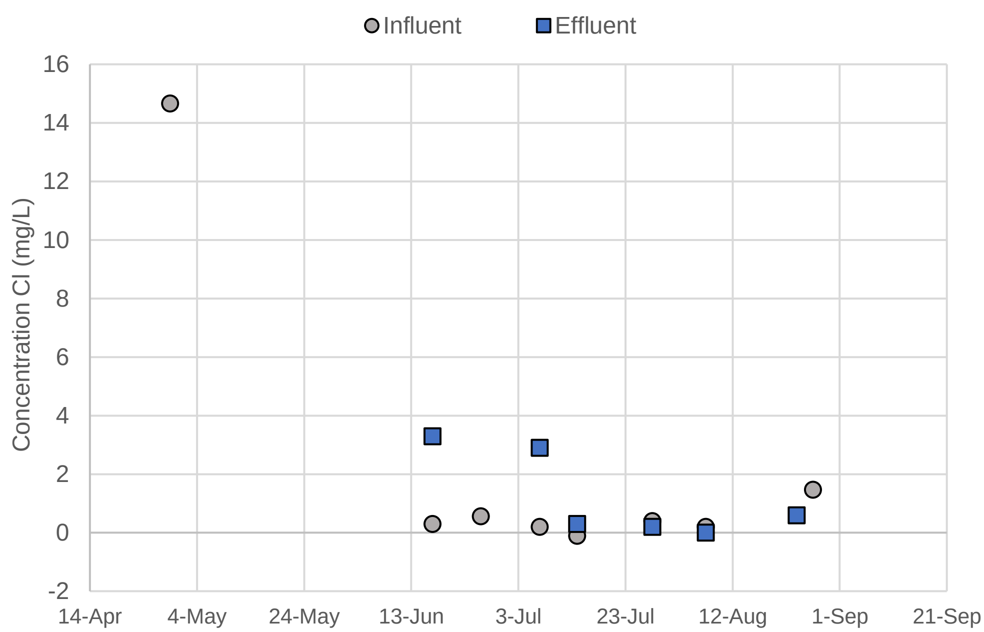


Figure 10. The influent and effluent concentration of chloride in the wetland over time.

The variation in the removal of load was similar to the concentration data partly due to the concentration of the high outliers in the flow data. Distributions for the influent and effluent loads were generated to show these load removals (Figure 11). The load removal for TSS was 73% on average and had a median removal of 83%. For TN, the load removal average and median are 53% and 77%, respectively. TP had an average and median load removal of 15% and 81%.

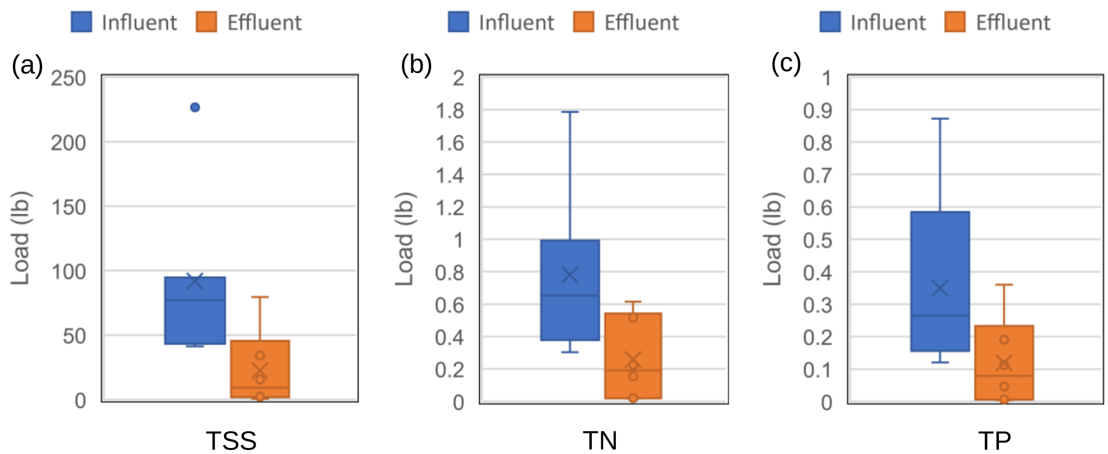


Figure 11. Difference in the distribution of influent and effluent pollutant loads for TSS (a), TN (b), and TP (c).

In addition to testing the influent and effluent, samples from an observation well were collected for three sampling events. One of those events had all three (influent, effluent, and the observation samples), another had an effluent and observation well sample, while the last event had an influent and observation well sample. The concentrations of the contaminants for these samples are represented in Figure 12. This figure shows that the concentration generally decreases from the influent sampling point to the observation well at the far end of the wetlands, then it increases from the observation well sample to the effluent sampling point. This was also represented in Table 2, showing the reductions between the influent and observation well, the observation well and effluent, and the influent and effluent for each contaminant.

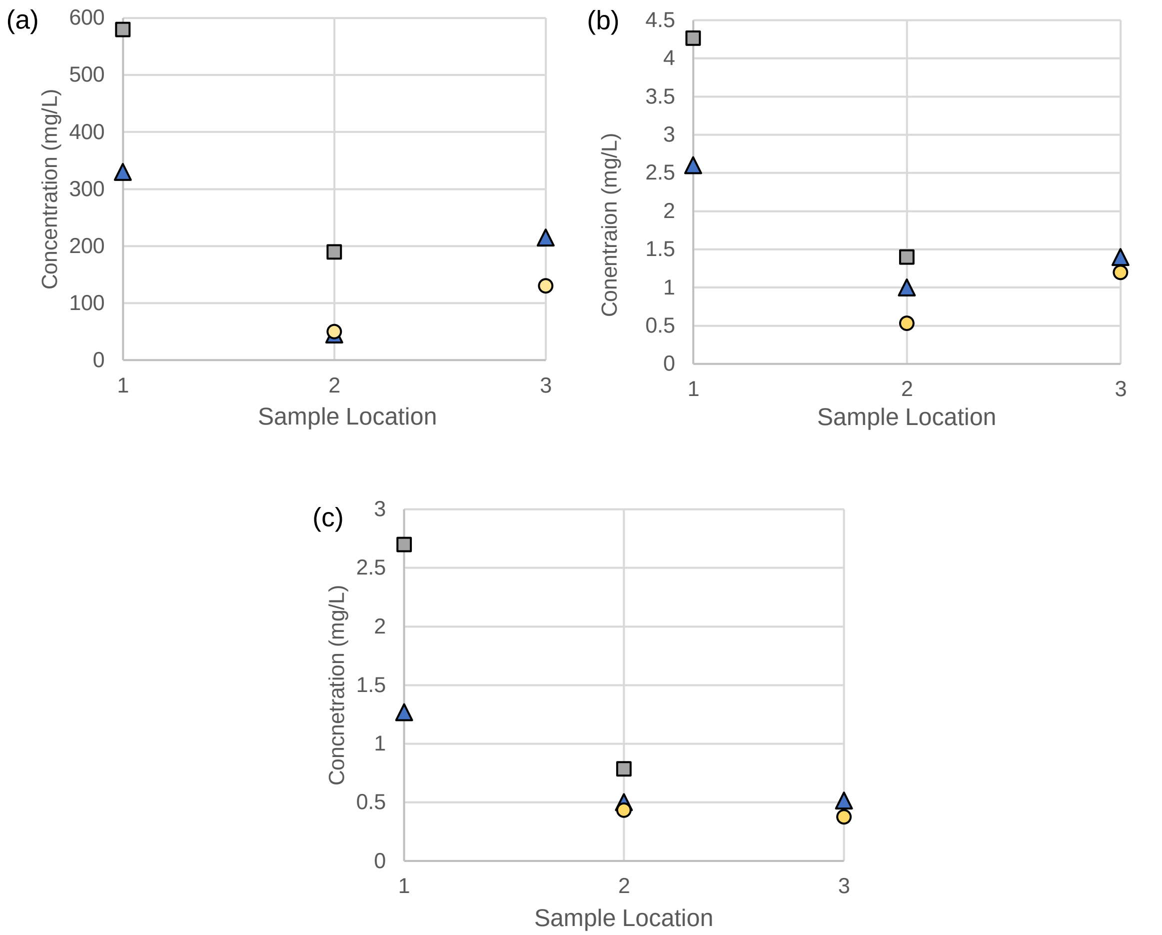


Figure 12. The concentration at different sampling locations in the wetland for TSS (a), TN (b), and TP (c). With the sample locations being inlet (1), observation well (2), and outlet (3). The various shapes indicate different sampling events.

Table 2. Summary of spatial reduction of pollutants in the subsurface gravel wetland

Parameter	Average Reduction		
	Influent and Observation Well	Observation Well and Effluent	Influent and Effluent
TSS	77%	-270%	35%
TN	64%	-82%	46%
TP	66%	5.3%	59%

5. DISCUSSION

Overall, the results show that the subsurface gravel wetland was effective at reducing volume. The subsurface gravel reduced an average of 11% of the storm runoff volume that entered the system and a median reduction of 74%. The average was affected by the outlying points, but the majority still shows reduction. The reduction of volume could be due to evapotranspiration or exfiltration. The surface was fully planted and most of the samples and data were obtained during the summer months (June-August) when median high temperatures are 79 F (U.S. Climate Data, 2021). However, it was unlikely that all the reduction was due to evapotranspiration. Some of the reduction could also be due to exfiltration. Although the system was supposed to be lined at the bottom, there may be horizontal exfiltration at higher water levels. The level in the wetland showed that the water decreased slowly over days after a storm; this could be exfiltration over those days after storm events. In this subsurface gravel wetland, the volume reduction was generally over 50% for each storm (9 out of 13), demonstrating that overall, the wetland reduces the volume of stormwater runoff. This was somewhat higher than another subsurface gravel wetland monitoring study that found that the majority (17 out of 23) of the storm events showed less than 50% volume reduction (J. J. Houle & Ballestero, 2020). This wetland showed to drain over a week after some storm events while in the other study the wetlands were designed to drain within 48 hours (J. J. Houle & Ballestero, 2020). This difference could explain the volume reduction difference. While there are other studies that monitored the water balance of subsurface gravel wetlands, they focus on the HRT and how that affected the contaminants rather than reporting influent and effluent volumes (Amado et al., 2012; Kabenge et al., 2018).

As expected, the subsurface gravel wetland generally reduced the peak flows (89% median). With a large sediment bay and large surface area and volume of the subsurface gravel wetland, it allows the system to capture large volumes and slowly release them over time. The underdrain of the system was an 18” rectangular pipe, which connects to a 6” pipe in the outlet structure where water then leaves through a 2.25” hole (Figure 2). The water must then fill the outlet structure (4-foot-by-4-foot) to 10 inches tall before crossing the weir and exiting into the stormwater system. With that buffer between the water exiting the wetland and entering the storm sewer, the flow exits the system slowly, therefore reducing peak flow rates. This was highlighted in the runoff event in Figure 8b, which took over a week to return to base water levels in the wetland.

TSS concentrations and loads were reduced by 49% and 73% on average, respectively. The results are comparable for the TSS reduction in other studies, which found reductions in concentrations of 58% (Amado et al., 2012) and 14-76% (Kabenge et al., 2018). It was expected that this wetland would have reduction of the TSS since other studies of subsurface gravel wetlands also had reduction of TSS (Amado et al., 2012; Kabenge et al., 2018). Removal mechanisms of TSS are most likely due to sedimentation and filtration (Clary et al., 2020). This wetland had multiple areas where this can occur. The runoff path through the gravel layer in the sediment bay promotes slow filtration and sedimentation. In addition, the long hydraulic residence time allows for sedimentation and filtration in the main wetland area itself. Finally, the pipe leading to the stormwater system from the outlet structure was raised from the bottom, providing opportunity for settling within the outlet structure itself.

While total nitrogen concentrations were on average lower in the effluent than the influent, this difference was not statistically significant ($p < 0.05$). In fact, during some runoff events, the effluent concentrations of TN appeared to increase. This could be due to several factors including low influent concentrations or specific removal processes. The concentrations in the inlet were at or below irreducible levels that the subsurface gravel wetland was unable to further reduce. As a comparison, a similar-sized wetland had average reduction of 20% TN and 25% TP; however, in that study, the wetland had an inlet concentration of 20-166 mg/L of TN and 2-23 mg/L of TP (Amado et al., 2012). This was an order of magnitude larger than the inlet concentrations of the wetland in this study, which are 2.80 mg/L TN and 1.29 mg/L TP on average. For the effluent concentrations, the same study showed 12-113 mg/L and 1.5-15 mg/L for TN and TP, respectively (Amado et al., 2012). The average effluent concentration for TN was 1.8 mg/L, which was close to the irreducible concentration of TN for stormwater practices of 1.9 mg/L (Schueler, 2000), and similar to the median effluent concentration across 14 other wetland studies of 1.4 mg/L (Clary et al., 2020). Therefore, due to influent concentrations that are only slightly higher than the irreducible concentrations, it was not surprising that these reductions were marginal. To that end, in other subsurface gravel wetland studies where a higher percentage of TN reduction was observed, their influent concentrations were much higher. For example, 61% reduction in concentration of TN was observed with an average influent concentration of 18.8 mg/L (Wu et al., 2011), and 63% reduction was observed with an influent concentration of 10 mg/L (Huett et al., 2005).

There could be a few reasons that the reduction of nitrogen concentrations was inconsistent or negative. Negative reduction values signify an increase in concentration from the influent to the effluent. There are several processes within the subsurface gravel wetland that could contribute to changes in nitrogen. Nitrogen reduction in these systems was complex due to the diversity of nitrogen species and various mechanisms for treatment. It was hypothesized that subsurface gravel wetlands remove nitrogen through nitrification followed by denitrification in the unsaturated and saturated zones (J. Houle et al., 2012). It could be that the gravel was not maintaining a consistent saturated zone, which would indicate the wetland was oversized. It could also be that the water was not spending enough time in the saturated zone to be fully denitrified. In other studies with more consistent reduction of nitrogen, the hydraulic retention time was at least a day (Huett et al., 2005; Kabenge et al., 2018). Other processes by which nitrogen was reduced in wetlands, which was a minor contributor to the overall reduction mechanism, are sedimentation and plant uptake (Clary et al., 2020). Since TSS shows reduction in the concentration and load, it indicates sedimentation was occurring; thus, some of the reduction of nitrogen could be caused by sedimentation.

For total phosphorus, the majority of the samples had a reduction in concentration from the influent to effluent with a median reduction of 38%, and only one sample had a negative reduction in concentration. In comparison, other studies of subsurface gravel wetlands found mean influent and effluent concentrations of 0.58 mg/L and 0.05 mg/L (Huett et al., 2005) and 1.56 mg/L and 0.724 mg/L (Wu et al., 2011) with reductions of 85% and 63%, respectively (Huett et al., 2005; Wu et al., 2011). While the average influent concentration of TP in this study was close to the other studies at 1.29 mg/L, this study had a less median reduction. However, the data was skewed by a sample with a low influent concentration of 0.22 mg/L near the irreducible concentration of total phosphorus (0.2 mg/L) (Schueler, 2000). Therefore, this data point was likely due irreducible concentration in the influent, rather than a failure of the subsurface gravel wetland itself. The average reduction of total phosphorus with inlet concentrations above 0.25 mg/L was 45%. Studies suggest the main way phosphorus was removed was through sorption onto the gravel media (Bixler et al., 2019; Huett et al., 2005; Kabenge et al., 2018). This process would be less hindered than the microbial transformations nitrogen must go through, suggesting that this may be a good method for phosphorus reduction. The other methods that could be reducing phosphorus in the system are sedimentation and plant uptake (Clary et al., 2020). Because the TSS had significant reductions in concentration and load, it suggests sedimentation was occurring properly, thus could be a source of phosphorus reduction.

The concentrations of chloride in the influent and effluent were variable over the study period. The subsurface gravel wetland had no mechanisms for chloride reduction; therefore, as expected, the wetland experienced increases during the late spring, followed by flushing during the early summer. This was evident in that the first sample in April had a high influent concentration when there was likely residual salt from deicing on the road and/or settled within the inlet pipe. In the outlet, the concentrations generally decreased throughout early summer from

3.1 mg/L (mid-June to mid-July) to 0.28 mg/L (mid-July to August). This drop could be due to flushing where each runoff event flushes out salts contained in the existing water in the wetland, thereby decreasing the concentration over time. This could also be due to residual salt in the outlet structure and pipe from winter storms that are mobilized during the summer rains observed in this study.

E. coli reduction was inconclusive due to issues over the study period with the testing method. It was a challenge to create plates that had a countable number of *E. coli*. Under lower concentrations, the E coli were too few to count and under higher concentrations, the plates would fill with other colonies. For the plates that were in the countable range, the reduction was variable. To that end, there were not any studies related to *E. coli* reduction in subsurface gravel wetlands.

During two runoff events the concentrations of pollutants in the observation well were generally at or below the concentrations in the outlet. This could indicate that as the water enters the middle of the wetland most of the removal processes have occurred that reduce the pollutant concentrations. Furthermore, the hydraulic designs of the wetland indicate that runoff flow down to the far end (west) of the wetland and back up to the pipe (east), where it enters the outlet structure through a perforated underdrain. However, for smaller storms the flows may not reach the far end of the wetland where the observation wells are located. While there were storms in which standing water was found on the top of the wetland, it was possible that smaller runoff events did not result in large volumes reaching the end of the wetland. The larger runoff events that cause the observation well sample bottle to fill may therefore contain lower concentrations of pollutants due to dilution of larger runoff entering the wetland.

6. CONCLUSIONS

6.1 Key Finding

The objective of this thesis was to evaluate the performance of the subsurface gravel wetland in Oshkosh, WI. The hydrologic and water quality performance was evaluated for this wetland for over a year. The results indicate the subsurface gravel wetland reduced peak flows, volumes, and pollutant loads from TSS, TP, and TN. The results also indicate the reduction of TSS and TP concentrations and flushing of accumulated Cl^- in the system, but trends were unclear for TN and *E. coli*. This study had several key findings which can be used for other subsurface gravel wetlands in the Wisconsin:

- The subsurface gravel wetland significantly reduced peak flow and volumes with a median reduction of 89% and 74%, respectively.
- TSS concentrations were reduced by 49% in the subsurface gravel wetland, most likely due to sedimentation and filtration.
- The influent concentrations of nutrients were in many cases at or below the irreducible concentration for TN (1.9 mg/L) and TP (0.2 mg/L) (Schueler, 2000), resulting in average concentration increases of 21% and 0.2%.
- In cases where influent concentrations were above irreducible levels, TP reduction was 45% (influent $\geq$ 0.25 mg/L) and TN reduction was 38% (influent $\geq$ 2.5 mg/L).
- Despite several cases where pollutant concentrations increased, the pollutant loads (TSS, TN, and TP) were reduced on average due to volume reduction.
- Cl^- concentrations in the inlet and outlet decreased over time, indicating the salt from winter was flushed from the system in late spring and early summer.

6.2 Future Work

Based upon the outcomes of this study, there is future work that could be performed to better understand the function of this and other subsurface gravel wetlands. Continued monitoring of this wetland could be performed to evaluate the operation of the wetland in the long term and over the early spring and late fall months. Additionally, this study did not evaluate the species of nitrogen or phosphorus and evaluating the different species could provide a clearer indicator of the removal processes occurring within the wetland. Future work could also study the pollutant movement within the wetland. This could be performed by testing samples from each of the observation wells and the inlet and outlet, which would provide a spatial representation of the reduction of contaminants within the wetland. This study provides some indication the observation well at the far end had similar or greater reductions in concentrations than the outlet, thus looking at the pollutants from each well may provide more information on this wetlands function. Also, increased study and monitoring of the *E. coli* in the wetland would be helpful since this study did not result in *E. coli* conclusions. Overall, this study provides promising results for the use of subsurface gravel wetlands in Wisconsin for reduction of volumes, peak flows, and most pollutants.

BIBLIOGRAPHY

Amado, L., Albuquerque, A., & Espírito Santo, A. (2012). Influence of stormwater infiltration on the treatment capacity of a LECA-based horizontal subsurface flow constructed wetland. *Ecological Engineering*, *39*, 16–23. https://doi.org/10.1016/j.ecoleng.2011.11.009

Billore, S. K., Singh, N., Sharma, J. K., Dass, P., & Nelson, R. M. (1999). Horizontal subsurface flow gravel bed constructed wetland with Phragmites karka in Central India. In *Water Science and Technology* (Vol. 40, Issue 3, pp. 163–171). https://doi.org/10.1016/S0273-1223(99)00461-8

Bixler, T. S., Houle, J., Ballestero, T., & Mo, W. (2019). A dynamic life cycle assessment of green infrastructures. *Science of the Total Environment*, *692*, 1146–1154. https://doi.org/10.1016/j.scitotenv.2019.07.345

Brown and Caldwell. (2021). *City of Oshkosh Storm Water Management Overview for Storm Water Utility Appeals Board*.

Centers for Disease Control and Prevention. (2021). *E. coli (Escherichia coli)*. https://www.cdc.gov/ecoli/ecoli-symptoms.html

Clary, J., Leisenring, M., Jones, J., Hobson, P., & Strecker, E. (2020). *International Stormwater BMP Database: 2020 Summary Statistics*. The Water Research Foundation. www.waterrf.org

Cole-Parmer. (2021). *Total Suspended Solids (TSS) Method and Procedure*. Cole-Parmer.

Environmental Protection Agency. (2021a). *Indicators: Phosphorus*. https://www.epa.gov/national-aquatic-resource-surveys/indicators-phosphorus

Environmental Protection Agency. (2021b). *What is a Wetland?* https://www.epa.gov/wetlands/what-wetland

Environmental Protection Agency. (2021c). *What is green infrastructure?* EPA.Gov. https://doi.org/10.4324/9780203121993-6

Environmental Protection Agency. (2021d). *Why are Wetlands Important ?* https://www.epa.gov/wetlands/why-are-wetlands-important

HACH. (2015). *Nitrogen, Total Persulfate Digestion Method ~ Method 10072*. 1–8.

HACH. (2018). *Chloride, Method 10291 TNTplus 879 Test*. 1–4.

HACH. (2021). *TNT843 Phosphorus , Reactive (Orthophosphate) and Total*. 4–7.

Houle, J. J., & Ballestero, T. P. (2020). Some Performance Characteristics of Subsurface Gravel Wetlands for Stormwater Management. *University of New Hampshire Scholars' Repository*.

Houle, J., Roseen, R., Ballestero, T., Watts, A., Puls, T., & Gilbert, H. (2012). *Subsurface Gravel Wetland for Stormwater Management*.

Huett, D. O., Morris, S. G., Smith, G., & Hunt, N. (2005). Nitrogen and phosphorus removal from plant nursery runoff in vegetated and unvegetated subsurface flow wetlands. *Water Research*, *39*(14), 3259–3272. https://doi.org/10.1016/j.watres.2005.05.038

Kabenge, I., Ouma, G., Aboagye, D., & Banadda, N. (2018). Performance of a constructed wetland as an upstream intervention for stormwater runoff quality management. *Environmental Science and Pollution Research*, *25*(36), 36765–36774. https://doi.org/10.1007/s11356-018-3580-z

Lee, C. G., Fletcher, T. D., & Sun, G. (2009). Nitrogen removal in constructed wetland systems. *Engineering in Life Sciences*, *9*(1), 11–22. https://doi.org/10.1002/elsc.200800049

LeFevre, G. H., Paus, K. H., Natarajan, P., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering*, *141*(1), 04014050. https://doi.org/10.1061/(asce)ee.1943-7870.0000876

Murphy, S. (2007). *General Information on Solids*. City of Boulder/USGS Water Quality Monitoring. http://bcn.boulder.co.us/basin/data/NEW/info/TSS.html

Neralla, S., Weaver, R. W., Lesikar, B. J., & Persyn, R. A. (2000). Improvement of domestic wastewater quality by subsurface flow constructed wetlands. *Bioresource Technology*, *75*(1), 19–25. https://doi.org/10.1016/S0960-8524(00)00039-0

Sacco, A., Cirelli, G. L., Ventura, D., Barbagallo, S., & Licciardello, F. (2021). Hydraulic performance of horizontal constructed wetlands for stormwater treatment: A pilot-scale study in the Mediterranean. *Ecological Engineering*, *169*(June). https://doi.org/10.1016/j.ecoleng.2021.106290

Schueler, T. (2000). Irreducible Pollutant Concentrations Discharged From Stormwater Practices. *The Practice of Watershed Protection*, *2*(2), 377–380. http://www.cwp.org/online-watershed-library/search_result?search_phrase=Irreducible+Pollutant+Concentrations+Discharged+From+Stormwater+Practices&catid=0&ordering=newest&search_mode=all&search_where%5B%5D=search_name&search_where%5B%5D=search_description

U.S. Climate Data. (2021). *U.S. Climate Data - Climate - Oshkosh, WI*.

USEPA. (2002). *Method 1604: Total Coliforms and Escherichia coli in Water by Membrane Filtration Using a Simultaneous Detection Technique (MI Medium). U.S. Environmental Protection Agency Office of Water. Washington. EPA-821-R-02-024. September*, 18. http://www.epa.gov/nerlcwww/1604sp02.pdf

USGS. (2018). *Nitrogen and Water*. USGS: Water Science School. https://www.usgs.gov/special-topic/water-science-school/science/nitrogen-and-water?qt-science_center_objects=0#qt-science_center_objects

Wadzuk, B. M., Rea, M., Woodruff, G., Flynn, K., & Traver, R. G. (2010). Water-quality performance of a constructed stormwater wetland for all flow conditions. *Journal of the American Water Resources Association*, *46*(2), 385–394. https://doi.org/10.1111/j.1752-1688.2009.00408.x

Washington State University. (2021). *90° Triangular Notch Weirs*. http://irrigation.wsu.edu/Content/Calculators/Water-Measurements/90-Degree-Triangular-Notch-Weirs.php

Wildey, R., Houle, J. J., Ballestero, T. P., Fowler, G., Briggs, J., Roseen, R. M., & Avellaneda, P. (2009). Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions. *Journal of Environmental Engineering*, *135*(3), 128–137.

Wisconsin Department of Transportation. (1997). *FDM 13-10 Attachment 5.2 Runoff Coefficients (C), Rational Formula, and Runoff Coefficients for Specific Land Uses*.

Wu, H., Zhang, J., Li, P., Zhang, J., Xie, H., & Zhang, B. (2011). Nutrient removal in constructed microcosm wetlands for treating polluted river water in northern China. *Ecological Engineering*, *37*(4), 560–568. https://doi.org/10.1016/j.ecoleng.2010.11.020

Xylem. (2022). *WL-16 Pressure Transducer and Datalogger Combination Specification Sheet*.

APPENDIX

A1. Subsurface gravel wetland designs

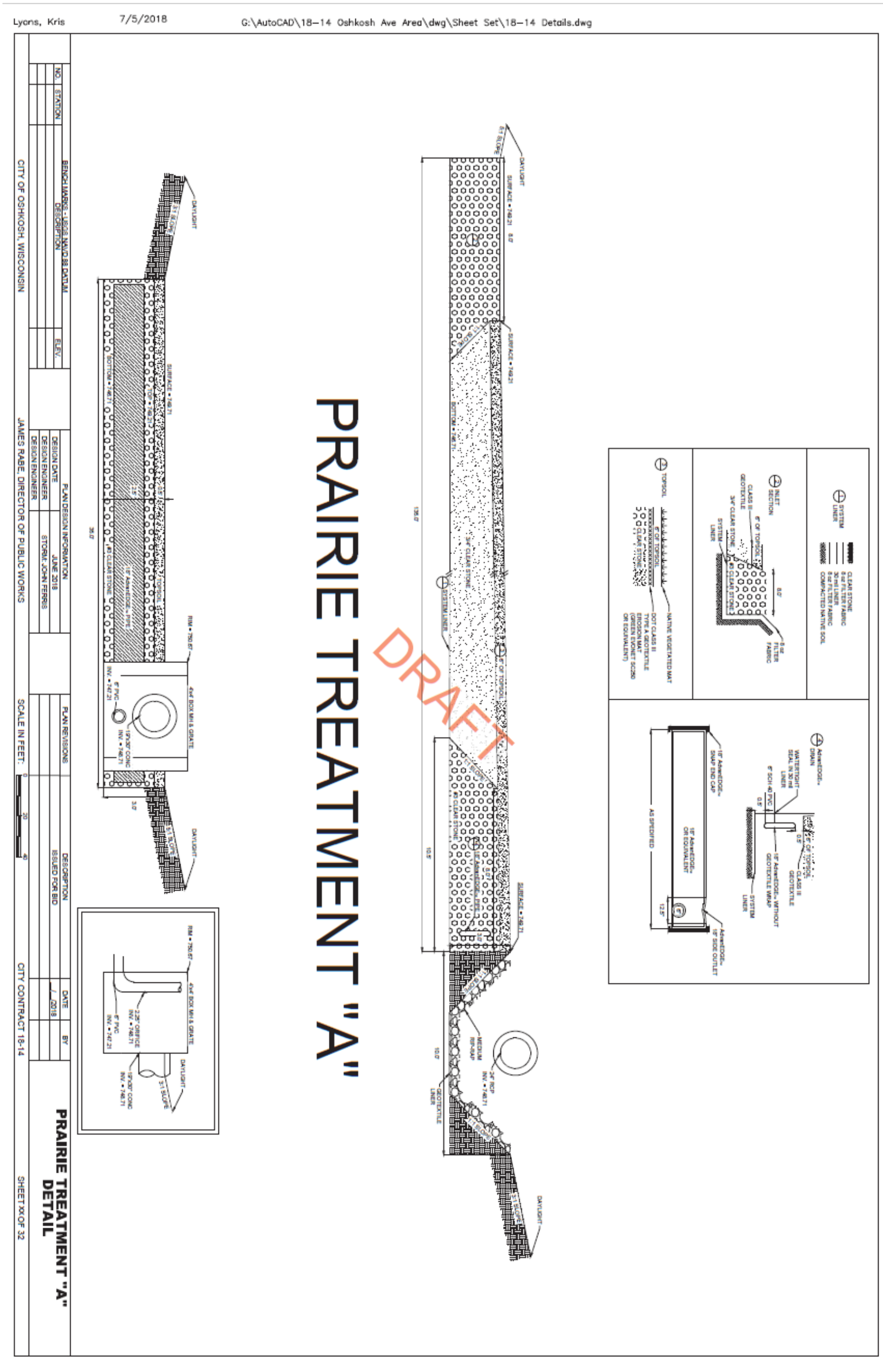


Figure 13. Engineering diagram of the subsurface gravel wetland.

A2. Backwater at inlet pipe

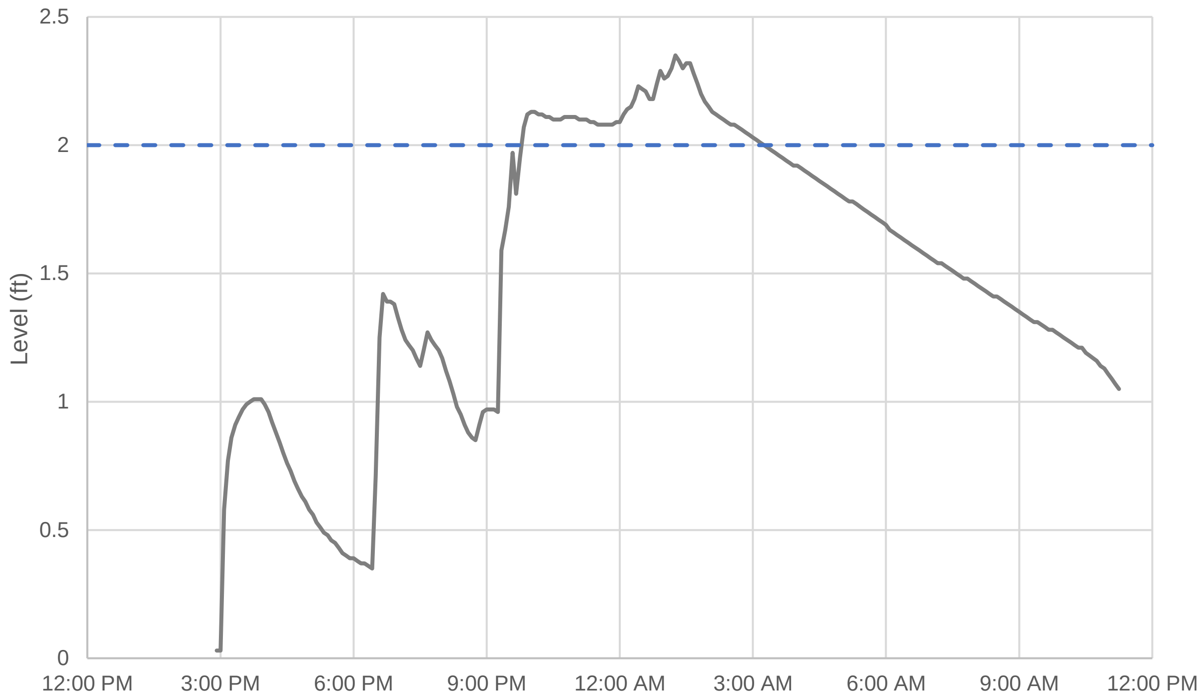


Figure 14. This shows the inlet level for a storm on July 14, 2021, and the dashed line shows the max height available in the inlet pipe.

A3. Distribution of Volume Reduction and Peak Flow Reduction

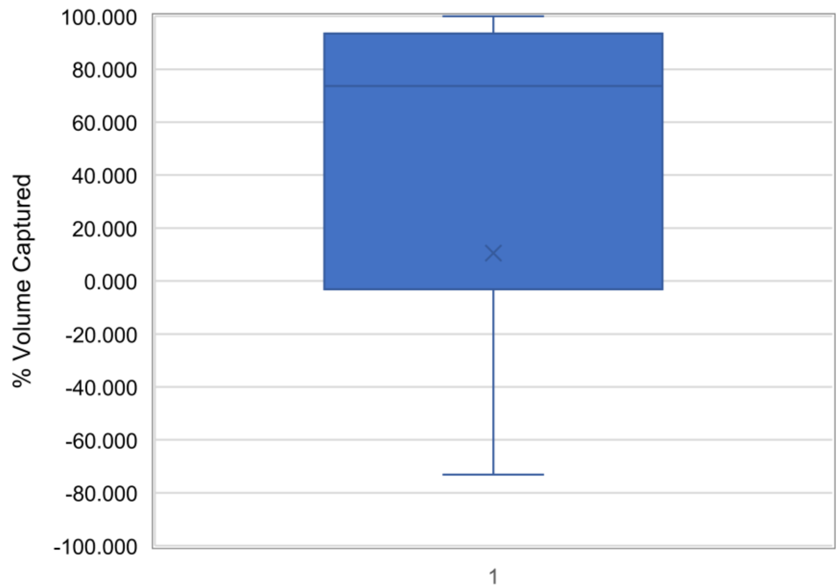


Figure 15. Distribution of volume captured values within the subsurface gravel wetland

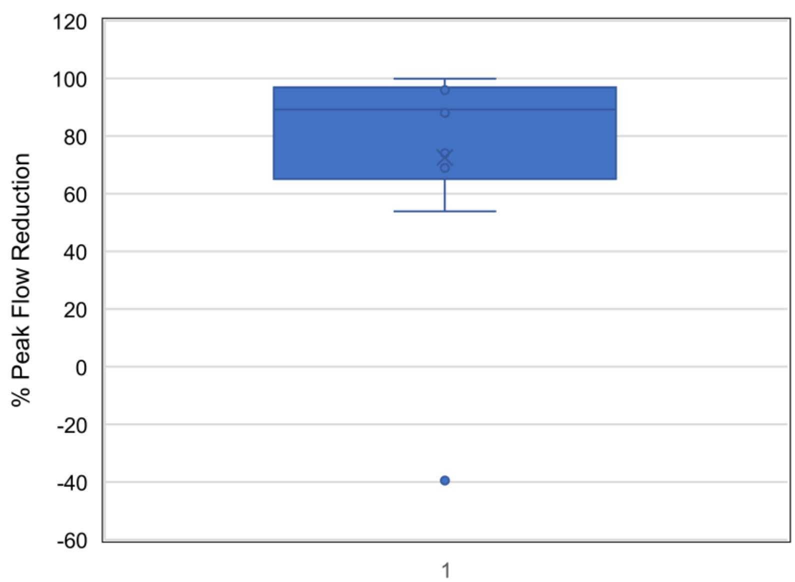


Figure 16. Distribution of peak flow reduction within the subsurface gravel wetland