Case Study

Hydrologic and Water Quality Performance of Two Bioswales at an Urban Farm

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Abstract: Many postindustrial cities are transforming underused areas into urban agriculture, which presents unique stormwater management challenges. One way to manage runoff from urban agriculture is to use green stormwater infrastructure; however, to date, green stormwater infrastructure has largely been applied to treat runoff from impervious surfaces and its application to urban agricultural runoff is underexplored. This study seeks to fill this gap by monitoring two bioswales collecting and treating runoff from an urban farm in Milwaukee, WI. To do so, the influent and effluent at each bioswale was sampled and tested for total suspended solids (TSS), total phosphorus, and total nitrogen. Both bioswales were effective at reducing volume, peak flows, total phosphorus concentrations, and high concentrations of TSS (>25 mg/L) but had mixed results in reducing total nitrogen concentrations and TSS at low influent concentrations (25 mg/L). Large volume capture and exfiltration resulted in load reduction (median 98%) across all pollutants. Overall, this project demonstrates the feasibility of bioswales for reducing pollutant loads from urban farms, which may have different pollutant concentrations within stormwater runoff than other typical urban settings. **DOI: 10.1061/JSWBAY.0000990.** *© 2022 American Society of Civil Engineers.*

Introduction

Many postindustrial cities face the challenge of repurposing the urban landscape in a way that transforms abandoned or underused areas into vibrant, diverse, economically thriving communities. One way in which cities are doing this is by creating urban farms where industrial or residential areas once existed within the city (Carlet et al. 2017). This can provide beneficial uses to the surrounding community including food access, positive health impacts, and green space (Horst et al. 2017). However, this is also a challenge for urban stormwater management as pollutants from urban agricultural runoff must be mitigated. Green infrastructure, such as bioretention or bioswales, is one way to do this by capturing, treating, and infiltrating runoff at the source. This method of treatment is synergistic with the long-term strategies of many cities who have ambitious goals to invest in green infrastructure that are estimated to cost \$1.3 billion in Milwaukee (Milwaukee Metropolitan Sewerage District 2018), \$2.4 billion in Philadelphia (City of Philadelphia and USEPA 2011) and \$5.3 billion in New York City (Bloomberg and Holoway 2010), and all of which include bioretention and bioswales within their plans.

Bioretention utilizes landscaped depressions in the ground that are designed to slow, treat, and infiltrate stormwater runoff on-site. Bioswales are a form of bioretention that use similar treatment processes but are also used to convey water. The hydrologic benefits of these systems are typically a reduction in volume and peak flows (Poresky et al. 2011; Purvis et al. 2019). In addition, bioswales have been shown to be a good practice for reducing pollutants such as suspended solids (Clary et al. 2020), which are removed primarily by the filtering properties of bioswale media as well as sedimentation in the collection basins. Regarding nutrients, bioswales have had mixed results, with a review of bioswale monitoring studies finding significant increases in total and dissolved phosphorus concentrations (n = 34 monitoring studies), yet significant decreases across all forms of nitrogen (n = 14 studies) (Clary et al. 2020). However, even in cases where concentrations increase, overall load reductions could be observed through significant exfiltration of volume (Poresky et al. 2011).

While bioswales have been shown to be a good treatment option for managing urban stormwater runoff, it is unclear how this translates to runoff from urban farms. Most of the referenced monitoring studies collect runoff from urban areas, and while a limited number of studies have monitored green infrastructure performance in an agricultural setting (Dietz 2016; Kokkinos 2017; Shrestha et al. 2020), in each case runoff was collected from pavement and buildings. Therefore, monitoring studies of urban green stormwater infrastructure applied in agricultural settings are currently lacking. This is important as runoff from agricultural areas could have different concentrations of pollutants, including suspended solids and nutrients, as compared to urban land cover, such as pavement and buildings (Chen and Chang 2014; Ghane et al. 2016). In addition, the peak runoff, time to peak, and fraction of runoff entering the bioswale from the drainage area may be less than that of impervious urban surfaces due to the greater infiltration capacity of agricultural land cover. As such, green stormwater infrastructure practices that are typical to urban settings may experience different hydrologic and pollutant inputs when treating urban agricultural runoff, which in turn could impact their overall performance.

To that end, the key objective of this research was to monitor the hydrologic and water quality performance of two bioswales at an urban farm in Milwaukee, WI. We hypothesized that agricultural runoff would have higher total suspended solids (TSS) and nutrient concentrations in their influent compared to other urban bioswales, and that the bioswales would be able to effectively reduce these concentrations. To do so, we monitored the flow rate and water

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Note. This manuscript was submitted on September 21, 2021; approved on February 18, 2022; published online on May 17, 2022. Discussion period open until October 17, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Sustainable Water in the Built Environment***, © ASCE, ISSN 2379-6111.

quality—TSS, total phosphorus (TP) and total nitrogen (TN)—in the influent and effluent of the bioswales over a 7-month period. We analyzed this data to determine hydrologic performance in terms of volume removed and peak flow reductions, as well as the water quality performance in terms of reductions in concentrations and pollutant loads. In doing so, we seek to provide data that can help to support the use of green infrastructure in the treatment of runoff in urban agricultural settings.

Methods and Materials

Site Description

The study location is an urban farm that has two fields—north field (1,254 m^2) and south field (1,350 m^2)—that are managed by Cream City Farms, a Community Supported Agricultural (CSA) organization. During the monitoring period, the CSA farmed a mix of vegetables including lettuces, herbs, melons, onions, squash, potatoes, tomatoes, turnips, and beans within each field. Both fields were fertilized with compost and planted throughout the spring. Each of these farm fields drain into their own bioswales (Fig. 1) that capture and treat the runoff.

The north bioswale and south bioswale are 73 m and 35 m long, respectively, with a 0.6% slope, 0.3 m topsoil, and natural vegetation. Both bioswales have a 0.1 m (4-in.) perforated PVC underdrain that discharges into a common underground cistern. The cistern is used as storage for irrigation of the farm and overflows into the combined sewer system. The cistern also has an active control valve that can divert storage from the cistern to the combined sewer system in the case where runoff from an anticipated storm might produce volume in excess of the capacity. Monitoring at the site was conducted from April 2019 through March 2020.

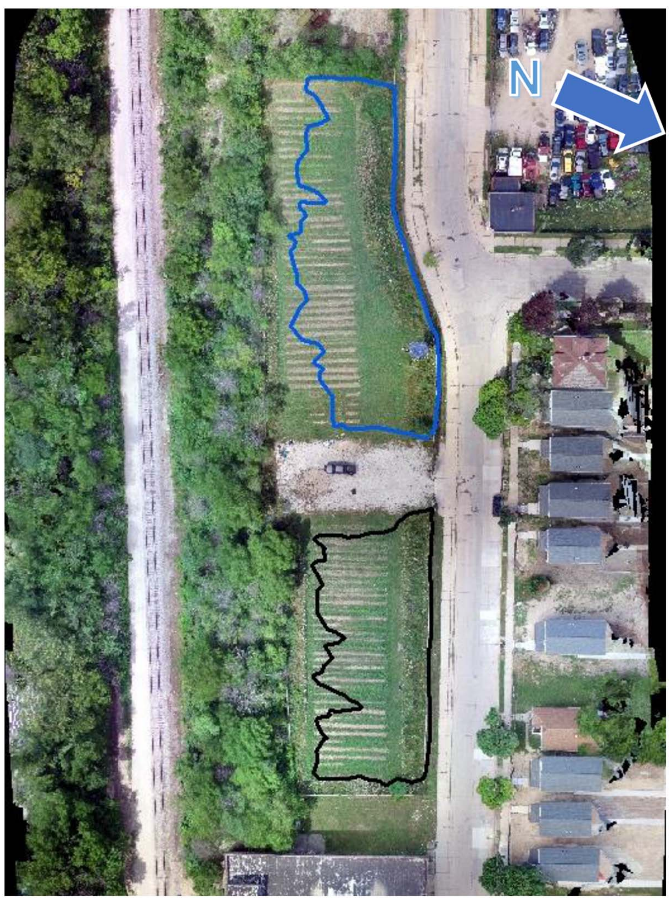

Fig. 1. Overhead view of Cream City Farms. The fields are shown as the tilled areas buffered by forest on the west and the bioswales on the east. Using drone imagery and structure-from-motion analysis, we estimated the watershed area of each bioswale as represented by the blue outline (north bioswale) and black outline (south bioswale). (Image by Walter McDonald.)

Monitoring Equipment and Methods

The goal of the monitoring study was to evaluate the performance of the bioswales by measuring the flow rate and water quality entering the bioswales through overland flow and exiting the bioswales through their underdrains. Because runoff enters the bioswales as overland flow, rain gauge data was used to model runoff into the system. Specifically, a Texas Electronics tipping bucket rain gauge with a 6" diameter funnel and Onset brand HOBO pendant data logger were installed at the site to capture rainfall volume [Fig. 2(a)]. Using this data, runoff was estimated using the EPA stormwater management model (SWMM) model (USEPA 2005).

To evaluate the area that drains to each bioswale, imagery from a Matrice 100 unmanned aerial vehicle (UAV) was processed using structure-from-motion (SfM) to estimate elevations. The UAV collected images at 50 m height with 95% overlap of images. These images were then processed within Pix4D Mapper software using SfM to calculate a three-dimensional position for each pixel based upon the overlapping images (Snavely et al. 2008). Site imagery and elevation data were then analyzed using ArcMap software to delineate the watersheds for each bioswale (Fig. 1).

The watershed areas delineated from the drone data were then used to develop the SWMM model to estimate runoff volumes into the bioswales. The model contained four subcatchments: one subcatchment for each of the farm fields and one subcatchment for each of the bioswales. Model parameters were derived from on-site measurements as well as engineering as-built drawings (Table 1). Rainfall inputs into the model came from the on-site rain gauge, infiltration was estimated using the Natural Resources Conservation Service (NRCS) method, evaporation was estimated using average monthly values from the National Oceanic and Atmospheric Administration (NOAA) (Farnsworth et al. 1982), and the water was routed using the kinematic wave method. The model was simulated continuously over the entire project period (April 2019–March 2020) and the influent volumes during runoff events were used to compute pollutant loads entering into the bioswales. Because it was not possible to directly measure overland flow into the bioswales, the influent volumes were uncalibrated; however, the models were calibrated to the outflow of the bioswales using a storm event from April 29, 2019.

To measure the flow rate in the bioswale underdrains, the outflow pipes were fitted with Open Channel Flow 0.18 m (0.6 ft) HS flume boxes [Fig. 2(b)]. Two ISCO 6712 autosamplers took continuous water level measurements in the flume boxes. To measure water level, one autosampler used a bubbler water level meter (ISCO 730 Bubbler Flow Module) and the other used a pressure transducer (ISCO 720 Submerged Probe Flow Module). The water level readings from within the flume were then used to estimate flow rates (Open Channel Flow 2020). The autosamplers also collected samples of flow from the underdrain to test for water quality parameters. The two autosamplers used flow measurements to collect flow-weighted water samples during periods of underdrain flow. In each case, the autosamplers were triggered to begin sampling once the water level was detected in the flume, indicating a runoff event. In addition, a camera was placed in the vault and recorded time-lapsed imagery to verify runoff events.

Fig. 2. (a) Tipping bucket rain gauge at Cream City Farms, with the north bioswale in the background; (b) view into manhole to junction box where two flumes measure underdrain flow from both bioswales; and (c) picture of influent sampling structure (plastic ground covering to prevent erosion around bottle not pictured). (Images by Elizabeth Regier.)

Table 1. List of parameters and their data sources used within the SWMM model

Parameter	Data source
Dates of storms	Rain gauge
Precipitation	Rain gauge
Subcatchment area	Drone imagery and ArcGIS
Subcatchment width	Drone imagery and ArcGIS
Farm field average slope	Structure-from-motion digital elevation model and GIS
Subcatchment percent impervious	Drone imagery and ArcGIS
Subarea routing	Structure-from-motion digital elevation model and GIS
Bioswale slope	Engineering drawings
Bioswale berm height	Engineering drawings
Bioswale soil thickness	Engineering drawings
Bioswale storage thickness	Engineering drawings

Because flow entered into the bioswales as overland flow, we were not able to sample the entire volume. Therefore, we chose to take a representative sample of overland flow from the farm fields entering each bioswale. While this approach does not capture the full influent volume, this limitation is one in which many monitoring studies operate when capturing samples of overland flow (Braswell et al. 2018; Li et al. 2009). To collect samples, holes were dug into the ground at the collection points and Thermo Scientific Nalgene Storm water samplers were partially buried. A French drain approximately 2 m in length was installed on either side to funnel overland runoff into the samplers [Fig. 2(c)]. One-liter collection bottles were placed in the samplers before each storm and were removed after the storm. In many cases these inflow samples were considered flow-weighted because they did not fill up completely and, therefore, collected all overland flow that passed through the sampling area. In a few large events, the samplers did fill completely, which weights the sample slightly toward the beginning of the storm. This approach collects what is known as the "first-flush" of runoff pollution, which contains the highest levels of pollutant concentrations (Lee et al. 2002).

Water Quality Testing

Prior to runoff events, the autosamplers at the site were filled with ice packs before a storm to preserve samples. The autosamplers were triggered to collect effluent after the detection of flow in the underdrains. Samples were then collected shortly after rainfall and transported in a cooler from the field to the Water Quality Center at Marquette University for testing. Inflow and outflow TN tests were performed on unfiltered samples using the Hach 10071 Test 'N Tube Low Range Persulfate Digestion method (Hach 2014). TP was measured on unfiltered samples using the Hach method 10209 Spectrophotometer. Ultra-low-range, low-range, or high range kits were used depending on the concentration of the sample (Hach 2015, 2016a, b). A volume of the samples was filtered to perform tests on dissolved phosphorus (DP) utilizing the phosphorus testing methods above for filtered samples. Pall 47-mm diameter A/E glass fiber filters and Merck 0.7 μm pore sized, 47-mm diameter hydrophilic glass fiber filters were used for filtration. TSS tests were performed according to Standard Methods for Water and Wastewater testing (American Public Health Association 2005). When possible, samples were tested in duplicate.

Data Analysis Methods

The total volume of runoff into each bioswale was estimated using the SWMM model, and the total outflow volume for each storm was estimated from the flowrate measurement according to the following equation:

$$V(l) = \sum_{i=1}^{n} \left(\frac{x_i - x_{i-1}}{2} \right) \times (t_i - t_{i-1}) \quad (1)$$

where V = total volume over the course of the storm; n = number of flowrate measurements over the storm; x_i = flowrate measurement in liters per minute; and t = time between flowrate measurements, which was 5 min at our site.

Comparison of inflow and outflow contaminant loading rates (in grams) for each storm required that flow volumes be multiplied by measured contaminant concentrations (in milligrams per liter) as follows:

$$L(g) = V \times C \times \frac{1}{1{,}000} \quad (2)$$

where L = total load in grams; V = total volume in liters; and C = total concentration in milligrams per liter.

Water quantity metrics were computed for each event using ratios of the outflow to inflow as defined in the following equations (Davis 2008):

$$R_{volume} = \frac{V_{out}}{V_{in}} \quad (3)$$

$$R_{peak} = \frac{q_{peak-out}}{q_{peak-in}} \quad (4)$$

$$R_{delay} = \frac{t_{q-peak-out}}{t_{q-peak-in}} \quad (5)$$

$$R_{conc} = \frac{C_{out}}{C_{in}} \quad (6)$$

$$R_{load} = \frac{L_{out}}{L_{in}} \quad (7)$$

where R_{volume} is the ratio of the total volume of outflow (V_{out}) to the volume of inflow (V_{in}); R_{peak} is the ratio of the peak outflow in liters per minute ($q_{peak-out}$) to the peak runoff into the bioswale in liters per minute ($q_{peak-in}$); R_{delay} is the ratio of the time of peak outflow in hours ($t_{q-peak-out}$) to the time of peak inflow in hours ($t_{q-peak-in}$); R_{conc} is the ratio of the outflow contaminant concentration in milligrams per liter (C_{out}) to the inflow contaminant concentration in milligrams per liter (C_{in}); and R_{load} is the ratio of the outflow contaminant load in grams (L_{out}) to the inflow contaminant load in grams (L_{in}).

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

$$Parameter\, Reduction = (1 - R) \times 100\% \quad (8)$$

where R is a ratio of volume, peak, delay, 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.

Results

Over the course of the monitoring period, there were 47 rainfall events recorded at the south and north bioswales. Of these rainfall events, 25 in the north and 46 in the south produced a detectable level of outflow. However, not all of these events produced enough outflow in the underdrain for sampling, with only 9 events in the north and 35 events in the south bioswales producing over 0.5 L of sampled outflow. Because of this, the number of overall water quality samples varied based upon the availability of an adequate volume of inflow or outflow. This constrained our total number of samples for which we could directly compare influent to effluent between 2 and 10 storm events, depending upon the contaminant. Additionally, while the south bioswale produced outflow in the underdrain in 98% of the storms, the north bioswale only produced outflow in the underdrain in 54% of storms. This is due to a crack in the junction box below the underdrain in the north bioswale that allowed water to seep from the bioswale through the crack into the underground storage tank. This was verified by a camera installed within the junction box and confirmed by engineering consultants who inspected the site. The following sections summarize the hydrologic and water quality performance of the two bioswales.

Hydrologic Performance

Both bioswales reduced volume, peak flow rates, and time to peak across the storms captured; however, a crack in the junction box resulted in the north bioswale appearing to perform better than the south bioswale across most metrics (Table 2). For volume, this is reflected in a lower volume ratio and percent of water that was removed. This is also evident in Figs. 3(a and d), which show the effluent and influent volumes across all storms. From these figures, the north bioswale reduces the volume across all storm events. In comparing these events to the precipitation volume, the north bioswale required a rainfall volume of at least 3.5 cm to generate flow in the underdrain, while the south bioswale required 0.6 cm. In terms of peak flows, both saw peak flow rate reductions above 94% [Figs. 3(b and e)] and peak delay ratios above 2.7. However, the peak flows were not always delayed, as shown in Figs. 3(c and f).

Water Quality Performance

Pollutant Concentrations

Overall, both bioswales had a reduction in TP, with mixed results for TSS and TN (Figs. 4 and 5). Using the Wilcoxon signed-rank test, only TP in the south bioswale had statistically significant differences between the influent and effluent concentrations across all captured runoff events. Similar to the volume and peak flow analysis, there were less events captured in the north bioswale than the south. In addition, the number of events varies based upon the allowable number of tests due to the sampling volume or the availability of tests. As such, there were several events in which

Table 2. Average water quantity statistics for the north and south bioswale

Parameter	North bioswale	South bioswale
Volume ratio (effluent:influent)	0.0036	0.49
Volume reduction (L)	3,649	1,706
Volume reduction (%)	99.7	51
Peak ratio (effluent:influent)	0.0015	0.057
Peak reduction (L/min)	114	83
Peak reduction (%)	99.8	94.3
Peak delay ratio (effluent:influent)	8.77	2.79
Peak delay (h)	17	3.96

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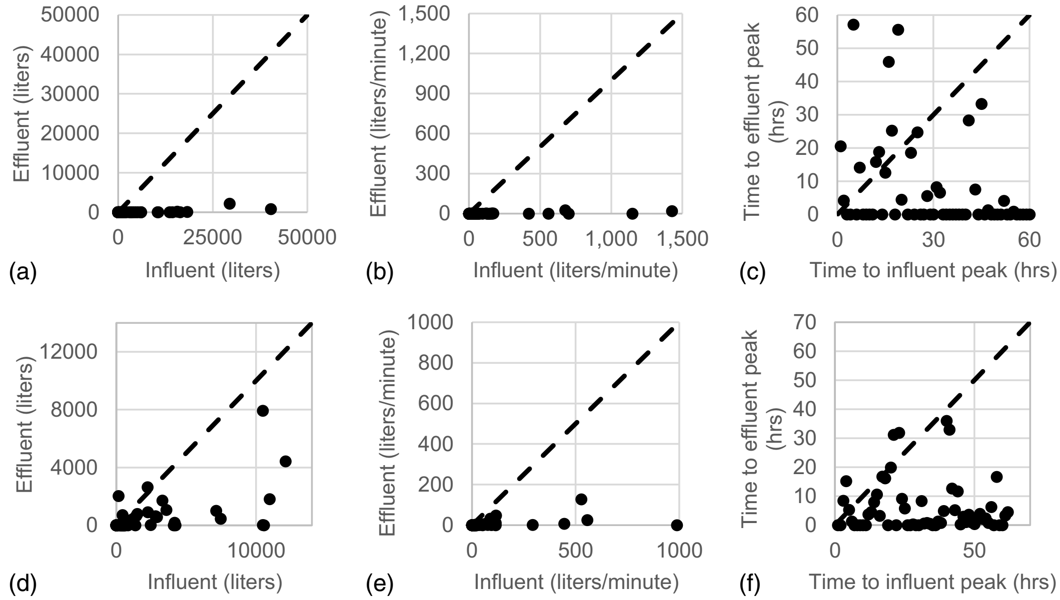

Fig. 3. North bioswale (a) water volume; (b) peak flows; and (c) time to peak by event, and South bioswale (d) water volume; (e) peak flows; and (f) time to peak by event.

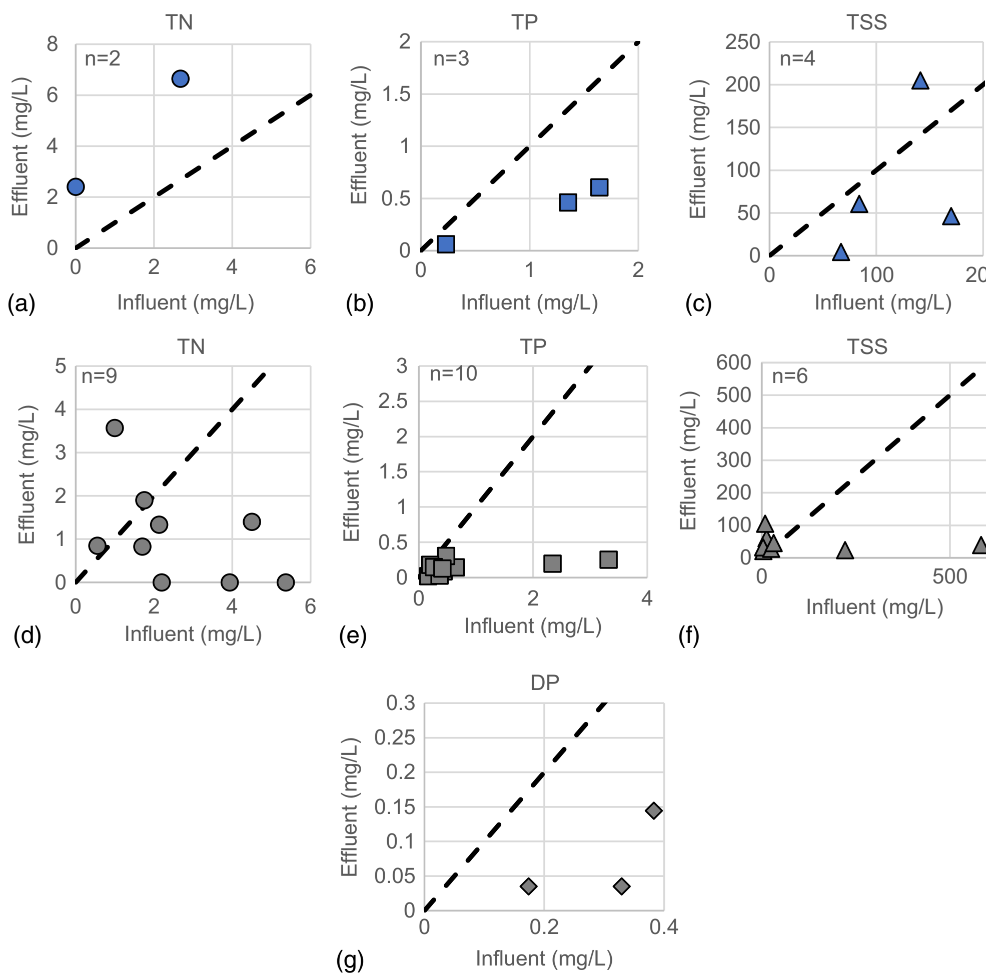

Fig. 4. Concentrations in the influent and effluent at the north bioswale for (a) TN; (b) TP; and (c) TSS, and at the south bioswale for (d) TN; (e) TP; (f) TSS; and (g) DP.

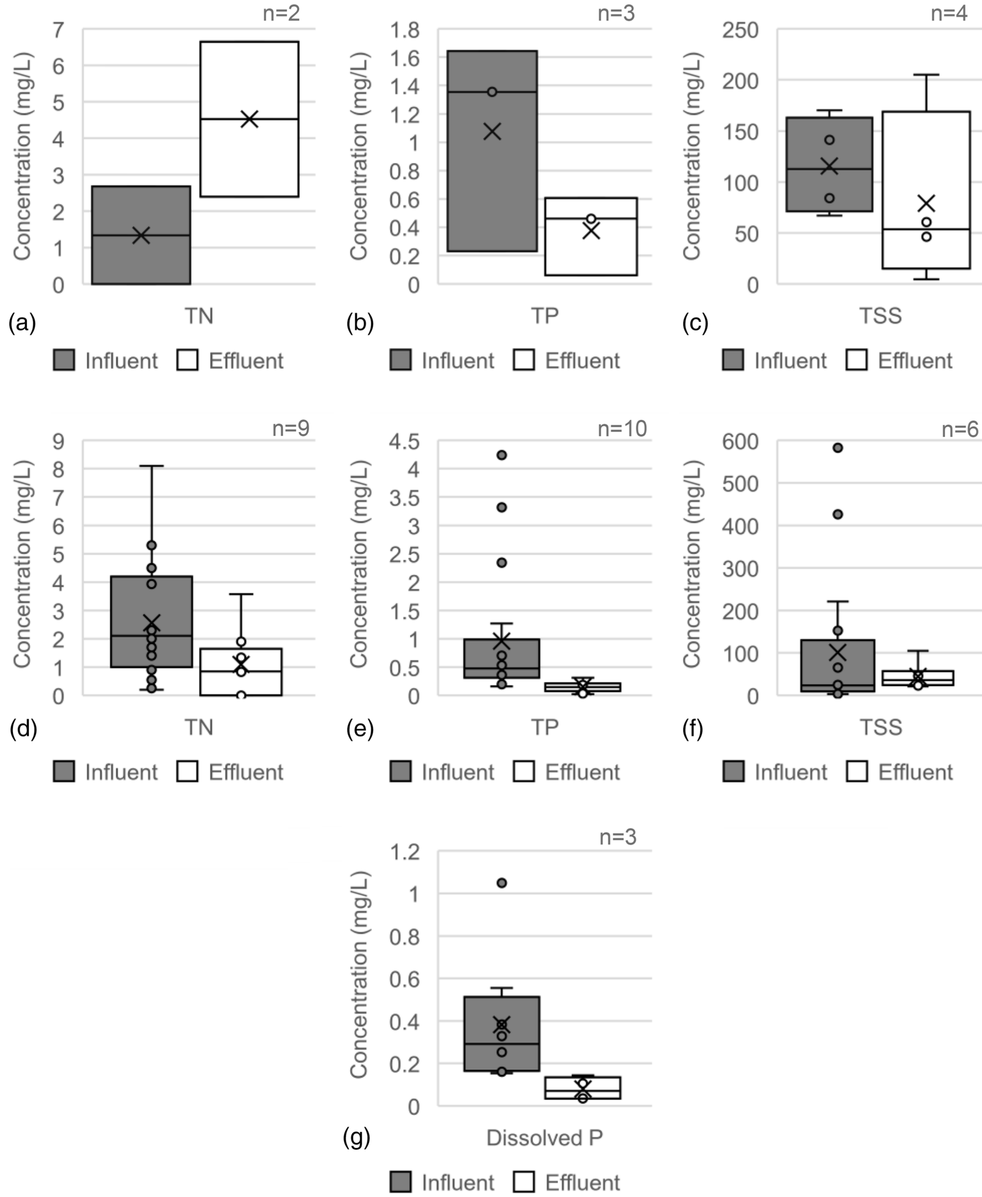

Fig. 5. Box and whisker plots illustrating the distribution of the influent and effluent concentrations at the north bioswale for (a) TN; (b) TP; and (c) TSS, and at the south bioswale for (d) TN; (e) TP; (f) TSS; and (g) DP.

Table 3. Summary of bioswale pollutant concentrations

Bioswale	Pollutant	Median influent concentration (mg/L); (n)	Median effluent concentration (mg/L); (n)	Median reduction in concentration (%); (n)
North bioswale	TN	3.70 (16)	4.53 (2)	−510 (2)
	TP	0.57 (17)	0.46 (3)	71 (3)
	DP	0.40 (9)	0.29 (1)	28 (1)
	TSS	50.80 (17)	68.56 (4)	48 (4)
South bioswale	TN	2.05 (18)	0.83 (11)	45 (9)
	TP	0.50 (17)	0.12 (14)	69 (10)
	DP	0.29 (8)	0.07 (4)	80 (3)
	TSS	17.14 (14)	25.67 (14)	−38[a] (8)

[a]Reduction of 91% for influents conc. above median (25 mg/L).

only either influent or effluent were captured as summarized in Table 3.

TP concentrations had a median reduction of 71% and 69% in the north and south bioswales, respectively. In addition, the north bioswale only had 1 event where DP was sampled in both the inflow and outflow with a reduction of 28%, whereas the south bioswales saw reduction of 80% across 3 events in which inflow and outflow could be sampled. The north bioswale saw a reduction in

Table 4. Summary of bioswale pollutant loads

Bioswale	Pollutant	Median influent load (g); (n)	Median effluent load (g); (n)	Median reduction in pollutant load (%); (n)
North bioswale	TN	9.37 (16)	1.24 (2)	97 (2)
	TP	4.17 (17)	0.05 (3)	99 (3)
	DP	2.22 (9)	0.23 (1)	99 (1)
	TSS	142.37 (17)	37.37 (4)	98 (4)
South bioswale	TN	3.85 (18)	0.30 (11)	99 (9)
	TP	2.06 (17)	0.03 (14)	99 (10)
	DP	0.83 (8)	0.20 (4)	100 (3)
	TSS	63.59 (14)	7.87 (14)	66 (8)

TSS concentrations with a median reduction of 48%, while the north bioswales saw a median increase of 38%. However, for larger events in which the influent concentration was greater than 25 mg/L, the TSS concentrations were reduced by 91%. Finally, the north bioswale saw a median increase in TN concentrations, while the south bioswale saw a median reduction of 45%, with reductions in 6 out of 9 events.

Pollutant Loads

Table 4 summarizes the median influent load and median effluent load across all samples, as well as the median reduction in pollutant loads across all paired samples (e.g., when both influent and effluent samples were captured). As shown, the south bioswale had median nutrient load reductions of nearly 100%, and median TSS load reductions of 66%. In the case of the north bioswale, the median reductions in nutrient loading in the north bioswale were all above 97%.

Discussion

This study presents the results of monitoring two bioswales in Milwaukee, WI over a seven-month period. The bioswales were effective at capturing runoff volumes, with 51% volume removal on average in the south bioswale. In addition, both bioswales reduced overall concentrations of TP, but TSS and TN mitigation showed mixed results. Even so, large volume reduction resulted in load reductions even in cases where the concentration of pollutants increased. While one of the bioswales had structural deficiencies that influenced our ability to capture the entire effluent, the results have implications for the use of green infrastructure to manage stormwater runoff, particularly in urban agricultural settings.

Both bioswales effectively reduced total effluent volumes and reduced peak flow rates. This was most likely caused by a combination of evapotranspiration and exfiltration. The north bioswale was influenced by a crack in the junction box below the underdrain that resulted in a volume removal of 99% across all storms. However, the south bioswale had no noticeable structural defects and had a volume reduction of 51% across all storms. This is comparable to a 42% median reduction found across 13 bioswale studies and a 52% median reduction found across 20 monitoring studies of bioretention with underdrains (Poresky et al. 2012). The difference in the function of the bioswales was also evident in their reduction of peak flow rates with the north and south bioswale reducing peak flows by 99% and 94%, respectively.

The bioswales were, on average, ineffective at reducing TSS concentrations at influent levels under 25 mg/L. This is not unfounded in literature, as other studies found a net export of TSS from bioretention, which could be due to media flushing (Hunt et al. 2006, 2008). In our case, there was actually a median TSS removal of 91% for influent concentrations above 25 mg/L. Green stormwater infrastructure has been shown to have irreducible levels of pollutants (Brown and Hunt 2011; Hunt et al. 2008; Passeport et al. 2009) and these results may suggest that the bioswales may have an irreducible concentration of TSS. In addition, the median influent concentration of TSS in the bioswales were 17 mg/L (south) and 50 mg/L (north), which are both within the quartile range for influent concentrations found within the best management practice (BMP) database (10–62 mg/L) (Clary et al. 2020). This suggests that the concentrations of suspended solids coming from these agricultural fields were not noticeably higher than those from studies collecting runoff from other urban areas.

Both bioswales reduced TP and DP concentrations and loads. This was surprising as most bioretention and bioswale monitoring studies indicate an increase in both TP and DP (Clary et al. 2020). However, across the studies in the BMP database, the median bioswale influent concentrations for DP (0.048 mg/L) and TP (0.129 mg/L) are much lower than those for our bioswales (DP 0.29 mg/L and 0.4 mg/L; and TP 0.5 mg/L and 0.57 mg/L;) (Clary et al. 2020). This suggests that these bioswales may be effective at reducing concentrations due to the higher pollutant concentrations in the influent from runoff of the farm fields as compared to typical urban land uses. Removal mechanisms could be filtration or soil and plant uptake. However, due to the lack of reduction in TSS at low influent concentrations, if filtration of particulate phosphorus was the primary mechanism for phosphorus removal, there may have been little change, or even an increase, in DP concentrations. Therefore, there may likely be sorption of DP to the soils or plant uptake.

The bioswales were less effective at mitigating nitrogen with an increase in TN concentrations of 510% in the north bioswale and a removal of 45% in the south bioswale. This could be due to several factors, including the high influent concentrations, low number of samples for the north bioswale (2), or specific removal processes. Median influent concentrations in the north (3.7 mg/L) and south (2.05 mg/L) bioswales were above those found in the BMP database (median 0.71 mg/L) (Clary et al. 2020). Additionally, nitrogen removal in bioretention and bioswales is a complex matter due to the diversity of nitrogen species and various mechanisms for treatment (Li and Davis 2014). For example, if anaerobic conditions are too persistent, nitrification of ammonia to nitrite and then nitrate can be inhibited (Hunt et al. 2006). However, if anaerobic conditions are not sufficiently present, denitrification of nitrate to dinitrogen or nitrous oxide gas may not occur (Hunt et al. 2008). Even if aerobic and anaerobic conditions are properly balanced through the incorporation of an internal saturated zone in the bottom of the structure, there may not be enough organic carbon for denitrifying microbes to use for denitrification (Passeport et al. 2009). Furthermore, in some cases ammonification and nitrification of organic nitrogen can lead to nitrogen export in these systems

(Clary et al. 2020). Given this complexity, it is therefore unsurprising in our case that TN outcomes were mixed in the bioretention systems in this study. Based upon the data collected, it is unclear which processes are leading to the results that are observed within the samples collected. Testing of influent and effluent samples for different nitrogen species could be helpful in determining what processes may be hindered in the bioswales.

The monitoring data suggests there were several ways in which the influent from agricultural runoff is different from that of urban runoff in typical bioretention settings. The first is in the higher influent pollutant concentrations than what is typically found in urban runoff. While influent TSS concentrations were within the interquartile range of influent concentrations from other bioswale studies in urban areas (Clary et al. 2020), this was not the case for nutrients. The median concentrations of influent TP, DP, and TN at each bioswale were above the 75% quartile for influent concentrations from those summarized in the BMP database (Clary et al. 2020). This suggests that infrastructure to treat runoff from urban farms may need to treat higher concentrations of nutrients. To that end, the data in this case showed that the bioswales were effective at reducing concentrations of phosphorus with high influent concentrations.

One practical application of this study is in providing context for regulators that want to attribute removal credits to bioretention on urban farms. In the case of Wisconsin, municipalities are credited with 80% removal of TSS and 0% TP in the outflow of an underdrain for bioswales. Any water that is infiltrated receives 100% removal. This study indicates that the flow through the underdrain did not meet the requirements of TSS with a median removal of 48% and −38% for the north and south bioswales, respectively. However, the south bioswale saw 91% removal of TSS for influent concentrations that were above 25 mg/L. Bioswales saw removal of TP concentrations with median reductions in the south bioswale of 69% and in the north bioswale of 71%. This indicates that current regulatory criteria may overestimate TSS removal while underestimating TP removal from bioswales that collect runoff from urban agriculture.

Overall, the performance of bioswales indicates that they were largely successful in mitigating runoff volume and nutrient loads from an urban farm; however, the practices had mixed results in reducing TSS and TN concentrations. This is important, as cities are increasingly turning to urban agriculture as a way to reduce their ecological footprint by providing more local produce and a way to reduce the prevalence of urban food deserts (Carlet et al. 2017). As city planners consider future redevelopment efforts, green stormwater infrastructure may be an effective way to ensure that pollutant runoff from fertilized agricultural fields is treated before entering the stormwater system.

Conclusions

The main objective of this work was to evaluate the performance of two bioswales in mitigating runoff volume and pollution from an urban farm. This was done through monitoring over the course of seven months and results indicate that the bioswales were effective at exfiltrating volume, delaying peak flows, and reducing nutrient loads. The bioswales reduced overall volume and phosphorous concentrations from the influent to effluent but had mixed results with TN and TSS removal. From this study there were several key findings:

- The bioswales had a large difference in volume removal with an average volume removal of 99.7% in north bioswale and 51% in south bioswale. This is suspected to be due to cracking in the underground structure that conveys flow from the north bioswale, making the exfiltrated volume appear high;
- The south bioswale reduced concentrations of TSS by 91% for runoff events with influent concentrations greater than 25 mg/L, but were not as effective at removing lower concentrations. This may suggest a level at which sediment concentrations are irreducible;
- The median influent concentrations of nutrients (TP, DP, and TN) at the bioswales in this study were all above the 75% quartile for influent concentrations in urban bioswales, as summarized in the BMP database (Clary et al. 2020). This confirms the hypothesis that influent nutrient concentrations from agricultural runoff in this case study would be greater than those from urban runoff;
- Reduction of TP concentrations—71% in the north bioswale and 69% in the south bioswale—may be due to particulate removal processes or phosphorus reactions with metals;
- Nitrogen removal showed mixed results with a median increase in the north and decrease in the south bioswales. Poor removal in the north bioswale may be due to high influent concentrations, a small sample size (2), or a soluble form of nitrogen combined with a lack of anaerobic conditions for biological removal; and
- Even in cases where the concentrations of pollutants increased from the influent to the effluent, the large volume removal at the bioretention sites resulted in a decrease in pollutant loads.

Overall, the results of this study suggest that the use of bioswales for mitigating runoff from urban agriculture could be an effective way to meet volumetric and water quality goals. As post-industrial cities look for ways to revitalize urban centers, the adoption of urban agriculture could present unique challenges for stormwater and combined sewer systems. Studies such as this can help to improve our understanding of how a changing urban landscape can be managed to ensure downstream flood and water quality goals are met.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request, including all monitoring data.

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