RESEARCH & DEVELOPMENT

Bioswale Design Optimization for Enhanced Application and Pollutant Removal

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16. Abstract

The impacts of impervious areas (e.g., parking lots, roadways, rooftops) on stormwater runoff and ultimately stream health is well documented. Bioswales are an emerging technology used to convey and treat runoff from impervious surfaces. These stormwater control measures (SCMs) combine the treatment mechanisms of bioretention cells and the conveyance function of vegetated swales by including an engineered media, gravel layer, and perforated underdrain beneath a vegetated channel. This research sought to answer how the inclusion of forebays and internal water storage (IWS) as well as longitudinal slope and length and check dams affect bioswale performance by (1) conducting trials on six plot-scale bioswales to identify the importance of various design features, (2) monitoring two field-scale bioswales for water quality and hydrology in the Piedmont ecoregion of North Carolina, (3) monitoring two field-scale bioswales for water quality and hydrology in the Coastal Plain ecoregion of North Carolina, and (4) developing a tool to assist with bioswale designs. Results from the study found (1) check dams can improve exfiltration, or the volume reduction provided by bioswales, (2) IWS most likely contributes to bioswales functioning as conveyance rather than detention practices, (3) bioswales can provide better water quality treatment than swales with and without check dams, and (4) length does not appear to be a significant design characteristic for reducing overflow and increasing exfiltration and/or discharge through an underdrain system.

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Executive Summary

The impacts of impervious areas (e.g., parking lots, roadways, rooftops) on stormwater runoff and ultimately stream health is well documented. Bioswales are an emerging technology used to convey and treat runoff from impervious surfaces. These stormwater control measures (SCMs) combine the treatment mechanisms of bioretention cells and the conveyance function of vegetated swales by including an engineered media, gravel layer, and perforated underdrain beneath a vegetated channel. This research sought to answer how the inclusion of forebays and internal water storage (IWS) as well as longitudinal slope and length and check dams affect bioswale performance by (1) conducting trials on six plot-scale bioswales to identify the importance of various design features, (2) monitoring two field-scale bioswales for water quality and hydrology in the Piedmont ecoregion of North Carolina, (3) monitoring two field-scale bioswales for water quality and hydrology in the Coastal Plain ecoregion of North Carolina, and (4) developing a tool to assist with bioswale designs. Results from the study found (1) check dams can improve exfiltration, or the volume reduction provided by bioswales, (2) IWS most likely contributes to bioswales functioning as conveyance rather than detention practices, (3) bioswales can provide better water quality treatment than swales with and without check dams, and (4) length does not appear to be a significant design characteristic for reducing overflow and increasing exfiltration and/or discharge through an underdrain system. Important design criteria developed from the project include a (1) length to watershed area ratio of 75 ft of bioswale to 1 ac of watershed area, (2) minimum bottom width of 3.0 ft, and (3) maximum side slope of 3:1 (H:V). Additionally, bioswales should include check dams and a forebay to reduce overflow and increase exfiltration. IWS can be included for bioswales constructed in hydrologic soil group A or B in-situ soils. Results from the water quality data indicate that bioswales should be designated as a primary SCM or standalone practice that can be used to meet water quality regulations. The proposed effluent total nitrogen and total phosphorus concentrations for bioswales are 0.79 and 0.14 mg/L, respectively.

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List of Acronyms and Abbreviations

ac: acre(s)
CAAE: Center for Applied Aquatic Ecology
Cd: cadmium
cf: cubic feet
cfs: cubic feet per second
CN: curve number
Cu: copper
ft: foot (feet)
HPTRM: high-performance turf reinforcement mat
hr: hour
in: inch(es)
IWS: internal water storage
mg/L: milligram per liter
min: minute(s)
NCDEQ: North Carolina Department of Environmental Quality
NCDOT: North Carolina Department of Transportation
NCSU: North Carolina State University
NEST: New Stormwater Technology
$NO_{2,3}$-N: nitrate-nitrite nitrogen
NRCS: Natural Resources Conservation Service
NSE(s): Nash-Sutcliffe Efficienc(ies)
O-PO_4^{3-}: orthophosphate
Pb: lead
PSD: particle size distribution
PQL: practical quantification limit
s: second(s)
SCS: Soil Conservation Services
SCM(s): stormwater control measure(s)
SECREF: Sediment and Erosion Control Research and Education Facility
sf: square feet
TIA: total impervious area
TKN: total Kjeldahl nitrogen
TN: total nitrogen
TP: total phosphorus
TSS: total suspended solids
µg/L: micrograms/liter
µm: micrometer
WSS: Water Sciences Section
Zn: zinc

Introduction

The impacts of impervious areas (e.g., parking lots, roadways, rooftops) on stormwater runoff and ultimately stream health is well documented. O'Driscoll et al. (2010) reported stream degradation occurs in watersheds with as little as 6% total impervious area (TIA). Baruch et al. (2018) studied seven streams in the Raleigh-Durham metropolitan area in North Carolina and found the density of drainage networks and roads are better predictors for macroinvertebrate health than TIA. Baruch et al. (2018) also found that aquatic ecosystem health decreased with increasing directly connected impervious areas draining to streams. As of 2021, there are over four million miles of highways constructed throughout the United States (FHWA, 2023). Stormwater control measures (SCMs) used to mitigate runoff from roadways include vegetated swales, dry ponds, permeable pavement, and vegetated filter strips (e.g., Winston et al., 2012; Wissler et al., 2020).

Bioswales are an emerging technology used to convey and treat runoff from impervious surfaces. These SCMs combine the treatment mechanisms of bioretention cells and the conveyance function of vegetated swales by including an engineered media, gravel layer, and perforated underdrain beneath a vegetated channel (Figure 1). The inclusion of the engineered media and gravel layer helps promote exfiltration (Regier & McDonald, 2022) and pollutant removal (Purvis et al., 2018). However, the effects of design parameters such as forebays, internal water storage (IWS), longitudinal slope and length, and check dams on bioswale performance has yet to be quantified. Additionally, limited research exists on the water quality and hydrologic benefits of bioswales in North Carolina. This research sought to answer these questions by (1) conducting trials on six plot-scale bioswales to identify the importance of various design features, (2) monitoring two field-scale bioswales for water quality and hydrology in the Piedmont ecoregion of North Carolina, (3) monitoring two field-scale bioswales for water quality and hydrology in the Coastal Plain ecoregion of North Carolina, and (4) developing a tool to assist with bioswale designs.

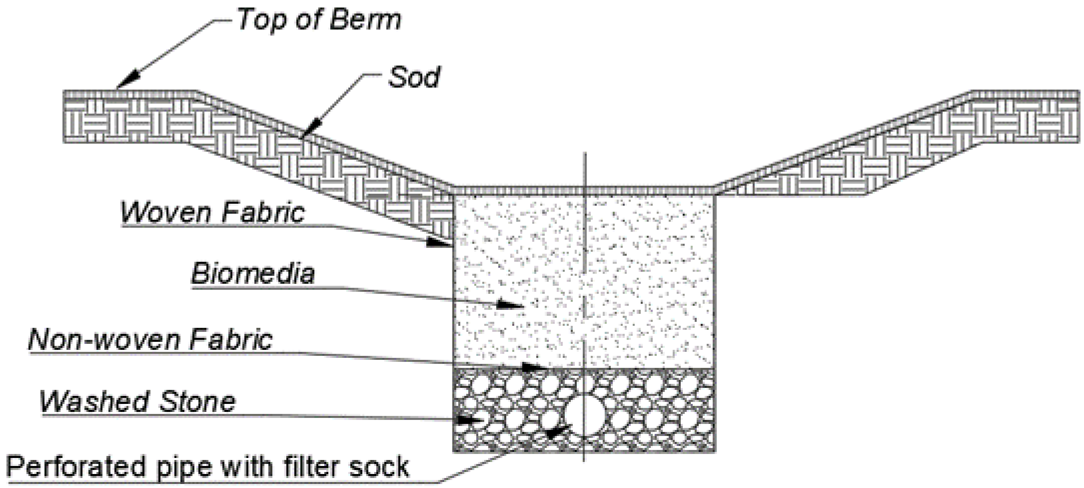

Figure 1. Cross-section of typical bioswale (Source: Jonathan Page, NCSU)

Methods

Objective One: Plot-Scale Bioswales

The plot-scale trials occurred at the North Carolina State University (NCSU) Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, North Carolina. An on-site pond served as the water source for the trials, and flow rates from the pond to the bioswales were controlled using a gate valve. Each bioswale had a rip-rap lined forebay, length of 33, 66, or 100 ft, longitudinal slope of 1 or 4%, and vegetative cover of Centipede sod (*Eremochloa ophiuroides*) (Figure 2; Table 1). The bioswales also had a base width of 3.0 ft, side slopes of 3:1, and a bioretention media depth of 2.0 ft (Figure 3). The media consisted of 85 to 88% sand, 8 to 12% fines (clay and silt), and 3 to 6% organic matter with a P-index of 10 to 30 (10 to 36 ppm). Bioswales #1 and #4 were retrofitted with check dams after initial hydrologic testing. For bioswale #1, the four check dams were 1.0 ft in height and spaced apart approximately 25 ft on center; the last check dam was placed at the end of the bioswale. Bioswale #4 had two 0.50 ft tall check dams spaced 50 ft apart. The check dams had a 4:1 (H:V) side slope, top width of 2.0 ft, and did not cause tailwater conditions. The check dams were constructed of bioretention media, Pyramat® (75 high-performance turf reinforcement mat (HPTRM)) geotextile fabric, and Centipede sod (*Eremochloa ophiuroides*).

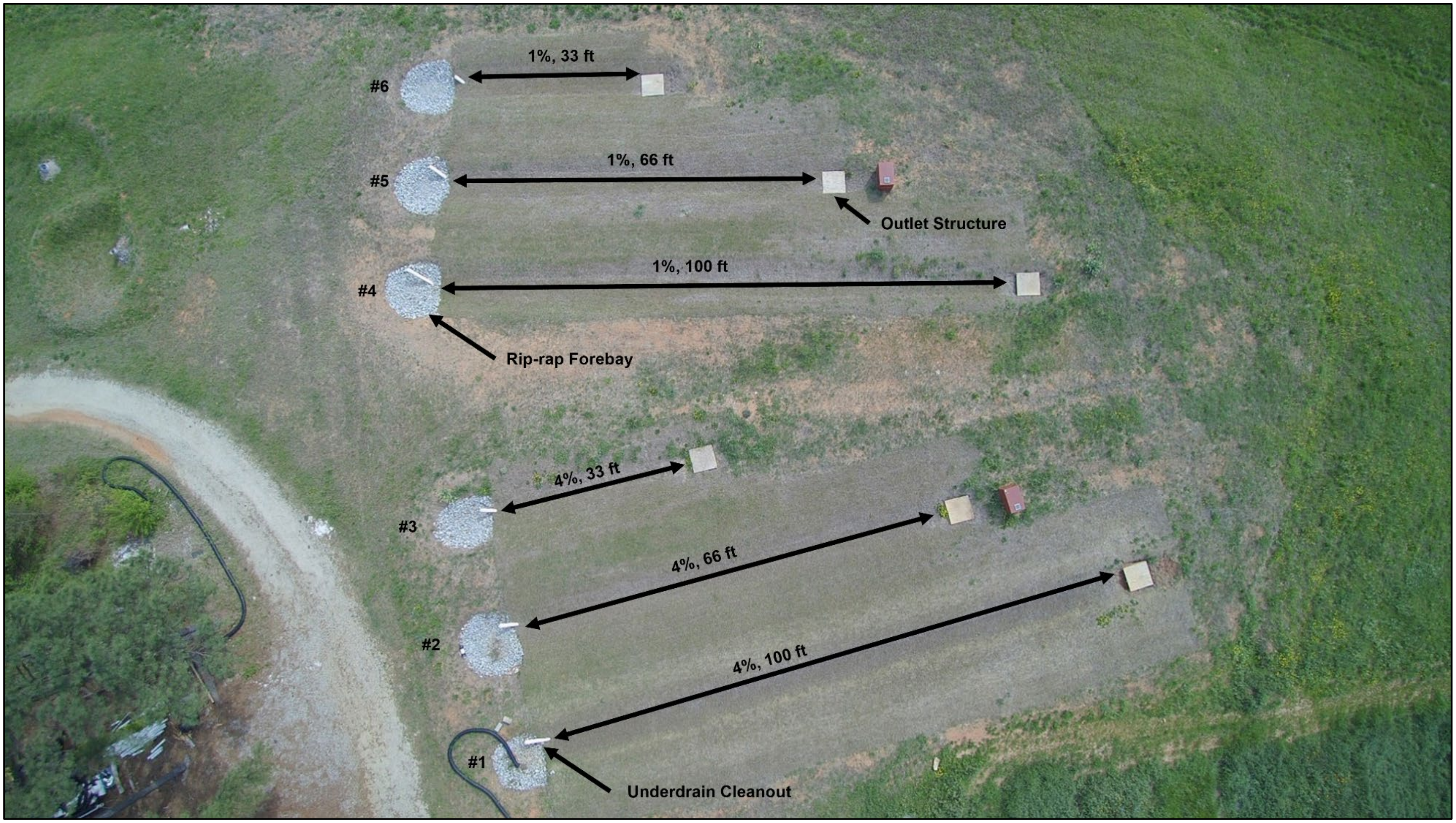

Figure 2. Aerial image of plot-scale bioswales (Source: Dr. Richard McLaughlin, NCSU)

Table 1. Summary of plot-scale bioswale characteristics

Characteristic/Bioswale	#1	#2	#3	#4	#5	#6
Forebay length (ft)	9.0					
Forebay pool depth (ft)	0.50					
Media depth (ft)	2.0					
Based width (ft)	3.0					
Underdrain length (ft)	95	61	28	95	61	28
Longitudinal length (ft)	100	66	33	100	66	33
Longitudinal slope (%)	4.0			1.0		
Internal water storage	No	No	Yes	No	No	Yes
Retrofitted check dams	4	-	-	2	-	-
Surface geometry	Trapezoidal					
Surface side slopes (H:V)	3:1					
Media void storage (cf)	180	119	59	180	119	59
Gravel layer void storage (cf)	112	74	37	112	74	37

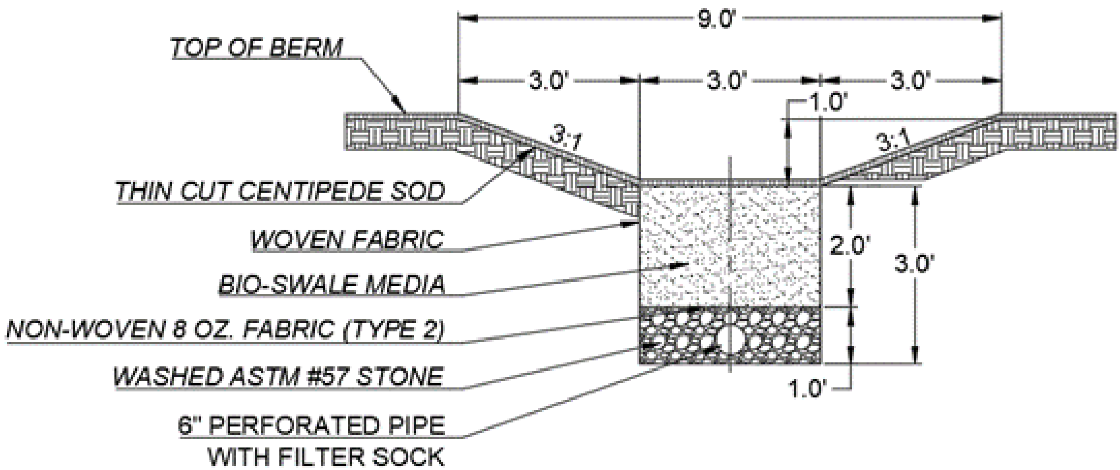

Figure 3. Cross-section of plot-scale bioswales (Source: Jonathan Page, NCSU)

A single, existing structure consisting of a baffle and 30° V-notch weir (Figure 4) measured inflow to each bioswale (Equation 1). The outlet of each bioswale was retrofitted with a wooden monitoring box that included separate 60° V-notch weirs (Equation 2) and baffles to measure overflow and underdrain flow (Figure 5). Each monitoring station was equipped with a Teledyne ISCO 6712 (Lincoln, Nebraska) automated sampler and ISCO 730^{TM} bubbler flow module to measure flow and, if applicable, collect flow-paced samples.

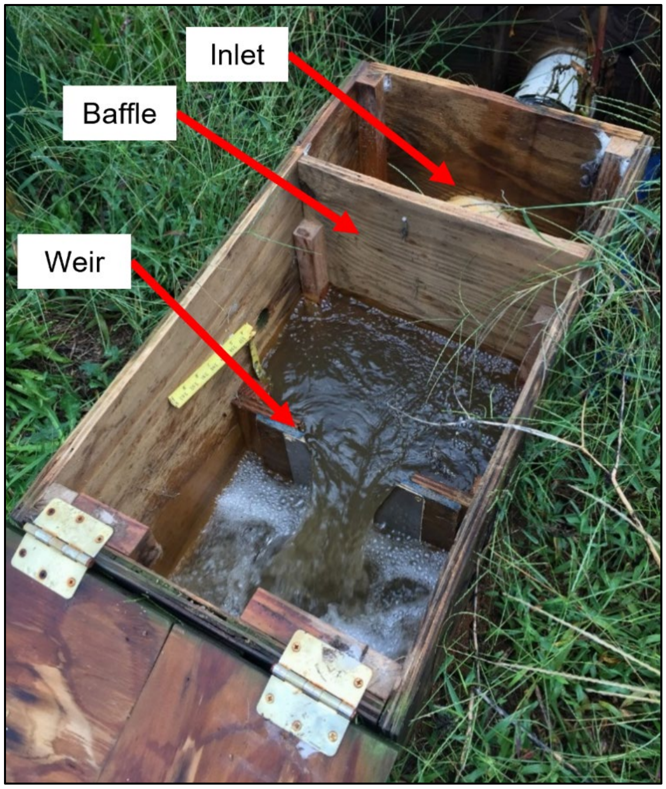

Figure 4. Plot-scale bioswale inlet monitoring structure

$Q = 0.676*H^{2.5}$ Equation 1

Where:

Q = flow rate (cfs)

H = water level above 30° V-notch weir invert (ft)

$Q = 1.443*H^{2.5}$ Equation 2

Where:

Q = flow rate (cfs)

H = water level above 60° V-notch weir invert (ft)

Figure 5. Plot-scale bioswales overflow and underdrain monitoring structure

Hydrologic testing occurred on bioswales #1 and #4 due to their longer length (100 ft), which allowed for a full range of overflow conditions to be monitored that might not otherwise be quantified on the shorter swales (e.g., outflow infiltrating within 80 ft of the inlet). The water supply pond and existing inlet limited the range of flow rates that were tested. The pond could only supply a maximum of 10,594 cf of water, and the maximum flow rate for the weir was 0.68 cfs. Pre-retrofit, bioswales #1 and #4 were tested using a front-weighted hydrograph that decreased in flow rate every 30 minutes for a duration of 4 hr. On average, the initial peak flow rate was 0.45 cfs. Bioswale #1 and #4 were tested four and five times, respectively. Post-retrofit, the average initial peak flow rate was 0.28 cfs, and testing occurred four times for each bioswale. The initial peak flow rate was adjusted post-retrofit to ensure tailwater conditions did not occur.

Bioswales #3 and #6 (33 ft each, 4% and 1% slope, respectively) were tested for water quality performance. Each test simulated a 2 hr water quality event with a peak intensity of 0.75 in/hr (NCDEQ, 2020) and Soil Conservation Services (SCS) Type II rainfall distribution (NRCS, 2019). The simulated watershed was a 0.32 ac roadway with a curve number (CN) of 98. The existing infrastructure (pond, gate valve, inlet) limited the testing to a hydrograph with six, 20 min steps (Figure 6). Each hydrograph was spiked with pollutants (Table 2) to create synthetic runoff based on highway stormwater and other simulated bioretention studies (Davis et al., 2003; Hsieh & Davis, 2005; Kayhanian et al., 2007). The pollutants were thoroughly mixed into sediment prior to testing. Throughout the hydrograph, the spiked sediment was added at a regular rate, by hand or feathering, prior to the runoff passing over the inlet weir. During preliminary testing, the outlet structure for bioswale #3 lifted approximately 1 ft due to buoyancy and created a *de facto* IWS. IWS is a temporary saturated zone in the media, which can promote denitrification and exfiltration (Brown & Hunt, 2011; H. Li et al., 2009; Passeport et al., 2009). For statistical purposes, bioswale #6 was retested for water quality after the underdrain was retrofitted with an upturned elbow to create 1 ft of IWS.

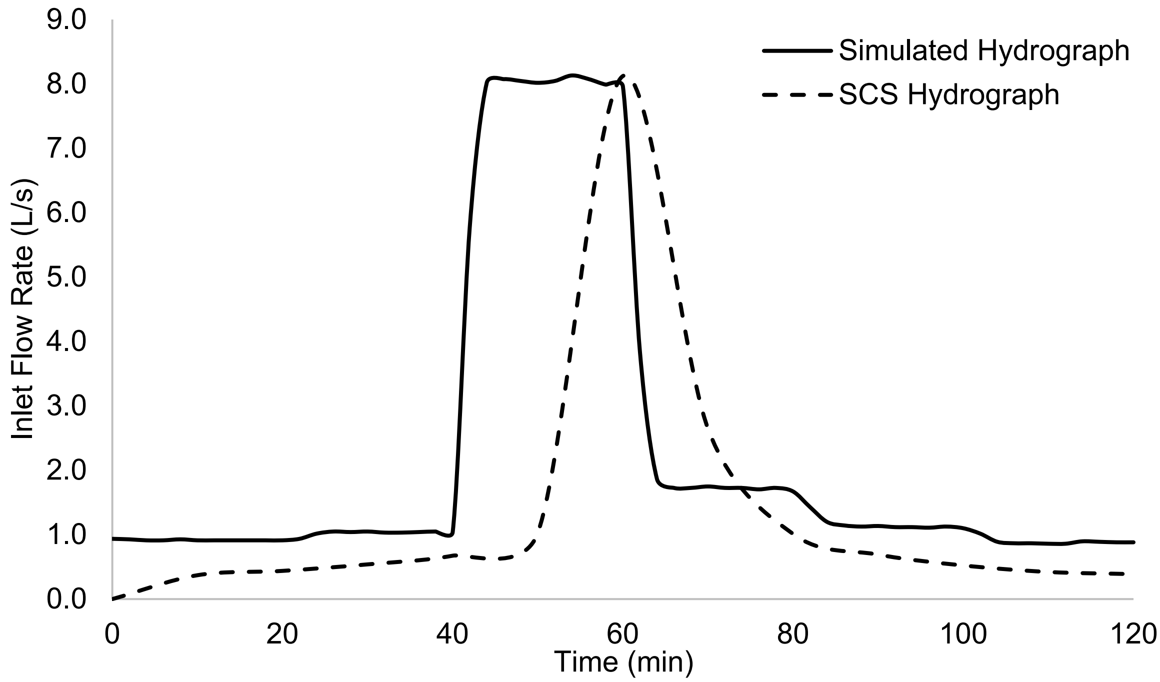

Figure 6. SCS hydrograph and typical inflow hydrograph for plot-scale testing

Table 2. Spiked inflow concentrations for plot-scale water quality testing

Pollutant	**Mean Inflow Concentration ± Standard Deviation (µg/L)**	**Chemical Source**
Total suspended solids	44 mg/L ± 10	Silt loam (5% clay, 64% silt, 31% sand)
Total Kjeldahl nitrogen	667 ± 110	Sodium nitrate ($NaNO_3$)
Nitrate-nitrite nitrogen	165 ± 75	Sodium nitrate ($NaNO_3$)
Total phosphorus	1834 ± 270	Sodium phosphate (Na_2HPO_4)
Orthophosphate	1787 ± 266	Sodium phosphate (Na_2HPO_4)
Total cadmium	7.46 ± 1.8	Cadmium chloride ($CdCl_2$)
Total copper	10.08 ± 2.5	Copper sulfate ($CuSO_4$)
Total lead	13.15 ± 4.4	Lead nitrate ($Pb(NO_3)_2$)
Total zinc	31.50 ± 7.0	Zinc chloride ($ZnCl_2$)

Composite samples collected at the inflow, overflow, and underdrain were analyzed for total suspended solids (TSS), total Kjeldahl nitrogen (TKN), nitrate-nitrite nitrogen ($NO_{2,3}$-N), total phosphorus (TP), orthophosphate ($O\text{-}PO_4^{3-}$), total cadmium (Cd), total copper (Cu), total lead (Pb), and total zinc (Zn) (Table 3). Total nitrogen (TN) was calculated as the sum of TKN and $NO_{2,3}$-N. The samplers' composite bottles were cleaned onsite using deionized water, and the samples were transported on ice (less than 4°C) to the NC State University Center for Applied Aquatic Ecology (CAAE) for sediment and nutrient analyses and the North Carolina Department of Environmental Quality (NCDEQ) Water Sciences Section (WSS) Chemistry Laboratory (Raleigh, North Carolina) for metal analyses. Outflow, or the combination of overflow and underdrain flow, pollutants were estimated using a volume-weighted average (Equation 3).

Table 3. Practical quantification limits for monitored pollutants (APHA, 2012)

Pollutant	**Practical Quantification Limit (µg/L)**	**Analytical Method**
TSS	Dependent upon volume filtered	SM 2540 D
TKN	280	EPA Method 351.2, Rev. 2.0
$NO_{2,3}$- N	11.2	EPA Method 353.2, Rev. 2.0
TP	10	EPA Method 365.1, Rev. 2.0
$O\text{-}PO_4^{3-}$	12	
Total Cd	0.5	EPA Method 200.8, Rev. 5.4
Total Cu	2.0	
Total Pb	2.0	
Total Zn	10	

$$P_{out} = \frac{V_{over} * P_{over} + V_{under} * P_{under}}{V_{over} + V_{under}} \quad \text{Equation 3}$$

Where:

P_{out} = outflow pollutant concentration (mg/L)

V_{over} = overflow volume (cf)

P_{over} = overflow pollutant concentration (mg/L)

V_{under} = underdrain flow volume (cf)

P_{under} = underdrain flow pollutant concentration (mg/L)

Particle size distribution (PSD) tests were conducted for simulations with sufficient outflow volume. Samples were taken to the North Carolina State University Department of Marine, Earth, and Atmospheric Sciences Lab (Raleigh, North Carolina) for analysis using a Beckman Coulter laser diffraction particle size analyzer. Results were reported as the differential volume percentage for particles ranging from 0.04 to 2000 µm in diameter (Beckman

Coulter, 2024). These data were used to calculate d_{10}, d_{50}, and d_{90} values as well as the percentage of sand, silt, and clay within each sample. Clays, silts, and sands are defined as particles with diameters less than 2 μm, between 2 and 50 μm, and greater than 50 μm, respectively (USDA, 1999). Outflow d_{10}, d_{50}, and d_{90} values and percentages of clay, silt, and sand were calculated using Equation 3 if PSD data were collected for overflow and underdrain samples.

For each trial, the peak flow rate and runoff volume were identified for each monitoring station using the recorded water level data and Equation 1, 2, and/or 4 (Figure 7). Overflow and underdrain volumes were summed at each time step to calculate the outflow volume, and the outflow flow rate was calculated using Equation 5. The volume of runoff exfiltrating into the in-situ soils was estimated using Equation 6. Overflow, underdrain flow, and exfiltration were also calculated as a percentage of inflow (Equation 7). Peak flow rate and volume reduction were calculated using Equation 8.

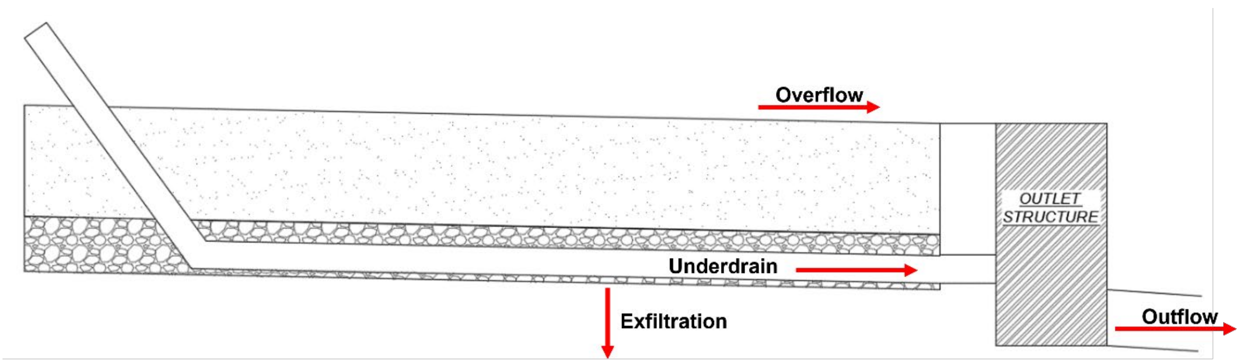

Figure 7. Bioswale hydrologic fates

$V = Q_i * t_i$ Equation 4

Where:

V = volume (cf)

Q_i = flow rate at time step i (cfs)

t = time step (s)

$$Q_{out} = \frac{V_{over,i} + V_{under,\,i}}{(t_{i+1} - t_i) * 86{,}400} \qquad \text{Equation 5}$$

Where:

Q_{out} = outflow flow rate (cfs)

$V_{over,i}$ = overflow volume at time step i (cf)

$V_{under,i}$ = underdrain flow volume at time step i (cf)

t = time step (min)

$$V_e = V_{inflow} - V_{over} - V_{under} \qquad \text{Equation 6}$$

Where:

V_e = estimated exfiltration volume (cf)

V_{inflow} = inflow volume (cf)

V_{over} = overflow volume (cf)

$V_{under,}$ = underdrain flow volume (cf)

$$P_{in} = \frac{V}{V_{in}} * 100\% \qquad \text{Equation 7}$$

Where:

P_{in} = percentage of inflow (%)

V = overflow, underdrain flow, or exfiltration volume (cf)

V_{in} = inflow volume (cf)

$$P_R = \frac{Q_{in} - Q_{over}; Q_{under}; Q_{out}}{Q_{in}} * 100\% \qquad \text{Equation 8}$$

Where:

P_R = peak flow rate (volume) reduction (%)

QP_{in} = inflow peak flow rate (cfs) (volume; cf)

QP_{over} = overflow peak flow rate (cfs) (volume; cf)

QP_{under} = underdrain flow peak flow rate (cfs) (volume; cf)

QP_{out} = outflow peak flow rate (cfs) (volume; cf)

Peak flow rates, runoff volumes, and pollutant concentrations were also tested for significant differences using RStudio™ (RStudio Team, 2023). Paired data were first tested for normality using the Shapiro-Wilk test. Normally distributed data were analyzed using the

Student's t-test after testing for equal variances. Non-normal data were tested for symmetry using the Miao, Gel, and Gastwirth symmetry test (Miao et al., 2006). Symmetrical data were analyzed with the Wilcoxon rank-sum test, and non-symmetrical data were analyzed using the sign test. A significance level of 0.05 ($\alpha = 0.05$) was used for all analyses. Overflow, underdrain, and outflow nutrient concentrations were also compared to water quality thresholds established for Piedmont stream health (McNett et al., 2010) using exceedance probability plots. Median TSS concentrations were compared to North Carolina standards to determine if bioswales are a primary or secondary practice; primary refers to SCMs that can be used as stand-alone devices to meet water quality regulations (NCDEQ, 2023).

Objective Two: 50-98 Bioswales

The NC 50 and NC 98 interchange in Wake County, North Carolina was retrofitted with six bioswales, and NC State University monitored two of the bioswales for water quality and hydrologic improvement (BS2 and BS4) (Figure 8; Table 4). Typically, soils in this area are tight and infiltration is often limited (USDA- NRCS, 2019). Each bioswale had a specified base width and similar cross-section as the plot-scale bioswales (Figure 3). The 2.0 ft of media included in the bioswales followed the specifications used for the plot-scale bioswales (Table 1). Both bioswales had at least one check dam that had an upstream and downstream slope of 4:1 (H:V), top width of 2.0 ft, and height of 0.50 ft; the check dams were constructed using in-situ soil. BS4 also had IWS and a Class A rip-rap lined forebay.

Figure 8. Aerial of BS2 and BS4 bioswale watersheds (Source: Google Maps)

Table 4. Summary of 50-98 BS2 and BS4 bioswale characteristics

Characteristic/Bioswale	BS2	BS4
Drainage area (ac)	3.41	1.78
Percent impervious (%)	14	13
In-situ soil[a]	Cecil sandy loam	
Forebay length (ft)	-	34
Forebay pool length (ft)	-	9.0
Forebay pool depth (ft)	-	1.5
Forebay width (ft)	-	7.0
Media depth (ft)	2.0	
Base width (ft)	4.0	5.0
Underdrain length (ft)	72	57
Longitudinal length (ft)	88	77
Longitudinal slope (%)	1.79	2.93
Internal water storage	No	Yes (1.3 ft)
Check dams (ea)	2	3
Surface geometry	Trapezoidal	
Surface side slopes (H:V)	3:1	
Surface area (sf)	1,144	1,079
Drainage area: surface area	130:1	72:1
Impervious area: surface area	18:1	9:1
Vegetative cover	Centipede sod (*Eremochloa ophiuroides*)	
Media void storage (cf)	201	230
Gravel layer void storage (cf)	127	148
Surface storage (cf)	49	85

[a] USDA- NRCS (2019)

The grassed BS2 inlet was retrofitted with a cross-channel, 90° V-notch weir (Figure 9; Equation 9) and an ISCO 6712 sampler to collect flow-paced water quality samples and record water level data. The existing concrete outlet structure immediately downslope of BS2 was retrofitted with 60° V-notch weirs (Equation 2) and automated samplers to collect overflow and underdrain data (Figure 10).

Figure 9. BS2 inlet weir and portion of watershed

$$Q = 2.5 * H^{2.5}$$ Equation 9

Where:

Q = flow rate (cfs)

H = water level above 90° V-notch weir invert (ft)

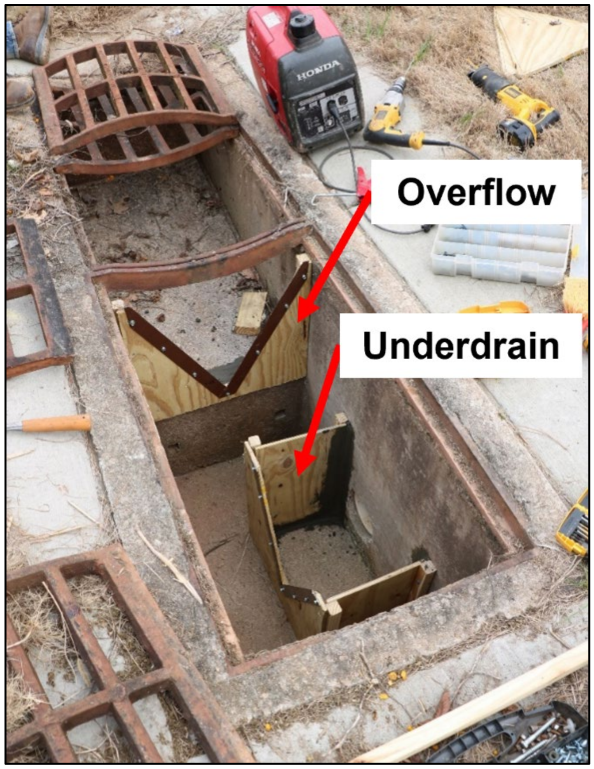

Figure 10. BS2 overflow and underdrain weirs

For BS4, an ISCO sampler and 120° V-notch were installed across the channel and downslope of the forebay to monitor for flow and collect samples (Figure 11). Throughout the monitoring period, the check dam immediately downslope of the BS4 inlet weir caused tailwater conditions and submerged the weir. Inflow volumes and peak discharges were estimated using the Discrete Natural Resources Conservation Service (NRCS) CN Method (Equations 10 through 12) and Rational Method (Equations 13 and 14), respectively. Water quality sampling was triggered when 0.05 in of rain fell during a 60 min period; samples were collected every two minutes after an additional 0.03 in of rain fell. The existing concrete outlet structure downslope of the bioswale was retrofitted with samplers and a 90° (Equation 9) and 60° V-notch weir (Equation 2) to monitor overflow and underdrain flow, respectively (Figure 12). For both bioswales, the volume of rainfall landing directly on the bioswale was estimated using Equation 15 and added to the measured or estimated inflow volume. The same procedures used to collect, process, and analyze the hydrologic and water quality data collected from the plot-scale bioswales were applied to BS2 and BS4.

Figure 11. BS4 forebay, inlet weir, and portion of watershed

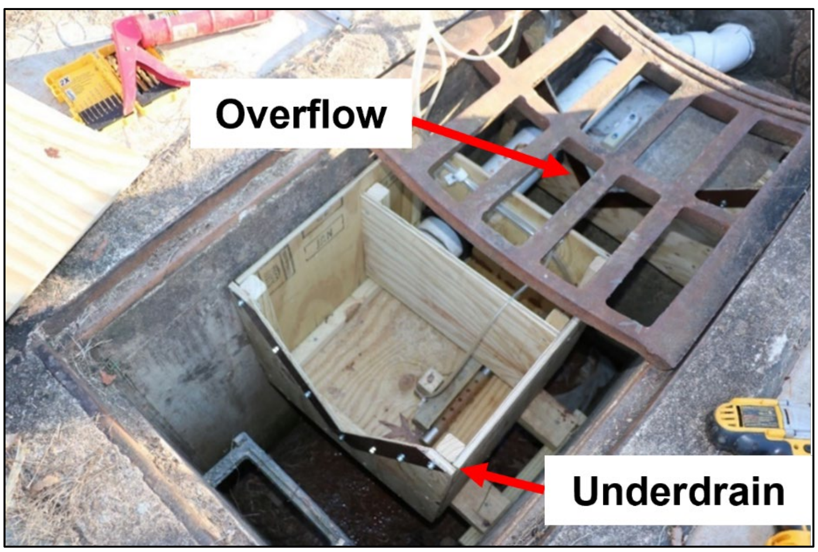

Figure 12. BS4 overflow and underdrain weirs

$$S = \left(\frac{1000}{CN} - 10\right) \quad \text{Equation 10}$$

$$Q^* = \left(\frac{(P - 0.2S)^2}{P + 0.8S}\right) \quad \text{Equation 11}$$

$$V = 3630 * Q^* * A \quad \text{Equation 12}$$

Where:

V = runoff volume (cf)

Q* = runoff depth (in)

A = watershed area (ac)

P = total rainfall depth (in)

S = maximum potential retention (in)

CN = curve number (89 for pervious, 98 for impervious) (unitless)

$$C = \frac{C_{impervious} * Area_{impervious} + C_{pervious} * Area_{pervious}}{Area_{impervious} + Area_{pervious}} \quad \text{Equation 13}$$

$$Q = C * i * A \quad \text{Equation 14}$$

Where:

Q = peak flow rate (cfs)

C = composite Rational Coefficient (0.297) (unitless)

$C_{impervious}$ = Rational coefficient for impervious area (0.95) (unitless)

$C_{pervious}$ = Rational coefficient for pervious area (0.20) (unitless)

i = maximum rainfall intensity (in/hr)

A = total watershed area (ac)

$A_{impervious}$ = impervious area (0.22 ac)

$A_{pervious}$ = impervious area (1.56 ac)

$$V_{rain} = \frac{P}{12} * SA \quad \text{Equation 15}$$

Where:

V_{rain} = volume of rainfall landing on bioswale (cf)

P = total rainfall depth (in)

SA = bioswale surface area (sf)

Objective Three: 40-95 Bioswales

Bioswales BSN and BSS were installed along the exit ramps at the Interstate 40 (I-40) and Interstate 95 (I-95) interchange in Benson, North Carolina (Figure 13; Table 5), where the soils are typically sandier and the potential for infiltration is greater (USDA- NRCS, 2019). These bioswales were also monitored for water quality and hydrologic improvement. Each bioswale had a specific base width and similar cross-section as the plot-scale and 50-98 bioswales (Figure 3). Each bioswale had 2.0 ft of media that followed the specifications used for the plot-scale bioswales (Table 1), rip-rap forebay, and a check dam located at the end of bioswale. The check dams were 1.0 ft tall, 4.0 ft wide, constructed with in-situ soil, and covered with Centipede sod (*Eremochloa ophiuroides*).

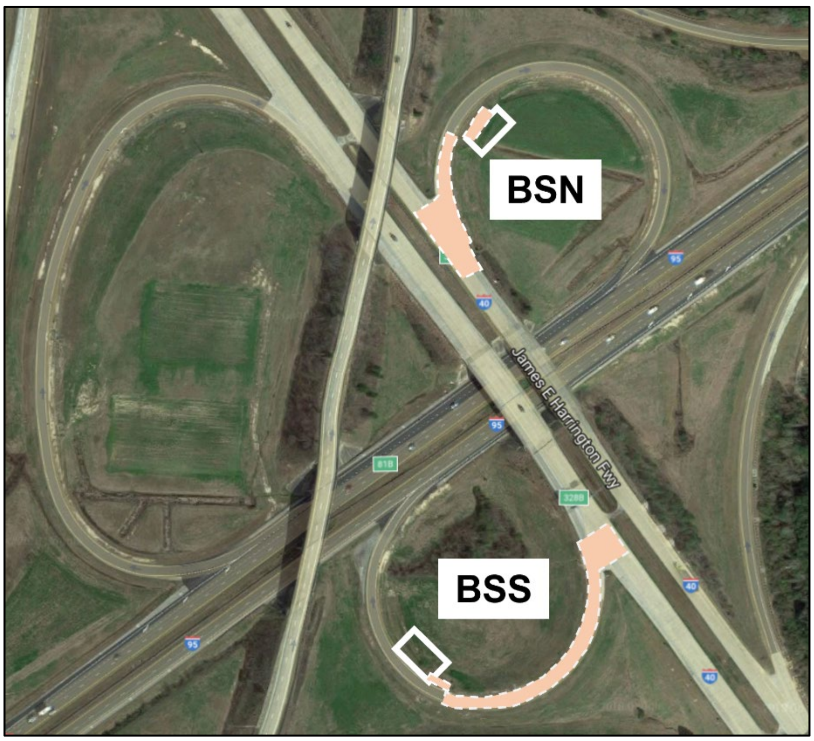

Figure 13. Aerial of BSN and BSS location and watershed (Source: Google Maps)

Table 5. Summary of 40-95 BSN and BSS bioswale characteristics

Characteristic/Bioswale	**BSN**	**BSS**
Drainage area (ac)	0.47	0.62
Percent impervious (%)	74	78
In-situ soil[a]	Norfolk loamy sand	Gilead sandy loam
Forebay length (ft)	9.0	
Forebay pool depth (ft)	0.50	
Media depth (ft)	2.0	
Base width (ft)	3.0	3.5
Underdrain length (ft)	44	18
Longitudinal length (ft)	50	25
Longitudinal slope (%)	1.0	
Check dams (ea)	1.0	
Surface geometry	Trapezoidal	
Surface side slopes (H:V)	3:1	
Vegetative cover	Centipede sod (*Eremochloa ophiuroides*)	
Media void storage (cf)	111	48
Gravel layer void storage (cf)	70	30
Surface storage (cf)	92	39

[a] USDA- NRCS (2019)

Unlike the plot-scale and 50-98 bioswales, runoff entered BSN and BSS via an inlet pipe that discharged perpendicularly into the bioswale (Figure 14). Each inlet was retrofitted with a wooden box and 60° V-notch weir that was directly connected to the inlet pipe. Due to a lack of a stilling basin in the weir box, the velocity of approach or the runoff's velocity was not reduced, which caused inaccurate flow readings throughout the monitoring period (Teledyne ISCO, 2016). Additionally, runoff estimated using the CN Method (Equations 10 through 12) was less than the sum of the measured overflow and underdrain flow. As a result, exfiltration could not be estimated using Equation 6, and inflow was approximated as the sum of the measured overflow and underdrain flow (Equation 16). Overflow and underdrain flow were measured using 45° V-notch weirs (Equation 17; Figure 15) and automated samplers. Hydrologic data and flow-paced samples from the inflow, overflow, and underdrain were collected, processed, and analyzed using the same methods as the plot-scale and 50-98 bioswales.

Figure 14. Inlet and forebay (left) and weir box (right) for BSN and BSS bioswales

$V_{inlet} = V_{over} + V_{under}$ Equation 16

Where:

V_{inlet} = estimated inflow volume (cf)

V_{over} = measured overflow volume (cf)

V_{under} = measured underdrain volume (cf)

$Q = 1.035 * H^{2.5}$ Equation 17

Where:

Q= flow rate (cfs)

H = water level above 45° V-notch weir invert (ft)

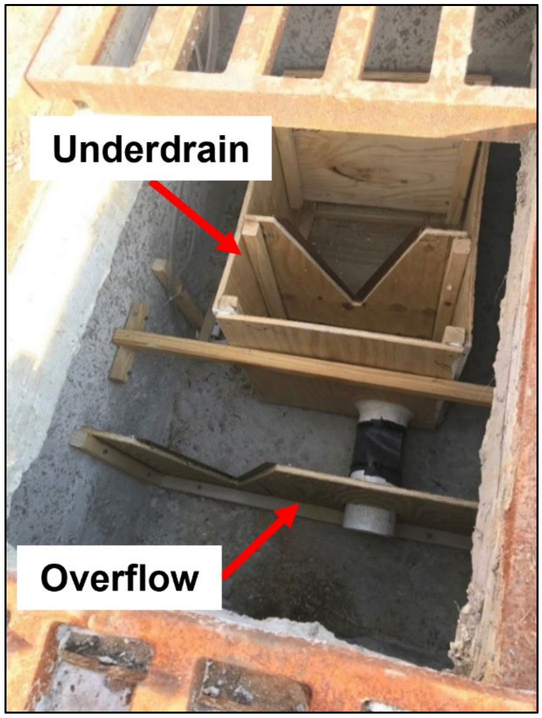

Figure 15. BSN and BSS overflow and underdrain weirs

Objective Four: Design Tool

Scaled and non-correlated variables or predictors fitted a generalized linear mixed effects model to predict a bioswale's overflow, underdrain, and exfiltration volume as a percentage of the inflow (Table 6). The foundation for this model were the repeated measurements taken at BS2, BS4, and SECREF bioswales #1 (with and without check dams), #3 with IWS, #4 (with and without check dams), and #6 (with and without IWS). The final models were chosen using backwards selection, with a significance level of 0.05 ($\alpha = 0.05$). Q-Q plots of the residuals and Nash-Sutcliffe Efficiencies (NSEs) verified model legitimacy. NSEs of at least 0.65 indicate the model is a good fit to the data (Ritter & Muñoz-Carpena, 2013). The analyses used 70% of the data to build the regression models in RStudio™ (RStudio Team, 2023), and the remaining 30% to calculate the NSEs. Thien and Yeo (2022) recommends that at least 70% of the data is allocated towards building or training models.

Table 6. Summary of predictors for bioswale design tool

Predictor	Range/Response
Base width (ft)	3.0-5.0
Longitudinal length (ft)	33 to 98
Longitudinal slope (%)	1.0-2.93
Forebay	Yes (1) or no (0)
Internal water storage	
Check dam(s)	

Results and Discussion

Objective One: Hydrology

The plot-scale trials occurred from November 2016 to August 2017, and the number of trials ranged from four to 10. For bioswale #1 without check dams, the median inflow, overflow, underdrain, outflow, and exfiltration volumes were 3,774, 766, 2,069, 2,745, and 831 cf, respectively (Table 7). Underdrain flow accounted for more than 50% of the total inflow while 27% of the total inflow was converted to exfiltration (Figure 16). Anderson et al. (2016) monitored three bioswales in Salinas, California and found the bioswales infiltrated between 83 and 95% of the runoff. On average, two bioswales in Milwaukee, Wisconsin reduced at least 51% of the runoff volumes (Regier & McDonald, 2022). Purvis et al. (2019) reported runoff from more than 36 monitored storm events was completely infiltrated by a bioswale in Boliva, North Carolina. The longitudinal slope for the swales monitored by Anderson et al. (2016), Purvis et al. (2019), and Regier & McDonald (2022) was 1, 0.5, and 0.6%, respectively. Bioswale #1 without check dams most likely had less exfiltration compared to other bioswales due to its steep slope (4%; Table 1).

Table 7. Summary of bioswale #1 without check dams hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	2,828	3,556	3,774	4,143	5
Inflow (cfs)	0.32	0.46	0.47	0.54	
Overflow (cf)	58	578	766	924	
Overflow (cfs)	0.07	0.28	0.35	0.45	
Underdrain (cf)	1,272	2,036	2,069	2,748	
Underdrain (cfs)	0.13	0.20	0.19	0.29	
Outflow (cf)	2,131	2,613	2,745	3,029	
Outflow (cfs)	0.31	0.44	0.36	0.60	
Exfiltration (cf)	697	943	831	1,292	

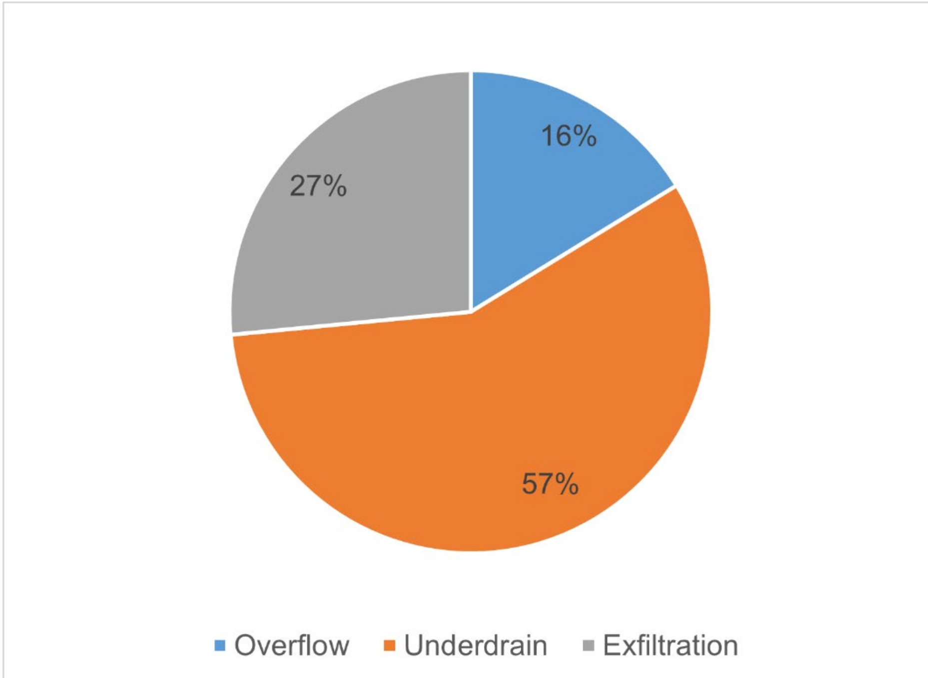

Figure 16. Runoff fates as percentage of total inflow for bioswale #1 without check dams

With check dams, bioswale #1 did not experience any overflow, and the median inflow, underdrain, outflow, and exfiltration volumes were 2,615, 1,380, 1,379, and 1,227 cf, respectively (Table 8). Compared to the trials without check dams, the amount of exfiltration accounting for the total inflow increased from 27 to 47% (Figure 17). Previous research has shown the volume reduction provided by vegetated swales increases with the inclusion of check dams (e.g., Davis et al., 2012; Winston et al., 2019).

Table 8. Summary of bioswale #1 with check dams hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	2,427	2,629	2,615	2,861	4
Inflow (cfs)	0.23	0.25	0.25	0.27	
Overflow (cf)	0	0	0	0	
Overflow (cfs)	0	0	0	0	
Underdrain (cf)	1,210	1,398	1,380	1,624	
Underdrain (cfs)	0.12	0.14	0.14	0.15	
Outflow (cf)	1,210	1,398	1,379	1,624	
Outflow (cfs)	0.12	0.14	0.14	0.15	
Exfiltration (cf)	1,073	1,231	1,227	1,398	

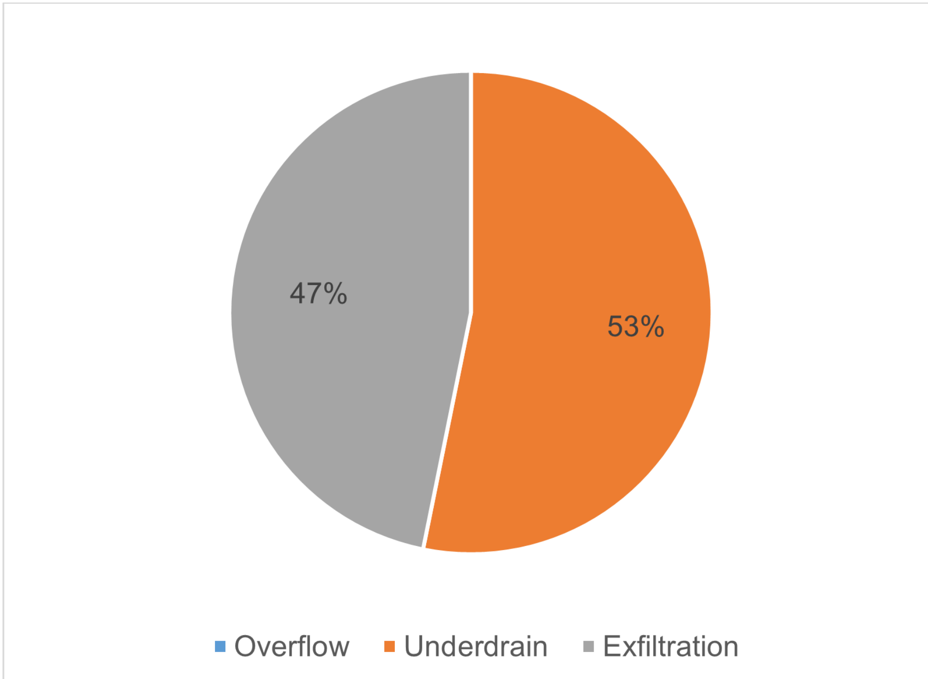

Figure 17. Runoff fates as percentage of total inflow for bioswale #1 with check dams

Table 9 and Figure 18 summarize the hydrologic data for bioswale #4 without check dams. Inflow, overflow, underdrain flow, outflow, and exfiltration ranged from 7,038 to 10,402, 232 to 1,691, 951 to 2,549, 2,122 and 2,949, and 4,916 and 7,510 cf, respectively. Unlike bioswale #1, 71% of the total inflow for bioswale #4 was converted to exfiltration. This bioswale most likely experienced exfiltration similar to the values reported by Anderson et al. (2016), Purvis et al. (2018) and Regier & McDonald (2022) because of its 1% slope (Table 1).

Table 9. Summary of bioswale #4 without check dams hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	7,038	9,251	9,783	10,402	4
Inflow (cfs)	0.36	0.43	0.43	0.50	
Overflow (cf)	232	937	912	1,691	
Overflow (cfs)	0.10	0.16	0.16	0.23	
Underdrain (cf)	951	1,715	1,679	2,549	
Underdrain (cfs)	0.09	0.24	0.19	0.48	
Outflow (cf)	2,122	2,651	2,767	2,949	
Outflow (cfs)	0.29	0.38	0.32	0.57	
Exfiltration (cf)	4,916	6,600	6,987	7,510	

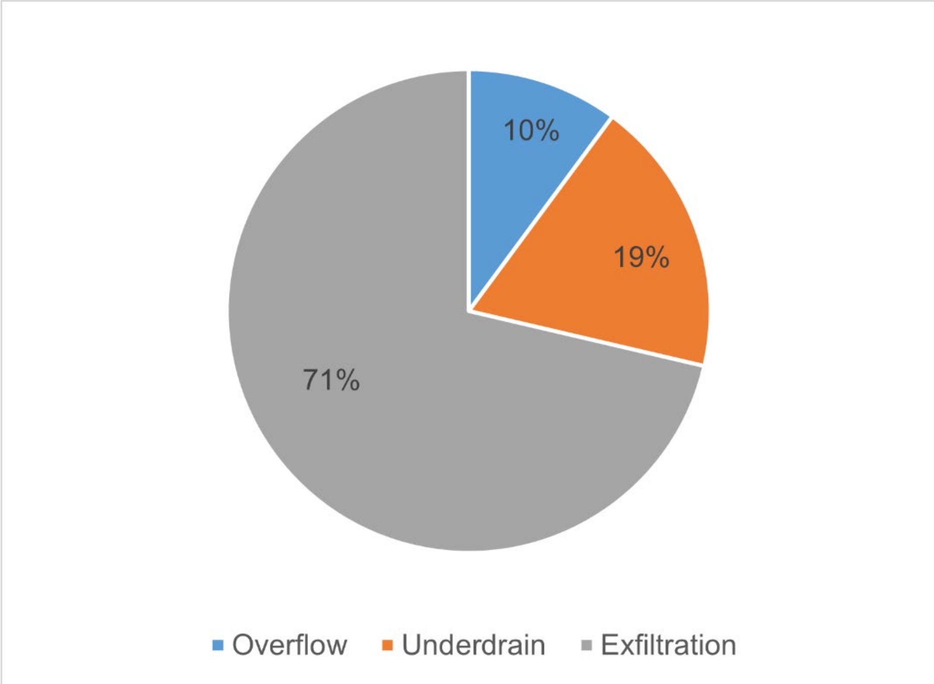

Figure 18. Runoff fates as percentage of total inflow for bioswale #4 without check dams

Comparable to bioswale #1 with check dams, bioswale #4 with check dams did not experience any overflow (Table 10; Figure 19). Inflow, underdrain flow, and exfiltration varied between 2,507 and 3,306, 1,636 and 2,376, and 871 and 1,088 cf, respectively. Exfiltration as a percentage of the total inflow decreased from 71 to 33%. Exfiltration most likely decreased due to the differences between inflow volumes pre- and post-retrofit. The mean inflow pre-retrofit volume was 9,251 cf (Table 9) while the post-retrofit volume was 2,900 cf (Table 10). The mean underdrain volumes pre- and post-retrofit were comparable (1,715 cf vs. 1,942 cf) suggesting that the increased ponding had limited impacts on the swale's ability to exfiltrate runoff.

Table 10. Summary of bioswale #4 with check dams hydrologic data

Parameter	**Minimum**	**Mean**	**Median**	**Maximum**	**Number of trials**
Inflow (cf)	2,507	2,900	2,894	3,306	4
Inflow (cfs)	0.25	0.29	0.27	0.37	
Overflow (cf)	0	0	0	0	
Overflow (cfs)	0	0	0	0	
Underdrain (cf)	1,636	1,942	1,878	2,376	
Underdrain (cfs)	0.16	0.19	0.19	0.24	
Outflow (cf)	1,636	1,942	1,878	2,376	
Outflow (cfs)	0.16	0.19	0.19	0.24	
Exfiltration (cf)	871	959	937	1,088	

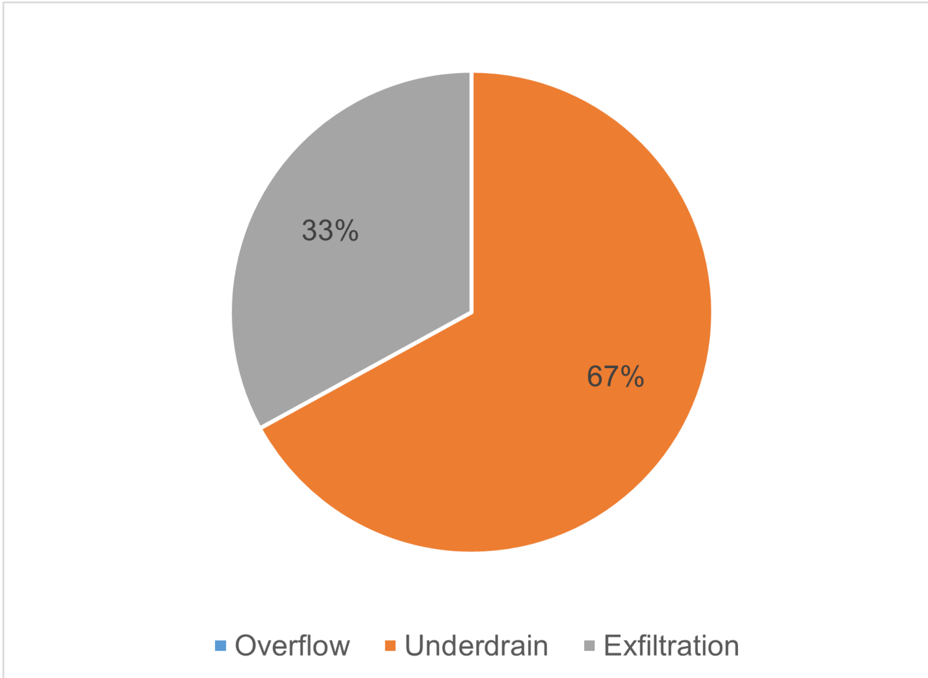

Figure 19. Runoff fates as percentage of total inflow for bioswale #4 with check dams

Table 11 and Figure 20 describe the hydrologic data for bioswale #3 with IWS. The median inflow, overflow, underdrain flow, outflow, and exfiltration volumes were 590, 239, 101, 278, and 344 cf, respectively. More than 80% of the total inflow was converted overflow or exfiltration. The substantial percentage of overflow (41%) was most likely due to the bioswale's steep slope (4%; Table 1). It is also possible overflow occurred more frequently due to the bioswale's IWS. IWS creates a level, saturated zone within the bioswale media; however, the bottom of the bioswale is not level. This causes a decrease in the availability of unsaturated media to store runoff and promote exfiltration along the length of the swale (Figure 21). In other words, IWS causes less unsaturated media to be available as runoff progresses from the bioswale's inlet to its outlet. It is possible the lack of unsaturated media was exacerbated by the length of bioswale #3 (33 ft; Table 1).

Table 11. Summary of bioswale #3 with IWS hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	577	609	590	660	9
Inflow (cfs)	0.28	0.30	0.30	0.31	
Overflow (cf)	163	249	239	349	
Overflow (cfs)	0.20	0.22	0.21	0.27	
Underdrain[a] (cf)	82	103	101	132	
Underdrain[a] (cfs)	0.01	0.02	0.02	0.04	
Outflow[a] (cf)	158	257	278	378	
Outflow[a] (cfs)	0.22	0.24	0.23	0.29	
Exfiltration (cf)	262	352	344	451	

[a] Discharged from IWS

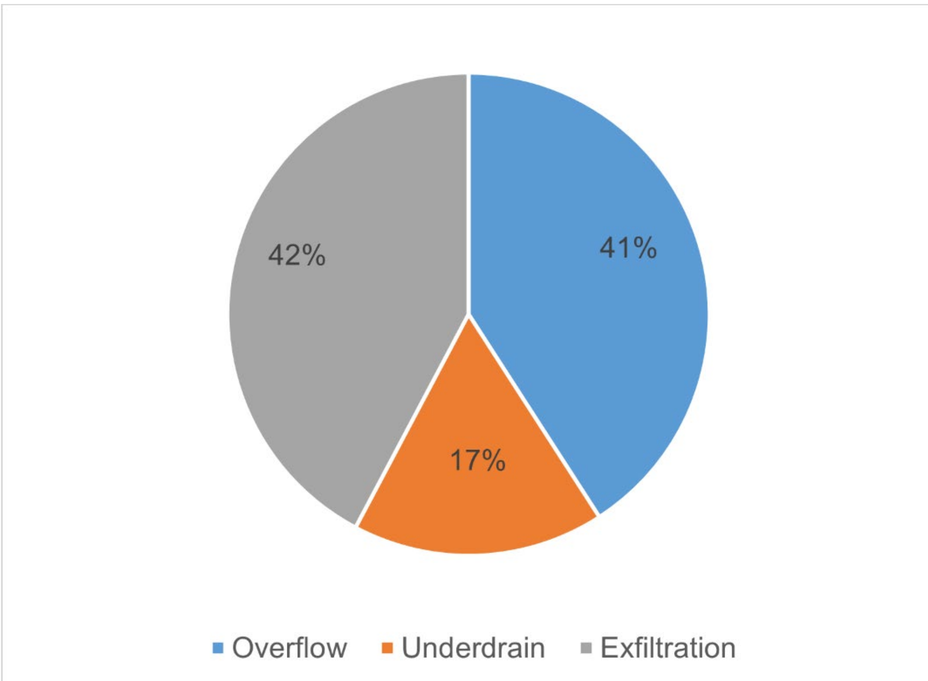

Figure 20. Runoff fates as percentage of total inflow for bioswale #3 with IWS

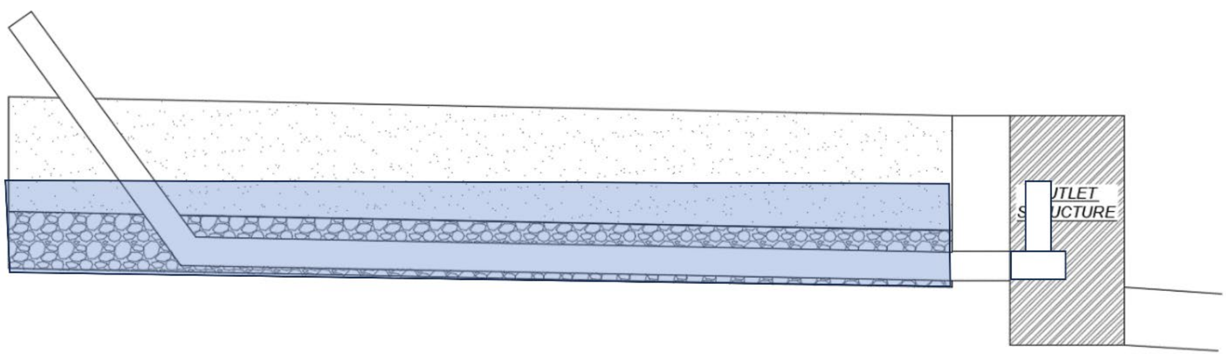

Figure 21. Schematic of available unsaturated media (saturated media shown in blue)

Median inflow, overflow, underdrain, outflow, and exfiltration volumes for bioswale #6 without IWS were 559, 75, 219, 291, and 269 cf, respectively (Table 12). The percentage of total inflow converted to overflow, underdrain flow, and exfiltration were 13, 34, and 53%, respectively (Figure 21). The percentages of overflow and exfiltration further support the conclusion that increasing slope increases overflow or the likelihood of the bioswale functioning more as a conveyance (e.g., swale) rather than a detention device (e.g., bioretention cell).

Table 12. Summary of bioswale #6 without IWS hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	527	628	559	1,175	10
Inflow (cfs)	0.28	0.29	0.29	0.31	
Overflow (cf)	8	82	75	150	
Overflow (cfs)	0.02	0.09	0.09	0.14	
Underdrain (cf)	101	214	219	325	
Underdrain (cfs)	0.04	0.10	0.08	0.16	
Outflow (cf)	183	296	291	367	
Outflow (cfs)	0.15	0.18	0.18	0.21	
Exfiltration (cf)	191	333	269	851	

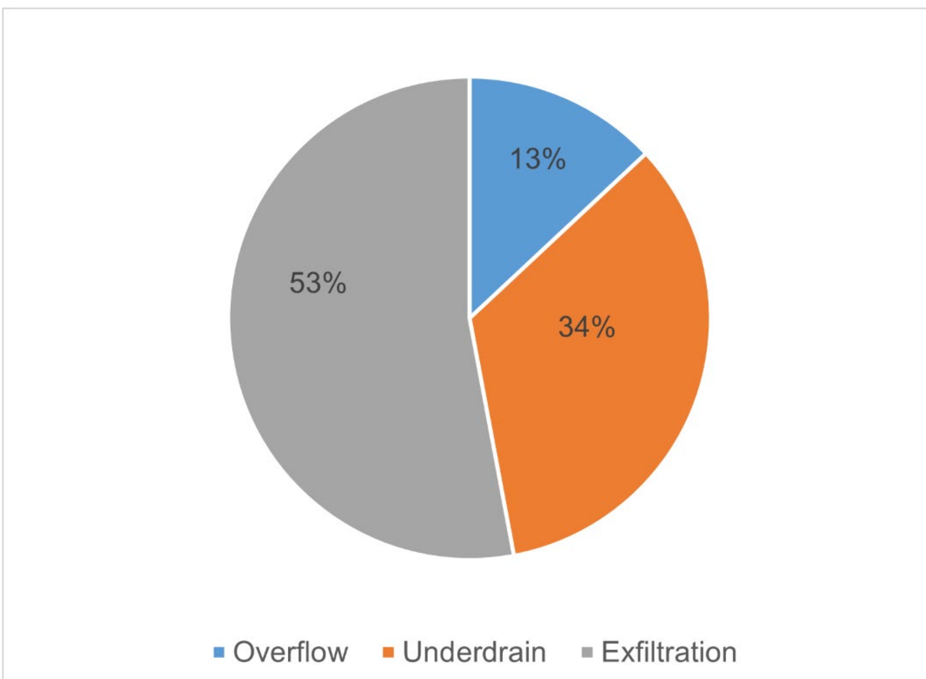

Figure 22. Runoff fates as percentage of total inflow for bioswale #6 without IWS

Table 13 and Figure 23 describe the hydrologic data for bioswale #6 with IWS. The inclusion of IWS increased the amount of overflow from 13 to 24% and decreased exfiltration from 53 to 43%. The slope and length of bioswale #6 (1%, 100 ft; Table 1) most likely dampened the impacts of IWS with respect to exfiltration and overflow.

Table 13. Summary of bioswale #6 with IWS hydrologic data

Parameter	Minimum	Mean	Median	Maximum	Number of trials
Inflow (cf)	562	604	616	651	5
Inflow (cfs)	0.27	0.29	0.29	0.30	
Overflow (cf)	99	142	137	189	
Overflow (cfs)	0.10	0.13	0.13	0.15	
Underdrain[a] (cf)	186	201	200	221	
Underdrain[a] (cfs)	0.03	0.05	0.05	0.08	
Outflow[a] (cf)	307	343	328	380	
Outflow[a] (cfs)	0.16	0.18	0.18	0.19	
Exfiltration (cf)	234	261	266	293	

[a] Discharged from IWS

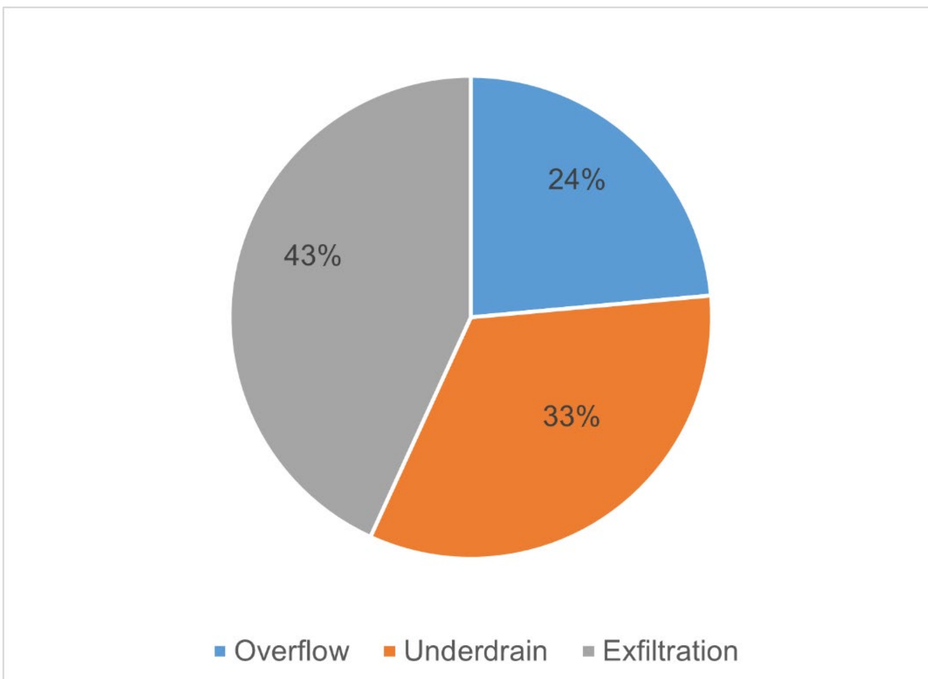

Figure 23. Runoff fates as percentage of total inflow for bioswale #6 with IWS

On average, there was a reduction between inflow and outflow volumes and peak discharges (Table 14). The reduction in volume and peak discharge ranged between 56 and 71% and 15 and 44%, respectively, and the results are similar to values reported for swales studied along the east coast of the United States. Winston et al. (2018) monitored a swale retrofitted with check dams in Knightdale, North Carolina and reported with and without check dams the average volume reduction was 17 and 20%, respectively. The average peak flow reduction with and without check dams was 44 and 48%, respectively. Davis et al. (2012) found swales with check dams in Maryland had an average volume reduction between 27 and 63%. Knight et al. (2013) studied a swale without check dams in Wilson, North Carolina and reported the average volume reduction was 23%. The results from these trials suggest bioswales can provide more volume reduction and peak flow mitigation than swales with and without check dams.

Table 14. Mitigation between inflow and outflow runoff volumes and peak discharges for SECREF bioswales

Swale	Mean Volume Reduction (%)	Median Volume Reduction (%)	Mean Peak Discharge Reduction (%)	Median Peak Discharge Reduction (%)
Bioswale #1 without check dams	26	27	15	0
Bioswale #1 with check dams	47	47	44	43
Bioswale #3 with IWS	42	43	18	19
Bioswale #4 without check dams	71	71	8	24
Bioswale #4 with check dams	33	34	33	34
Bioswale #6 without IWs	51	49	39	39
Bioswale #6 with IWS	43	42	39	40

Table 15 and Table 16 summarize the statistical comparisons between inflow, overflow, underdrain, and outflow runoff volumes and peak discharges, respectively. Except for bioswale #1 with check dams and bioswale #4 with and without check dams, there were significant (α = 0.05) differences between inflow, overflow, underdrain, and outflow volumes and peak discharges. These significant differences along with the average reductions in runoff volumes and peak flow rates (Table 14) suggest bioswales can function as detention practices and be used to meet regulations requiring peak discharge attenuation and/or volume reduction.

Table 15. Statistical comparisons between runoff volumes

Swale	Comparison	Test	p-value[a]
Bioswale #1 without check dams	Inflow versus overflow	Student's t-test	**$1.46*10^{-5}$**
	Inflow versus underdrain		**0.01**
	Inflow versus outflow		**0.02**
Bioswale #1 with check dams	Inflow versus overflow	Sign Test	0.06
	Inflow versus underdrain	Student's t-test	**$1.12*10^{-4}$**
	Inflow versus outflow		**$1.12*10^{-4}$**
Bioswale #3 with IWS	Inflow versus overflow		**$1.45*10^{-11}$**
	Inflow versus underdrain		**$1.47*10^{-11}$**
	Inflow versus outflow		**$7.33*10^{-7}$**
Bioswale #4 without check dams	Inflow versus overflow	Sign Test	0.06
	Inflow versus underdrain	Student's t-test	**$9.38*10^{-5}$**
	Inflow versus outflow		**$2.18*10^{-3}$**
Bioswale #4 with check dams	Inflow versus overflow	Sign Test	0.06
	Inflow versus underdrain	Student's t-test	**$6.05*10^{-3}$**
	Inflow versus outflow		**$6.05*10^{-3}$**
Bioswale #6 without IWs	Inflow versus overflow	Sign Test	**$9.77*10^{-4}$**
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	**$9.77*10^{-4}$**
	Inflow versus outflow		**$9.77*10^{-4}$**
Bioswale #6 with IWS	Inflow versus overflow	Student's t-test	**$2.88*10^{-9}$**
	Inflow versus underdrain		**$1.25*10^{-8}$**
	Inflow versus outflow		**$2.27*10^{-6}$**

[a] Bolded values indicate significance with $\alpha = 0.05$

Table 16. Statistical comparisons of peak flows

Swale	Comparison	Test	p-value[a]
Bioswale #1 without check dams	Inflow versus overflow	Sign Test	0.31
	Inflow versus underdrain	Student's t-test	**$1.0*10^{-3}$**
	Inflow versus outflow		0.74
Bioswale #1 with check dams	Inflow versus overflow		**$2.0*10^{-4}$**
	Inflow versus underdrain		**$1.0*10^{-4}$**
	Inflow versus outflow		**$1.0*10^{-4}$**
Bioswale #3 with IWS	Inflow versus overflow		**$2.95*10^{-5}$**
	Inflow versus underdrain[b]		**$2.84*10^{-13}$**
	Inflow versus outflow[b]		**$2.24*10^{-4}$**
Bioswale #4 without check dams	Inflow versus overflow		**$2.0*10^{-3}$**
	Inflow versus underdrain		0.09
	Inflow versus outflow		0.49
Bioswale #4 with check dams	Inflow versus overflow		**$2.0*10^{-3}$**
	Inflow versus underdrain		**0.02**
	Inflow versus outflow		0.46
Bioswale #6 without IWs	Inflow versus overflow		**$2.0*10^{-8}$**
	Inflow versus underdrain		**$5.18*10^{-8}$**
	Inflow versus outflow		**$1.21*10^{-11}$**
Bioswale #6 with IWS	Inflow versus overflow	Sign Test	**0.03**
	Inflow versus underdrain	Student's t-test	**$6.67*10^{-9}$**
	Inflow versus outflow		**$2.53*10^{-7}$**

[a] Bolded values indicate significance with $\alpha = 0.05$

Objective One: Water Quality

Table 17 and Figure 24 summarize the water quality data for bioswale #3 with IWS. Median inflow TN, TP, and TSS concentrations were 0.79, 1.81, and 43 mg/L, respectively while overflow concentrations were 1.17, 1.87, and 23.5 mg/L, respectively. Underdrain TN, TP, and TSS concentrations were 0.81, 1.48, and 18.2 mg/L, respectively. Regier & McDonald (2022) found the median effluent TN, TP, and TSS concentrations for two urban farm bioswales ranged from 0.83 and 4.53, 0.12 and 0.46, and 25.7 and 68.6 mg/L, respectively. Xiao & McPherson (2011) studied a bioswale in Davis, California and found effluent TP concentrations were between 0.20 and 1.90 mg/L. The median TN, TP, and TSS concentrations from bioswale #3 with IWS are within the ranges reported by Regier & McDonald (2022) and Xiao & McPherson (2011). Shetty et al. (2019) monitored seven bioswales throughout Bronx, New York and determined the bioswales leached TP but that leaching decreased over time. It is possible the high TP concentrations discharged from bioswale #3 were a result of leaching and that effluent concentrations would decrease over time as more trials were conducted. It is also possible the bioswale exported pollutants because of the resuspension and mobilization of unbound pollutants (Bäckström, 2003; Luell et al., 2021; Stagge et al., 2012)

Table 17. Summary of bioswale #3 with IWS water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.55	0.68	0.66	0.82	8
$NO_{2,3}$ -N (mg/L)	0.09	0.13	0.13	0.21	8
TN (mg/L)	0.68	0.81	0.79	1.01	7
TP (mg/L)	1.44	1.81	1.81	2.20	9
O-PO_4^{3-} (mg/L)	1.41	1.76	1.74	2.22	9
TSS (mg/L)	21.0	43.0	43.0	58.0	9
Total Cd (µg/L)	5.40	7.13	7.10	10.0	9
Total Cu (µg/L)	7.90	10.1	9.90	16.0	9
Total Pb (µg/L)	8.20	13.2	12.0	22.0	9
Total Zn (µg/L)	24	31.6	29.0	43.0	9
Overflow					
TKN (mg/L)	0.61	0.89	0.89	1.16	8
$NO_{2,3}$ -N (mg/L)	0.16	0.22	0.23	0.27	8
TN (mg/L)	0.78	1.12	1.17	1.43	7
TP (mg/L)	1.68	1.86	1.87	2.01	9
O-PO_4^{3-} (mg/L)	1.55	1.81	1.85	1.97	9
TSS (mg/L)	17.1	25.8	23.5	41.7	9
Total Cd (µg/L)	0.87	2.27	2.00	4.10	9
Total Cu (µg/L)	9.10	14.8	15.0	22.0	9
Total Pb (µg/L)	5.60	9.69	7.90	18.0	9
Total Zn (µg/L)	13.0	21.1	20.0	32.0	9
Underdrain					
TKN (mg/L)	0.57	0.78	0.71	1.16	8
$NO_{2,3}$ -N (mg/L)	0.11	0.14	0.14	0.18	8
TN (mg/L)	0.68	0.94	0.81	1.34	7
TP (mg/L)	1.29	1.46	1.48	1.59	9
O-PO_4^{3-} (mg/L)	1.00	1.35	1.37	1.67	9
TSS (mg/L)	8.09	23.8	18.2	45.3	9
Total Cd (µg/L)	0.56	0.81	0.75	1.20	4
Total Cu (µg/L)	7.90	12.2	11.0	27.0	9
Total Pb (µg/L)	5.60	6.87	6.50	8.90	9
Total Zn (µg/L)	11.0	20.0	14.0	35.0	3
Outflow					
TKN (mg/L)	0.60	0.86	0.83	1.12	8
$NO_{2,3}$ -N (mg/L)	0.15	0.20	0.20	0.24	8
TN (mg/L)	0.76	1.06	1.04	1.36	7
TP (mg/L)	1.57	1.74	1.74	1.84	9
O-PO_4^{3-} (mg/L)	1.41	1.66	1.67	1.90	9
TSS (mg/L)	14.9	25.7	24.4	39.9	9
Total Cd (µg/L)	0.87	2.03	1.90	3.50	9
Total Cu (µg/L)	9.02	14.0	13.6	23.9	9
Total Pb (µg/L)	5.86	9.08	7.28	16.1	9
Total Zn (µg/L)	13.0	20.3	20.0	25.8	9

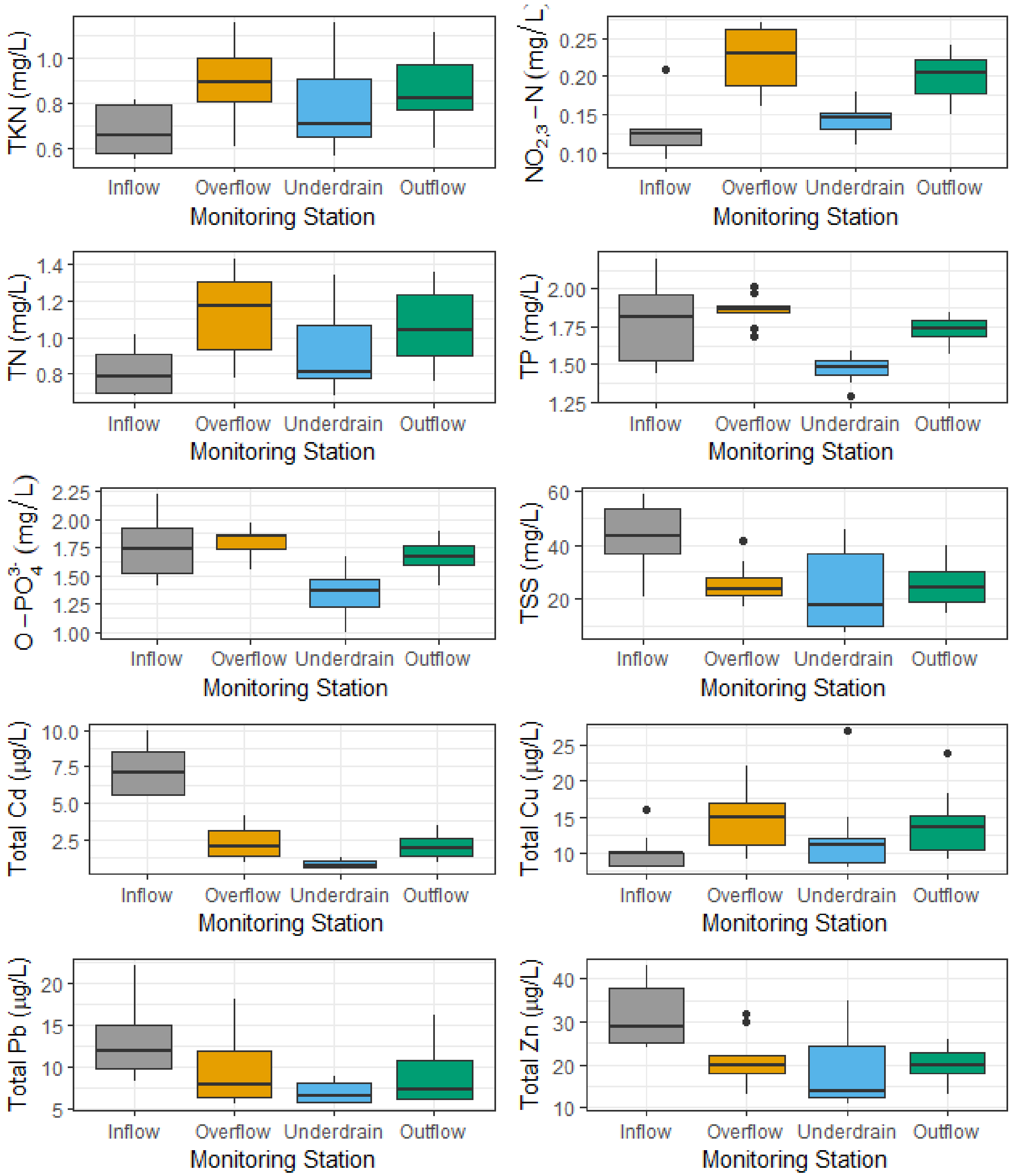

Figure 24. Boxplots of bioswale #3 with IWS water quality data

At least eight PSD samples were collected from each monitoring station (Table 18). The median d_{50} particle sizes for inflow, overflow, underdrain, and outflow volumes were 3.36, 3.06, 2.85, and 3.04 µm, respectively. The sediment used to simulate runoff from the highway was less coarse than values reported by previous studies monitoring roadways. Winston & Hunt

(2017) monitored nine catch basins draining roads maintained by the North Carolina Department of Transportation (NCDOT) for PSD and found the median d_{50} ranged from 32 to 167 µm. Across Ohio roadways, the median d_{50} from 176 sampled storm events was 52.5 µm (Winston et al., 2023). Most of the particles in the samples were dominated by silt (2 to 50 µm) supporting the possibility that pollutant removal was limited due to the resuspension of particles (Bäckström, 2003; Luell et al., 2021; Stagge et al., 2012). Deletic (1999) simulated storm events with a vegetated filter strip using runoff with a median d_{50} of 50 µm and reported the trapping efficiency of the filter strip improved with particles 60 µm or larger. Bäckström et al. (2006) determined a swale in Sweden effectively trapped particles larger than 25 µm for most storm events.

Table 18. Summary of bioswale #3 with IWS PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.10	0.10	0.10	0.11	9
d_{50} (µm)	3.06	3.85	3.36	5.36	
d_{90} (µm)	98.4	153	116	270	
Clay (%)	3.71	5.15	4.99	7.09	
Silt (%)	53.4	65.6	70.8	73.4	
Sand (%)	21.4	29.2	24.2	42.4	
Overflow					
d_{10} (µm)	0.09	0.10	0.10	0.10	8
d_{50} (µm)	2.79	3.11	3.06	3.52	
d_{90} (µm)	83.1	101	98.4	127	
Clay (%)	4.97	7.00	6.44	9.00	
Silt (%)	75.3	79.8	80.3	83.9	
Sand (%)	7.55	13.2	12.4	19.7	
Underdrain					
d_{10} (µm)	0.09	0.09	0.09	0.10	8
d_{50} (µm)	1.83	2.75	2.85	3.06	
d_{90} (µm)	39.1	82.4	86.8	98.4	
Clay (%)	5.65	8.16	7.86	11.6	
Silt (%)	81.7	83.8	83.6	86.4	
Sand (%)	5.22	8.01	7.32	12.6	
Outflow					
d_{10} (µm)	0.09	0.09	0.10	0.10	8
d_{50} (µm)	2.79	3.03	3.04	3.22	
d_{90} (µm)	83.1	97.2	97.0	109	
Clay (%)	5.99	7.30	6.75	9.10	
Silt (%)	77.4	80.8	81.4	84.2	
Sand (%)	7.41	11.9	11.9	15.8	

Median outflow TN, TP, and TSS concentrations for bioswale #6 without IWS were 0.81, 1.52, and 25.4 mg/L, respectively (Table 19; Figure 25). These median concentrations are within the ranges reported by Regier & McDonald (2022) and Xiao & McPherson (2011). The TN and TSS concentrations are comparable to swales without check dams or IWS. Stagge et al. (2012) monitored a swale in Savage, Maryland and reported the effluent TN, TP, and TSS concentrations ranged from 0 to 12.7, 0 to 1.20, and 0 to 31.7 mg/L, respectively. Knight et al. (2013) found the median TN, TP, and TSS concentrations from a swale in Wilson, North Carolina were 1.02, 0.17, and 10 mg/L, respectively. Luell et al. (2021) studied a swale without check dams treating highway runoff in Knightdale, North Carolina and found the mean effluent TN, TP, and TSS concentrations were 0.99, 0.16, and 39 mg/L, respectively.

Table 19. Summary of bioswale #6 without IWS water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
			Inflow		
TKN (mg/L)	0.55	0.71	0.71	0.95	9
$NO_{2,3}$ -N (mg/L)	0.11	0.13	0.13	0.15	9
TN (mg/L)	0.69	0.83	0.83	1.06	8
TP (mg/L)	1.39	1.82	1.82	2.19	10
O-PO_4^{3-} (mg/L)	1.16	1.74	1.76	2.16	10
TSS (mg/L)	20.5	39.6	40.6	53.6	10
Total Cd (µg/L)	4.50	7.55	7.70	9.40	10
Total Cu (µg/L)	8.20	10.3	9.65	12.0	10
Total Pb (µg/L)	8.00	12.3	12.5	18.0	10
Total Zn (µg/L)	23.0	31.4	29.5	45.0	10
			Overflow		
TKN (mg/L)	0.57	0.70	0.70	0.83	8
$NO_{2,3}$ -N (mg/L)	0.12	0.14	0.14	0.17	8
TN (mg/L)	0.68	0.83	0.82	0.97	7
TP (mg/L)	1.81	2.04	2.05	2.30	9
O-PO_4^{3-} (mg/L)	1.86	2.07	2.06	2.34	9
TSS (mg/L)	16.5	25.7	28.2	31.0	9
Total Cd (µg/L)	2.20	5.14	4.00	9.10	9
Total Cu (µg/L)	8.40	12.5	12.0	18.0	9
Total Pb (µg/L)	4.60	12.0	11.0	21.0	9
Total Zn (µg/L)	14.0	21.8	19.0	33.0	9
			Underdrain		
TKN (mg/L)	0.46	0.72	0.78	0.95	9
$NO_{2,3}$ -N (mg/L)	0.09	0.12	0.11	0.17	9
TN (mg/L)	0.56	0.83	0.78	1.12	8
TP (mg/L)	1.09	1.36	1.36	1.58	10
O-PO_4^{3-} (mg/L)	1.02	1.29	1.28	1.46	10
TSS (mg/L)	5.15	27.9	24.8	58.1	10
Total Cd (µg/L)	1.10	2.13	1.50	3.80	3
Total Cu (µg/L)	6.80	17.7	12.5	43.0	10
Total Pb (µg/L)	3.50	7.22	5.75	21.0	10
Total Zn (µg/L)	14.0	55.8	20.5	220	6
			Outflow		
TKN (mg/L)	0.55	0.73	0.78	0.95	9
$NO_{2,3}$ -N (mg/L)	0.11	0.13	0.13	0.17	9
TN (mg/L)	0.67	0.85	0.81	0.12	8
TP (mg/L)	1.47	1.55	1.52	1.72	10
O-PO_4^{3-} (mg/L)	1.27	1.49	1.49	1.72	10
TSS (mg/L)	11.2	29.9	25.4	58.1	10
Total Cd (µg/L)	1.76	4.45	3.85	9.10	10
Total Cu (µg/L)	7.55	16.9	12.3	43.0	10
Total Pb (µg/L)	5.49	9.24	7.93	21.0	10
Total Zn (µg/L)	14.0	43.5	23.4	220	10

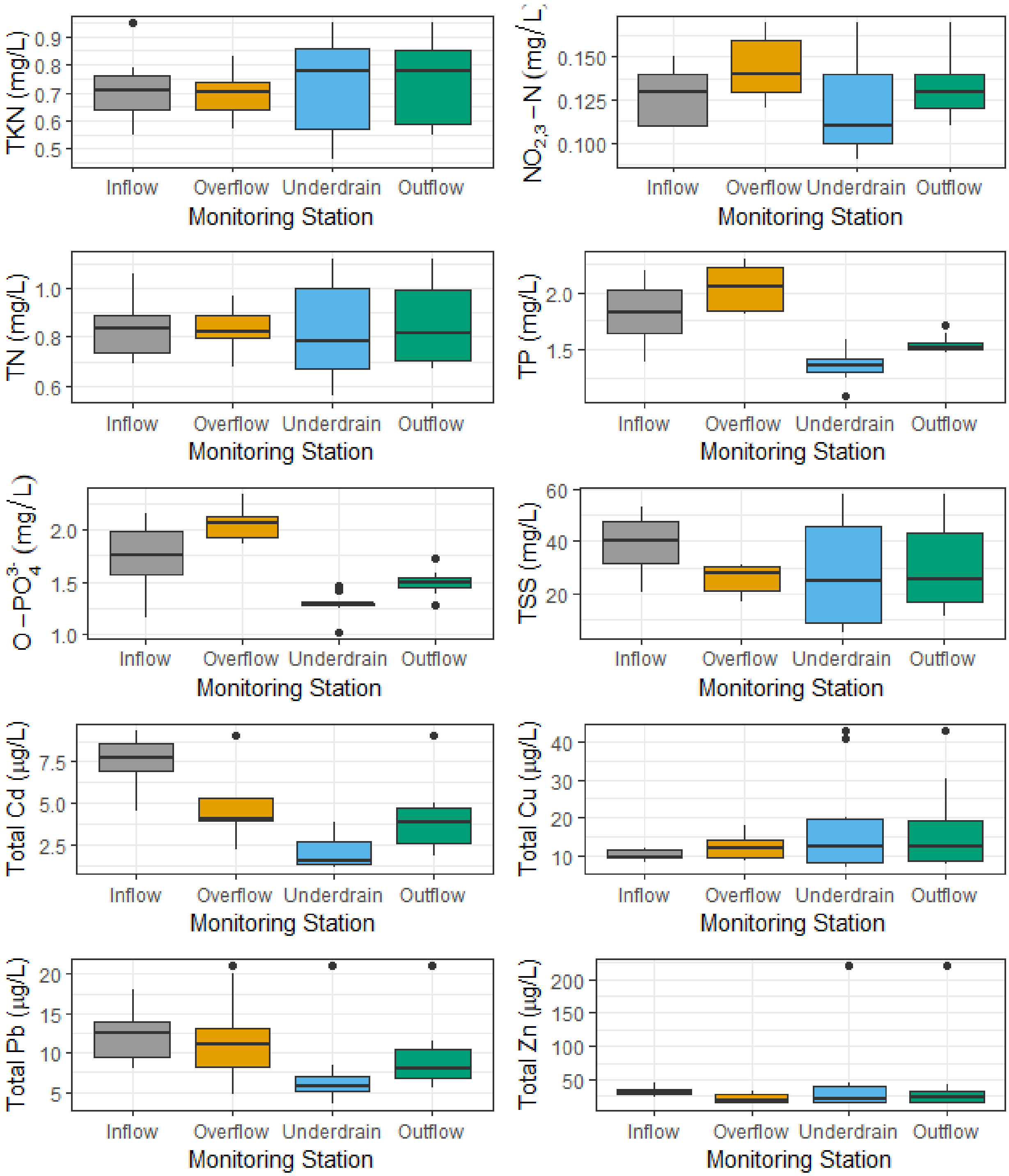

Figure 25. Boxplots of bioswale #6 without IWS water quality data

Between eight and 10 PSDs samples were collected for bioswale #6 without IWS (Table 20). Similar to bioswale #3 with IWS, the median d_{50} for inflow, overflow, underdrain, and outflow volumes were 3.36, 2.92, 2.54, and 2.71 µm, respectively.

Table 20. Summary of bioswale #6 without IWS PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.10				10
d_{50} (µm)	3.06	3.62	3.36	4.66	
d_{90} (µm)	98.4	135	116	209	
Clay (%)	2.74	4.81	4.70	6.26	
Silt (%)	48.6	65.4	67.8	72.9	
Sand (%)	21.6	29.8	27.6	48.6	
Overflow					
d_{10} (µm)	0.09	0.09	0.09	0.10	8
d_{50} (µm)	2.79	2.96	2.92	3.06	
d_{90} (µm)	83.1	92.5	90.5	98.4	
Clay (%)	4.08	5.41	4.80	7.56	
Silt (%)	69.8	75.6	75.5	81.9	
Sand (%)	10.5	19.0	20.0	26.2	
Underdrain					
d_{10} (µm)	0.09	0.09	0.09	0.11	9
d_{50} (µm)	1.75	2.43	2.54	3.06	
d_{90} (µm)	35.9	66.9	70.3	98.4	
Clay (%)	6.49	11.0	11.6	14.5	
Silt (%)	78.4	82.8	82.6	85.2	
Sand (%)	2.18	6.19	6.11	11.0	
Outflow					
d_{10} (µm)	0.09	0.09	0.09	0.11	10
d_{50} (µm)	1.92	2.58	2.71	3.03	
d_{90} (µm)	42.5	74.0	78.9	96.6	
Clay (%)	4.39	9.34	8.93	14.5	
Silt (%)	75.0	80.6	81.5	82.5	
Sand (%)	3.41	10.0	9.72	20.6	

Table 21 and Figure 26 summarize the water quality data for bioswale #6 with IWS. The outflow TN concentrations ranged from 0.80 to 0.93 and outflow TP concentrations varied between 1.55 and 1.71 mg/L, respectively. TSS concentrations were between 8.65 and 25.8 mg/L. Despite the inclusion of IWS, which typically improves nitrogen removal (Brown & Hunt, 2011; M.-H. Li et al., 2014), these concentrations are similar to the effluent water quality from bioswale #6 without IWS. It is possible the IWS retrofit did not improve nitrogen removal due to the runoff's short hydraulic retention time in the bioswale (less than three hours). Previous research has shown nitrogen removal improves with increasing hydraulic retention time (Brown & Hunt, 2011; Igielski et al., 2019; Martin et al., 2019).

Table 21. Summary of bioswale #6 with IWS water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.53	0.70	0.69	0.92	5
$NO_{2,3}$ -N (mg/L)	0.23	0.29	0.30	0.34	5
TN (mg/L)	0.87	0.99	0.93	1.17	5
TP (mg/L)	1.58	1.88	1.73	2.45	5
O-PO_4^{3-} (mg/L)	1.65	1.89	1.76	2.40	5
TSS (mg/L)	30.8	41.6	37.2	57.6	5
Total Cd (µg/L)	7.20	9.55	10.0	11.0	4
Total Cu (µg/L)	11.0	13.0	12.0	17.0	4
Total Pb (µg/L)	14.0	16.8	16.5	20.0	4
Total Zn (µg/L)	32.0	37.5	36.0	46.0	4
Overflow					
TKN (mg/L)	0.55	0.70	0.69	0.88	5
$NO_{2,3}$ -N (mg/L)	0.25	0.30	0.29	0.35	5
TN (mg/L)	0.90	1.00	1.01	1.14	5
TP (mg/L)	1.88	2.00	1.97	2.10	5
O-PO_4^{3-} (mg/L)	1.92	2.06	2.05	2.25	5
TSS (mg/L)	15.7	24.5	25.8	29.7	5
Total Cd (µg/L)	3.90	6.14	4.70	11.0	5
Total Cu (µg/L)	9.10	11.4	12.0	12.0	5
Total Pb (µg/L)	14.0	16.4	16.0	19.0	5
Total Zn (µg/L)	21.0	28.0	29.0	33.0	5
Underdrain					
TKN (mg/L)	0.46	0.53	0.47	0.72	5
$NO_{2,3}$ -N (mg/L)	0.17	0.23	0.25	0.28	5
TN (mg/L)	0.63	0.76	0.74	0.92	5
TP (mg/L)	1.27	1.37	1.31	1.52	5
O-PO_4^{3-} (mg/L)	1.28	1.39	1.38	1.55	5
TSS (mg/L)	4.13	7.16	5.32	13.9	4
Total Cd (µg/L)[a]	-				
Total Cu (µg/L)	4.70	6.00	5.50	8.20	5
Total Pb (µg/L)	4.30	5.02	5.20	5.90	5
Total Zn (µg/L)[a]	-				
Outflow					
TKN (mg/L)	0.50	0.61	0.62	0.71	5
$NO_{2,3}$ -N (mg/L)	0.21	0.26	0.27	0.31	
TN (mg/L)	0.80	0.87	0.89	0.93	
TP (mg/L)	1.55	1.63	1.63	1.71	
O-PO_4^{3-} (mg/L)	1.55	1.67	1.69	1.74	
TSS (mg/L)	8.65	16.2	14.8	25.8	
Total Cd (µg/L)	3.90	6.14	4.70	11.0	
Total Cu (µg/L)	6.89	8.28	8.35	9.42	
Total Pb (µg/L)	9.15	9.66	9.47	10.6	
Total Zn (µg/L)	21.0	28.0	29.0	33.0	

[a] Samples below PQL

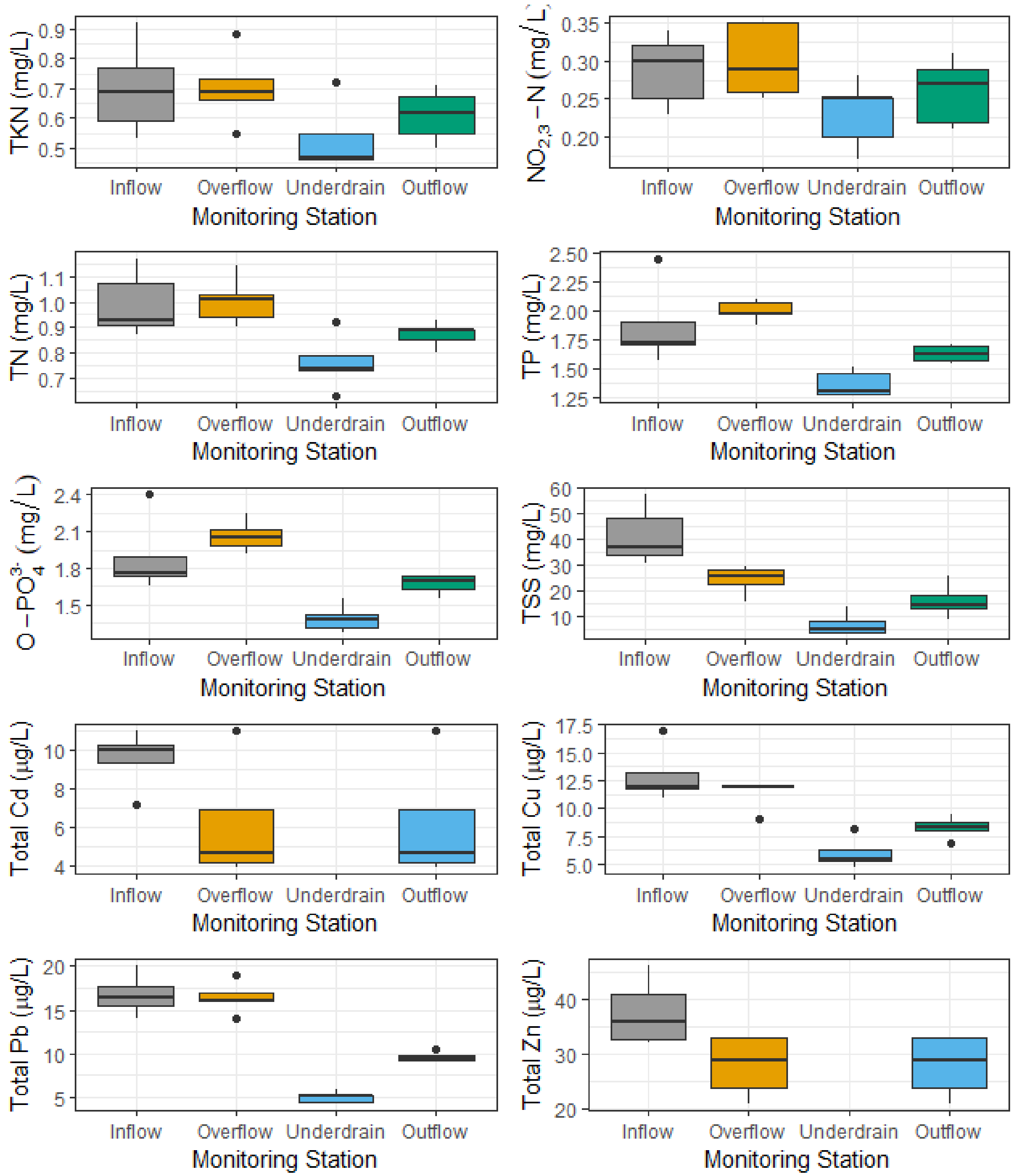

Figure 26. Boxplots of bioswale #6 with IWS water quality data

Five PSD samples were collected from each monitoring station for bioswale #6 with IWS (Table 22). The median percentage of silt comprising the inflow, overflow, underdrain, and outflow volumes were 55.9, 75.0, 83.0, and 80.3%, respectively. The percentage of clay and sand particles in the samples ranged from 4.74 to 7.77% and from 5.95 to 37.9%, respectively.

Table 22. Summary of bioswale #6 with IWS PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.10	0.10	0.10	0.11	5
d_{50} (µm)	3.36	4.60	3.86	6.46	
d_{90} (µm)	116	215	150	377	
Clay (%)	4.16	5.09	4.74	6.20	
Silt (%)	51.2	56.7	55.9	64.1	
Sand (%)	29.9	38.2	37.9	44.6	
Overflow					
d_{10} (µm)	0.09	0.09	0.09	0.10	5
d_{50} (µm)	2.92	2.98	2.92	3.06	
d_{90} (µm)	90.5	93.6	90.5	98.4	
Clay (%)	5.14	6.60	6.83	8.12	
Silt (%)	69.7	75.0	75.0	81.1	
Sand (%)	12.1	18.5	19.9	23.0	
Underdrain					
d_{10} (µm)	0.09	0.09	0.09	0.10	5
d_{50} (µm)	2.66	2.87	2.92	3.06	
d_{90} (µm)	76.4	87.8	90.5	98.4	
Clay (%)	7.07	9.13	7.77	15.8	
Silt (%)	78.3	84.0	83.0	88.0	
Sand (%)	4.72	6.92	5.95	9.25	
Outflow					
d_{10} (µm)	0.09				5
d_{50} (µm)	2.79	2.92	2.92	3.00	
d_{90} (µm)	83.4	90.4	90.5	95.0	
Clay (%)	6.32	8.07	7.47	12.2	
Silt (%)	74.6	80.0	80.3	82.6	
Sand (%)	10.2	11.9	11.8	13.4	

Bioswale #3 with IWS had the most significant differences between pollutant concentrations (Table 23). This is most likely due to overflow, underdrain, and outflow concentrations exceeding inflow concentrations (Table 17; Figure 24). Regardless of the underdrain configuration, there were minimal significant differences between concentrations for bioswale #6 (Tables 24 and 25). A lack of significant differences could be the result of the short hydraulic retention time and/or the resuspension of pollutants (Bäckström, 2003; Igielski et al., 2019; M.-H. Li et al., 2014; Luell et al., 2021; Martin et al., 2019; Stagge et al., 2012).

Table 23. Comparisons between pollutant concentrations for bioswale #3 with IWS

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Student's t-test	**0.01**
	Inflow versus underdrain		0.27
	Inflow versus outflow		**0.03**
TP	Inflow versus overflow		0.63
	Inflow versus underdrain		**0.01**
	Inflow versus outflow		0.49
TSS	Inflow versus overflow		**$3.0*10^{-3}$**
	Inflow versus underdrain		**0.01**
	Inflow versus outflow		**$3.0*10^{-3}$**
TKN	Inflow versus overflow		**0.02**
	Inflow versus underdrain		0.21
	Inflow versus outflow		**0.04**
$NO_{2,3}$ -N	Inflow versus overflow		**$4.0*10^{-4}$**
	Inflow versus underdrain		0.30
	Inflow versus outflow		**$1.0*10^{-3}$**
O-PO_4^{3-}	Inflow versus overflow		0.66
	Inflow versus underdrain		**$4.0*10^{-3}$**
	Inflow versus outflow		0.40
Total Cd	Inflow versus overflow		**$2.0*10^{-3}$**
	Inflow versus underdrain		**$3.0*10^{-3}$**
	Inflow versus outflow		**$1.0*10^{-3}$**
Total Cu	Inflow versus overflow		**0.01**
	Inflow versus underdrain		0.35
	Inflow versus outflow		**0.04**
Total Pb	Inflow versus overflow		0.15
	Inflow versus underdrain	Sign Test	**$2.0*10^{-3}$**
	Inflow versus outflow	Student's t-test	0.07
Total Zn	Inflow versus overflow		0.15
	Inflow versus underdrain		0.13
	Inflow versus outflow		0.05

[a] Bolded values indicate significance with $\alpha = 0.05$

Table 24. Comparisons between pollutant concentrations for bioswale #6

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Student's t-test	0.52
	Inflow versus underdrain		0.93
	Inflow versus outflow		0.82
TP	Inflow versus overflow		0.13
	Inflow versus underdrain		**$4.0*10^{-4}$**
	Inflow versus outflow		**0.01**
TSS	Inflow versus overflow		**$1.0*10^{-3}$**
	Inflow versus underdrain		0.14
	Inflow versus outflow		0.16
TKN	Inflow versus overflow		0.61
	Inflow versus underdrain		0.85
	Inflow versus outflow		0.71
$NO_{2,3}$ -N	Inflow versus overflow		0.15
	Inflow versus underdrain		0.36
	Inflow versus outflow	Wilcoxon Signed-Rank Test	0.46
$O\text{-}PO_4^{3-}$	Inflow versus overflow	Student's t-test	**0.02**
	Inflow versus underdrain		**$1.0*10^{-3}$**
	Inflow versus outflow		**0.04**
Total Cd	Inflow versus overflow[b]	-	-
	Inflow versus underdrain	Student's t-test	**$1.0*10^{-4}$**
	Inflow versus outflow	Sign Test	0.06
Total Cu	Inflow versus overflow	Student's t-test	0.08
	Inflow versus underdrain	Sign Test	0.83
	Inflow versus outflow	Wilcoxon Signed-Rank Test	0.97
Total Pb	Inflow versus overflow	Student's t-test	0.98
	Inflow versus underdrain		**0.02**
	Inflow versus outflow		0.11
Total Zn	Inflow versus overflow		**0.01**
	Inflow versus underdrain	Sign Test	0.34
	Inflow versus outflow		0.09

[a] Bolded values indicate significance with α = 0.05
[b] Sample size too small to run statistical analyses

Table 25. Comparisons between pollutant concentrations for bioswale #6 with IWS

Pollutant	**Comparison**	**Test**	**p-value[a]**
TN	Inflow versus overflow	Student's t-test	0.85
	Inflow versus underdrain		**0.01**
	Inflow versus outflow		0.09
TP	Inflow versus overflow	Sign Test	0.97
	Inflow versus underdrain		**0.03**
	Inflow versus outflow		**0.03**
TSS	Inflow versus overflow	Student's t-test	**0.02**
	Inflow versus underdrain	-	-
	Inflow versus outflow	Student's t-test	**$2.0*10^{-3}$**
TKN	Inflow versus overflow		0.98
	Inflow versus underdrain	-	-
	Inflow versus outflow	Student's t-test	0.29
$NO_{2,3}$ -N	Inflow versus overflow		0.70
	Inflow versus underdrain	-	-
	Inflow versus outflow	Student's t-test	0.36
$O\text{-}PO_4^{3-}$	Inflow versus overflow		0.26
	Inflow versus underdrain	Sign Test	**0.03**
	Inflow versus outflow		**0.03**
Total Cd	Inflow versus overflow	Student's t-test	0.08
	Inflow versus underdrain	-	-
	Inflow versus outflow	Student's t-test	0.08
Total Cu	Inflow versus overflow		0.28
	Inflow versus underdrain		**$4.0*10^{-3}$**
	Inflow versus outflow		**0.01**
Total Pb	Inflow versus overflow		0.81
	Inflow versus underdrain		**$1.0*10^{-4}$**
	Inflow versus outflow		**$1.0*10^{-3}$**
Total Zn	Inflow versus overflow		0.05
	Inflow versus underdrain	-	-
	Inflow versus outflow	Student's t-test	0.05

[a] Bolded values indicate significance with α = 0.05
[b] Sample size too small to run statistical analyses

Objective Two: Hydrology

For BS2, a total of 61 storm events were monitored from March 2017 to April 2018 (Table 26). The average rainfall depth and maximum 5-min intensity was 0.67 in and 1.03 in/hr, respectively. The antecedent dry period ranged from 0.30 to 37 days during the monitoring period.

Table 26. Summary of BS2 storm event characteristics

Parameter	Minimum	Mean	Median	Maximum	Number of monitored storms
Depth (in)	0.12	0.67	0.42	5.27	61
Maximum 5-minute intensity (in/hr)	0.12	1.03	0.69	4.68	
Average intensity (in/hr)	$3.33*10^{-3}$	0.11	0.05	0.72	
Duration (hr)	0.87	11	6.6	36	
Antecedent dry period (days)	0.30	6.7	4.3	37	

Table 27 and Figure 27 summarize the hydrologic data for BS2. Overflow volumes ranged from 0 to 15,028 cf while exfiltration volumes varied between 0 and 4,881 cf. Overflow, underdrain flow, and exfiltration accounted for 42, 31, and 27% of the total inflow, respectively. The volume reduction provided by exfiltration is similar to results reported by Davis et al. (2012) Knight et al. (2013) and Winston et al. (2018) for swales with and without check dams.

Table 27. Summary of BS2 hydrologic data

Parameter	Minimum	Mean	Median	Maximum
Inflow (cf)	0	1,485	554	21,114
Inflow (cfs)	0	0.32	0.10	1.83
Overflow (cf)	0	631	1	15,028
Overflow (cfs)	0	0.14	0	1.43
Underdrain (cf)	0	455	213	4,048
Underdrain (cfs)	0	0.04	0.03	0.24
Outflow (cf)	0	1,087	476	19,076
Outflow (cfs)	0	0.17	0.04	1.51
Exfiltration (cf)	0	405	97	4,881

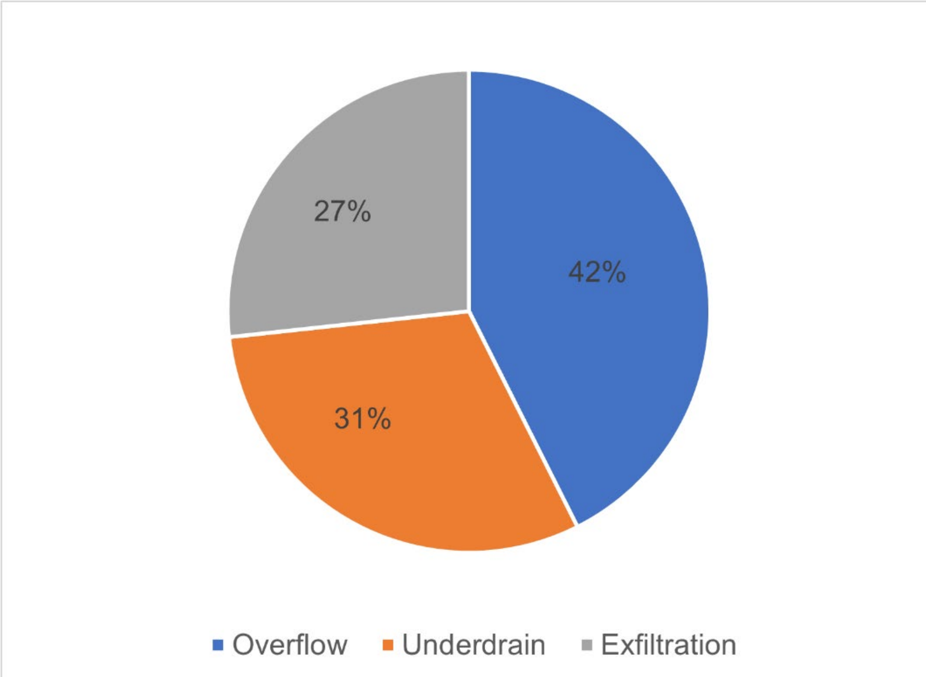

Figure 27. Runoff fates as percentage of total inflow for BS2

Both Davis et al. (2012) and Winston et al. (2018) reported volume reduction or exfiltration provided by swales with and without check dams with respect to storm size. Table 28 summarizes the percentage of exfiltration that occurred for small (< 0.75 in), moderate (0.75 to 1.50 in), and large (> 1.50 in) storm events (Winston et al., 2018). On average, BS2 reduced the runoff volume by 48% for small storms and 27% for moderate events. Winston et al. (2018) found a swale with and without check dams reduced runoff by 53 and 28%, respectively for small storms and 22 and 13% for moderate events, respectively. Davis et al. (2012) reported for moderate storms (0.91 to 1.30 in) swales with and without check dams reduced runoff by 63 and 27%, respectively. These results suggest bioswales can be as effective if not more as swales with check dams.

Table 28. Exfiltration as a percentage of inflow per storm event for BS2

Parameter/Storm size	**Small (< 0.75 in)**	**Moderate (0.75 to 1.50 in)**	**Large (>1.50 in)**
Minimum (%)	0	4	10
Mean (%)	48	27	35
Median (%)	43	26	18
Maximum (%)	100	62	77
Number of storms with estimated exfiltration	16	13	3

For BS4, 53 storm events were monitored from June 2017 to April 2018 (Table 29). The average rainfall depth was 0.62 in, and the average duration of storms was almost 8.5 hr. The average intensity of events was between 0.01 and 1.71 in/hr.

Table 29. Summary of BS4 storm event characteristics

Parameter	Minimum	Mean	Median	Maximum	Number of monitored storms
Depth (in)	0.12	0.62	0.44	2.79	53
Maximum 5-minute intensity (in/hr)	0.12	1.29	0.84	4.68	
Average intensity (in/hr)	0.01	0.19	0.06	1.71	
Duration (hr)	0.23	8.40	5.57	35.8	
Antecedent dry period (days)	0.34	5.97	4.32	36.4	

Table 30 and Figure 28 provide a summary of the hydrologic data for BS4. Inflow, overflow, underdrain flow, outflow, and exfiltration ranged from 84 to 11,986, 0 to 1,624, 0 to 935, 0 to 2,169, and 4 to 11,126 cf, respectively. Approximately 75% of the total inflow was exfiltrated and only 10% of the total inflow left the bioswale through the underdrain. Differences between the amount of runoff exfiltrated by BS2 and BS4 was most likely due to the bioswales' drainage area to surface area loading ratios (Table 4). BS2's loading ratio (130:1) was nearly twice as large as BS4's loading ratio (72:1). It is also possible BS4 exfiltrated more than BS2 because BS4 had an additional check dam, a forebay to store and slow down runoff, and less inflow (65,337 cf versus 55,669 cf).

Table 30. Summary of BS4 hydrologic data

Parameter	Minimum	Mean	Median	Maximum
Inflow (cf)	84	1,336	400	11,986
Inflow (cfs)	0.06	0.68	0.44	2.45
Overflow (cf)	0	180	0	1,624
Overflow (cfs)	0	0.11	0	2.23
Underdrain[a] (cf)	0	113	0	935
Underdrain[a] (cfs)	0	0.01	0	0.10
Outflow[a] (cf)	0	284	3	2,169
Outflow[a] (cfs)	0	0.12	0.01	2.23
Exfiltration (cf)	4	843	196	11,126

[a] Discharged from IWS

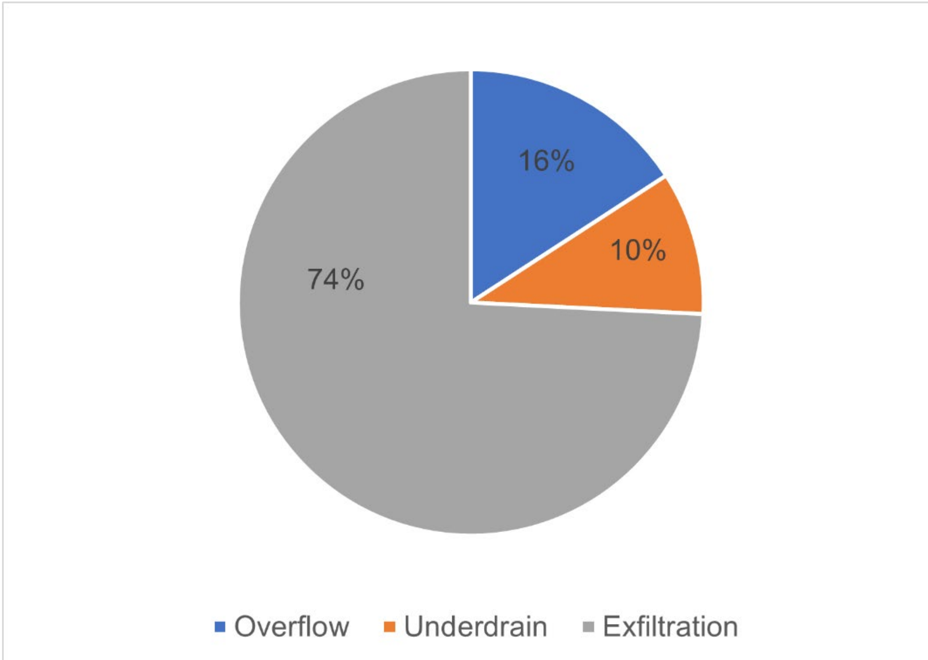

Figure 28. Runoff fates as percentage of total inflow for BS4

Thirty-five storm events were considered small (< 0.75 in) (Table 31). On average, BS4 reduced small and moderate storms by 85 and 67%, respectively. These results further suggest that bioswales with check dams are more effective than swales with check dams at reducing runoff volumes, especially for small and moderate events.

Table 31. Exfiltration as a percentage of inflow per storm event for BS4

Parameter/Storm size	Small (< 0.75 in)	Moderate (0.75 to 1.50 in)	Large (>1.50 in)
Minimum (%)	4	23	93
Mean (%)	85	67	
Median (%)	100	62	
Maximum (%)	100	100	
Number of storms with estimated exfiltration	35	13	1

The average volume reduction (inflow versus outflow) was 55 and 81% for BS2 and BS4, respectively while the peak flow reduction was 59 and 88%, respectively (Table 32). These reductions are larger than the average reductions in volume and peak discharge reported by Knight et al. (2013) and Winston et al. (2018) for swales with and without check dams in North Carolina. There were also significant differences between inflow, overflow, underdrain, and outflow volumes (Table 33) and peak flow rates (Table 34). These results suggest that bioswales with check dams can function as detention devices.

Table 32. Mitigation between inflow and outflow runoff volumes and peak discharges for 50-98 bioswales

Swale	Mean Volume Reduction (%)	Median Volume Reduction (%)	Mean Peak Discharge Reduction (%)	Median Peak Discharge Reduction (%)
BS2	55	55	59	72
BS4	81	99	88	100

Table 33. Comparisons between runoff volumes for 50-98 bioswales

Swale	Comparison	Test	p-value[a]
BS2	Inflow versus overflow	Wilcoxon Sign Rank Test	**$4.66*10^{-10}$**
	Inflow versus underdrain	Sign Test	**$4.66*10^{-10}$**
	Inflow versus outflow		**$4.66*10^{-10}$**
BS4	Inflow versus overflow		**$1.67*10^{-15}$**
	Inflow versus underdrain		**$1.67*10^{-15}$**
	Inflow versus outflow		**$1.67*10^{-15}$**

[a] Bolded values indicate significance with α = 0.05

Table 34. Comparisons between peak discharges for 50-98 bioswales

Swale	Comparison	Test	p-value[a]
BS2	Inflow versus overflow	Sign Test	**$1.86*10^{-9}$**
	Inflow versus underdrain		**$3.73*10^{-9}$**
	Inflow versus outflow		**$2.09*10^{-7}$**
BS4	Inflow versus overflow		**$1.31*10^{-12}$**
	Inflow versus underdrain		**$2.90*10^{-14}$**
	Inflow versus outflow		**$2.90*10^{-14}$**

[a] Bolded values indicate significance with α = 0.05

Objective Two: Water Quality

Median TN inflow, overflow, underdrain, and outflow concentrations for BS2 were 0.83, 0.83, 0.68, and 0.77 mg/L, respectively while median TP concentrations were 0.14, 0.14, 0.12, and 0.13, respectively (Table 35; Figure 29). Median TSS inflow, overflow, underdrain, and outflow concentrations were 27.0, 21.0, 10.0, and 13.0 mg/L, respectively. The median outflow concentrations are less than the concentrations reported by Regier & McDonald (2022) and Xiao & McPherson (2011) for bioswales without IWS and check dams. Stagge et al. (2012) found that a swale with check dams had average TN, TP, and TSS outflow concentrations of 4.80, 0.34, and 126 mg/L, respectively. These results suggest bioswales with check dams provide more pollutant removal than bioswales without check dams and swales with check dams. Note for BS2 total Cd samples were below the practical quantification limit (PQL) and were subsequently not included in the analyses.

Table 35. Summary of BS2 water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.44	1.01	0.77	2.85	22
$NO_{2,3}$ -N (mg/L)	0.02	0.07	0.06	0.20	24
TN (mg/L)	0.51	1.04	0.83	3.06	16
TP (mg/L)	0.07	0.15	0.14	0.30	16
O-PO_4^{3-} (mg/L)	0.02	0.04	0.03	0.12	23
TSS (mg/L)	9.00	41.0	27.0	202	15
Total Cu (µg/L)	2.70	4.40	3.50	10.0	12
Total Pb (µg/L)	2.00	4.83	3.40	13.0	8
Total Zn (µg/L)	11.0	53.4	29.5	320	14
Overflow					
TKN (mg/L)	0.40	0.80	0.76	1.14	13
$NO_{2,3}$ -N (mg/L)	0.02	0.07	0.06	0.17	15
TN (mg/L)	0.46	0.84	0.83	1.23	10
TP (mg/L)	0.08	0.16	0.14	0.28	11
O-PO_4^{3-} (mg/L)	0.02	0.05	0.04	0.14	15
TSS (mg/L)	12.0	31.0	21.0	82.0	10
Total Cu (µg/L)	2.50	3.38	3.15	4.70	4
Total Pb (µg/L)	2.10	4.10	4.10	6.10	2
Total Zn (µg/L)	13.0	31.3	26.0	62.0	7
Underdrain					
TKN (mg/L)	0.30	0.59	0.59	1.01	23
$NO_{2,3}$ -N (mg/L)	0.02	0.11	0.09	0.39	25
TN (mg/L)	0.35	0.66	0.68	0.95	17
TP (mg/L)	0.05	0.11	0.12	0.16	18
O-PO_4^{3-} (mg/L)	0.02	0.05	0.05	0.12	25
TSS (mg/L)	3.00	10.0	10.0	15.0	13
Total Cu (µg/L)	5.40	9.37	8.60	17.0	18
Total Pb (µg/L)	2.10	2.69	2.60	3.90	12
Total Zn (µg/L)	11.0	18.0	15.0	35.0	11
Outflow					
TKN (mg/L)	0.32	0.64	0.69	1.01	20
$NO_{2,3}$ -N (mg/L)	0.02	0.10	0.09	0.39	22
TN (mg/L)	0.38	0.70	0.77	0.95	17
TP (mg/L)	0.05	0.12	0.13	0.20	18
O-PO_4^{3-} (mg/L)	0.03	0.05	0.05	0.12	22
TSS (mg/L)	6.00	19.0	13.0	82.0	16
Total Cu (µg/L)	4.47	9.09	8.30	17.0	17
Total Pb (µg/L)	2.10	2.95	2.70	6.10	13
Total Zn (µg/L)	12.0	21.2	16.0	52.8	14

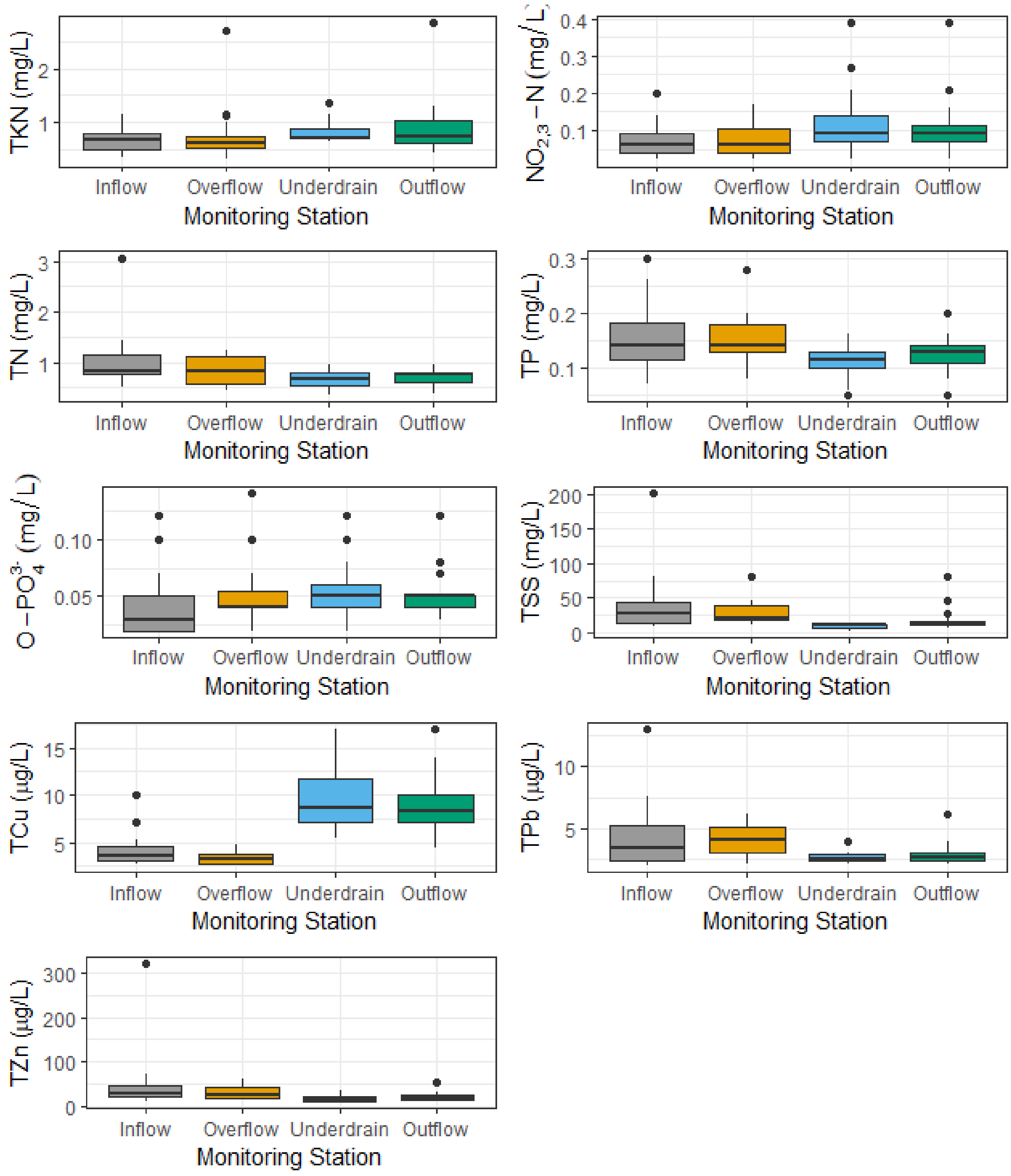

Figure 29. Boxplots of BS2 water quality data

For BS2, a maximum of 15 storm events were sampled for PSD data (Table 36). Most of the particles in the runoff volumes were composed of silt. The median percentages of silt particles ranged from 70.1 to 77% while clay comprised 6.63 to 8.20% of the particles in the samples. The median d_{50} for inflow, overflow, underdrain, and outflow volumes were 2.79, 2.79, 2.85, and 2.79 μm, respectively. Sediment within the inflow samples was less coarse than samples collected by Winston et al. (2023) and Winston & Hunt (2017) from roadways in Ohio and North Carolina, respectively.

Table 36. Summary of BS2 PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (μm)	0.09	0.09	0.09	0.10	12
d_{50} (μm)	2.66	2.87	2.79	3.52	
d_{90} (μm)	76.4	88.3	83.1	127	
Clay (%)	5.51	7.11	7.02	9.84	
Silt (%)	42.4	71.6	74.5	78.6	
Sand (%)	12.5	21.2	19.9	51.8	
Overflow					
d_{10} (μm)	0.09	0.09	0.09	0.10	8
d_{50} (μm)	2.42	2.81	2.79	3.06	
d_{90} (μm)	64.7	84.7	83.1	98.4	
Clay (%)	4.56	6.75	6.63	9.50	
Silt (%)	59.7	71.7	74.7	79.5	
Sand (%)	11.0	21.6	18.3	35.8	
Underdrain					
d_{10} (μm)	0.09	0.09	0.09	0.10	14
d_{50} (μm)	2.66	2.93	2.85	3.52	
d_{90} (μm)	76.4	91.5	86.8	127	
Clay (%)	4.92	8.22	8.20	12.9	
Silt (%)	61.0	75.6	77.3	82.7	
Sand (%)	4.35	16.2	14.4	34.1	
Outflow					
d_{10} (μm)	0.09	0.09	0.09	0.10	15
d_{50} (μm)	2.55	2.88	2.79	3.21	
d_{90} (μm)	71.0	88.6	83.1	107	
Clay (%)	4.92	7.79	7.60	12.9	
Silt (%)	6.40	60.1	70.1	82.7	
Sand (%)	4.35	30.5	21.5	79.2	

Unlike BS2, BS4 was retrofitted with check dams and IWS (Table 4). Median inflow, overflow, underdrain, and outflow TN concentrations were 2.04, 1.91, 1.23, and 1.68 mg/L, respectively (Table 37; Figure 30). Median TP and TSS inflow, overflow, underdrain, and outflow concentrations were 0.45, 0.44, 0.21, and 0.30 mg/L, respectively and 72.0, 47.0, 18.0, and 31.0 mg/L, respectively. Despite the inclusion of IWS, the median TN outflow concentration was greater than the median TN concentration from BS2. This could be the result of BS4 having larger inflow concentrations (2.04 mg/L versus 0.83 mg/L) as well as a steeper slope (2.93% versus 1.79%). Ekka et al. (2021) recommends a maximum slope of 3% to avoid short circuiting. However, the water quality from BS4 is less than the concentrations reported by

Regier & McDonald (2022), Stagge et al. (2012), and Xiao & McPherson (2011) for bioswales without IWS and check dams as well as swales with check dams. Note for BS4 total Cd samples were below the PQL and were subsequently not included in the analyses.

Table 37. Summary of BS4 water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.82	2.48	1.25	15.0	13
$NO_{2,3}$ -N (mg/L)	0.09	1.15	0.37	8.46	13
TN (mg/L)	0.96	4.65	2.04	23.4	8
TP (mg/L)	0.18	0.42	0.45	0.60	7
O-PO_4^{3-} (mg/L)	0.03	0.56	0.06	6.41	13
TSS (mg/L)	32.0	85.0	72.0	214	8
Total Cu (µg/L)	2.90	14.4	7.60	49.0	8
Total Pb (µg/L)	3.80	14.6	8.70	48.0	6
Total Zn (µg/L)	19.0	105	64.0	420	9
Overflow					
TKN (mg/L)	0.56	1.59	1.43	3.40	10
$NO_{2,3}$ -N (mg/L)	0.04	0.35	0.21	0.84	12
TN (mg/L)	0.75	2.10	1.91	4.22	7
TP (mg/L)	0.22	0.44	0.44	0.75	9
O-PO_4^{3-} (mg/L)	0.02	0.12	0.09	0.53	12
TSS (mg/L)	29.0	108	47.0	400	8
Total Cu (µg/L)	4.80	11.1	6.20	29.0	5
Total Pb (µg/L)	3.30	11.2	4.75	32.0	4
Total Zn (µg/L)	21.0	73.0	39.0	210	5
Underdrain					
TKN (mg/L)	0.55	1.08	1.00	2.07	13
$NO_{2,3}$ -N (mg/L)	0.14	0.38	0.24	1.41	14
TN (mg/L)	0.74	1.53	1.23	3.48	10
TP (mg/L)	0.12	0.26	0.21	0.80	11
O-PO_4^{3-} (mg/L)	0.02	0.11	0.04	0.74	12
TSS (mg/L)	8.00	33.0	18.0	141	10
Total Cu (µg/L)	6.50	8.39	8.10	11.0	7
Total Pb (µg/L)	2.40	3.57	3.50	4.70	7
Total Zn (µg/L)	17.0	56.3	30.0	220	7
Outflow					
TKN (mg/L)	0.56	1.34	1.32	2.48	10
$NO_{2,3}$ -N (mg/L)	0.17	0.45	0.26	1.23	11
TN (mg/L)	0.75	1.75	1.68	3.70	10
TP (mg/L)	0.14	0.35	0.30	0.78	11
O-PO_4^{3-} (mg/L)	0.02	0.12	0.08	0.68	13
TSS (mg/L)	14.0	79.0	31.0	370	10
Total Cu (µg/L)	6.66	8.08	7.40	11.0	5
Total Pb (µg/L)	2.40	3.71	4.01	4.70	5
Total Zn (µg/L)	17.0	32.6	30.0	55.4	5

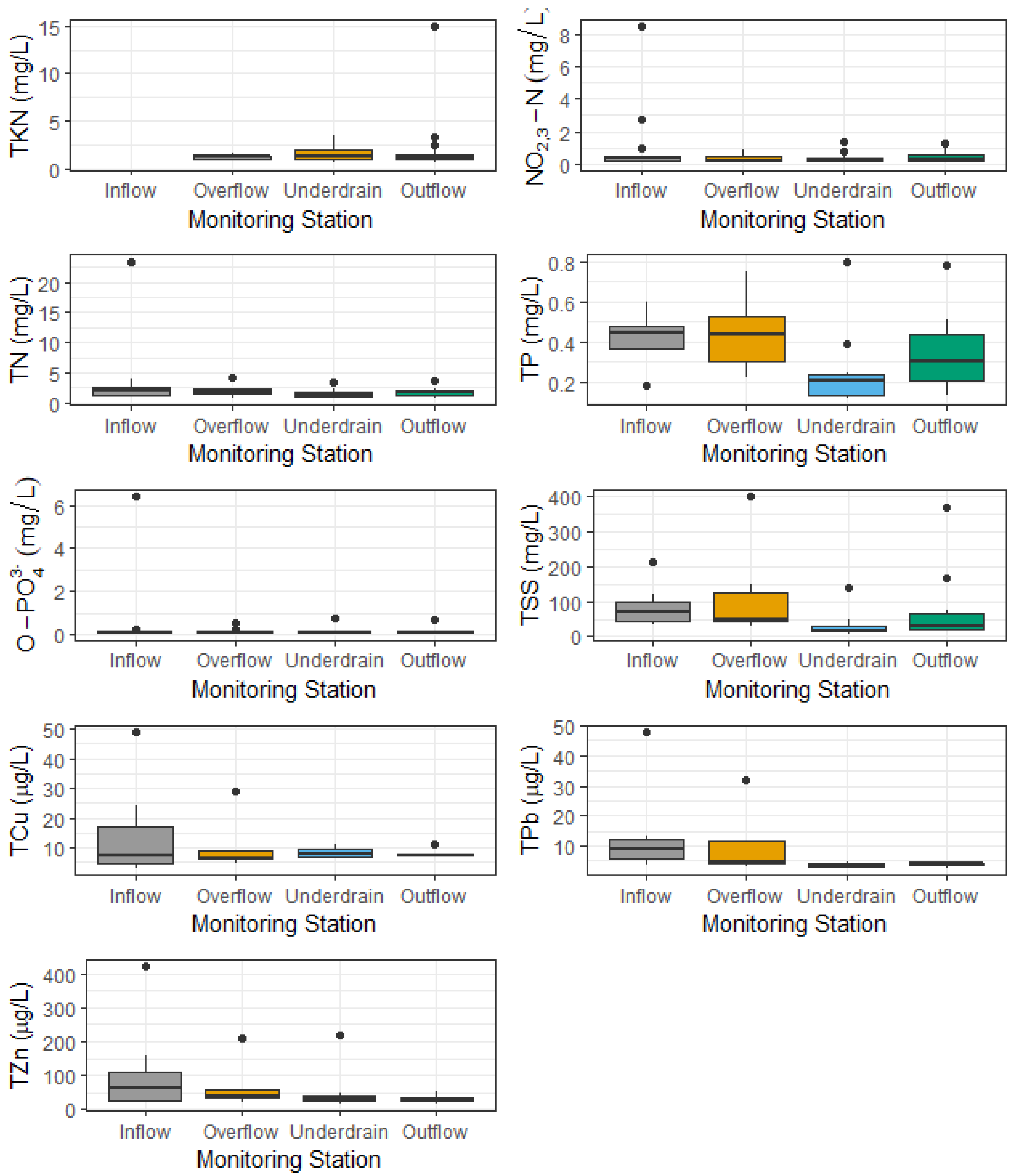

Figure 30. Boxplots of BS4 water quality data

Similar to BS2, a large portion of the particles in the samples were comprised of silt (73.7 to 75.9%) (Table 38). The median d_{50} in inflow, overflow, underdrain flow, and outflow samples were 2.61, 1.83, 2.79, and 2.79 µm, respectively.

Table 38. Summary of BS4 PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.09	0.10	0.09	0.11	4
d_{50} (µm)	2.21	2.62	2.61	3.06	
d_{90} (µm)	43.7	72.5	73.9	98.4	
Clay (%)	3.56	11.5	11.6	19.4	
Silt (%)	48.7	70.7	75.9	82.2	
Sand (%)	5.54	17.8	9.02	47.7	
Overflow					
d_{10} (µm)	0.08	0.09	0.09	0.10	7
d_{50} (µm)	1.32	2.16	1.83	3.21	
d_{90} (µm)	21.7	56.1	39.1	107	
Clay (%)	3.59	15.7	13.2	26.8	
Silt (%)	66.8	76.2	75.9	84.3	
Sand (%)	0	8.15	4.29	29.6	
Underdrain					
d_{10} (µm)	0.08	0.09	0.09	0.10	9
d_{50} (µm)	1.32	2.54	2.79	3.21	
d_{90} (µm)	21.7	73.4	83.1	107	
Clay (%)	8.43	17.5	14.7	33.3	
Silt (%)	65.1	74.1	73.7	78.7	
Sand (%)	0	8.40	6.63	17.4	
Outflow					
d_{10} (µm)	0.08	0.09	0.09	0.10	9
d_{50} (µm)	1.32	2.48	2.79	3.21	
d_{90} (µm)	21.7	70.4	83.1	107	
Clay (%)	6.76	15.7	12.1	28.0	
Silt (%)	70.0	75.3	75.7	84.3	
Sand (%)	0	9.04	6.26	23.3	

There were limited significant differences ($\alpha = 0.05$) between inflow, overflow, and underdrain pollutant concentrations for BS2 (Table 39) and BS4 (Table 40). Runoff volumes were dominated by silt particles (Table 36; Table 38), and it possible there was lack of pollutant removal due to the resuspension of pollutants (Bäckström, 2003; Luell et al., 2021; Stagge et al., 2012) or a lack of sedimentation, which has been identified a critical treatment mechanism for swales (Deletic, 1999; Ekka et al., 2021; Winston et al., 2017; Yu et al., 2001). Additionally, the lack of significant differences for BS4 could be caused by the number of samples influencing the p-values. Previous research has shown that p-values decrease with increasing sample sizes (Gómez-de-Mariscal et al., 2021; Thiese et al., 2016).

Table 39. Comparisons between BS2 pollutant concentrations

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Wilcoxon Signed-Rank Test	0.08
	Inflow versus underdrain		**$1.0*10^{-3}$**
	Inflow versus outflow	Sign Test	**0.02**
TP	Inflow versus overflow	Student's t-test	0.95
	Inflow versus underdrain		**0.03**
	Inflow versus outflow		0.10
TSS	Inflow versus overflow	Wilcoxon Signed-Rank Test	0.37
	Inflow versus underdrain		**$2.0*10^{-3}$**
	Inflow versus outflow		**0.02**
TKN	Inflow versus overflow		0.15
	Inflow versus underdrain		**$3.71*10^{-5}$**
	Inflow versus outflow		**$2.0*10^{-4}$**
$NO_{2,3}$ -N	Inflow versus overflow	Student's t-test	0.45
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	0.99
	Inflow versus outflow		0.99
$O\text{-}PO_4^{3-}$	Inflow versus overflow		0.99
	Inflow versus underdrain		0.98
	Inflow versus outflow		0.97
Total Cu	Inflow versus overflow	Sign Test	0.31
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	1.0
	Inflow versus outflow	Student's t-test	**$1.0*10^{-3}$**
Total Pb	Inflow versus overflow[b]	-	-
	Inflow versus underdrain	Sign Test	0.19
	Inflow versus outflow	Wilcoxon Signed-Rank Test	**0.03**
Total Zn	Inflow versus overflow		0.07
	Inflow versus underdrain		**0.01**
	Inflow versus outflow	Sign Test	**0.03**

[a] Bolded values indicate significance with α = 0.05
[b] Sample size too small to run statistical analyses

Table 40. Comparisons between BS4 pollutant concentrations

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Sign Test	0.69
	Inflow versus underdrain		0.06
	Inflow versus outflow	Wilcoxon Signed-Rank Test	0.08
TP	Inflow versus overflow	Student's t-test	0.86
	Inflow versus underdrain		**$2.71*10^{-5}$**
	Inflow versus outflow		**0.01**
TSS	Inflow versus overflow		0.14
	Inflow versus underdrain		**0.02**
	Inflow versus outflow		**0.04**
TKN	Inflow versus overflow	Wilcoxon Signed-Rank Test	0.11
	Inflow versus underdrain		**0.01**
	Inflow versus outflow	Sign Test	0.23
$NO_{2,3}$ -N	Inflow versus overflow		0.14
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	**0.01**
	Inflow versus outflow	Sign Test	0.23
O-PO_4^{3-}	Inflow versus overflow		0.96
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	0.08
	Inflow versus outflow	Sign Test	0.64
Total Cu	Inflow versus overflow	Student's t-test	0.53
	Inflow versus underdrain		0.20
	Inflow versus outflow		0.31
Total Pb	Inflow versus overflow		0.62
	Inflow versus underdrain	Sign Test	**0.03**
	Inflow versus outflow	Student's t-test	0.11
Total Zn	Inflow versus overflow		0.26
	Inflow versus underdrain		0.24
	Inflow versus outflow		0.15

[a] Bolded values indicate significance with $\alpha = 0.05$

Objective Three: Hydrology

Table 41 summarizes the characteristics of storm events monitored from December 2017 to May 2018 for BSN and BSS. The average storm depth and maximum 5-min intensity was 0.50 inches and 0.71 in/hr, respectively. The average antecedent dry period was approximately five days.

Table 41. Summary of BSN and BSS storm event characteristics

Parameter	Minimum	Mean	Median	Maximum	Number of monitored storms
Depth (in)	0.10	0.50	0.30	1.94	33
Maximum 5-minute intensity (in/hr)	0.12	0.71	0.42	3.00	
Average intensity (in/hr)	0.10	0.10	0.05	0.67	
Duration (hr)	0.20	9.81	6.43	40.5	
Antecedent dry period (days)	0.26	4.77	4.74	15.4	

Due to monitoring issues at the inlet, inflow was estimated as the sum of measured overflow and underdrain flow for BSN and BSS. The average inflow, overflow, and underdrain volumes for BSN were 740, 607, and 138 cf, respectively (Table 42). For BSS, the average inflow, overflow, and underdrain volumes were 577, 390, and 299 cf, respectively. Exfiltration most likely occurred in both bioswales given the sandy soils that exist at these sites (Table 5) (USDA- NRCS, 2019).

Table 42. Summary of BSN and BSS hydrologic data

Monitoring Station/Parameter	Minimum	Mean	Median	Maximum
BSN				
Inflow (cf)	0	740	414	3,161
Overflow (cf)	0	607	307	2,943
Overflow (cfs)	0	0.23	0.09	1.29
Underdrain (cf)	0	138	73	645
Underdrain (cfs)	0	0.01	0.01	0.05
BSS				
Inflow (cf)	0	577	199	3,064
Overflow (cf)	0	390	37	2,931
Overflow (cfs)	0	0.19	0.04	1.46
Underdrain (cf)	0	299	199	1,382
Underdrain (cfs)	0	0.03	0.04	0.08

Objective Three: Water Quality

Table 43 and Figure 31 summarize the water quality data collected from BSN. The median inflow, overflow, underdrain, and outflow TN concentrations were 1.26, 0.63, 1.24, and 0.81 mg/L, respectively, and median TP concentrations were 0.20, 0.16, 0.29, and 0.16 mg/L, respectively. Despite the export of TN and TP from the underdrain, the outflow concentrations are less than the concentrations reported by Knight et al. (2013), Luell et al. (2021), Regier & McDonald (2022), Stagge et al. (2012), and Xiao & McPherson (2011) for bioswales and swales without IWS. It is possible BSN exported TN and TP from the underdrain because of leaching from the bioswale's media. McPhillips et al. (2018) found a bioretention cell leached $NO_{2,3}$-N and soluble reactive phosphorus because the organic matter added to the media had a low carbon to nitrogen ratio and the media itself had a high phosphorus and carbon content. The media for the bioswales was not tested, and future studies should test the media to better understand the nutrient cycling that occurs within bioswales. Shetty et al. (2019) reported TP leaching from bioswales in New York decreased over time. However, the TP concentrations from BSN's underdrain were consistent throughout the monitoring period, and this may be a result of the limited number of storm events that occurred during the monitoring period (Tables 26 and 29).

Table 43. Summary of BSN water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.37	1.36	1.04	4.06	14
$NO_{2,3}$ -N (mg/L)	0.09	0.24	0.15	0.56	16
TN (mg/L)	0.47	1.62	1.26	4.36	13
TP (mg/L)	0.10	0.24	0.20	0.84	14
O-PO_4^{3-} (mg/L)	0.02	0.06	0.04	0.19	15
TSS (mg/L)	20.0	83.0	61.0	254	15
Total Cu (µg/L)	12.0	20.6	14.0	33.0	5
Total Pb (µg/L)	2.10	6.38	4.20	12.0	5
Total Zn (µg/L)	74.0	173	130	300	5
Overflow					
TKN (mg/L)	0.32	0.52	0.53	0.73	10
$NO_{2,3}$ -N (mg/L)	0.08	0.12	0.10	0.25	12
TN (mg/L)	0.40	0.63	0.63	0.85	9
TP (mg/L)	0.08	0.16	0.16	0.29	11
O-PO_4^{3-} (mg/L)	0.04	0.08	0.07	0.19	12
TSS (mg/L)	5.00	19.0	16.0	54.0	10
Total Cu (µg/L)	6.10	10.4	9.70	15.0	5
Total Pb (µg/L)	3.30	3.95	3.95	4.60	2
Total Zn (µg/L)	31.0	52.8	44.0	90.0	5
Underdrain					
TKN (mg/L)	0.58	0.82	0.79	1.21	15
$NO_{2,3}$ -N (mg/L)	0.23	0.41	0.41	0.63	16
TN (mg/L)	0.81	1.23	1.24	1.62	14
TP (mg/L)	0.05	0.28	0.29	0.53	15
O-PO_4^{3-} (mg/L)	0.07	0.15	0.14	0.45	15
TSS (mg/L)	6.00	14.0	13.0	22.0	12
Total Cu (µg/L)	12.0	18.5	14.5	39.0	6
Total Pb (µg/L)	2.80	4.28	3.90	6.50	6
Total Zn (µg/L)	24.0	36.2	31.5	60.0	6
Outflow					
TKN (mg/L)	0.24	0.59	0.62	1.01	15
$NO_{2,3}$ -N (mg/L)	0.05	0.23	0.19	0.63	16
TN (mg/L)	0.28	0.85	0.81	1.58	14
TP (mg/L)	0.05	0.17	0.16	0.34	15
O-PO_4^{3-} (mg/L)	0.04	0.09	0.07	0.16	15
TSS (mg/L)	6.00	18.0	15.0	53.0	12
Total Cu (µg/L)	4.63	14.7	11.8	39.0	6
Total Pb (µg/L)	2.80	4.24	4.00	6.50	7
Total Zn (µg/L)	19.2	46.5	45.4	74.0	6

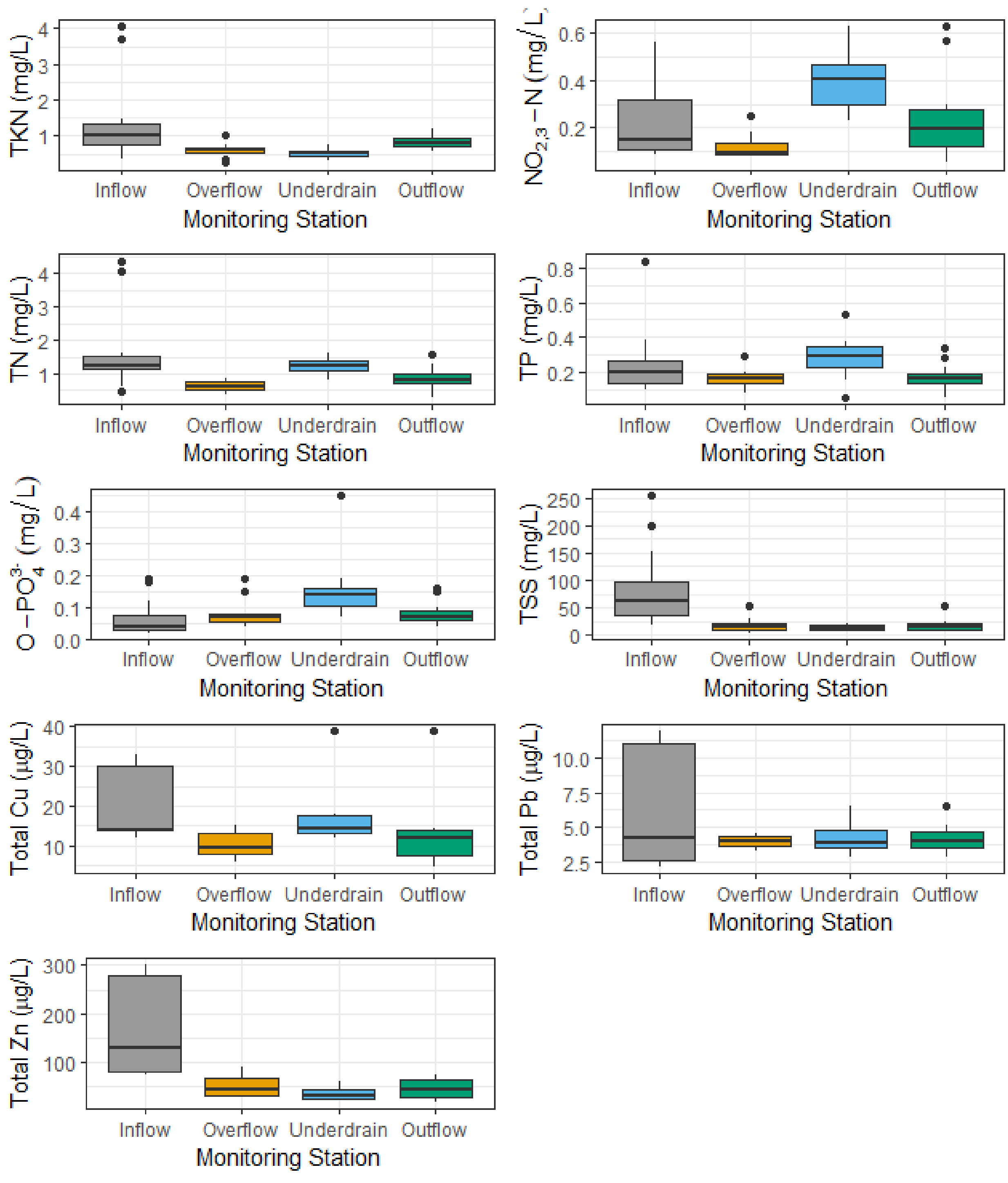

Figure 31. Boxplots of BSN water quality data

Table 44 provides a summary of the PSD data collected for BSN. The median d_{50} for inflow, overflow, underdrain, and outflow volumes were 3.52, 2.93, 3.06, and 2.94 µm. The percentages of clay, silt, and sand for outflow volumes ranged from 3.87 to 18.1%, 23.8 to 80.5%, and 6.01 to 73.5%, respectively.

Table 44. Summary of BSN PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.09	0.10	0.10	0.12	8
d_{50} (µm)	2.79	4.95	3.52	8.54	
d_{90} (µm)	83.1	270	127	624	
Clay (%)	0.10	3.62	3.49	6.10	
Silt (%)	3.06	47.0	53.3	70.5	
Sand (%)	24.5	49.6	43.0	98.4	
Overflow					
d_{10} (µm)	0.09	0.63	0.09	4.35	8
d_{50} (µm)	2.42	10.6	2.93	64.6	
d_{90} (µm)	31.1	83.7	83.1	116	
Clay (%)	0.10	5.61	5.86	8.32	
Silt (%)	3.06	67.0	73.5	83.1	
Sand (%)	10.8	27.6	20.4	98.4	
Underdrain					
d_{10} (µm)	0.09	0.09	0.10	0.10	8
d_{50} (µm)	2.21	2.92	3.06	3.21	
d_{90} (µm)	54.7	91.4	98.4	107	
Clay (%)	12.3	16.2	15.2	22.1	
Silt (%)	66.5	74.5	75.3	80.8	
Sand (%)	4.95	9.15	9.18	13.6	
Outflow					
d_{10} (µm)	0.09	0.43	0.09	3.10	9
d_{50} (µm)	2.50	7.71	2.94	46.0	
d_{90} (µm)	22.1	83.5	89.1	115	
Clay (%)	3.87	8.74	8.37	18.1	
Silt (%)	23.8	70.2	75.2	80.5	
Sand (%)	6.01	21.2	17.0	73.5	

Median inflow, overflow, underdrain, and outflow TN concentrations for BSS were 0.97, 0.71, 0.63, and 0.64 mg/L, respectively while median TP concentrations were 0.12, 0.09, 0.10, and 0.09 mg/L, respectively (Table 45; Figure 32). While TN and TP concentrations from the underdrain were less than inflow concentrations, $NO_{2,3}$-N concentrations from the underdrain were larger than inflow concentrations, and there was little to no difference between O-PO_4^{3-} concentrations from inflow and the underdrain. This further suggests the media potentially leached pollutants throughout the monitoring period.

Table 45. Summary of BSS water quality data

Pollutant	Minimum	Mean	Median	Maximum	Number of samples
Inflow					
TKN (mg/L)	0.41	1.35	0.90	5.53	15
$NO_{2,3}$ -N (mg/L)	0.03	0.16	0.11	0.46	16
TN (mg/L)	0.53	1.52	0.97	5.79	15
TP (mg/L)	0.05	0.17	0.12	0.60	16
O-PO_4^{3-} (mg/L)	0.01	0.04	0.03	0.09	10
TSS (mg/L)	14.0	44.0	32.0	98.0	13
Total Cu (µg/L)	6.20	9.32	8.30	15.0	6
Total Pb (µg/L)	2.90	4.13	4.40	5.10	3
Total Zn (µg/L)	65.0	118	98.0	220	6
Overflow					
TKN (mg/L)	0.29	0.48	0.44	0.69	7
$NO_{2,3}$ -N (mg/L)	0.06	0.12	0.10	0.27	9
TN (mg/L)	0.36	0.60	0.71	0.78	7
TP (mg/L)	0.03	0.09	0.09	0.15	10
O-PO_4^{3-} (mg/L)	0.01	0.03	0.02	0.04	7
TSS (mg/L)	12.0	27.0	17.0	68.0	8
Total Cu (µg/L)	4.10	7.83	7.10	13.0	4
Total Pb (µg/L)	3.20				1
Total Zn (µg/L)	39.0	61.3	43.0	120	4
Underdrain					
TKN (mg/L)	0.29	0.56	0.43	1.63	12
$NO_{2,3}$ -N (mg/L)	0.02	0.23	0.18	0.56	16
TN (mg/L)	0.40	0.82	0.63	2.12	11
TP (mg/L)	0.03	0.12	0.10	0.35	15
O-PO_4^{3-} (mg/L)	0.01	0.03	0.03	0.06	15
TSS (mg/L)	4.00	17.0	14.0	39.0	11
Total Cu (µg/L)	6.50	11.5	12.0	20.0	7
Total Pb (µg/L)	-				0
Total Zn (µg/L)	21.0	27.7	23.0	41.0	7
Outflow					
TKN (mg/L)	0.31	0.59	0.41	1.63	12
$NO_{2,3}$ -N (mg/L)	0.02	0.21	0.16	0.56	16
TN (mg/L)	0.41	0.84	0.64	2.12	11
TP (mg/L)	0.03	0.11	0.09	0.35	15
O-PO_4^{3-} (mg/L)	0.01	0.03	0.03	0.06	15
TSS (mg/L)	6.00	18.0	15.0	37.0	13
Total Cu (µg/L)	5.74	10.8	8.70	20.0	7
Total Pb (µg/L)	3.20				1
Total Zn (µg/L)	21.0	38.2	36.0	80.4	7

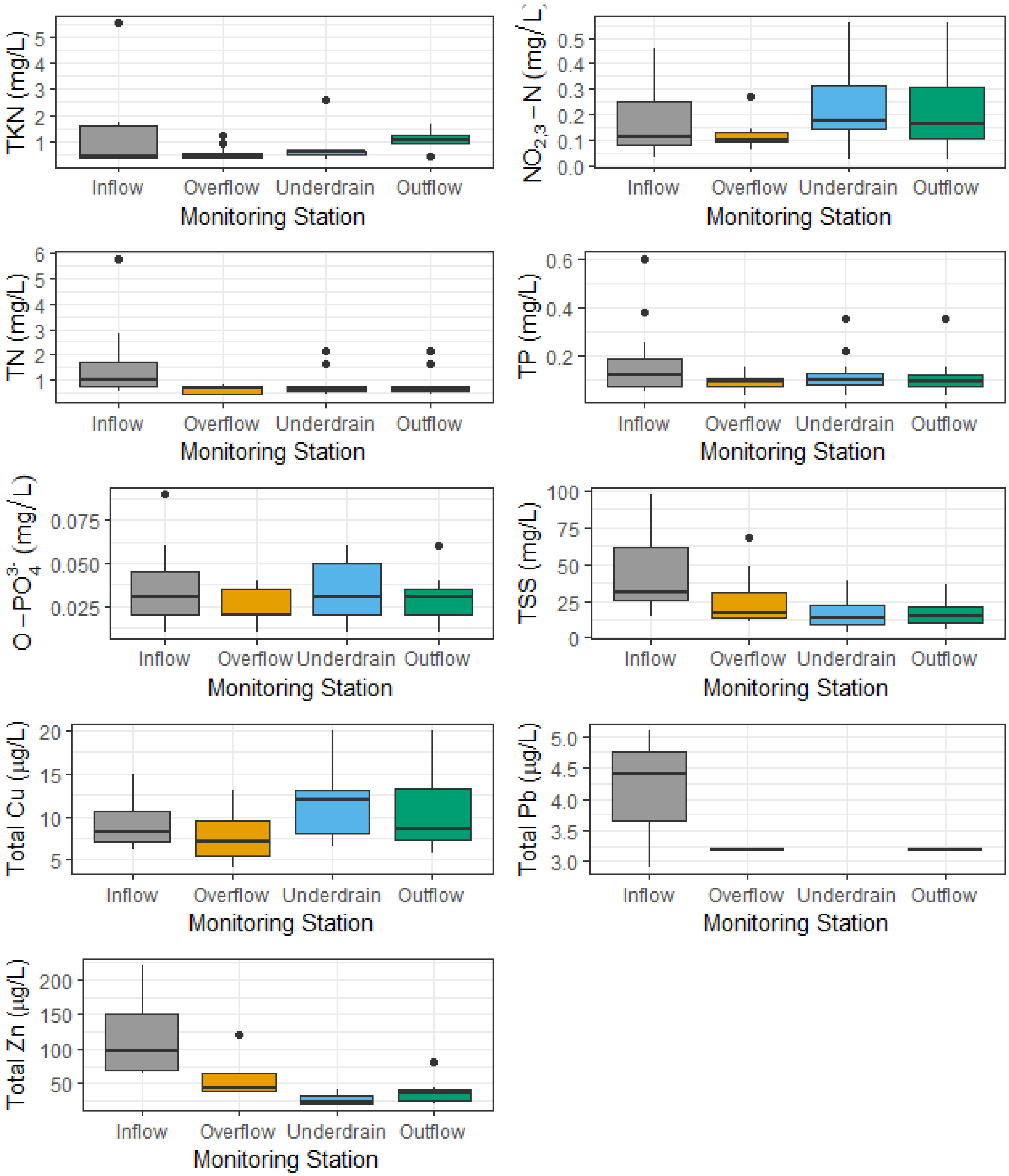

Figure 32. Boxplots of BSS water quality data

A minimum of four storm events were sampled for PSD data (Table 46). The median d_{50} for inflow, overflow, underdrain, and outflow volumes were 7.78, 2.92, 2.79, and 2.93 µm, respectively. Samples were dominated by silt particles (26.8 to 85.6%) followed by sand particles (0.37 to 71.4%).

Table 46. Summary of BSS PSD data

Parameter	Minimum	Mean	Median	Maximum	Count
Inflow					
d_{10} (µm)	0.11	0.11	0.11	0.12	7
d_{50} (µm)	7.42	7.79	7.78	8.54	
d_{90} (µm)	485	529	527	624	
Clay (%)	1.76	2.31	2.36	2.97	
Silt (%)	26.8	34.6	34.4	44.4	
Sand (%)	52.6	63.1	63.6	71.4	
Overflow					
d_{10} (µm)	0.09	0.09	0.09	0.10	4
d_{50} (µm)	2.79	2.92	2.92	3.06	
d_{90} (µm)	83.1	90.6	90.5	98.4	
Clay (%)	4.36	5.27	5.15	6.42	
Silt (%)	66.7	69.9	69.3	74.3	
Sand (%)	20.1	24.5	25.7	27.9	
Underdrain					
d_{10} (µm)	0.08	0.09	0.09	0.10	9
d_{50} (µm)	1.67	2.85	2.79	4.05	
d_{90} (µm)	33.0	90.2	83.1	163	
Clay (%)	5.17	10.9	9.56	23.4	
Silt (%)	73.2	78.2	76.9	85.6	
Sand (%)	0.37	10.9	13.1	20.3	
Outflow					
d_{10} (µm)	0.09	0.09	0.09	0.10	9
d_{50} (µm)	2.06	2.99	2.93	4.05	
d_{90} (µm)	51.2	97.1	90.8	163	
Clay (%)	4.94	9.08	8.90	15.3	
Silt (%)	72.7	76.8	76.9	80.1	
Sand (%)	7.42	14.1	13.9	22.4	

There was lack of significant differences ($\alpha = 0.05$) between inflow, overflow, underdrain, and outflow concentrations for BSN (Table 47) and BSS (Table 48). This is most likely due to the similarities between concentrations from each monitoring station, potential leaching from the media, and the number of samples included in the analyses affecting the p-values (Gómez-de-Mariscal et al., 2021; Thiese et al., 2016).

Table 47. Comparisons between BSN pollutant concentrations

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Student's t-test	**0.01**
	Inflow versus underdrain	Sign Test	0.61
	Inflow versus outflow	Wilcoxon Signed-Rank Test	**0.01**
TP	Inflow versus overflow	Student's t-test	0.28
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	0.95
	Inflow versus outflow	Sign Test	0.29
TSS	Inflow versus overflow	Wilcoxon Signed-Rank Test	**$1.0*10^{-3}$**
	Inflow versus underdrain		**$1.0*10^{-3}$**
	Inflow versus outflow		**0.02**
TKN	Inflow versus overflow	Student's t-test	**0.01**
	Inflow versus underdrain	Wilcoxon Signed-Rank Test	0.11
	Inflow versus outflow		**$1.0*10^{-3}$**
$NO_{2,3}$ -N	Inflow versus overflow	Sign Test	**$5.0*10^{-4}$**
	Inflow versus underdrain	Student's t-test	**$1.0*10^{-3}$**
	Inflow versus outflow		0.97
O-PO_4^{3-}	Inflow versus overflow	Wilcoxon Signed-Rank Test	0.90
	Inflow versus underdrain	Student's t-test	**$3.0*10^{-3}$**
	Inflow versus outflow	Wilcoxon Signed-Rank Test	0.95
Total Cu	Inflow versus overflow	Student's t-test	0.06
	Inflow versus underdrain		0.24
	Inflow versus outflow		0.06
Total Pb	Inflow versus overflow[b]	-	-
	Inflow versus underdrain	Student's t-test	0.53
	Inflow versus outflow		0.26
Total Zn	Inflow versus overflow		0.07
	Inflow versus underdrain		**0.04**
	Inflow versus outflow		0.06

[a] Bolded values indicate significance with $\alpha = 0.05$
[b] Sample size too small to perform statistical analyses

Table 48. Comparisons between BSS pollutant concentrations

Pollutant	Comparison	Test	p-value[a]
TN	Inflow versus overflow	Student's t-test	0.06
	Inflow versus underdrain	Sign Test	**$4.0*10^{-3}$**
	Inflow versus outflow		**$1.0*10^{-3}$**
TP	Inflow versus overflow	Student's t-test	0.11
	Inflow versus underdrain	Sign Test	0.29
	Inflow versus outflow		0.19
TSS	Inflow versus overflow	Wilcoxon Signed-Rank Test	**0.01**
	Inflow versus underdrain	Student's t-test	0.11
	Inflow versus outflow		**0.02**
TKN	Inflow versus overflow		0.05
	Inflow versus underdrain	Sign test	**$5.0*10^{-4}$**
	Inflow versus outflow	Wilcoxon Signed-Rank Test	**$5.0*10^{-4}$**
$NO_{2,3}$ -N	Inflow versus overflow	Student's t-test	0.95
	Inflow versus underdrain		0.07
	Inflow versus outflow		0.16
$O\text{-}PO_4^{3-}$	Inflow versus overflow	Sign test	0.50
	Inflow versus underdrain	Student's t-test	0.54
	Inflow versus outflow		0.83
Total Cu	Inflow versus overflow		0.72
	Inflow versus underdrain		0.68
	Inflow versus outflow		0.98
Total Pb	Inflow versus overflow[b]	-	
	Inflow versus underdrain[b]		
	Inflow versus outflow[b]		
Total Zn	Inflow versus overflow	Student's t-test	0.32
	Inflow versus underdrain		**0.02**
	Inflow versus outflow		**0.03**

[a] Bolded values indicate significance with α = 0.05
[b] Sample size too small to perform statistical analyses

Objective Four

Significant predictors (α = 0.05) for estimating overflow as the percentage of inflow were the bottom width of the bioswale and the presence of a forebay and IWS (Equation 18). The final model had a NSE of -0.12, which indicates the model poorly predicts the percentage of overflow as a percentage of inflow. The residuals from the model also suggest the model should not be used to predict overflow as a percentage of inflow (Figure 33). A model that should be used would have a NSE of at least 0.65 (Ritter & Muñoz-Carpena, 2013) and residuals that closely follow the 1:1 line. Despite the model's poor performance, the predictors and coefficients are appropriate to include in the model. For example, as the width and consequently the flow area increases the velocity decreases, which provides runoff with more opportunity to exfiltrate or be discharged through the underdrain system. Forebays provide additional storage which also increases the opportunity for runoff to exfiltrate or being discharged through the underdrain. IWS was shown to increase overflow for bioswale #3 and bioswale #6 with IWS.

$$Overflow = 16.34 - 11.04*W - 12.40*F + 12.85*IWS \quad \text{Equation 18}$$

where:
Overflow= overflow volume as a percentage of inflow volume (%)
W= bottom width of bioswale (ft)
F= presence of forebay (1 = yes, 0 = no)
IWS= presence of internal water storage (1 = yes, 0 = no)

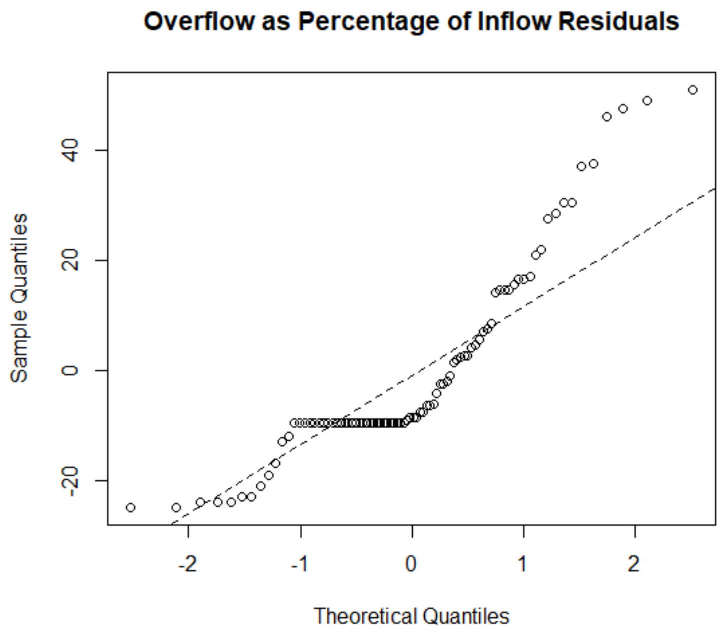

Figure 33. Residual plot for overflow regression equation

The final regression equation predicting underdrain volumes as a percentage of inflow volumes included the bioswale's bottom width and presence of check dams as significant predictors (Equation 19).The model had a NSE of 0.48, and the residuals suggested less variability in the data compared to the overflow data (Figure 34). Similar to overflow, the variables used to predict underdrain volumes as a percentage of inflow volumes are appropriate to include in the model. The presence of check dams provides more opportunity for ponded runoff to discharge through the underdrain system as shown by bioswales #1 and #4 with check dams and BS2.

Underdrain = 26.04 - 22.07*W + 12.94*CD Equation 19

where:
Underdrain= underdrain volume as a percentage of inflow volume (%)
W= bottom width of bioswale (ft)
CD = presence of check dams (1 = yes, 0 = no)

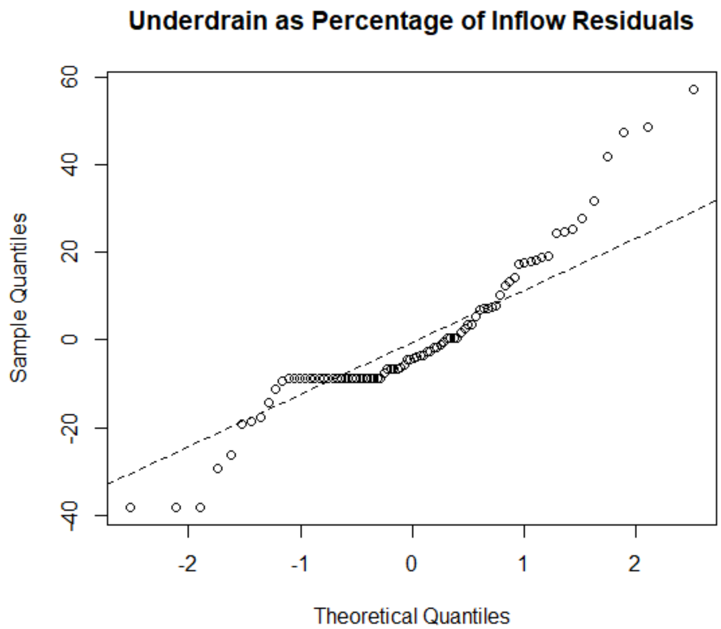

Figure 34. Residual plot for underdrain regression equation

There were no significant predictors for the final regression equation predicting exfiltration as a percentage of inflow (Equation 20), but the model had a NSE of 0.32. The residuals indicated variability within the data (Figure 35) and further suggested the model is not appropriate to use to predict exfiltration volumes as a percentage of inflow volumes.

Exfiltration = 58.34 + 12.97*W Equation 20

where:
Underdrain= underdrain volume as a percentage of inflow volume (%)
W= bottom width of bioswale (ft)

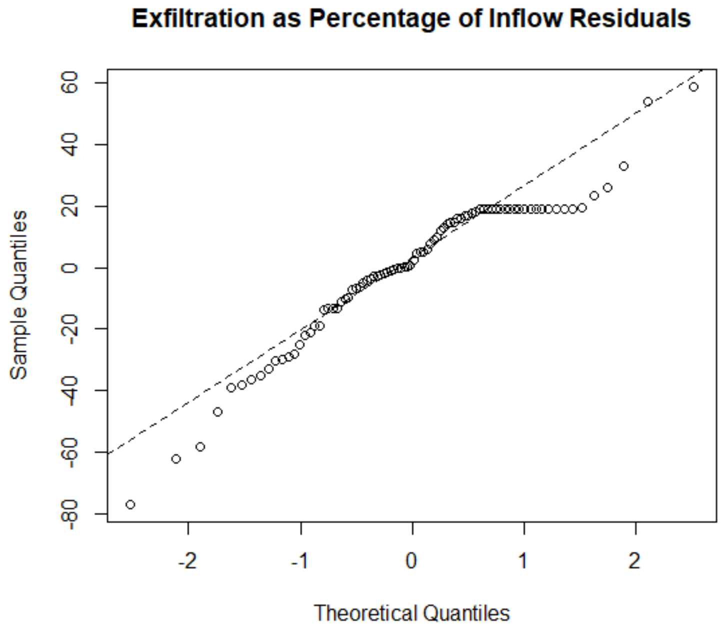

Figure 35. Residual plot for exfiltration regression equation

Implications of the Study

Each of the bioswale's outflow TN, TP, and TSS concentrations were compared to target effluent concentrations established by McNett et al. (2010) and NCDEQ (Water Quality Standards for High Quality Waters (2019). These thresholds were developed to gauge SCM nutrient treatment vis-á-vis the sensitivity of stream benthic macroinvertebrate populations. In the Piedmont ecoregion of North Carolina, "good-fair" thresholds for TN and TP are 1.17 and 0.13 mg/L, respectively (McNett et al., 2010); the TSS standard for high quality waters is 20 mg/L (Water Quality Standards for High Quality Waters, 2019). Exceedance probabilities for the TN "good-fair" threshold was between 0 and 76% (Table 49; Figure 36). Except for BS4, the bioswales exceeded the threshold at most 35% of the time. These results suggest that bioswales are an effective SCM to use in watersheds with TN regulations. The exceedance probabilities for the TP "good-fair" threshold were 17 from 100% Table 50; Figure 37), and the exceedance probabilities for the TSS high-quality waters standard ranged from 22 to 82% (Table 51; Figure 38). The bioswales most likely exceeded the TP and TSS thresholds more often than the TN threshold because of the resuspension of particles (Bäckström, 2003; Luell et al., 2021; Stagge et al., 2012).

Table 49. TN thresholds and bioswale exceedance probabilities (McNett et al., 2010)

Bioswale/Threshold	Excellent (0.69 mg/L)	Good (0.99 mg/L)	Good-Fair (1.17 mg/L)	Fair (2.16 mg/L)	Poor (7.59 mg/L)
BS2 (%)	59	0	0	0	0
BS4 (%)	100	83	76	20	0
BSN (%)	75	28	15	0	0
BSS (%)	45	21	19	0	0
Bioswale #3 with IWS (%)	100	64	35	0	0
Bioswale #6 without IWS (%)	78	31	0	0	0
Bioswale #6 with IWS (%)	100	0	0	0	0

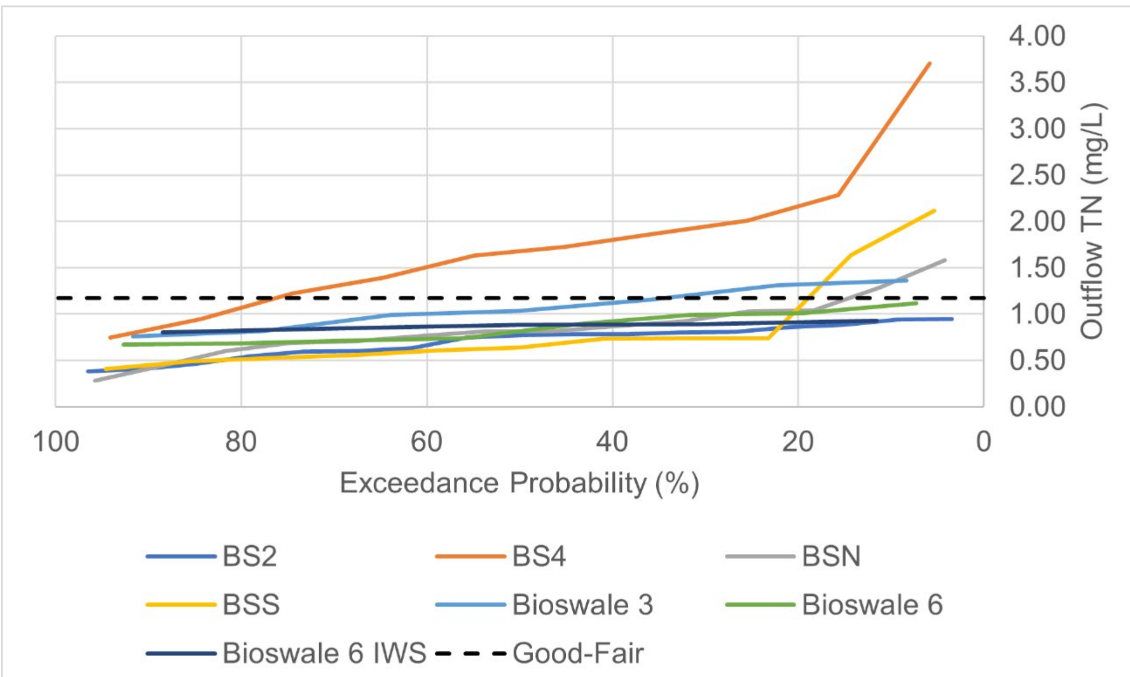

Figure 36. Exceedance probability plot for outflow TN concentrations (McNett et al., 2010)

Table 50. TP thresholds and bioswale exceedance probabilities (McNett et al., 2010)

Bioswale/Threshold	Excellent (0.06 mg/L)	Good (0.11 mg/L)	Good-Fair (0.13 mg/L)	Fair (0.22 mg/L)	Poor (0.63 mg/L)
BS2 (%)	95	64	53	0	0
BS4 (%)	100	100	100	67	10
BSN (%)	95	80	73	19	0
BSS (%)	83	37	17	8	0
Bioswale #3 with IWS (%)	100				
Bioswale #6 without IWS (%)					
Bioswale #6 with IWS (%)					

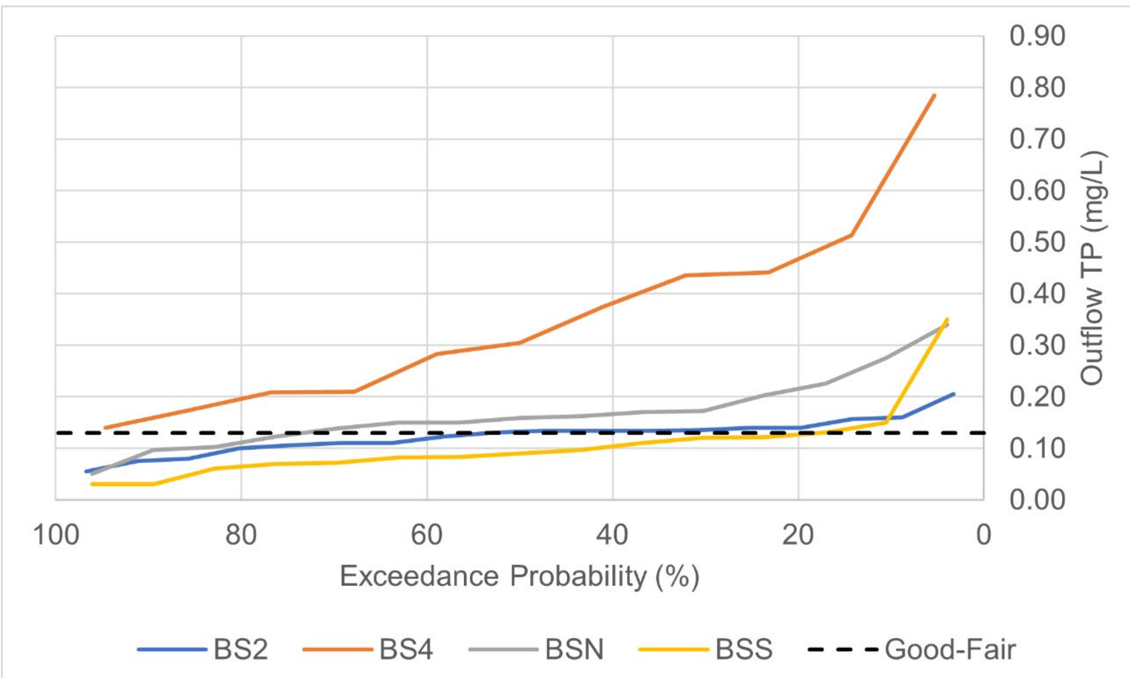

Figure 37. Exceedance probability plot for outflow TP concentrations without SECREF bioswales (McNett et al., 2010)

Table 51. TSS threshold and bioswale exceedance probabilities (Water Quality Standards for High Quality Waters, 2019)

Bioswale/Threshold	High Quality Waters (20 mg/L)
BS2 (%)	22
BS4 (%)	82
BSN (%)	35
BSS (%)	40
Bioswale #3 with IWS (%)	70
Bioswale #6 without IWS (%)	58
Bioswale #6 with IWS (%)	27

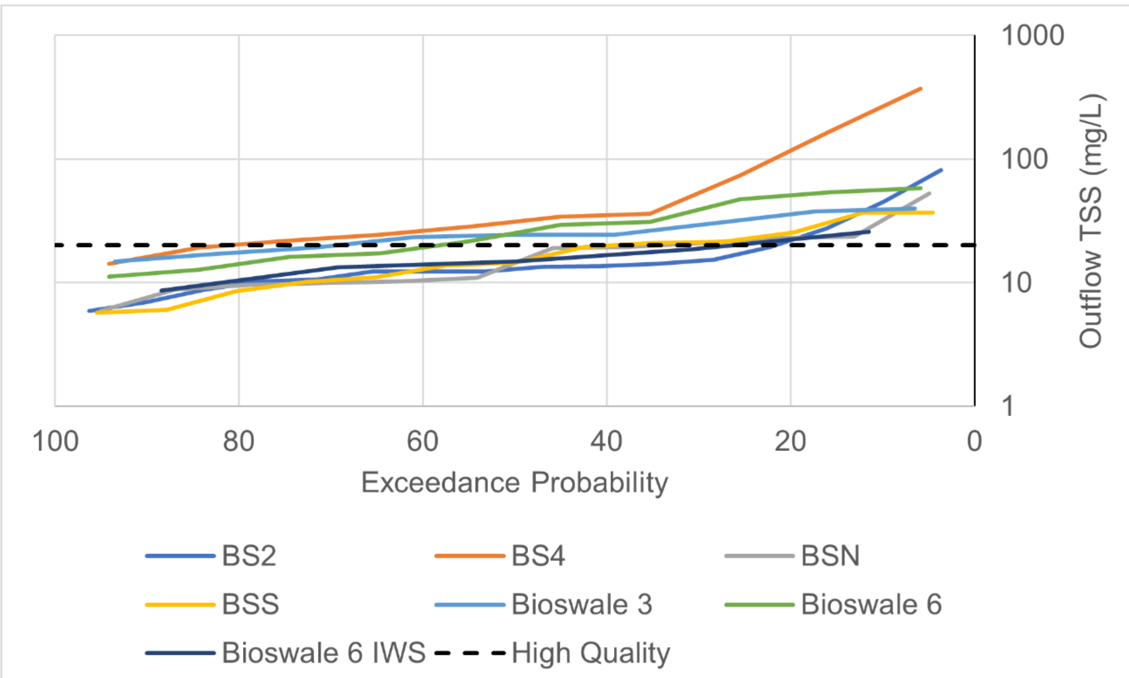

Figure 38. Exceedance probability plot for outflow TSS concentrations (Water Quality Standards for High Quality Waters, 2019)

Except for BS4, the TSS data indicated bioswales should be a primary SCM (Table 52) (NCDEQ, 2023). It is important to note the median TSS outflow concentration for BS4 only exceeded the effluent target of 25 mg/L by 3 mg/L. Typical SCMs used to treat highway runoff include filter strips, swales, and dry detention ponds (e.g., Boger et al., 2018; Luell et al., 2021; Wissler et al., 2020), which are easy to maintain and do not have constantly ponded water. However, these SCMs are considered secondary practices by NCDEQ. Designating bioswales as a primary practice would provide designers with an option to treat and convey highway runoff without ponding water to meet nutrient regulations. Using the data from the field-scale bioswales, the proposed effluent TN and TP concentrations for bioswales are 0.79 and 0.14

mg/L, respectively. These concentrations were determined using NCDEQ's New Stormwater Technology (NEST) procedure for practices applying to become approved SCMs in North Carolina (NCDEQ, 2023). The process includes screening influent concentrations using standards for TN (0.71 mg/L) and TP (0.05 mg/L) and then using the median of the effluent concentrations associated with the screened influent concentrations to propose concentrations for the state's SCM crediting document.

Table 52. Bioswale primary or secondary designation

Bioswale	Median TSS Inflow (mg/L)	Median TSS Outflow (mg/L)	Median Percent Removal (%)	Designation
BS2	27	12	34	Primary
BS4	80	28	66	Secondary
BSN	58	15	72	Primary
BSS	31	14	57	Primary

Proposed Design Criteria

Currently, there is a lack of design guidance for bioswales in North Carolina. The results from this study have resulted in preliminary design criteria that should be refined with future studies (Table 53):

Table 53. Proposed design criteria for bioswales in North Carolina

Bioswale Design Characteristic	Description
Length: watershed area	75 ft of bioswale per 1 ac of watershed area
Bottom width	Minimum of 3.0 ft
Side slope (H:V)	Maximum of 3:1
Conveyance	10-yr storm
Forebay	Include in the design
IWS	Include in the design for hydrologic soil group A and B soils Do not include in the design for hydrologic soil group C and D soils
Check dams	Include in the design

- Length: watershed area: the minimum bioswale length included in the study was 25 feet, and the bioswale had a watershed area of 0.32 ac (Table 5). The regression analysis found bioswale length is not a significant design characteristic (α = 0.05) for estimating overflow, underdrain, or exfiltration volumes as a percentage of inflow. It is possible the bioswales included in this study were sufficiently long to reduce overflow and thus increase the amount of runoff exfiltrated or discharged via an underdrain. The minimum length of bioswale required to exfiltrate or discharge runoff via an underdrain could be between 0 and 25 ft.

- Bottom width: the bioswales included in the study had a minimum bottom width of 3.0 ft. Width was a significant design characteristic for reducing overflow and increasing underdrain flow or exfiltration as a percentage of inflow.
- Side slope: each of the monitored bioswales had a side slope of 3:1. Ekka et al. (2021) recommends a minimum side slope of 3:1 to improve TN, TP, and TSS removal.
- Conveyance: the bioswale should be designed to convey the 10-yr storm to ensure vehicular safety concerns are adequately considered and mitigated. This is also in line with the current design standards for water quality swales (NCDEQ, 2020).
- Forebay: the inclusion of a forebay was a significant design characteristic for reducing overflow, and except for BS2 each of the monitored bioswales had a forebay. Forebays provide additional storage and can help reduce peak discharges. Forebays also help reduce maintenance burdens.
- IWS: IWS was a significant design characteristic for increasing overflow as a percentage of inflow. The hydrologic data from bioswale #3 and bioswale #6 with IWS support this finding from the regression analysis.
- Check dams: the inclusion of check dams was a significant design characteristic for increasing underdrain flow as a percentage of inflow. However, hydrologic data from bioswale #1 with check dams, BS2, and BS4 indicate check dams encourage exfiltration, especially for small to moderate storms (< 1.5 in) and help bioswales function as detention devices. Additionally, Ekka et al. (2021) recommends including check dams to improve TN, TP, and TSS removal.

Summary and Conclusions

Four plot-scale (bioswales #1, #3, #4, and #6) and field-scale bioswales (BS2, BS4, BSS, and BSN) were monitored for water quality and hydrologic improvement by NC State University. The following conclusions were drawn from the study:

- Check dams can improve exfiltration, or the volume reduction provided by bioswales, especially for bioswales that have a longitudinal slope greater than 1%. For bioswale #1 (4% slope), the amount of exfiltration as a percentage of the total inflow volume increased from 27 to 47% with the inclusion of check dams. BS2 (1.79% slope) and BS4 (2.93% slope) had two and three check dams, respectively and infiltrated 48 and 85% of small storm events (< 1.50 in), respectively.

- IWS most likely contributes to increased overflow. For bioswale #6, the percentage of overflow increased from 13 to 24% with the inclusion of IWS. Statistical analyses also showed that IWS was a significant design characteristic for increasing overflow when calculated as a percentage of inflow.
- TN, TP, and TSS outflow concentrations from the plot-scale and field-scale bioswales were less than concentrations monitored for swales with and without check dams (Knight et al., 2013; Luell et al., 2021; Stagge et al., 2012). Except for BS4, the field-scale bioswales only exceeded the "good-fair" threshold for TN (1.17 mg/L) (McNett et al., 2010) at most 35% of the time. This suggests bioswales are an effective SCM to use for watersheds with TN regulations. Bioswales most likely exceeded the "good-fair" threshold for TP (McNett et al., 2010) and the high-quality water threshold for TSS (Water Quality Standards for High Quality Waters, 2019) because of the resuspension of pollutants (Bäckström, 2003; Luell et al., 2021; Stagge et al., 2012).
- Data from the field-scale studies indicate bioswales should be designated as a primary SCM (NCDEQ, 2023). The proposed effluent TN and TP concentrations are 0.79 and 0.14 mg/L, respectively. A primary designation provides designers with an opportunity to meet water quality regulations adjacent to roadways without creating vehicular safety concerns due to ponded water.
- Important design characteristics to increase the likelihood of bioswales functioning as a detention rather than a conveyance device are the inclusion of a forebay and check dams. IWS may be included in bioswales with hydrologic soil group A or B in-situ soils. Length was not identified as a significant design characteristic for increasing exfiltration or discharge through an underdrain system. It is possible the monitored bioswales were sufficiently long to reduce overflow and thus increase the amount of runoff exfiltrated or discharged via an underdrain.
- Additional data are needed to develop a reliable model to predict overflow, underdrain, and exfiltration volumes as a percentage of inflow. The NSEs for the models ranged from -0.12 to 0.48, where 0.65 indicates the model is satisfactory to use (Ritter & Muñoz-Carpena, 2013). To prevent poorly performing models, future studies should ensure (1) the number of trials performed on plot-scale bioswales is equivalent, (2) the range of flow rates tested on plot-scale bioswales pre- and post-retrofit is comparable, and (3) hydrologic data can be reliably collected at each monitoring station for plot- and field-scale bioswales. The authors believe the inclusion of the BSN and BSS hydrologic data would have improved model performance.

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