Journal of Environmental Management 322 (2022) 116120

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Hydrologic and water quality performance of a subsurface gravel wetland treating stormwater runoff

Catherine Sullivan [a], Walter McDonald [a,*]

[a] Civil, Construction and Environmental Engineering, Marquette University, USA

ARTICLE INFO

Keywords:
Subsurface gravel wetland
Urban runoff
Non-point source pollution

ABSTRACT

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. They are unique to other types of green infrastructure in that they have a distinct fully saturated gravel layer below an occasionally saturated soil layer that influences pollutant removal processes. While they have been widely applied to treat wastewater, our understanding of their efficiency in treating stormwater with variable pollutant inputs is limited. To fill this gap, this study monitored the flow and water quality (total suspended solids, total nitrogen, total phosphorus, and chloride) in a subsurface gravel wetland in Oshkosh, Wisconsin at the influent, effluent, and in an observation well. Results from nine storm events indicated that the wetland had a median volume reduction of 74% and a median peak flow reduction of 89%. The reduction in pollutant concentrations where highly dependent upon the influent concentration. Average reductions of total suspended solids, total nitrogen, and total phosphorus were 49%, −21% and −0.2%, respectively, indicating an increase in nutrients; however, where influent concentrations were above irreducible levels, total phosphorus was reduced by 45% (influent ≥0.25 mg/L) and total nitrogen was reduced by 38% (influent ≥2.5 mg/L). Overall, this study shows that the subsurface gravel wetland performed similar to other types of green infrastructure and could be a good management practice to mitigate the harmful effects of stormwater runoff.

1. Introduction

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 or low impact development is an infrastructure type that captures, treats, and infiltrates water at the source. In doing so, it can be applied throughout a watershed as a part of a stormwater management plan to reduce downstream flooding and water quality impacts. One type of green infrastructure is wetlands that are typically planted systems with a regularly saturated soil layer (Environmental Protection Agency, 2021) and an emerging type of wetland designed for use as an urban stormwater practice is subsurface gravel wetlands.

Subsurface gravel wetlands function similarly to bioretention or bioswale systems in that they capture stormwater runoff through a vegetative depression, filter water through a subsurface media, and discharge excess runoff through an underdrain. This design, while not as broadly adopted as other types of green infrastructure, 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. Given these benefits, they are one of the most cost effective green infrastructure practices for reducing phosphorus and nitrogen (Bixler et al., 2020). Unique to subsurface gravel wetlands is a designed wetted region that serve to provide anaerobic conditions to further remove pollutants through biological processes. This is accomplished through two specific zones: a saturated gravel layer and an occasionally unsaturated soil layer. This has implications for the reduction of pollutants such as nitrogen, where both aerobic and anaerobic zones play a role. For example, 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). Because of these advantages, subsurface gravel wetlands have traditionally been applied to treat runoff from sources that are higher in pollutant concentrations than stormwater, such as wastewater (Garcia et al., 2010; Zhang et al., 2011), industrial (Angassa et al., 2022), or concentrated waste streams (Huett et al., 2005). However, their

* Corresponding author.
E-mail address: walter.mcdonald@marquette.edu (W. McDonald).

https://doi.org/10.1016/j.jenvman.2022.116120
Received 7 April 2022; Received in revised form 8 August 2022; Accepted 24 August 2022
Available online 5 September 2022
0301-4797/

application for treating urban stormwater runoff, with different timing, magnitude, and concentration of pollutants, is underexplored.

To that end, while there is a wealth of monitoring studies on green infrastructure practices that function similar to subsurface gravel wetlands, such as bioretention (Liu et al., 2014; Roy-poirier et al., 2010), bioswales (Purvis et al., 2018; Regier and McDonald, 2022), rain gardens (Sharma and Malaviya, 2021), and traditional wetlands (Fisher and Acreman, 2004), monitoring studies on the performance of subsurface gravel wetlands for treating stormwater runoff are lacking. Some studies have evaluated the performance of subsurface gravel wetlands for treating polluted river flows (Wu et al., 2011) or runoff from plant nurseries (Huett et al., 2005); however, these applications have different pollutant concentrations, runoff timing, and influent volumes than subsurface gravel wetlands that treat stormwater runoff from urban areas. The most comprehensive data on subsurface gravel wetlands treating urban stormwater runoff comes from researchers at the University of New Hampshire who have monitored several installations for over 12 years and have found pollutant removal efficiencies that are among the highest for green infrastructure through microbially-mediated removal in anaerobic saturated gravel zones (Houle and Ballestero, 2020). However, it is unclear how these systems perform in different climates and under various pollutant loadings, as well as how specific design characteristics (hydraulic retention time, wetland area, saturated depth, etc.) influence pollutant removal. Therefore, before subsurface gravel wetlands become more broadly considered as a stormwater treatment option, studies are needed that can verify their performance in the field and improve our understanding of their pollutant removal mechanisms. Doing so can shed light on their value considering the wealth of green infrastructure options available to treat stormwater runoff.

The goal of this study is to evaluate the hydrologic and water quality performance of a field-scale subsurface gravel wetland in Wisconsin, USA. The specific objectives to meet this goal are (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, and chloride), and (4) apply the data to evaluate the hydrologic performances (volume and peak flow reduction) and water quality performance. In doing so, this study hopes to provide valuable data and information to inform future designs and uses of subsurface gravel wetlands for treating stormwater runoff.

2. Materials and methods

2.1. Site description

The subsurface gravel wetland is located in Oshkosh, Wisconsin and collects stormwater runoff from a street in a newly constructed business park (Fig. 1). The surface area of the subsurface gravel wetland is 40-by-10 m and treats a drainage area of about 7700 m^2 that is 57% impervious and includes street (3600 m^2), sidewalk (800 m^2), and landscaped areas (3300 m^2). Stormwater enters the wetland through a 61 cm (24-inch) pipe that collects runoff from four grates in the road. This inlet pipe discharges into a pretreatment sediment bay (3 m $\times$ 3 m) where it then infiltrates through large stone aggregate into the wetland system. The wetland then 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.

Within the outlet structure, water is discharged from the underdrain through a vertical pipe that contains a 5.7-cm hole at the elevation of the outlet pipe, and a 15.2 cm (6-inch) overflow 0.6 m above. This allows for the slow release of water from the wetland system. The outlet structure itself is a 1.2 m by 1.2 m concrete structure with an overflow grate on top. The water exits the structure through a 48 cm by 76 cm elliptical pipe that is connected to the storm sewer system. The pipe is 22 cm off the bottom to allow water to accumulate and solids to settle in the structure.

2.2. Monitoring approach

Numerous parameters were monitored to understand the hydrologic and water quality performance including flow rate, rain volume, and concentration of total suspended solids, total nitrogen, total phosphorus, and chloride. 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 measuring precipitation depth and intensity to validate the influent flow rates, which was collected from a Texas Electronics 15 cm (6 inch) 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 8 km south of the study site. The following sections outline the additional flow and water quality monitoring equipment.

2.2.1. Hydrologic monitoring

The flow rate in outlet pipe was monitored using 90-degree V-notch weir and level sensors (Figure SI-1). The outlet pipe had redundant level sensors including a Global Water WL16 vented water level logger, as well as an ISCO 730 bubbler (effluent), which were calibrated prior to

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

deployment. During deployment the water level readings between the devices remained consistent; therefore, water level from the bubbler meter was used to then compute flow rates using the following equation for a 90-degree v-notch weir:

$$Q = 1.34H^{2.48} \quad \text{[Equation 1]}$$

where Q is the volumetric flow rate in cubic meters per second and H is the height over the weir of the water in meters (USBR, 1997).

In the outlet structure, the invert of the pipe exiting the structure is roughly 25 cm from the bottom of the structure. A v-notch weir is placed at the face of the outlet pipe and two level sensors are placed within the outlet structure to estimate the water level within the structure and compute the flow exiting the system. In addition, there is a Global Water WL16 level sensor placed in the middle observation well to track the water level within the wetland.

A v-notch weir and two redundant pressure transducers were used to estimate flow rate in the inlet pipe and activate the autosampler (Figure SI-1). However, during the monitoring period backwater effects were observed at the inlet pipe during the end of successive large rainfall events, when the basin would fill to the top. This made it difficult to determine inflow at the end of large rainfall events that occurred in succession. Therefore, for the purpose of volumetric computations, the flow rate for the inlet was estimated using the rain gauge at the site (Figure SI-2). The rational method was applied to estimate input volumes from rainfall data collected by the rain gauge using the following equation:

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

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 was selected for concrete since the street and sidewalk which contribute the most to the runoff are concrete. The value used was 0.8 based on the concrete range (Wisconsin Department of Transportation, 1997).

2.3. 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, and chloride. 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 bubbler (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 19 m^3 of water passing the sensor, while the outlet was set to collect a 100 mL sample every 0.2 m^3 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.

2.3.1. 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, and chloride. Total suspended solids were tested using the Standard Methods for Water and Wastewater testing (American Public Health Association, 2005). The total nitrogen was tested using the Hach Method 10,071 Test'N'Tube using persulfate digestion (HACH, 2015). The total phosphorus was tested using the Hach low range total phosphorus test (HACH,). The chloride was performed using Hach TNTplus Chloride test using the Iron(III)-thiocyanate method (HACH. n.d.-a,HACH, 2022).

2.4. Data analysis

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

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

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 is determined by multiplying the volume of a storm with the concentration of each pollutant.

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

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 ($q_{peak\text{-}out}$) and the peak inlet flow rate ($q_{peak\text{-}in}$), $R_{concentration}$ 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 (Rey and Neuhäuser, 2011). For these tests the statistical significance level was set to 0.05.

3. 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. TSS, Total Nitrogen, Total Phosphorus, and

Chloride tests were performed on all samples; however, three of the samples tested for phosphorus came in under the analytical methods detection limit.

3.1. Hydrologic performance

The subsurface gravel wetland captured and removed a median of 73.7% of the total runoff volume, totaling 1180 m^3 of water across 13 events (Table 1). This is further illustrated in Fig. 2a, which plots the influent and effluent volume for each runoff event and demonstrates that the wetland captures and infiltrates volumes across most storms. The average precipitation recorded was 4.9 cm with an average storm length of 3.9 h. 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 h. In addition to volume reductions, the magnitude of peak flows was also reduced by 73% (average) 89% (median), with a clear increase in effluent peak flows for larger influent peaks (Table 1 and Fig. 2b). Fig. 3 also illustrates 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 wetland appears to have a linear trend between rainfall depth and volume reduction. There were instances in which the effluent was larger than the influent in both volume and peak flow rate due to the storage of stormflow from previous runoff event (e.g., Fig. 2); thus, there are two events with a negative volume reduction in Fig. 3.

In Fig. 4a, the water level in the influent pipe, effluent pipe, and observations well are illustrated as a function of time, highlighting how the water level functions in the wetland during a runoff event. The influent and effluent pipe levels have been adjusted to reflect the water level over the weir. As illustrated, the water level in the influent increases quickly in response to rainfall, which then subsequently causes 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 then remain somewhat steady and gradually decrease over time as the wetland releases the captured runoff. This is further illustrated in Fig. 4b, which shows the water level in the wetland slowly receding over time until it gets back down to base levels after a week.

3.2. Water quality performance

The influent and effluent concentration data is shown in Fig. 5 for each contaminant: TSS, TN, TP, and Cl. Each graph has a diagonal dashed line showing the point where the influent and effluent would be equal – points below the line indicate a reduction in concentration, while points above the line indicate an increase in concentration. Additionally, the TSS, TP, and TN graphs have a vertical dashed line showing the irreducible concentration. This value represents the influent concentration that wetlands are unlikely to reduce any further through treatment processes (Schueler, 2000). Therefore, points with influent concentration near or below this line may represent concentrations that cannot be further reduced by the subsurface gravel wetland. The TSS average reduction is 49% with a median reduction of 37.5% with some reduction in all samples. For TN, the average and median reductions are −20.8% and −12.5%, 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 is 38%. The TP average reduction is - 0.218% with a median reduction is 38.3%. The singular event with a TP concentration increases between influent and effluent has 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 increases to 45%.

Table 1
Hydrologic performance summaries of the subsurface gravel wetland.

Metric	Average	Median
Volume Ratio (Effluent: Influent)	0.89	0.26
Volume Reduction (m^3)	91	84
Volume Reduction	11%	74%
Peak Flow Ratio (Effluent: Influent)	0.27	0.11
Peak Flow Reduction	73%	89%

In Fig. 6, the distributions of the influent and effluent concentrations for all the contaminants are shown. Events that had only outlet or inlet samples are also included in this figure. The distributions in Fig. 6 show that for TSS, TN, and TP, the influent samples had a 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.

The Chloride concentration over time for the influent and effluent are illustrated in Fig. 7, which 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.

The reduction in load followed a similar trend to the aggregated concentration data. Distributions for each contaminant's influent and effluent loads are represented in Figure SI-3. The load reduction for TSS is 72.9% on average and has a median reduction of 83.5%. For TN, the load reduction average and median are 52.9% and 77.3%, respectively. TP has an average and median load reduction of 15.4% and 81.3%.

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 each event are represented in Fig. 8. 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 is further summarized in Table 2, showing the reductions between the influent and observation well, the observation well and effluent, and the influent and effluent for each pollutant.

4. Discussion

Overall, the results show that the subsurface gravel wetland is effective at reducing runoff volume. The subsurface gravel removed 56% of the total storm runoff volume that entered the system. The removal of volume could be due to evapotranspiration or exfiltration. The surface is 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 is unlikely that all the removal is due to evapotranspiration. Some of the reduction could also be due to exfiltration. Although the system is lined at the bottom, it only extends vertically two feet and therefore there is likely horizontal exfiltration at higher water levels. In addition, there may be sources of uncertainty in the volumetric data from the modeling approach for the influent or the computation of flow using a water level and weir. 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 is 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 and Ballestero, 2020). While there are other studies that monitored at the water balance of subsurface gravel wetlands, they focus on the hydraulic residence time rather than reporting influent and effluent volumes (Amado et al., 2012; Kabenge et al., 2018).

The subsurface gravel wetland generally reduced the peak flows (89% median). With a large sediment bay and large surface area and

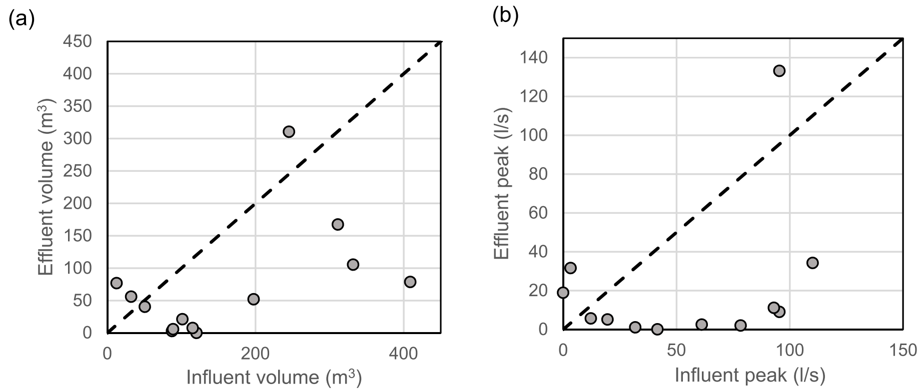


Fig. 2. Comparison of the influent and effluent volume (a) and peak flows (b), with the dashed line represented as a 1:1 relationship.

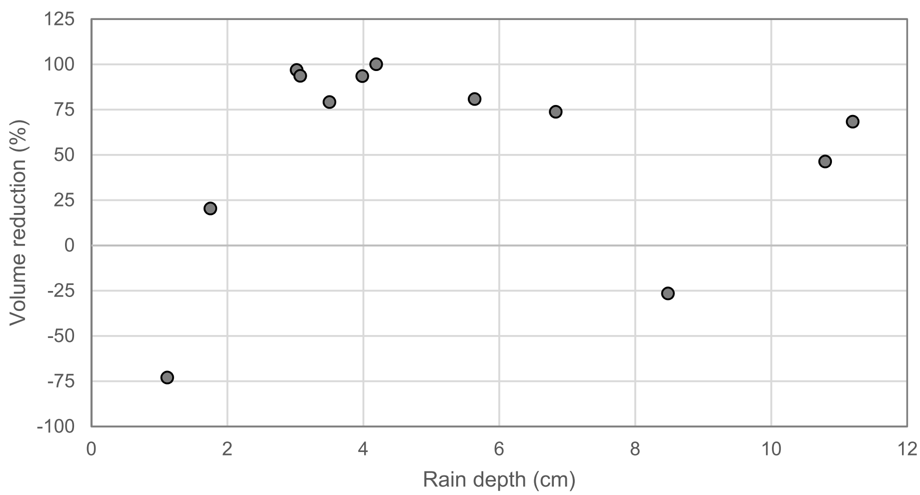


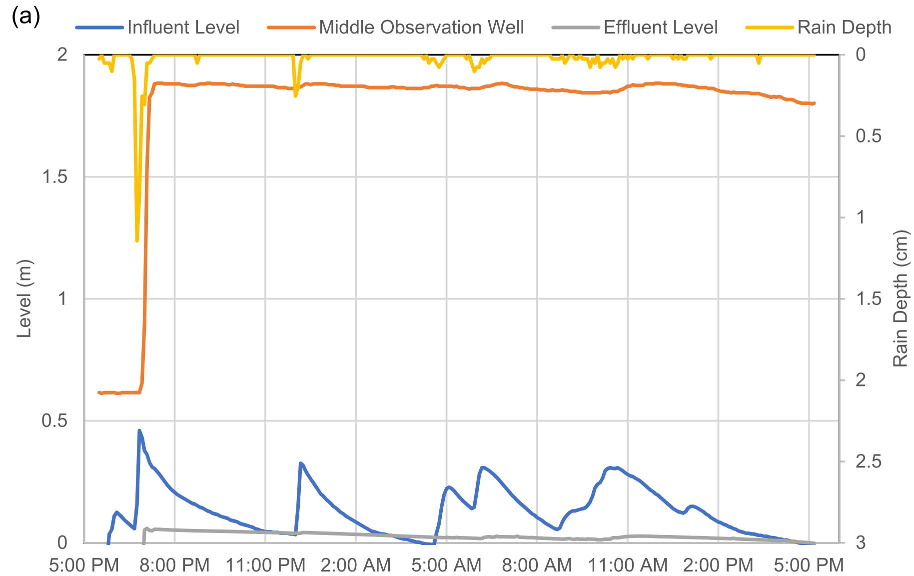
Fig. 3. The percent volume reduction over different rainfall depths. Not illustrated is the low outlier at 0.4 cm that had a negative volume removal.

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 is a 15.2 cm pipe, which has an upturned elbow in the outlet structure where water then leaves through a 5.7 cm hole. The water must then fill the outlet structure (1.2 m by 1.2 m) to 25.4 cm before crossing the weir and exiting into the stormwater system. Given the long hydraulic flow route and the small effluent hole, the flow exits the system slowly thereby reducing peak flow rates.

TSS concentrations and loads were reduced by 49.2% and 72.9% on average, respectively. The results are comparable for the TSS removal in other studies, which found reductions in concentrations of 58% (Amado et al., 2012) and in loads of 14–76% (Kabenge et al., 2018). Removal mechanisms of TSS are most likely due to sedimentation and filtration. This wetland has 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 is raised from the bottom providing opportunity for settling within the outlet structure.

While Total Nitrogen concentrations were on average lower in the effluent than the influent, this difference was not statistically significant. 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 could be at irreducible levels that the subsurface gravel wetland is unable to further reduce. As a comparison, a similar-sized subsurface wetland at a wastewater treatment plant had average removal of TN and TP as 20% and 25%, respectively; 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 is 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); however, the average effluent concentration for TN in this study was 1.8 mg/L, which is close to the irreducible concentration of TN for stormwater practices of 1.9 mg/L (Schueler, 2000). Therefore, due to influent concentrations that are only slightly higher than the irreducible concentrations, it is not surprising that as a percentage these reductions were marginal. To that end, in other subsurface gravel wetland studies where a higher percentage of TN concentrations were reduced, their influent sources were from river flows and plant nursery runoff and therefore the influent concentrations were also much higher. For example, 61% reduction in concentration of TN was observed with an average influent concentration from river flows of 18.84 mg/L (Wu et al., 2011), and 63.4% reduction was observed with an influent concentration of 10 mg/L from plant nursery runoff (Huett et al., 2005).

Apart from irreducible concentrations of nitrogen, there could be alternative reasons that the reduction of nitrogen concentrations is inconsistent or negative. Negative removal values signify an increase in concentration from the influent to the effluent. To the extent that nitrogen reduced or increased, there are several processes within the subsurface gravel wetland that could contribute. Nitrogen removal in these systems is complex due to the diversity of nitrogen species and various mechanisms for treatment. It is hypothesized that subsurface



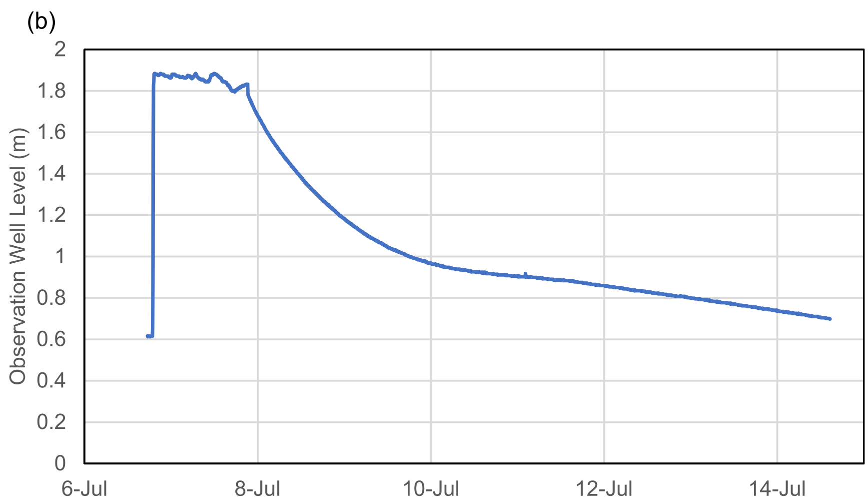


Fig. 4. The level of influent, effluent, and middle observation well and the rain volume (a), and the level of the middle observation well (b), are shown over time for a single storm event.

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 is not maintaining a consistent saturated zone which would indicate the wetland is oversized, or that there is not enough organic carbon within the gravel layer for the denitrifying communities to thrive. It could also be that the water is not spending enough time in the saturated zone to be fully denitrified. In other studies with more consistent removal of nitrogen, the hydraulic retention time was at least a day (Huett et al., 2005; Kabenge et al., 2018). Another process by which nitrogen is removed from wetlands, which is a minor contributor to the overall removal mechanism, is sedimentation and plant uptake (Clary et al., 2020). Since TSS shows reduction in the concentration and load, it indicates sedimentation is occurring thus some of the removal of nitrogen could be caused by sedimentation. In addition, there also could be atmospheric deposition of nutrients through dry fallout and rainfall on the surface of the wetland, or ammonification and nitrification of organic nitrogen within the bioretention, that are unaccounted for.

For total phosphorus, the majority of the samples had a reduction in concentration from the influent to effluent with a median reduction of 38.3% and only one sample had a negative reduction in concentration. In comparison, other studies of subsurface gravel wetlands that treated plant nursery runoff and river flows 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) indicating removals of 84.5% and 63%, respectively. While the average influent concentration of TP in this study (1.29 mg/L) is close to the other studies, this study had a lower median reduction. However, the data is 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 is likely due to low concentration in the influent, rather than a failure of the subsurface gravel wetland itself. The average removal of total phosphorus with inlet concentrations above 0.25 mg/L was 45%. The main removal mechanisms for phosphorus in this system are likely sedimentation, filtration, and plant uptake within the wetland (Bixler et al., 2019; Huett et al., 2005; Kabenge et al., 2018). To that end, because the TSS had significant reductions in concentration and load, it suggests sedimentation and filtration of particulates is occurring

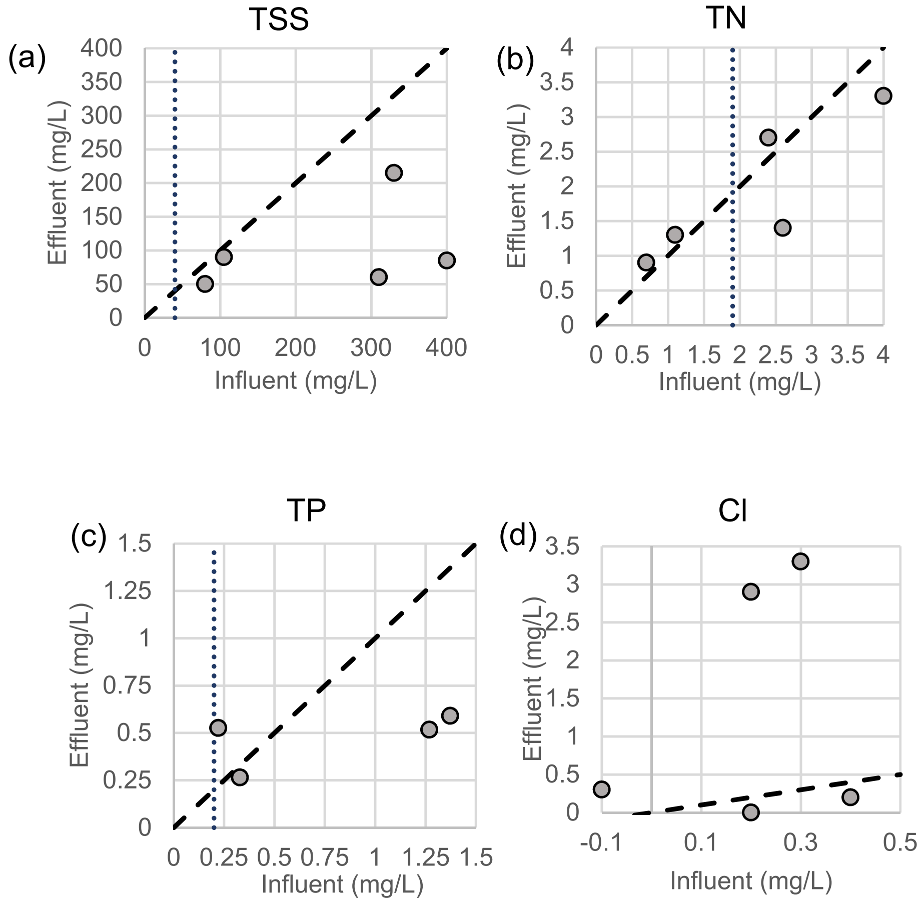


Fig. 5. Influent and effluent concentrations in the wetland for (a) TSS, (b) TN, (c) TP, and (d) Cl. With TSS, TN, and TP also containing vertical lines which represent the irreducible concentration.

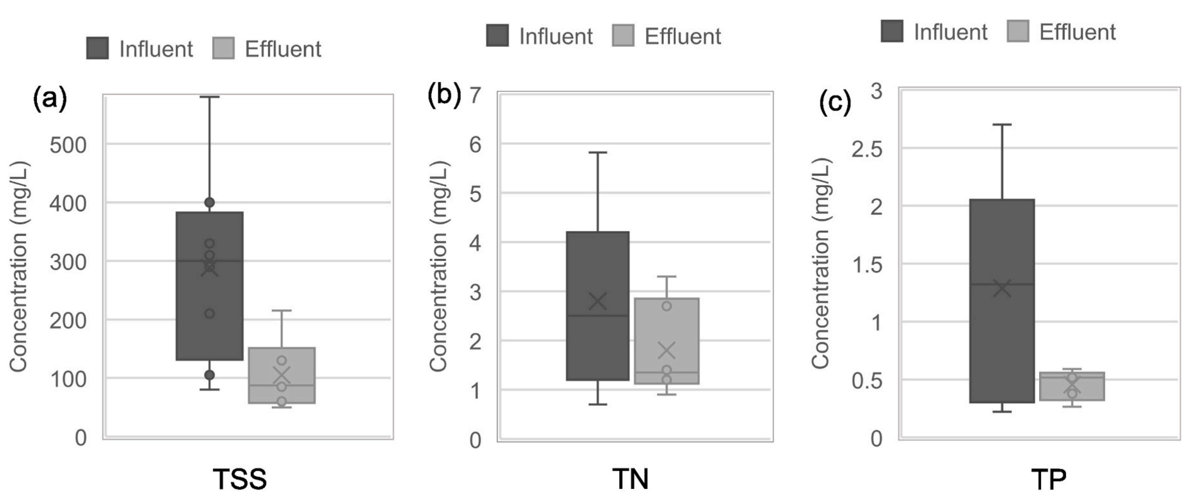


Fig. 6. Distribution of the influent and effluent concentrations in the influent and effluent samples for (a) TSS, (b) TN, and (c) TP.

properly thus this 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 has no mechanisms for chloride removal; 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 stored 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.

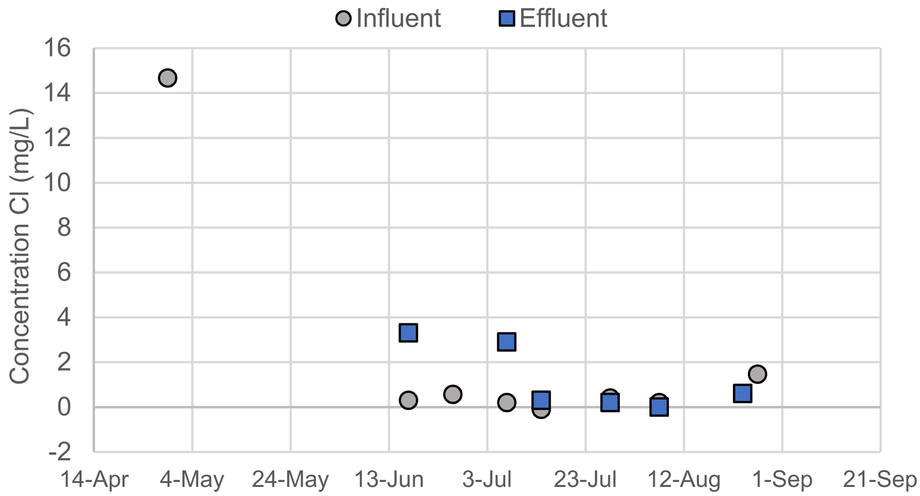


Fig. 7. The influent and effluent concentration of Chloride in the wetland over time.

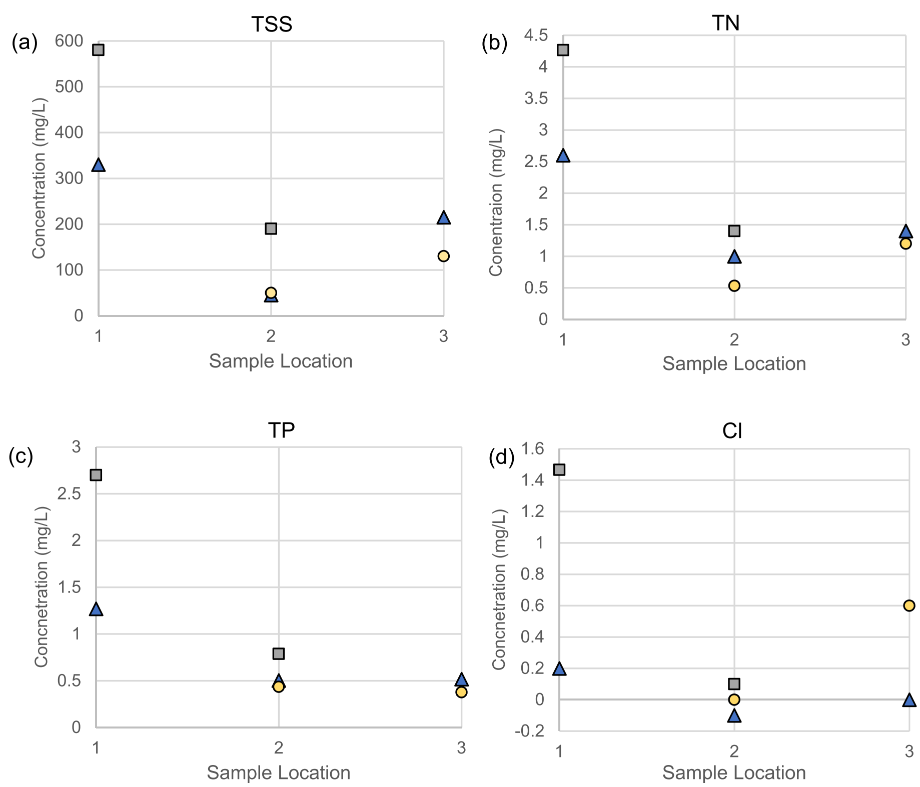


Fig. 8. The concentration at different sampling locations in the wetland for TSS (a), TN (b), TP (c), and Cl (d). With the sample locations being inlet (1), observation well (2), and outlet (3). The various shapes indicate different stormflow sampling dates.

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

Pollutant	Average Removal		
	Influent and Observation Well	Observation Well and Effluent	Influent and Effluent
TSS	77%	−270%	35%
TN	64%	−83%	46%
TP	66%	5.0%	59%
Cl	120%	100%	100%

5. Conclusions

This study evaluated the performance of the subsurface gravel wetland in Oshkosh, WI and results indicate that the subsurface gravel wetland reduces peak flows, volumes, and pollutant loads from TSS, TP, and TN. The results also demonstrated a reduction of TSS and flushing of accumulated Cl in the system; however, reduction of TN and TP was less clear and likely influenced by the influent concentrations. Instances of no removal or increases in pollutant concentrations from the influent to the effluent corresponded with low concentrations in the influent that were unable to be reduced any further. To that end, average reductions of total suspended solids, total nitrogen, and total phosphorus were 49%, −21% and −0.2%, respectively, indicating an increase in nutrients; however, where influent concentrations were above irreducible levels, total phosphorus was reduced by 45% (influent $\geq$0.25 mg/L) and total nitrogen was reduced by 38% (influent $\geq$2.5 mg/L). Despite this, the large volumetric reduction of the system resulted in median pollutant load reductions above 77% for TN and TP. Future monitoring could further investigate the pollutant removal under various influent loadings across more storms and test for different species of nutrients to elucidate the mechanisms influence pollutant removal. As subsurface gravel wetlands grow as a stormwater treatment option, monitoring studies such as this can together help improve our understanding of subsurface gravel wetland function.

Credit author statement

Catherine Sullivan: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.; Walter McDonald: Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Walter McDonald reports financial support was provided by Fund for Lake Michigan.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the Fund for Lake Michigan for supporting this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116120.

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

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