RESEARCH & DEVELOPMENT

Dry Retention Optimization for Enhanced Application and Pollutant Removal

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NCDOT Project 2018-03
FHWA/NC/2018-03
January 2021

Dry Retention Optimization for Enhanced Application and Pollutant Removal: Controlled Plot Trials

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NCDOT Research Project 2018-03

Final Report

North Carolina Department of Transportation

January 2021

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Technical Report Documentation Page

1. Report No. 2018-03	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Dry Retention Optimization for Enhanced application and Pollutant Removal Controlled Plot Trials		5. Report Date January 2021 6. Performing Organization Code
7. Author(s) Amber Ellis William F. Hunt, III, PhD, PE		8. Performing Organization Report No.
9. Performing Organization Name and Address North Carolina State University 3100 Faucette Drive Raleigh, North Carolina 27695		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report January 2019 – January 2021 14. Sponsoring Agency Code
Supplementary Notes:		

16. Abstract

Dry detention basins (DDBs) are a common type of stormwater control measure (SCM) designed to mitigate the adverse impacts of increased runoff associated with urbanization. Under current standards, DDBs are primarily designed for issues related to water volume, such as flooding and erosion. However, attention is increasingly turning to issues of water quality. The documented water quality performance of standard DDBs varies widely, but pollutant removal is generally limited.

This study examined four retrofit designs and their abilities to improve DDB pollutant removal efficiency via a series of controlled plot trials conducted on a DDB at North Carolina State University's Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. Retrofit configurations included the addition of porous coir baffles (B), a floating skimmer outlet (S), and an internal water storage (IWS) system. A dual retrofit design that employed a skimmer outlet and porous baffles in tandem (S+B) was also included. Each of the four retrofit configurations and a standard DDB control design (C) were tested using pollutant-spiked water to simulate runoff from 0.5-, 1.0-, and 2.0-inch rain events from a 0.1 acre watershed. Each configuration was tested at each storm size in duplicate, resulting in n=6 for each design. Comparisons of influent and effluent concentrations of total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4^+), nitrate/nitrite nitrogen (NO_X), total nitrogen (TN), orthophosphate (OPO_4^-), total phosphorus (TP), and a series of dissolved metals (Cd, Cu, Pb, Zn) quantified water quality performance.

All basin configurations, including the control, significantly and substantially reduced TSS from the inlet to the outlet at rates higher than those reported in the literature and in crediting documents, but there was no evidence of differences in TSS removal among designs. While no particular basin configuration provided significantly better TN removal, data suggests that retrofits causing prolonged saturation (S, S+B, IWS) could improve denitrifications potential. The IWS basin captured TP at significantly higher rates than the other designs, but all effluent concentrations were substantially lower than the TP effluent concentration credit assigned by the North Carolina Department of Environmental Quality (NCDEQ). The optimal hydraulic retention time (HRT), highly controlled influent concentrations, and relatively large particle sizes could partially account for the observed TSS, TN, and TP removal. With the exception of the baffles basin exporting Cd, none of the configurations had any significant impacts on the effluent concentrations of the dissolved metals.

This study does not provide evidence that any of the analyzed basin configurations improve water quality treatment of DDBs in both significant and substantial ways, likely due to the high overall performance of every basin design. However, data trends suggest that retrofitting DDBs with an IWS system could improve cumulative load reductions through increased infiltration. Future research is needed to assess the hydrologic performance of IWS in DDBs.

17. Key Words	18. Distribution Statement
Detention basins, Runoff, Retrofitting, Skimmer, Baffles, Internal water storage	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

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Executive Summary

Dry detention basins (DDBs) are a common type of stormwater control measure (SCM) designed to mitigate the adverse impacts of increased runoff associated with urbanization. Under current standards, DDBs are primarily designed to mitigate issues related to water volume, such as flooding and erosion. However, attention is increasingly turning to issues of water quality. The documented water quality performance of standard DDBs varies widely, but pollutant removal is generally limited.

Methods

This study examined four retrofit designs and their abilities to improve DDB pollutant removal efficiency via a series of controlled plot trials conducted on a DDB at North Carolina State University's Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. Basin configurations included:

- the addition of porous coir baffles (B)
- a floating skimmer outlet (S)
- an internal water storage (IWS) system
- a dual retrofit design that employed a skimmer outlet and porous baffles in tandem (S+B)
- a standard DDB to be used as a control (C)

Each of the five configurations were tested using pollutant-spiked water to simulate runoff from 13-, 25-, and 50-mm rain events from a 400 m^2 watershed. Each configuration was tested at each storm size in duplicate, resulting in n=6 for each configuration. Water quality was quantified via comparisons of influent and effluent concentrations of the following parameters:

- total suspended solids (TSS)
- total Kjeldahl nitrogen (TKN)
- ammonia nitrogen (NH_4^+)
- nitrate/nitrite nitrogen (NO_X)
- total nitrogen (TN), orthophosphate (OPO_4^-)
- total phosphorus (TP)
- a series of dissolved metals (Cd, Cu, Pb, Zn)

Results

All basin configurations, including the control, significantly and substantially reduced TSS from the inlet to the outlet at rates higher than those reported in the literature and in crediting documents, but there was no evidence of differences in TSS removal among designs. While no particular basin configuration provided significantly better nitrogen removal, data suggests that retrofits causing prolonged saturation (S, S+B, IWS) could improve denitrifications potential. The IWS basin captured TP at significantly higher rates than the other designs, but effluent concentrations from all designs were substantially lower than the TP effluent concentration credit assigned by the North Carolina Department of Environmental Quality (NCDEQ). The optimal hydraulic retention time (HRT), highly controlled influent concentrations, and relatively large particle sizes could partially account for the observed TSS, TN, and TP removal. With the exception of the baffles basin exporting Cd, none of the configurations had any significant impacts on the effluent concentrations of the dissolved metals.

Recommendations

This study does not provide evidence that any of the analyzed basin configurations improve water quality treatment of DDBs in both significant and substantial ways, likely due to the high overall performance of every basin design. However, data trends suggest that retrofitting DDBs with an IWS system could improve cumulative load reductions. Future research is needed to assess the hydrologic performance of IWS in DDBs.

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List of Acronyms and Abbreviations

ANCOVA = Analysis of Covariance

B = Baffles Configuration

CAAE = Center for Applied Aquatic Ecology at NC State University

Cd = Cadmium

Cdi = Influent Dissolved Cadmium Concentration

Cdre = Dissolved Cadmium Removal Efficiency

Cu = Copper

DDB = Dry Detention Basin

DOC = Dissolved Organic Carbon

EMC = Event Mean Concentration

$EMC_{influent}$ = Influent Event Mean Concentration

$EMC_{effluent}$ = Effluent Event Mean Concentration

HRT = Hydraulic Residence Time

IWS = Internal Water Storage

K_{SAT} = Saturated Hydraulic Conductivity

MPD = Modified Philip-Dunn

MRE = Mean Removal Efficiency

NCDEQ = North Carolina Department of Environmental Quality

NCDOT = North Carolina Department of Transportation

NCSU = NC State University

NH_4^+ = Ammonia Nitrogen

NOi = Influent NO_X Concentration

NOre = NO_X Removal Efficiency

NO_X = Nitrate/Nitrite Nitrogen

NPDES = National Pollutant Discharge Elimination System

OPO_4^- = Orthophosphate

Pb = Lead

PSD = Particle Size Distribution

RE = Removal Efficiency

S = Skimmer Configuration

S+B =Skimmer and Baffles Configuration

SECREF = Sediment and Erosion Control Research and Education Facility

SCM = Stormwater Control Measure

TKN = Total Kjeldahl Nitrogen

TP = Total Phosphorus

TSS = Total Suspended Solids

Zn = Zinc

Introduction

As the population across the United States continues to urbanize, proper stormwater management is crucial to the health and preservation of our water resources (US EPA, 2003). With increased development comes an increase in an area's impervious surface coverage. By limiting the ability of water to naturally infiltrate into the soil, impervious surfaces increase the volume and velocity of the landscape's associated runoff during storm events, resulting in flooding, erosion, ecosystem disturbances, property damage, and public safety issues (Paul & Meyer, 2001). Among the many tools stormwater engineers have at their disposal to mitigate these adverse impacts is the dry detention basin (DDB), but DDB's have historically been designed primarily to address the issues of flooding and erosion, with minimal regard for pollutant removal (Stanley, 1996).

Research focused on other stormwater control measures (SCMs) as well as sediment and erosion control practices suggests that simple retrofit design elements could improve the water quality performance of DDBs. The addition of porous baffles and a skimmer outlet have improved the particulate pollutant removal of sedimentation basins (Thaxton & McLaughlin, 2005), while installing an internal water storage (IWS) system improved the overall water quality treatment of both permeable pavement systems and bioretention cells (Wardynski et al., 2013; Brown & Hunt, 2011). The potential for porous baffles, a skimmer outlet, and an IWS system to improve a DDB's water quality performance is the subject of this study.

Result of Literature Review

Current Design and Performance

In the United States, the EPA regulates stormwater discharge as a part of the National Pollutant Discharge Elimination System (NPDES) (Clean Water Act, 33 U.S.C. §1251 *et seq.*, 1972). Under the NPDES program, the EPA delegates permitting and regulatory authority to the state governments. This division of authority results in a variety of design standards and performance thresholds across the nation. Most DDBs, however, share several design elements. DDBs are typically shallow, grassed depressions that collect runoff during storm events and release it slowly over time (NCDOT, 2012).

Standard design for DDBs includes a small drawdown orifice at the bottom of the basin such that peak flow out is much lower than peak flow into the basin for a given design storm (Middleton & Barrett, 2008). This drawdown orifice is typically housed within a larger, multi-stage riser structure that allows the DDB to pass large storms safely and with some peak flow mitigation. Some states have additional design requirements, such as trash racks, to help prevent clogging and filter debris (NCDEQ, 2017a). In all cases, water immediately begins draining from the DDB upon entering, and little or no water stays in the basin indefinitely or between storm events. Therefore, DDBs provide modest particulate pollutant removal via sedimentation. However, recent research suggested that other pollutant removal mechanisms could be employed through basin modification (Middleton & Barrett, 2008; McPhillips & Walter, 2015).

Published mean DDB pollutant removal efficiency data varied widely with geographic location, specific pollutant, and DDB sizing (Table 1). Differences in storm size, influent concentration, and meteorological conditions lead to performance variation within the same basin in ways that have not yet been directly quantified or modelled (Shammaa et al., 2002).

Because peer-reviewed studies were conducted in different locations, under different conditions, and with different calculation methodologies, it was not possible to make direct comparisons. Additionally, the wide range of reported performance limited any generalized characterization of DDB removal efficiency. When taken together, however, DDBs generally removed particulate pollutants much better than dissolved pollutants. This trend is consistent with research that showed that the primary pollutant removal mechanism in DDBs is sedimentation (Middleton & Barrett, 2008).

Table 1. Mean pollutant removal efficiencies (%) in dry detention basin studies

	DDB Study									
	Birch et al. (2006)	Guo (1997)	Pope & Hess (1988)	Stanley (1996)	Schueler et al. (1992)					
Location	Sydney, Australia	NJ	Topeka, KS	Greenville, NC	VA1	VA2	MD1	MD2	TX	KS
Drainage Area (ac)	-	7,240	-	81,000	88	11.4	34	16.8	28	12.3
Design Storm (in)	-	-	-	0.5	-	0.22	0.3	0.5	0.5	3.42
Shape	Rectangular	Square	-	Square	-	-	-	-	-	-
TSS	40	65	2.5	68	14	51.5	70	87	30	3
TDP*	-	-	0	(-16)	-	-	-	-	-	-
PO_4*	-	-	-	19	-	-	-	-	-	-
PP	-	-	-	34	-	-	-	-	-	-
TP	(-5)	-	18.5	14	20	48	13	26	18	19
NO_x*	(-46)	-	20	(-8)	9	-	-	(-10)	52	20
NH_4*	-	-	69	(-2)	-	-	-	-	-	-
DKN*	-	-	-	(-11)	-	-	-	-	-	-
TKN	56	-	-	-	-	30	-	-	-	-
PN	-	-	-	47	-	-	-	-	-	-
TN	28	-	-	26	10	42.5	24	-	35	-
Cd	-	-	-	24	-	-	-	-	-	-
Cr	0	-	-	42	-	-	-	-	-	-
Cu	23	-	-	29	-	-	-	-	31	-
Fe	3	-	-	-	-	-	-	-	-	-

Mn	43	-	-	-	-	-	-	-	-	-
Ni	1	-	-	40	-	-	-	-	-	-
Pb	41	-	66	44	-	32	62	-	29	66
Zn	41	-	65	27	(-10)	32	57	-	(-38)	65

* Indicates dissolved pollutant species

Analyzed parameters include: total suspended solids (TSS), total dissolved phosphorus (TDP), orthophosphate (PO_4), particulate phosphate (PP), total phosphate (TP), nitrate/nitrite (NO_x), ammonia (NH_4), dissolved Kjeldahl nitrogen (DKN), total Kjeldahl nitrogen (TKN), particulate nitrogen (PN), and total nitrogen (TN)

Porous Baffles

Porous baffles are permeable barriers that transect the flow path within a practice and are commonly used in sedimentation basins to treat construction runoff (Figure 1). In a set of controlled field experiments, Thaxton and McLaughlin (2005) demonstrated that the presence of porous jute/coir baffles increased the sediment capture effectiveness of a sediment retention pond, as compared to (1) a pond without baffles and (2) a pond with baffles made of different materials. While the study was conducted on a sediment retention pond rather than a DDB,

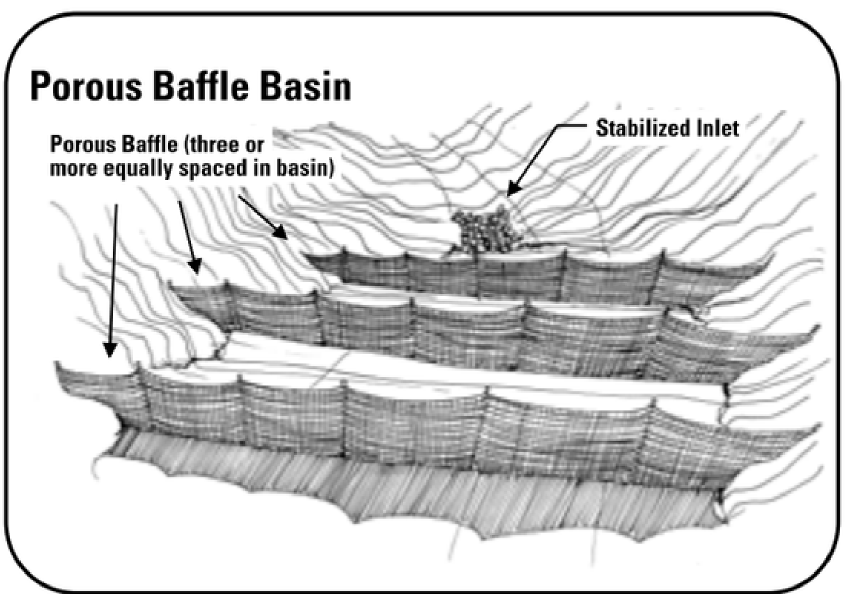

Figure 1. Typical sediment basin with baffles (McLaughlin, 2015)

sedimentation is the primary pollutant removal mechanism for both, and their construction is quite similar (Thaxton & McLaughlin, 2005).

Research conducted by Vaze and Chiew (2004) indicated that capturing smaller particles is critical for improving water quality. Sediment is a pollutant to which other pollutants readily adsorb, such as heavy metals and nutrients (Hunt & Lord, 2006). In stormwater, dissolved nitrogen and phosphorous comprise only 20 - 50% of the total nutrient load, with the remainder attached primarily to small sediment particles (Vaze & Chiew, 2004). While nearly half of the sediment load associated with runoff is of the coarsest fraction, the coarsest particles carry less than 15% of the associated nutrient load (Vaze & Chiew, 2004).

Skimmer Outlet Structures

Sediment capture can be improved by employing a skimmer. A skimmer is a specialized outlet structure that discharges water from the pond's surface, rather than the pond's bottom (Millen et al., 1997). While other designs are currently being researched (Pilon et al., 2016), a skimmer typically consists of a buoyant head containing a small orifice that is connected to the main outlet pipe at the bottom of the basin via a series of pipes and flexible hoses (Figure 2). This allows the basin to dewater at a constant rate from the top of the water column where water contains the least amount of sediment (Millen et al., 1997). In this way, skimmer outlet

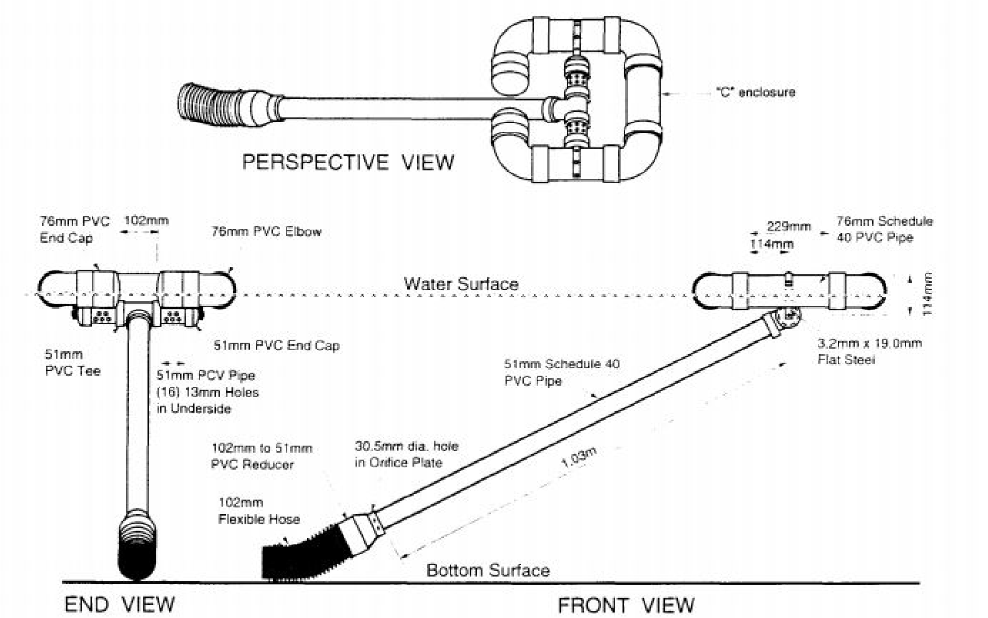

Figure 2. Typical Skimmer Outlet Device (Millen et al., 1997)

modification increases sedimentation without requiring hydraulic residence time to increase (Jarrett, 2001; Pilon et al., 2016).

In a set of field experiments, the addition of a skimmer outlet device reduced effluent TSS concentrations by 45% and decreased the average size of the captured particles (Millen et al., 1997). While all basins captured 100% of particles over 75 µm, the basin with the skimmer outlet captured 10% more particles between 6 and 12 µm (Millen et al., 1997). Jarrett (2001) conducted another series of controlled experiments with similar results. The basin with a typical drawdown orifice exported 1.8 times more TSS than the basin with a skimmer outlet, despite each having the same hydraulic residence time (Jarrett, 2001).

Skimmer Outlet and Porous Baffles

The North Carolina Department of Transportation's (NCDOT) standard skimmer sedimentation basin employs a skimmer outlet and porous baffles in tandem (Figure 3; NCDOT, 2015). In a monitoring study conducted by McCaleb and McLaughlin (2008), this configuration captured 99% of influent sediment with proper maintenance, while basins with traditional outlet structures and no baffles captured <40%. Skimmer maintenance was a factor in performance, however,

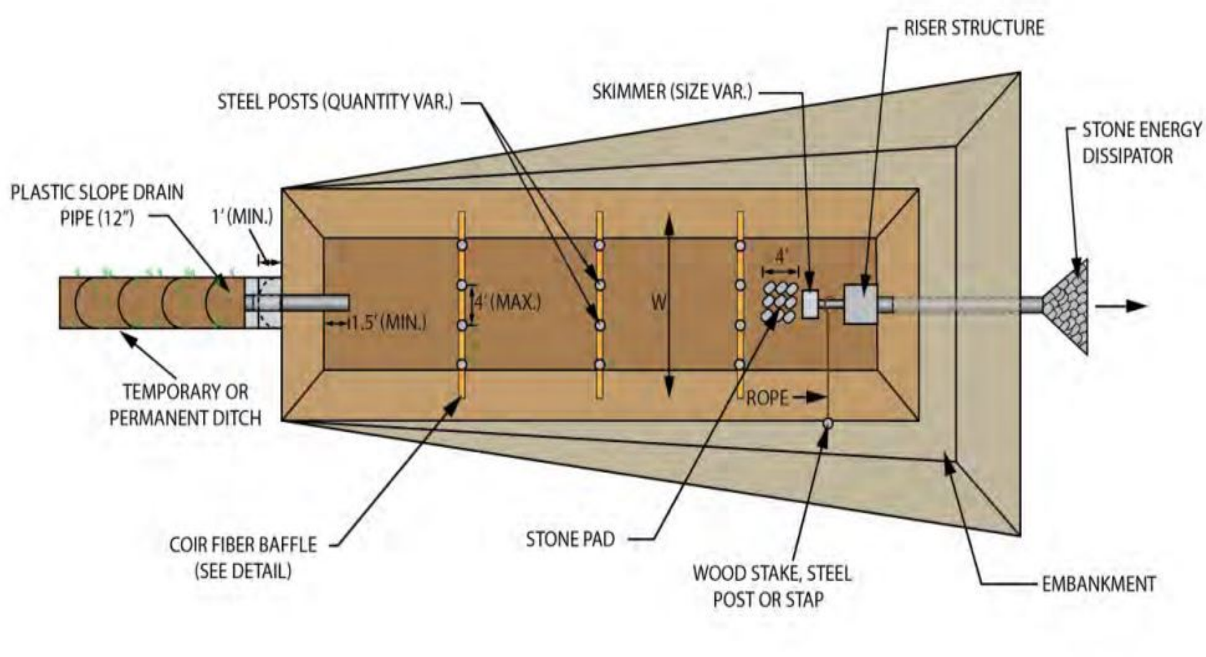

Figure 3. Typical sediment basin with porous baffles and a skimmer outlet (NCDOT, 2015)

and when it became “mired in sediment” the basin captured only 76% of TSS (McCaleb & McLaughlin, 2008). In a subsequent monitoring study, the inclusion of a skimmer outlet had negligible impact on TSS removal in a sediment basin equipped with porous baffles and polyacrylamide treatment (a flocculating agent) (McLaughlin et al., 2009).

Internal Water Storage (IWS)

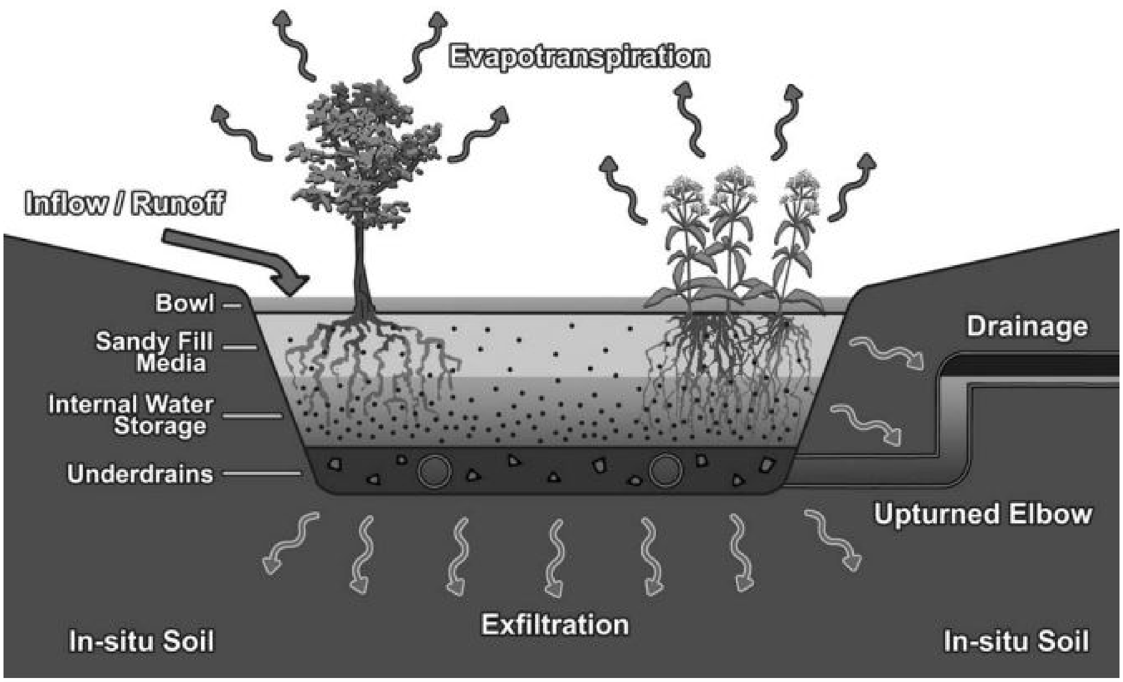

Figure 4. Bioretention cell schematic showing the location of IWS (Brown et al., 2009)

Internal Water Storage (IWS) is a specific type of a subsurface saturation zone that has been studied within the context of various SCMs. Typically found in filtration practices with underdrains, IWS uses an elevated outlet to store water below the surface and within a fill media (Figure 4). When implemented within bioretention cells in North Carolina and Texas, IWS systems increased the removal of NO_X, suggesting the creation of an anoxic environment that induced denitrification (Brown & Hunt, 2011; Li et al., 2014). However, the presence of an IWS system did not guarantee saturation or the accompanying conditions that are conducive to denitrification. Rather, it was dependent on underlying infiltration rates and media composition (Hunt et al., 2012). If runoff exfiltrated too quickly, anoxic conditions did not form, and

Figure 4. Bioretention cell schematic showing the location of IWS (Brown et al., 2009)

While it can limit denitrification in IWS systems, increased exfiltration improved SCMs’ removal of pollutant loads (Hunt et al., 2012). By reducing the total runoff volume entering receiving waterways, exfiltration in SCMs necessarily reduces the associated pollutant loads while simultaneously providing additional peak flow mitigation. IWS use in bioretention and permeable pavement designs yielded higher removal efficiencies for dissolved pollutant loads, even among low hydraulic conductivity in clay soils (Hunt et al., 2006; Wardynski et al., 2013). Even among clay soils with low hydraulic conductivity, permeable pavement systems with IWS resulted in a 22% volume reduction via exfiltration (Braswell et al., 2018).

While exfiltration is currently a minimal consideration in the construction and performance of standard DDBs (NCDEQ, 2017b), it can be the primary dewatering mechanism, and many DDBs can completely dewater in less than seven days through exfiltration alone (Bidelspach et al., 2004). However, infiltration-dependent designs are project-specific, as infiltration rates depend on the site conditions and underlying soil characteristics (NCDEQ, 2017b). Because IWS retrofits decrease DDB storage capacity with the addition of a fill media and retain water inter-event, if infiltration rates are sufficiently low, flooding risks can increase during successive storm events (Papa et al., 1999).

Discussion and Future Work

At the present, the majority of DDB research is conducted through field monitoring alone (McPhillips & Walter, 2015; Middleton & Barrett, 2008; Birch et al., 2006; Stanley, 1996). While field monitoring is a valuable way to assess DDB function, the lack of controlled variables makes it difficult to compare DDB design variations among various studies. Researchers are reliant on (often unpredictable) weather during field monitoring, leading to small data sets and difficulty in drawing conclusions.

To directly analyze whether the retrofit options outlined in this paper will improve DDB water quality treatment, a plot study was used to test a control against multiple design adjustments. Having a robust and extensive set of experimental data that mimics field conditions but controls for variables that are not being directly analyzed is key. A series of designed experiments that controls for variables such as geographic location, influent concentration, storm size, and HRT allowed for a direct comparison of pollutant removal performance between basin designs and retrofit options.

Materials and Methods

QAPP Process

An original QAPP was submitted to and approved by DOT in April 2019, however, changes were made in July 2019 to the proposed antecedent dry period. However, further changes were jointly decided upon by NCSU and NCDOT in May 2020 in response to the covid-19 pandemic as well as preliminary lab results. Originally, all configuration and storm size combinations were to be performed in triplicate (n=54). Combinations were, instead, performed in duplicate (n=36) to accommodate the abridged timeline presented by the covid-19 pandemic. Additionally, the NCSU-BAE lab was to perform the sample analysis with some duplicates analyzed by the EPA certified lab at NCSU's Center for Applied Aquatic Ecology (CAAE) for comparison. After unsatisfactory performance regarding blank analysis and holding times in the BAE lab, all samples were to be analyzed by CAAE. The result was that only 3 trials (all baffles basin configuration trials) from 2019 were included in the final data set, and all others were completed in 2020.

The updated QAPP reflecting these changes and the ultimate experimental protocol was officially submitted in July 2020 and is attached to this report.

__Site Description and Constraints__

The controlled plot trials were conducted at NC State University's (NCSU) Sediment and Erosion Control Research and Education Facility (SECREF), located on Lake Wheeler Road in

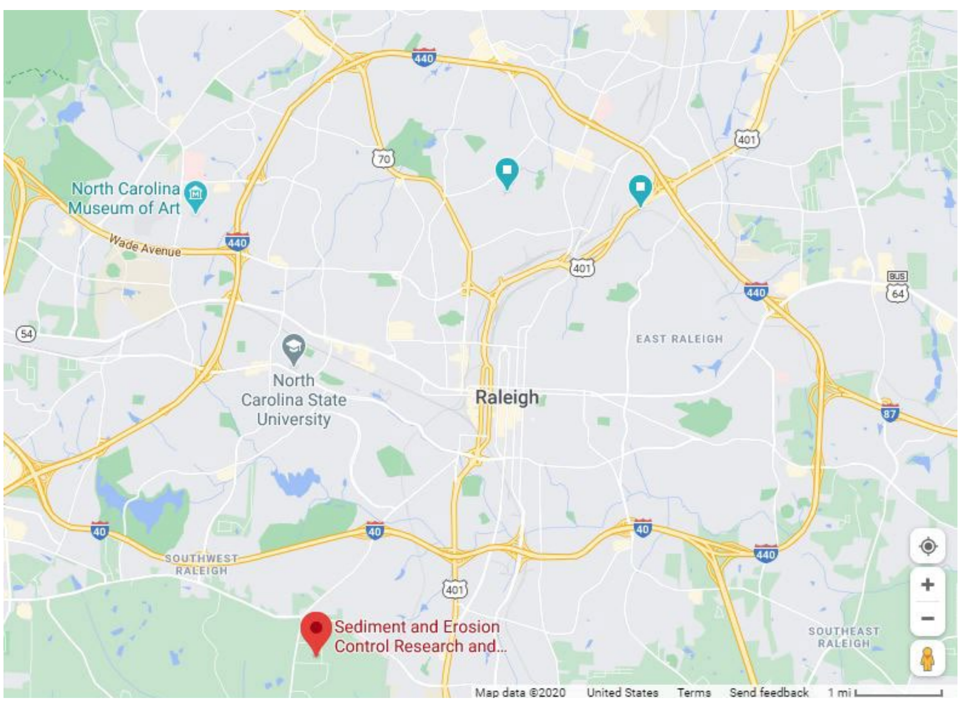

Figure 5. NCSU's Sediment and Erosion Control Research and Education Facility location (Google Maps, 2020)

Raleigh, NC (Figure 5). SECREF is five miles from NCSU's campus and hosts educational workshops and research projects pertaining to stormwater management and sediment and erosion control.

DDB Characterization

A pond was converted into a DDB and retrofitted with each design configuration. The resulting DDB was approximately 30 ft long, 15 ft wide, and held a maximum volume of approximately 1000 ft^3 (Figure 6, Table 2). A stage-storage table was calculated using survey data and AutoCad Civil 3D 2021 (Autodesk, San Rafael, CA). Side slopes varied from 3:1 to 1:1, with the steepest slopes being near the outlet.

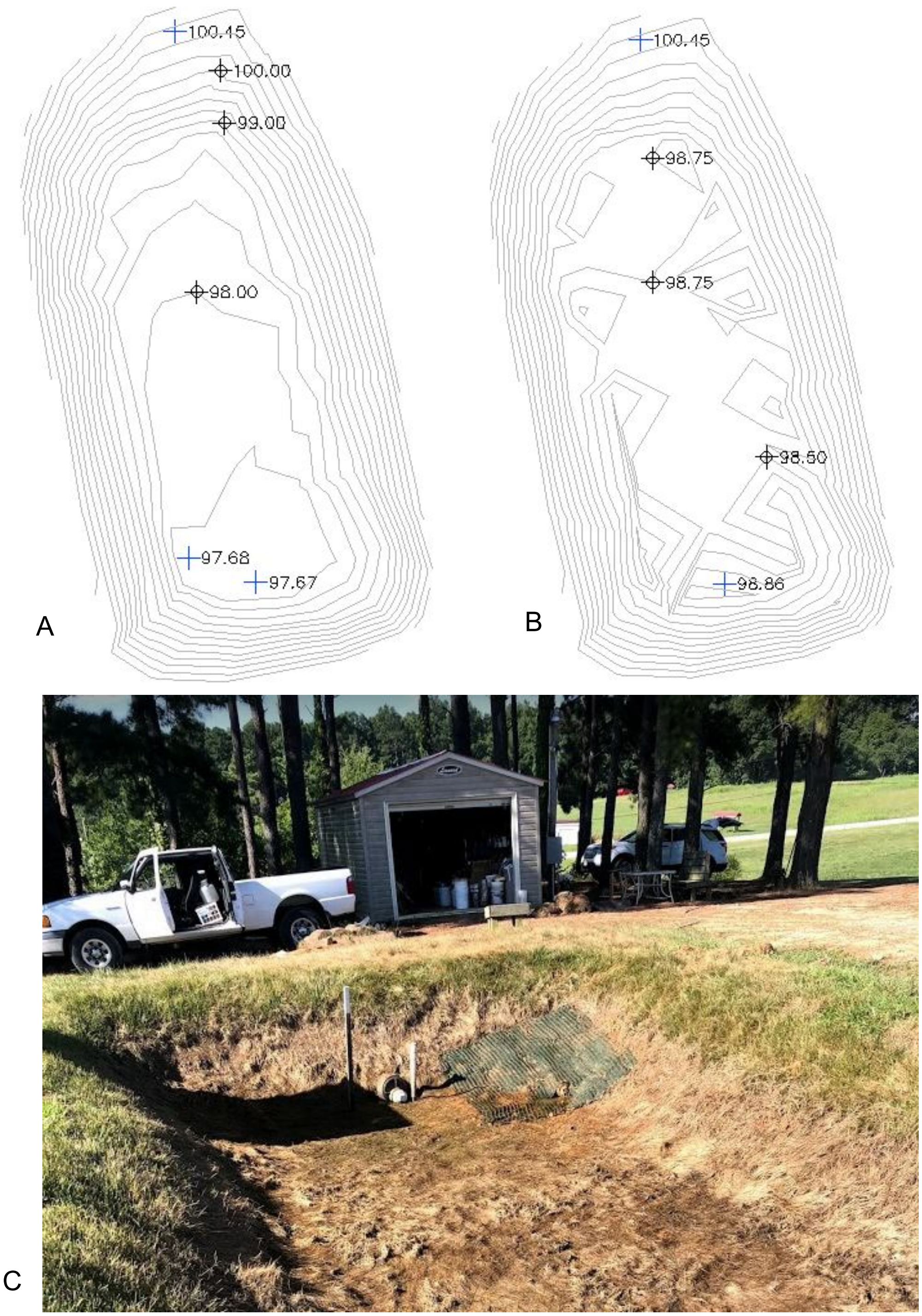

Figure 6. Trial DDB topography with the inlet noted at the top (100.45'). A. Basin with skimmer connection (97.68') and control outlet (97.67') elevations noted. C, B, S+B, and S basins all shared this topography B. Basin with IWS topography and outlet elevation noted C. Control basin drawdown position (figure is not representative of vegetation during trials)

Table 2. Control DDB stage-storage table

Contour Elevation (ft)	Contour Area (ft^2)	Incremental Depth (ft)	Average End Method		Conic Method	
			Incremental Volume (ft^3)	Cumulative Volume (ft^3)	Incremental Volume (ft^3)	Cumulative Volume (ft^3)
97.75	46.08	N/A	N/A	0.00	N/A	0.00
98.00	137.68	0.25	22.97	22.97	21.95	21.95
98.25	204.41	0.25	42.76	65.73	42.49	64.44
98.50	255.69	0.25	57.51	123.24	57.39	121.83
98.75	302.03	0.25	69.72	192.96	69.63	191.47
99.00	337.05	0.25	79.89	272.84	79.85	271.31
99.25	368.18	0.25	88.15	361.00	88.13	359.44
99.50	399.41	0.25	95.95	456.95	95.92	455.36
99.75	431.89	0.25	103.91	560.86	103.89	559.25
100.00	467.22	0.25	112.39	673.25	112.36	671.61
100.25	504.17	0.25	121.42	794.67	121.40	793.00
100.50	538.94	0.25	130.39	925.06	130.36	923.36

Hydrology

Soil saturated hydraulic conductivity (K_{SAT}) measurements were attempted using a Modified Philip-Dunn (MPD) Triple Infiltrometer (Upstream Technologies, New Brighton, MN) (ASTM, 2018). Three separate attempts each produced a K_{SAT} of effectively zero. A full-basin retention test was also conducted by filling the basin and monitoring the water level to assess side slope infiltration rates. The water level dropped less than 0.5 inches in 48 hours.

An earthen dam replaced a metal sluice gate during the DDB's initial construction. After preliminary hydrology and infiltration tests, water began seeping through the dam during trials at variable and hard to measure rates. Given these constraints, this study focused solely on the water quality treatment provided by DDBs as quantified by pollutant event mean concentrations (EMCs), rather than by total load reductions or any metrics of hydrologic performance.

Retrofit Configuration Descriptions

This study compares the water quality treatment of four DDB retrofit design additions: porous baffles, skimmer outlet, porous baffles and skimmer outlet, and an IWS system. These retrofit configurations were also compared to a standard, or control, DDB design.

Control

The control configuration was constructed in accordance with standard DDB guidance and requirements (NCDEQ, 2017c). This included a 0.5-inch drawdown orifice drilled into the PVC outlet pipe cap (Figure 7) positioned on the DDB's bottom (Figure 8). Fescue sod was installed during construction but prolonged inundation inhibited growth (Figure 6c). Volunteer vegetation was allowed to colonize the DDB and covered approximately 95% of the surface area at the time of trials (Figure 8). No vegetative maintenance (mowing, trimming, etc.) occurred in the DDB during the four months of testing. While some DDBs in residential or highly trafficked areas may receive regular vegetative maintenance, many on commercial and government properties are only mowed once or twice a year (NCDOT, 2010). NCDOT, for example, lists no required, mowing interval for DDB's in its maintenance and inspection manual (NCDOT, 2010). Maintenance conditions for this study are, therefore, reflective of field conditions experienced by many DDBs.

Figure 7. Baseline outlet orifice drilled into outlet pipe cap

Figure 8. Control DDB configuration with representative vegetation

Porous Baffles

Two porous coir baffles with 0.5-inch openings (65 g/ft^2) (Figure 9), were installed across the width of the basin in the standard, double layer design achieved by folding over the baffle material. The baffles were 3-ft high, placed every 10-ft along the basin length (Figure 10, Figure 11), and constructed according to NCDOT's standard specifications with one important divergence (NCDOT, 2012). Design standards require metal posts and hanging wire to secure the baffles, but because dissolved metals were a parameter of study, these were replaced with wooden posts and nylon wire to avoid introducing additional metals. The same outlet structure was used as described for the control. Due to the previously detailed need to switch labs during the middle of the project, half of the baffles trials were conducted in the summer of 2019, while the other half were conducted in the summer of 2020. All construction, methods, and analyses were constant for both periods.

Figure 9. Coir baffle material

Figure 10. DDB with porous baffles

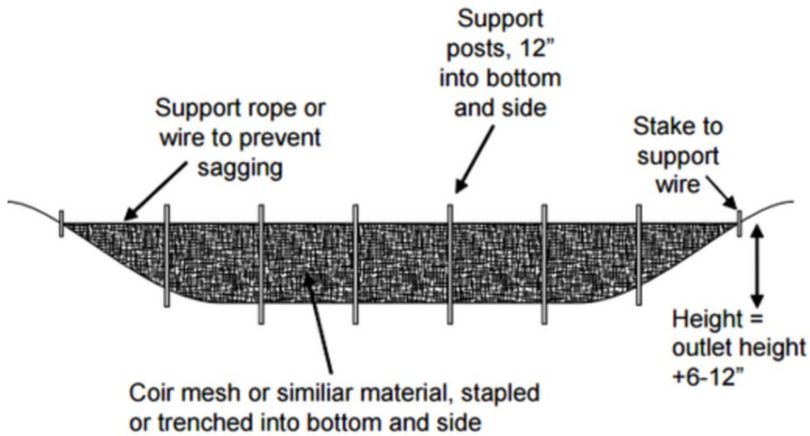

Figure 11. Baffle installation guidance (McLaughlin, 2015)

Skimmer

A 2.0-inch Faircloth Skimmer (J. W. Faircloth & Son, Inc., Hillsborough, NC) with a 0.5-inch drawdown orifice (Figure 12) was installed per the manufacturer's instructions (J.W. Faircloth & Son, Inc., 2020). Sizing was determined using the manufacturer's instructions such that the approximate drawdown times for each storm size were equivalent to those of other configurations. The skimmer was attached to an outlet pipe that was separate from the drawdown shared by the control, baffles, and IWS confirmations, but the two were in close proximity to one another within the DDB (Figure 13). The control outlet pipe remained in the basin during the skimmer trials but was capped. The configuration that employed the skimmer and baffles in tandem (Figure 14) used the same installation specifications previously detailed.

Figure 12. 2-inch skimmer with 13mm plug orifice

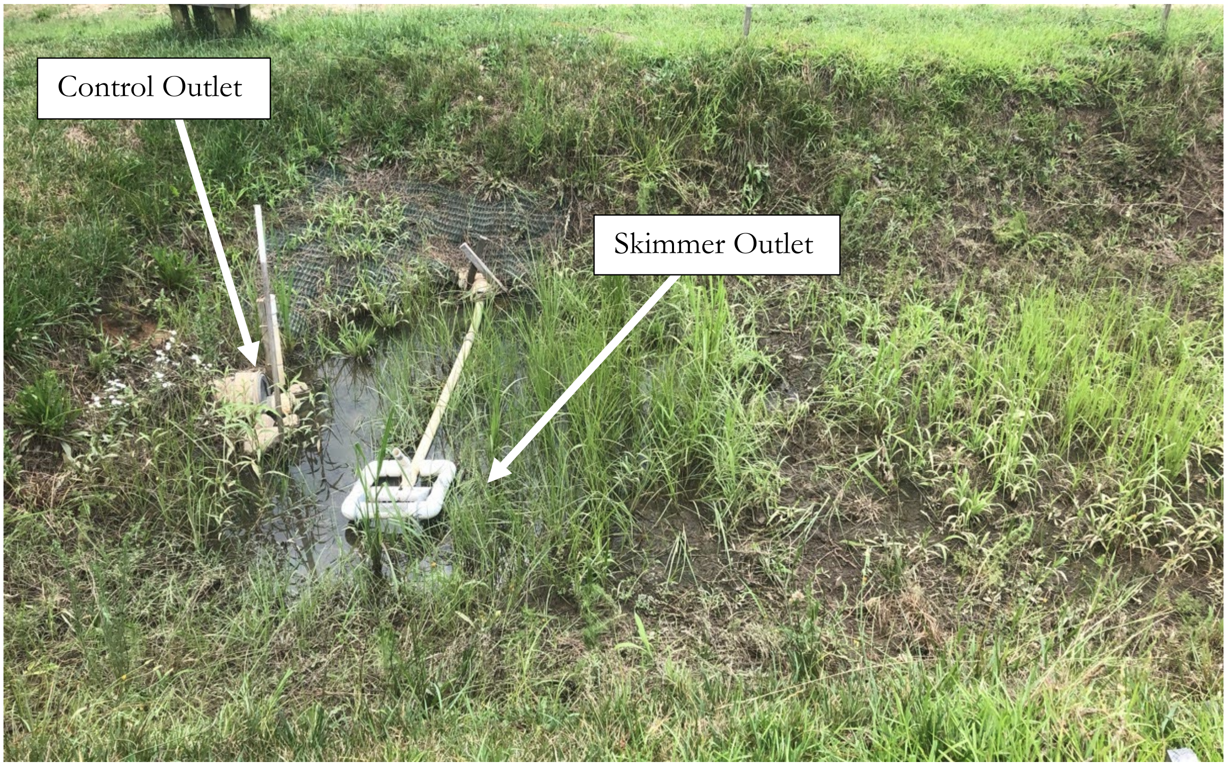

Figure 13. Skimmer outlet placement in relation to the control outlet (capped)

Figure 14. DDB configuration with porous baffles and skimmer in tandem (photo taken in 2019 before trials began)

Internal Water Storage (IWS)

To install the IWS system, the control drawdown orifice was elevated approximately 1-ft (Figure 15). This orifice elevation was roughly one-third the total depth of the basin and nearly one-half the maximum water depth of the largest storm. Washed #57 stone was used as fill up to the orifice level (Figure 16). This IWS design differs from many standard designs used in bioretention or permeable pavement systems (NCDEQ, 2017b) in that is contains no underdrain system. Site constraints and the existing outlet structure prevented the use of an underdrain, and an elevated orifice was used instead. The skimmer outlet shown in Figure 15 was capped.

Experimental Design and Set-Up

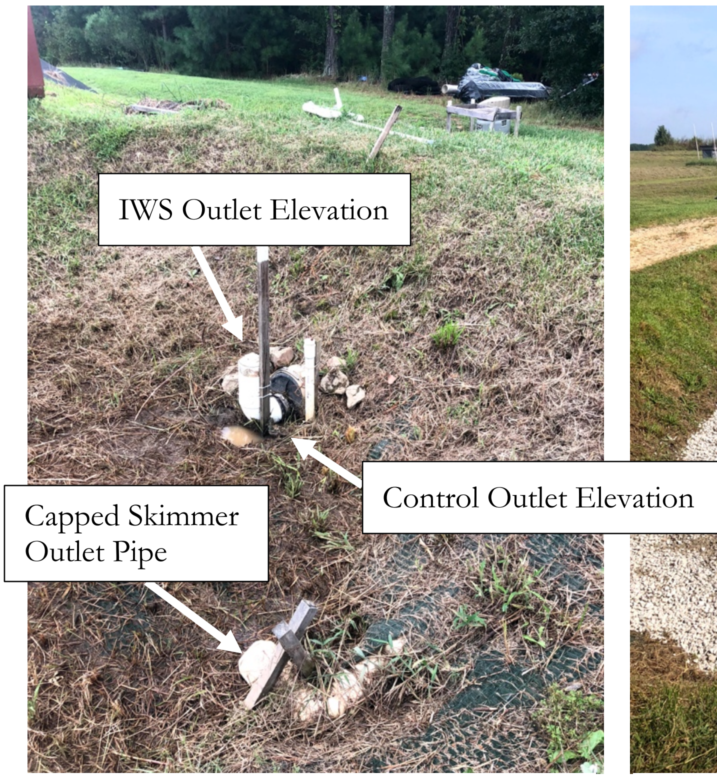

Figure 15. Elevated outlet orifice in IWS configuration pre-gravel installation

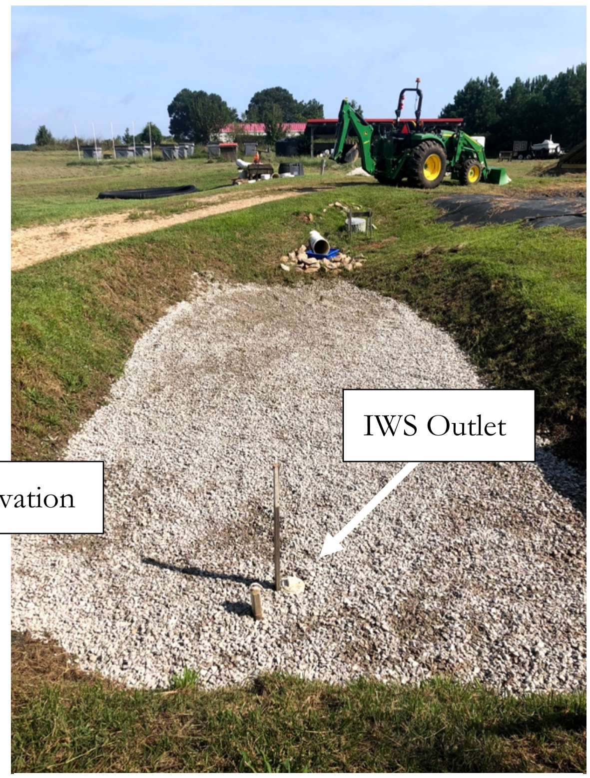

Figure 16. IWS basin configuration with #57 stone fill

5x3 Factorial Cross and Randomization

The controlled plot trials had a 5x3 full factorial design. The five basin configurations were crossed with three storm sizes (small, medium, and large), and each cross was replicated once, resulting in a total sample size of n = 30 (6 trials for each basin configuration) (Table 3).

Table 3. Controlled Plot Trials Replications: 5 x 3 Factorial Cross Design

Storm Size	Basin Configuration				
	Control	Baffles	Skimmer	Skimmer + Baffles	IWS
Small	2	2	2	2	2
Medium	2	2	2	2	2
Large	2	2	2	2	2

Trials could not be completely randomized based on basin configuration due to construction and installation constraints. Therefore, all 6 trials for a given basin design were completed consecutively before the next basin design was installed. The sequence of the 6 trials for each basin design was randomized with respect to storm size; however, this randomization was sometimes altered to maximize timeline efficiency according to the weather. For instance, if the randomized order called for a large storm but the forecast predicted rain within the drawdown period, a small or medium storm trial was conducted in its place, rather than postponing the trial. The implications of this randomization strategy are discussed along with statistical analysis.

Storm Sizes

The three storm sizes refer to increasing water depths within the experimental DDB. They are denoted “small,” “medium,” and “large,” and correspond to total volumes of approximately 200, 400, 800 ft^3, respectively. These storm sizes act as a proxy for hydraulic residence time (HRT), with the larger storms having a greater HRT. Because HRT impacts pollutant removal but is not the object of study (Shammaa et al., 2002), its systematic variation allowed for the associated effects to be statistically isolated and quantified.

The small, medium, and large storm trials occurred over the course of 20, 30, and 60 minutes, respectively, and took approximately 12, 18, and 24 hours to draw down (Table 4). Additionally, each storm was split into time steps, or increments of time, which determined the flow pacing for the trial and the storm’s inflow hydrograph.

Table 4. Storm size details summary

Storm Size	Approximate Volume (m^3)	Inflow Time (mins)	Approximate Outflow Time (hrs)	Time Step (mins)
Small	200	20	12	5
Medium	400	30	18	5
Large	800	60	24	10

Temperature and Influent Concentration Controls

Trials were only conducted when the ambient air temperatures were above 50°F, as lower temperatures increase water's viscosity, thereby decreasing sedimentation rates (Roseen et al., 2009). Influent concentration was controlled by pre-measuring pollutant inputs and adding them to ambient water to create synthetic stormwater runoff. Influent event mean concentration (EMC) targets were determined based on average concentrations from field data collected during other DDB studies within NCSU's Biological and Agricultural Engineering stormwater research group (Table 6; Wissler et al., 2020). Pollutant inputs were calculated by multiplying target concentrations (mg/L) by target storm volumes (L) (Table 5). Amounts of water-soluble chemical compounds containing each pollutant were pre-measured by mass in the lab and taken to the field for use in the trials.

Table 5. Pollutant spike values summary

Pollutant	Influent EMC Target (μg/L)*	Chemical Compound Added	Total Mass Added Per Storm (g)		
			Small	Medium	Large
TSS	48 mg/L	Soil	581.74	1201.54	2302.5
Total Nitrogen	1700	Sodium Nitrate ($NNaO_3$)	10.30	21.28	40.77
Total Phosphorus TP	280	Sodium Phosphate (Na_2HPO_4)	1.70	3.50	6.72
Cd	0.5	Cadmium Chloride ($CdCl_2$)	0.03	0.05	0.10
Cu	5.4	Copper Sulfate ($CuSO_4$)	0.07	0.14	0.26
Pb	20	Lead Nitrate (N_2O_6Pb)	0.06	0.13	0.25
Zn	28	Zinc Chloride ($ZnCl_2$)	0.34	0.70	1.34

*unless otherwise noted

Experimental Procedures

Inflow Hydrograph

Each trial was a simulated storm event and was conducted in the same way, regardless of basin design. A large source pond was connected to the experimental DDB through an underground pipe network (Figure 17). A butterfly valve that could be incrementally opened by turning a handle controlled the flow through the system and was used to create center-weighted storms for each target storm size (Figure 18; Table 6).

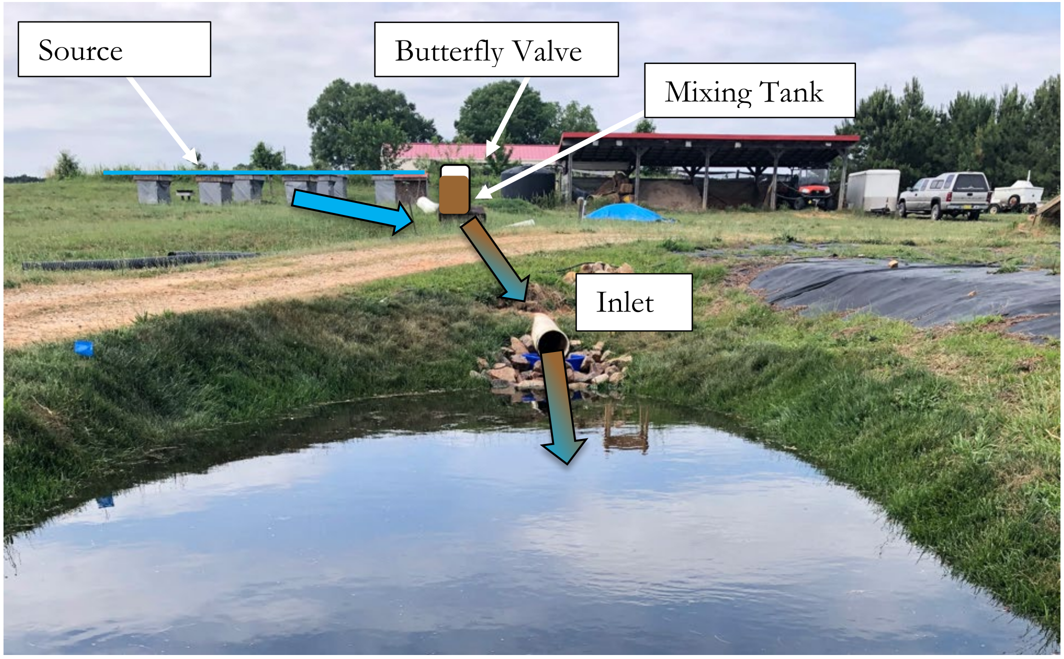

Figure 17. Trial DDB experimental set-up

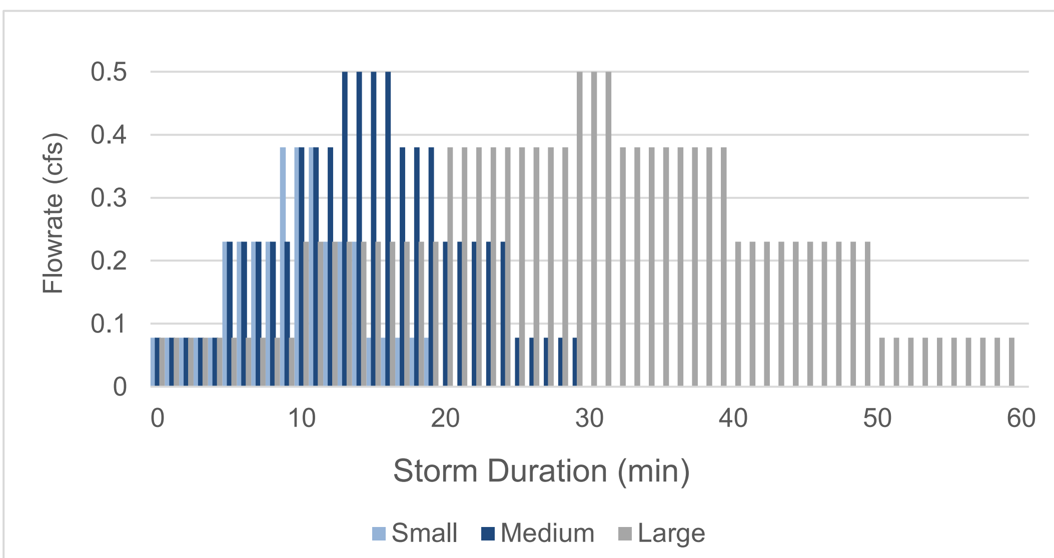

Figure 18. Idealized design storm hydrographs used in controlled plot trials

Table 6. Time-step duration, flow, and volume for each idealized storm size

Small			Medium			Large		
Time Step (minute)	Flow Rate (cfs)	Cumulative Volume (ft^3)	Time Step (minute)	Flow Rate (cfs)	Cumulative Volume (ft^3)	Time Step (minute)	Flow Rate (cfs)	Cumulative Volume (ft^3)
0:00	0.078	0	0:00	0.078	0	0:00	0.078	0
0:05	0.23	23.4	0:05	0.23	23.4	0:10	0.23	46.8
0:09	0.38	78.6	0:10	0.38	92.4	0:20	0.38	184.8
0:12	0.23	147	0:13	0.5	160.8	0:29	0.5	390
0:15	0.078	188.4	0:17	0.38	280.8	0:32	0.38	480
0:20	0	211.8	0:20	0.23	349.2	0:40	0.23	662.4
			0:25	0.078	418.2	0:50	0.078	800.4
			0:30	0	441.6	0:60	0	847.2

The idealized, target storms are based on expected flow rates for given turn increments (e.g., one half-turn was expected to produce a flow of 0.078 cfs). However, the relationship between flow and valve-turns was dependent on many variables, such as the stage of the source pond and lubrication of the valve. The storms presented in Table 6 were the framework for each storm but were manually calibrated at each time-step. Immediately after the valve was turned, stage measurements and adjustments were made to ensure adequate flow. Representative inflow hydrographs for each storm size are included in Appendix A.

Matrix Spikes

Premeasured pollutant masses (Table 5) were transported to the field site for each trial. Sediment was sourced from Triangle Landscape Supply and contained approximately 69% sand, 19% silt, and 12% clay before processing. Sediment was dried for at least 24 hours at 38°C, hand ground with a mortar and pestle, then passed through #10 (0.08-inch) and #35 (0.02-inch) sieves and weighed. Therefore, the resulting sediment input contained medium sand and finer. The measured nutrient and metal loads were combined with sediment inputs and transported in plastic zip-top bags.

Before the simulated storms, a 50-gallon mixing tank and a 100-gallon reservoir tank were filled with ambient water from the source pond. The entire mass of pollutants was added to the mixing tank before the trial began and was stirred by a small, battery-powered boat motor for at least 15 minutes (Figure 19). During the trial, the valve of the mixing tank was opened, allowing the mixture to drain. This highly concentrated pollutant slurry mingled with the inflowing ambient

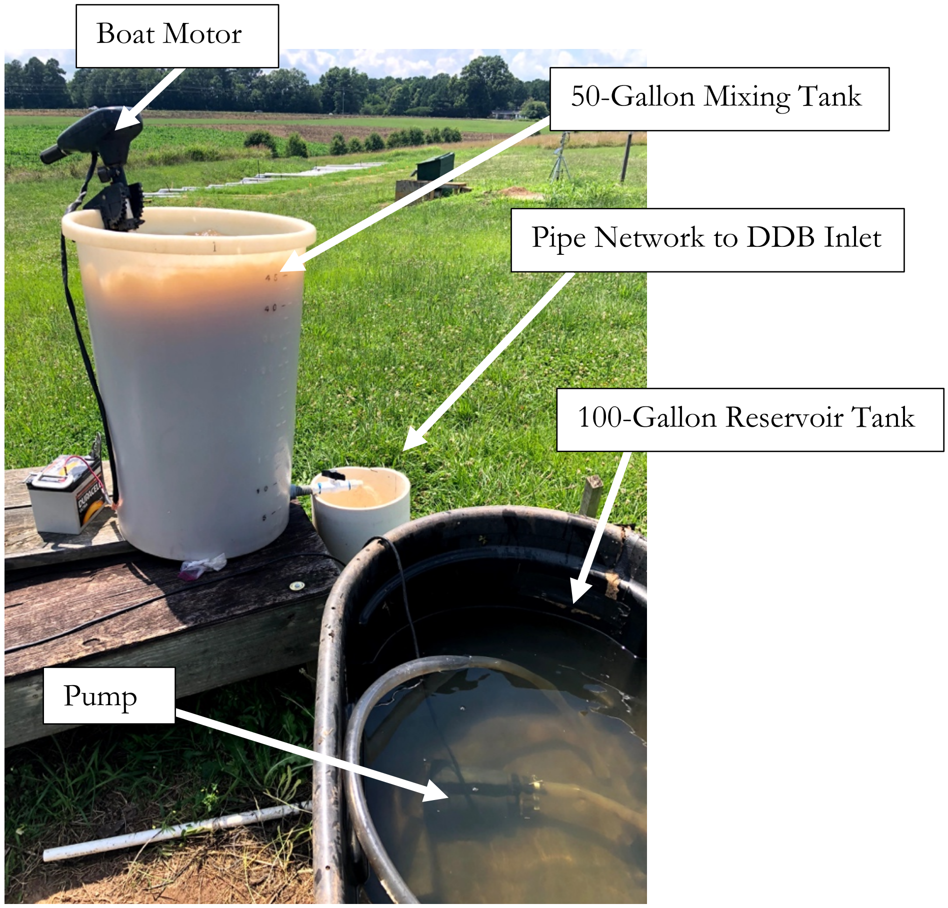

Figure 19. Matrix spike set-up

pond water in the pipe network to create the synthetic stormwater entering the DDB (Figure 17). When the water level of the mixing tank dropped to 25 gallons, it was refilled by pumping water from the reservoir.

The mixing tank had an adjustable butterfly valve, and the degree to which it was opened during the trial corresponded to the length of the storm. To ensure all the pollutants drained from the mixing tank, the flow rate was adjusted such that the mixing tank was replenished four times (using all the water in the reservoir tank), regardless of storm length. Therefore, the small storm required the valve to be open 2/3, the medium storm required it to be half open, and the large storm required it to be only 1/3 open.

This matrix spiking process resulted in the highest concentration of pollutants entering the basin during the beginning of the storm, as the pollutant slurry was diluted each time water was added to the mixing tank from the reservoir. While partially due to site constraints, this process also represents the "first-flush" phenomenon, whereby the first portion of stormwater carries the highest proportion of the pollutant load (Hathaway & Hunt, 2011; Shammaa et al., 2002). Additionally, all water quality samples were collected as flow-paced composite samples taken across the length of the entire storm. Therefore, the impacts of the pollutant input timing were assumed minimal.

Antecedent and Concurrent Weather Conditions

Previously, a tiered antecedent dry period was to be observed before all trials, based on the size of the rain event. 0-0.5" events would require no antecedent dry period, 0.5-1.0" events would require a 12 hour antecedent dry period, and 1.0"+ events would require a 24 hours antecedent dry period. However, due to time constraints exacerbated by the Covid-19 pandemic, this antecedent dry period protocol was shortened to 12 hours after any ponded water, be it from natural or simulated storm events. All trials were conducted after at least 12 hours had passed since the previous event's outflow. This condition was met regardless of whether the flow was caused by natural or simulated storm events and regardless of which drawdown orifice was active. In the rare case of simultaneous natural and simulated storms, the trial was considered valid only if the fraction of precipitation that fell within the basin was less than 20% of the simulated storm volume. This means that at least 80% of every trial storm inflow was captured for analysis; any such anomalies are noted in Appendix B.

Data Collection

Water Quality Sampling

Water quality samples were collected from the inlet and outlet for each simulated storm event. Each sample was a composite comprised of at least fifty 100 mL, flow-paced subsamples. 100 mL subsamples were taken after the appropriate volume had passed over the weir for the given storm size (Table 7) and were deposited in a single 10 L collection bottle. Both the inlet and outlet sampling were paced at the same flow increments. The concentrations associated with the resulting influent and effluent composite samples represented the trial's event mean concentrations (EMCs).

Table 7. Composite sample flow-pacing for each storm size (ft^3/subsample)

Small	Medium	Large
3	5	10

Samples were collected with an automated portable sampler (Model 6712; Teledyne-Isco™, Lincoln, NE). Manning's Equation (Manning, 1891) was used to calculate influent velocity (Eq 1) and flow (Eq 2) for the 300mm diameter PVC inlet pipe (Figure 20). Flow area and wetted perimeter were calculated using water depth within the pipe, as measured by an ISCO™ 730 bubbler modules (Teledyne-Isco™, Lincoln, NE). A roughness coefficient of 0.01 was used (Bishop & Jeppson, 1975).

$$V = \frac{1.49}{n}(R)^{\frac{2}{3}}S^{\frac{1}{2}} \qquad \text{Eq. 1}$$

$V = velocity\left(\frac{ft}{s}\right)$

$n = roughness\ coefficient$

$R = Hydraulic\ Radius\ (ft)$

$S = pipe\ slope\ \left(\frac{ft}{ft}\right)$

$$Q = VA \qquad \text{Eq. 2}$$

$Q = flowrate\ \left(\frac{ft^3}{s}\right)$

$V = velocity\ \left(\frac{ft}{s}\right)$

$A = flow\ area\ (ft^2)$

Figure 20. Inlet pipe

Figure 21. Outlet weir boxes with un-pictured ISCO sampler to the left

Because the drawdown for the control, baffles, and IWS configurations used a different outlet pipe network than the skimmer and skimmer + baffles configuration, two separate outlet weir boxes were constructed (Figure 21). Both were outfitted with 22.5º v-notch weirs and ISCO™ 730 bubbler modules (Teledyne-Isco™, Lincoln, NE) with which to measure depth and calculate flow via the weir equation (Eq 3, Francis, 1884).

$$Q = C_d(H^{2.5}) \quad \text{Eq. 3}$$

$$Q = flowrate\left(\frac{ft^3}{s}\right)$$

$$C_d = V - notch\ weir\ coefficient\ \left(\frac{\mathrm{ft}^{0.5}}{\mathrm{s}}\right)(0.497\ for\ 22.5^{\circ})$$

$$H = head\ above\ notch\ invert\ (ft)$$

Because both outlet weir boxes were open to ambient conditions (Figure 21), they were scrubbed by hand with a soft-bristle brush and flushed with water from a nearby well for at least 20 minutes before each trial. This process removed any organic detritus such as leaves or grass clippings as well as any algal accumulation that occurred between trials (Figure 22) that might have artificially inflated outlet nutrient concentrations.

Figure 22. Algae and organic debris removed from outlet weir box before sampling

<u>Hydrologic monitoring</u>

While hydrology was not a focus of this study and site constraints limited the possibility of hydrologic analyses, hydrologic data were collected for the purposes of the flow-paced water quality sampling previously described and for storm characterization. The same ISCO samplers collecting water quality samples also recorded flow data at the inlet and outlet. HOBO™ Water Level Data Loggers (Model U20L-04; Onset Computer Corporation, Bourne, MA) were used to record the water levels in the DDB for each trial.

<u>Water Quality Analysis</u>

Water quality performance was quantified using removal efficiency (RE) (Eq. 4) for all measured constituents (Table 9).

$$RE\ (\%) = 100 * \left(1 - \frac{EMC_{effluent}}{EMC_{influent}}\right) \qquad \text{Eq. 4}$$

$EMC_{effluent} = Event\ Mean\ Concentration\ of\ the\ effluent$

$EMC_{influent} = Event\ Mean\ Concentration\ of\ the\ influent$

Nutrient species and TSS were analyzed at North Carolina State University's Center for Applied Aquatic Ecology (CAAE) Laboratory, and dissolved metal species were analyzed at the North Carolina Department of Environmental Quality's (DEQ) Water Sciences Laboratory. Standard EPA-approved analytical methods and sample handling/preservation were used (Table 8).

Statistical Analysis

The significance of each basin configuration's RE for each pollutant was tested with a two-tailed t-test (H_0: RE=0; H_A: RE≠0). Data were visually inspected for extreme divergences from normality, but no formal normality tests were conducted as sample sizes (n=6) were too small to generate adequate power. Required t-test assumptions were considered met, given that, with the exception of cases of extreme skew, two-tailed t-tests are sufficiently robust against type I errors for many non-normal distributions (Lumley et al., 2002; Sawilowsky & Blair, 1992), often even in samples sizes as small as n=5 (Sullivan & D'Agostino, 1992).

Differences in the REs for each pollutant parameter due to basin configuration were tested using a 2-factor, analysis of covariance (ANCOVA). Basin configuration was a fixed, categorical, independent variable, while removal efficiency was the dependent variable. Due to the documented relationship between hydraulic retention time and removal efficiency (Shammaa et al., 2002; Whipple & Randall, 1983), the models also included storm size as a fixed, categorical, blocking factor that was crossed with basin configuration. The term was included in the models regardless of statistical significance as a description and characterization of the experimental structure (E. Griffith, professional communication, November 10, 2020).

Table 8. Water Quality Analysis – Constituent and Methods Summary

Constituent	Analysis Method	PQL (µg/L)	Handling	Preservation
Total Suspended Solids (TSS)	Std. Method 2540D	-	1 L plastic bottle	On ice
Ammonia Nitrogen (NH_4^+)	Std. Method 4500 NH3 HEPA Method 350-1	17.5	125 mL plastic bottle	On ice
Total Kjeldahl Nitrogen (TKN)	EPA Method 351.1	280	125 mL plastic bottle	On ice
Nitrate/Nitrite Nitrogen (NO_X)	Std. Method 4500 NO3 FEPA Method 353.3	11.2	125 mL plastic bottle	On ice
Total Nitrogen (TN)	TN = NO_X+TKN	-	-	-
Ortho-Phosphate (OPO_4^-)	Std. Method 4500 P FEPA Method 365.1	12	glass bottle filtered in field (0.45 micron syringe)	On ice; bottle pre-acidified by lab
Total Phosphorus (TP)	Std. Method 4500 P FEPA Method 365.1	10	125 mL plastic bottle	On ice
Dissolved Cadmium (Cd)	EPA Method 200.8	0.5	500mL plastic bottle; filtered in field (0.45 micron vacuum)	1 + 1 HNO_3 to pH < 2[26]
Dissolved Copper (Cu)	EPA Method 200.8	2.0	500mL plastic bottle; filtered in field (0.45 micron vacuum)	1 + 1 HNO_3 to pH < 2[26]
Dissolved Lead (Pb)	EPA Method 200.8	2.0	500mL plastic bottle; filtered in field (0.45 micron vacuum)	1 + 1 HNO_3 to pH < 2[26]
Dissolved Zinc (Zn)	EPA Method 200.8	10	500mL plastic bottle; filtered in field (0.45 micron vacuum)	1 + 1 HNO_3 to pH < 2[26]

Influent concentration was used as a fixed, continuous, covariate variable, because influent concentration necessarily impacts removal efficiency, both mathematically and logically (Eq. 4). Models were first fit with an interaction effect between basin configuration and influent concentration but were refit without the interaction if it was determined statistically insignificant. An alpha value of 0.05 was used for all analyses. Residuals were visually inspected for normality and constant variance. If, in the initial ANCOVA, the basin configuration was found to have statistically significant impacts on removal efficiency, a Tukey's multiple comparison procedure was conducted on the least-squares means to determine which pairwise differences in basin configuration were statistically significant.

All statistical analyses were conducted using SAS statistical computing software (Version 3.8, SAS Institute Inc., Cary, NC). Example SAS code is included in Appendix C.

Statistical Implications of Non-Random Experimental Structure

The experiments were not conducted according to a completely randomized design. This is common in agricultural and industrial research, where logistical constraints often partially determine experimental design and procedure, particularly in split-plot designs (Box, 1996). The impacts of such non-random, split-plot experimental structures typically have minimal impact on the conclusions one is able to draw from the resulting data (Box, 1996). While the study presented herein is not a true split-plot design due to the lack of whole-plot (basin configuration) replicates, a visual inspection of the data similarly suggested that the impacts of the non-random design are minimal. Data were inspected for trends in RE according to storm size order, basin configuration order, as well as trial order, and there were no indications of trends substantial enough to warrant further statistical quantification (E. Griffith, professional communication, November 10, 2020). Sample plots used for data inspection can be found in Appendix D.

Results and Discussion

Total Suspended Solids

Each basin configuration significantly reduced the amount of TSS from inlet to outlet (Table 9). Significant EMC reductions are consistent with the literature (Birch et al., 2006; Stanley, 1996); however, the magnitude of reduction for every basin configuration, including the control, is much larger than most documented values and current removal credits (NCDEQ, 2017a).

Table 9. TSS EMCs and MREs for each basin configuration. Values in bold indicate a MRE that is significantly different than 0 (p<0.05).

Basin Configuration	Mean Concentration (mg/L)		Mean Removal Efficiency (%)	p-value
	Influent	Effluent		
B	59.2	9.98	82.67	**<0.0001**
C	80.3	8.93	88.50	**<0.0001**
IWS	73.8	6.75	90.67	**<0.0001**
S	78.5	7.75	89.67	**<0.0001**
S+B	99.6	12.43	85.67	**<0.0001**

In North Carolina, SCMs are categorized as either primary or secondary practices based upon their TSS removal rates, as documented in research studies (NCDEQ, 2017a). Primary practices provide adequate water quality treatment to act as stand-alone practices, while secondary SCMs are used in series and/or for pretreatment (NCDEQ, 2017a). Because DDBs are classified as a secondary practice, it was unexpected that the mean effluent EMCs were all markedly below the maximum allowable value for a primary practice (Figure 23).

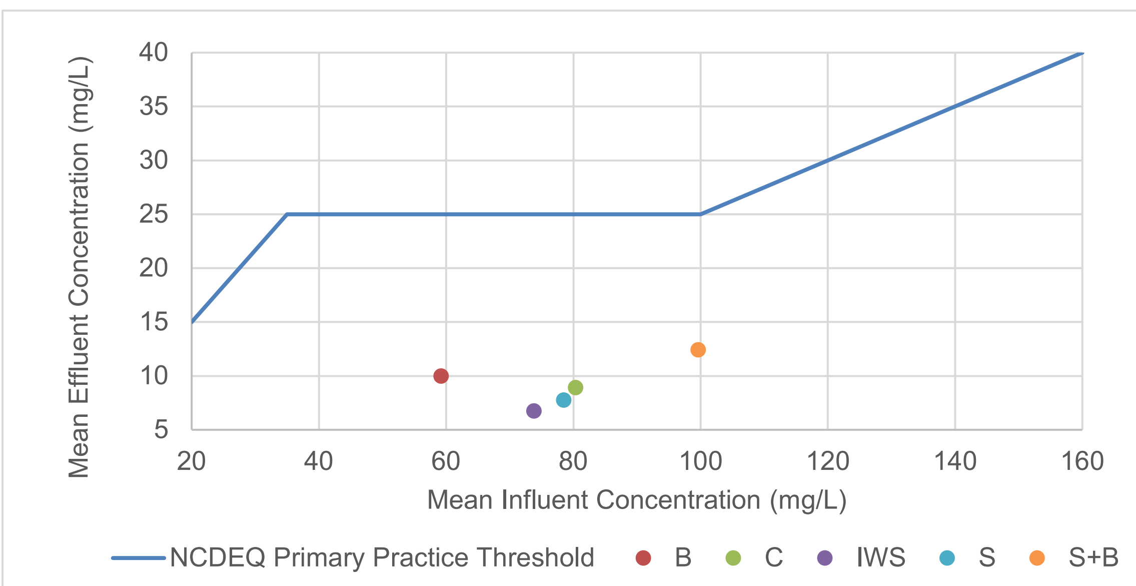

Figure 23. Mean effluent TSS EMCs for each basin configuration as compared to the primary practice threshold (NCDEQ, 2017a).

The designs were specifically chosen for study based on their ability to increase sedimentation in other practices, so such results are not entirely surprising for each of the retrofit configurations. Expectedly, basin configuration had a significant effect on TSS RE in the ANCOVA analysis (Table 10). Unexpectedly, the retrofits did not remove TSS at a rate significantly different than that of the control basin, nor did any one retrofit outperform the others by any statistically significant margin (Table 11). The ANCOVA analysis indicated that more variance in REs existed between basin configurations than within them (after controlling for influent concentration and storm size). However, the absence of any significant pairwise difference suggests that the effect of basin configuration was too small to detect given the sample size and/or there was too much variability within the samples to make confident claims.

Table 10. ANCOVA model parameter significance for each basin configuration's TSS RE. Values in bold indicate that the parameter has a statistically significant effect on TSS RE ($p<0.05$).

Model Parameter	p-value
Basin Configuration	**0.0115**
Influent Concentration	**0.0249**
Basin Configuration * Influent Concentration	N/A
Storm Size	0.3977

The IWS basin was on the cusp of outperforming the B and S+B basins by statistically significant margins ($p=0.0888$ and $p=0.0683$, respectively). However, even if considered statistically significant, the difference is unsubstantial, with less than 6mg/L difference between the mean effluent concentrations for the basins.

Table 11. Pairwise comparisons of each basin's TSS RE. Values in bold indicate that the TSS RE least squares means for the pair are significantly different after the Tukey-Kramer adjustment ($p<0.05$).

Comparison Pair		p-value
B	C	0.5398
B	IWS	0.0888
B	S	0.2589
B	S+B	0.9995
C	IWS	0.7963
C	S	0.9816
C	S+B	0.4004
IWS	S	0.9773
IWS	S+B	0.0683
S	S+B	0.1795

Nitrogen

All basin configurations except B significantly reduced both NH_4^+ and NO_X concentrations from inlet to outlet (Table 12). Conversely, the B configuration was the only basin with a significant MRE for TKN, and it was negative. The export of TKN with no significant change in NH_4^+ suggests an influx of organic nitrogen, the source of which is uncertain. Vegetation decomposition could have been the source, though none was directly observed. It is important to note that the baffles basin was the only configuration with trials split between 2019 and 2020 (Appendix B). While no performance variance between the two years was detected, this could have impacted the basin's organic nitrogen performance. If the baffles themselves were the source of organic nitrogen, the same result would be expected of the S+B basin, but its insignificant export prevents such a conclusion.

Table 12. Nitrogen species EMCs and REs for each basin configuration. Values in bold indicate a MRE that is significantly different than 0 (p<0.05).

Nitrogen Species	Basin Configuration	Mean Concentration (µg/L)		Mean Removal Efficiency (%)	p-value
		Influent	Effluent		
NH_4^+	B	98.43	61.39	18.5	0.3479
	C	45.01	22.89	39.0	**0.0041**
	IWS	43.92	25.77	39.0	**0.0001**
	S	51.96	31.65	38.5	0.0064
	S+B	62.57	31.65	45.8	**0.0011**
TKN	B	1040	1213	-17.17	**0.0209**
	C	938.9	974.7	-4.33	0.5116
	IWS	896.9	873.9	2.50	0.3512
	S	1092	1136	-4.50	0.5501
	S+B	1238	1234	-0.167	0.9579
NO_X	B	327.3	270.0	8.00	0.7202
	C	426.1	233.3	44.8	**0.0002**
	IWS	432.4	279.3	35.0	**0.0002**
	S	487.6	211.0	53.8	**0.0003**
	S+B	577.7	234.8	50.2	**0.0015**
TN	B	1368	1483	-10.33	0.1001
	C	1365	1208	11.00	0.1091
	IWS	1329	1153	13.17	**0.0014**
	S	1580	1347	13.50	0.0513
	S+B	1815	1469	16.83	**0.0219**

While all but the B configuration produced positive MREs for TN, only the IWS and S+B basins had MREs that varied significantly from zero (Table 12). The IWS and skimmer outlet basins were unique in that they allowed some amount of ponded water to remain within the basin between storm events. This is true, too, for the S basin, which did not meet the threshold for statistical significance but was on the cusp (p=0.0513). Such persistent saturation could have created the necessary anoxic conditions for denitrification to occur (Collins et al., 2010). Denitrification rates vary widely and are dependent on many different factors (Sirivedhin & Gray, 2006). Given this variability as well as the lack of significant pairwise comparisons (Table 14), it is impossible to definitively claim increased denitrification with the presented data. However, increased denitrification is consistent both with the positive, significant NO_X REs for IWS, S, and S+B configurations in this study as well as peer-reviewed studies naming subsurface saturation as a driver of denitrification in DDBs (McPhillps & Walter, 2015).

Importantly, all basin configurations, excepting the baffles basin, performed better in terms of total nitrogen than current crediting documents predicted in terms of exceedance probability (Eq. 5, Figure 24).

$$Exceedance\ Probability = 100 * \frac{m}{n+1} \quad \text{Eq. 5}$$

$m = rank\ of\ EMC\ data\ point\ when\ data\ are\ sorted\ from\ smallest\ (1)\ to\ largest\ (n)$

$n = total\ number\ of\ data\ points$

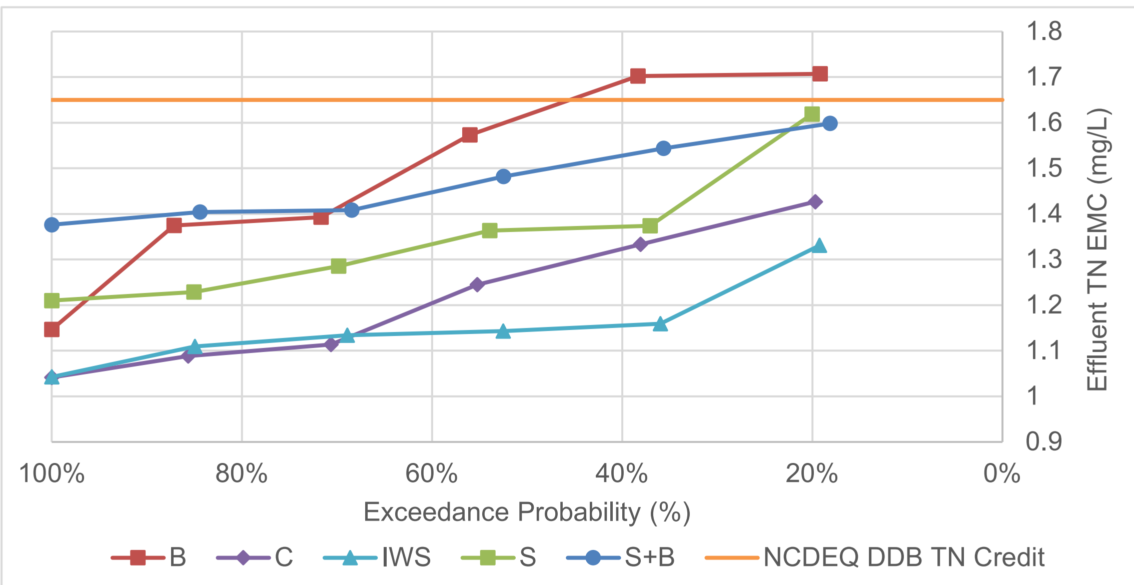

Figure 24. Exceedance probability of TN EMC for each basin configuration compared with the NCDEQ credit of 1.65 mg/L (NCDEQ, 2017a)

Basin configuration had a significant effect on NO_X and TN RE, and both NH_4^+ (p=0.0712) and TKN (p=0.0526) were near the boundary of significance (Table 13). However, only TKN and TN exhibit any significant pairwise differences, all between the baffles configuration and others (Table 14). These differences are likely due to the suspected organic nitrogen inputs previously discussed.

Table 13. ANCOVA model parameter significance for each basin configurations RE of nitrogen species. Values in bold indicate that the parameter has a statistically significant effect on removal efficiency ($p<0.05$).

Model Parameter	p-value			
	NH_4^+	TKN	NO_X	TN
Basin Configuration	0.0712	**0.0526**	**0.0027**	**0.0003**
Influent Concentration	**0.0223**	0.2556	**0.0090**	**0.0011**
Basin Configuration * Influent Concentration	N/A	N/A	**0.0090**	N/A
Storm Size	0.7319	0.3622	0.5008	0.2254

Table 14. Pairwise basin configuration comparisons of REs of nitrogen species. Values in bold indicate that RE least squares means for the pair are significantly different after the Tukey-Kramer adjustment ($p<0.05$).

Comparison Pair		p-value			
		NH_4^+	TKN	NO_X	TN
B	C	0.0593	0.2283	0.8496	**0.0014**
B	IWS	0.1591	**0.0326**	0.3696	**0.0003**
B	S	0.2114	0.4508	0.9194	**0.0104**
B	S+B	0.1065	0.4814	0.6961	0.0877
C	IWS	0.9768	0.7767	0.7878	0.9630
C	S	0.9372	0.9877	0.9978	0.9656
C	S+B	0.9925	0.9986	0.9955	0.8169
IWS	S	0.9997	0.5843	0.5418	0.7210
IWS	S+B	0.9999	0.8060	0.9297	0.5229
S	S+B	0.9970	0.9999	0.9456	0.9762

There is a significant interaction between the effects of basin configuration and influent concentration on NO_X RE, which muddles the interpretation of the pairwise differences and indicates that the B configuration (and to a lesser extent, the C configuration) performs worse than the others in clean watersheds where influent concentration is lower, and better than the others in dirty watersheds where influent concentration is high (Figure 25). However, the data set is small (n=6) and primarily clustered where RE differences are smallest (200 µm/L < NOi < 500 µm/L), making further extrapolation unfounded.

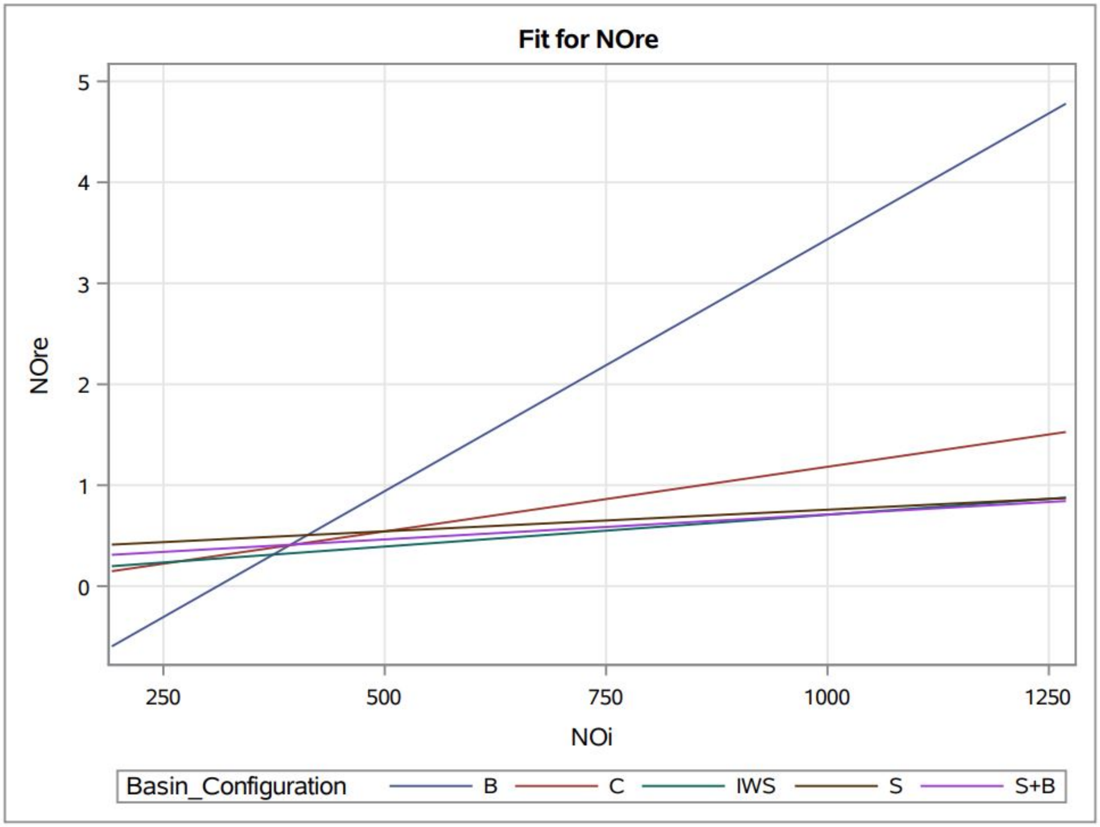

Figure 25. Interaction plot between the effects of influent NO_X (NOi) concentration and basin configuration on NO_X removal efficiency (NOre), averaged over the effect of storm size

Phosphorus

While each retrofit design resulted in a reduction of TP from the inlet to the outlet, only the IWS basin produced a significant MRE (Table 15). Basin configuration did have a significant effect on TP (Table 16), with the IWS basin removing significantly more TP than the B, C, and S+B basins (Table 17). Phosphorous readily adsorbs to soil particles (Sparks, 2003), and adsorption is a primary phosphorous removal mechanism in SCMs (Rosenquist et al., 2010). IWS's TP capture could be a function of its high TSS capture. Though not statistically different than the other configurations, the IWS basin did have the highest sediment capture rate (91%, Table 15).

The C, IWS, S, and S+B basins significantly reduced OPO_4^- EMCs. The baffles basin was the only configuration to not significantly reduce OPO_4^-. Notably, the baffles basin also had the lowest influent OPO_4^- concentration. It was not possible to directly control the influent OPO_4^- concentrations, only the TP concentrations. Since the TP concentrations for the baffles do not significantly differ from the others, the OPO_4^- concentration differences were likely due to environmental impacts. Given that the methods for preparing the synthetic stormwater and all environmental factors kept as constant as possible (temperature, mixing time, etc.) it is unclear why this difference occurred, but it likely impacted removal efficiency.

Basin configuration did have a significant effect on OPO_4^- RE (Table 16), with the S+B removing significantly more OPO_4^- than the B and C basins (Table 17). OPO_4^- reductions for all basins were higher than most documented ranges for DDBs in North Carolina (Stanley, 1996; Mazer, 2018; Wissler, 2019), and every basin, including the control, produced effluent EMCs well below the NCDEQ effluent TP concentration credit (Figure 26).

Table 15. Phosphorous species EMCs and REs for each basin configuration. Values in bold indicate a MRE that is significantly different than 0 ($p<0.05$).

Nitrogen Species	Basin Configuration	Mean Concentration (µg/L)		Mean Removal Efficiency (%)	p-value
		Influent	Effluent		
TP	B	142.8	140.9	-1.83	0.8787
	C	149.3	133.0	10.8	0.1407
	IWS	140.6	87.0	37.8	**<0.0001**
	S	173.7	123.4	26.0	0.3896
	S+B	201.9	142.5	22.0	0.0664
OPO_4^-	B	33.48	26.51	24.5	0.2006
	C	80.10	60.05	24.8	**0.0228**
	IWS	80.2	33.1	59.7	**0.0021**
	S	85.3	34.3	59.8	**0.0003**
	S+B	65.7	6.42	83.7	**<0.0001**

Table 16. ANCOVA model parameter significance for each basin configurations RE of phosphorous species. Values in bold indicate that the parameter has a statistically significant effect on removal efficiency ($p<0.05$).

Model Parameter	p-value	
	TP	OPO_4^-
Basin Configuration	**0.0003**	**0.0011**
Influent Concentration	**<0.0001**	0.8906
Basin Configuration * Influent Concentration	N/A	N/A
Storm Size	**0.0233**	0.1206

Table 17. Pairwise basin configuration comparisons of RE of phosphorous species. Values in bold indicate that RE least squares means for the pair are significantly different after the Tukey-Kramer adjustment ($p<0.05$).

Comparison Pair			p-value	
			TP	OPO_4^-
B	C	0.6047	1.0000	1.0000
B	IWS	**0.0002**	0.1701	0.1701
B	S	0.1378	0.1820	0.1820
B	S+B	0.9283	**0.0038**	**0.0038**
C	IWS	**0.0053**	0.1167	0.1167
C	S	0.8254	0.1133	0.1133
C	S+B	0.9838	**0.0029**	**0.0029**
IWS	S	0.0703	1.0000	1.0000
IWS	S+B	**0.0040**	0.4499	0.4499
S	S+B	0.5083	0.4715	0.4715

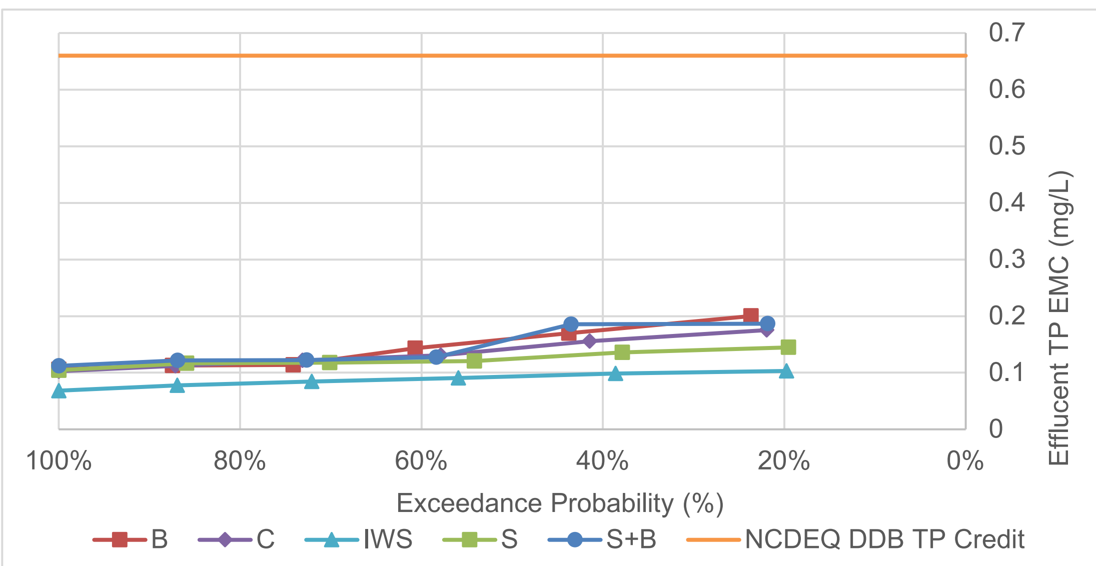

Figure 26. Exceedance probability of TP EMCs for each basin configuration as compared with the NCDEQ credit of 0.66 mg/L (NCDEQ, 2017a)

Heavy Metals

There was no significant Cd EMC change from inlet to outlet in any basin configuration (Table 18). Every design exported Cu and Zn, and while only a few were statistically significant (Table

18), it reflected a trend consistent with DDB field studies (Wissler, 2019). Cd, Cu, and Zn readily bind to dissolved organic carbon (DOC) (Sparks, 2003), which could have leached from the basin during trials (Shafer et al., 1997). Though all four metals readily adsorb to soil particles, Pb has the least affinity for DOC, existing primarily in suspended particulate matter (Shafer et al., 1997). This higher likelihood of Pb removal via sedimentation could explain why the B, IWS, and S+B basins significantly reduced Pb, and why Pb was the only dissolved metal with primarily positive REs.

Table 18. Dissolved heavy metals EMCs and REs for each basin configuration. Values in bold indicate a MRE that is significantly different than 0 (p<0.05).

Dissolved Metal	Basin Configuration	Mean Concentration (µg/L)		Mean Removal Efficiency (%)	p-value
		Influent	Effluent		
Dissolved Cd	B	1.44	2.33	-100	0.3727
	C	1.70	1.70	-3.83	0.6951
	IWS	2.43	2.98	-36.8	0.2796
	S	1.55	1.65	-10.7	0.4455
	S+B	1.57	1.42	3.83	0.7487
Dissolved Cu	B	5.08	6.90	-38.2	**0.0462**
	C	6.65	7.38	-13.5	0.2121
	IWS	6.31	8.27	-38.7	0.1734
	S	5.68	7.37	-34.8	**0.0193**
	S+B	7.07	8.00	-22.8	0.3606
Dissolved Pb	B	4.80	3.12	28.5	**0.0181**
	C	5.75	3.53	28.5	0.2598
	IWS	5.53	3.22	41.2	**0.0003**
	S	5.32	4.53	-5.50	0.8995
	S+B	6.65	3.07	45.2	**0.0045**
Dissolved Zn	B	13.8	20.2	-54.8	0.0914
	C	19.2	23.0	-39.0	0.1972
	IWS	25.2	31.0	-51.7	0.2119
	S	14.3	22.3	-64.0	**0.0078**
	S+B	18.5	22.	-41.8	0.1164

Basin configuration did not have an impact on the RE of Cu, Pb, nor Zn (Table 19). While Zn was on the cusp (p=0.0550), the IWS and B configurations were the only two that differed significantly, with MREs of -51.7% and -54.8%, respectively (Table 20). This difference's significance is likely due to IWS's large spread of values, more so than a reflection of performance.

While some configurations resulted in statistically significant removal efficiencies, the lack of statistically significant pairwise comparisons limits any substantive conclusions about relative performance.

Table 19. ANCOVA model parameter significance for each basin configurations RE of dissolved heavy metals. Values in bold indicate that the parameter has a statistically significant effect on removal efficiency (p<0.05).

Model Parameter	p-value			
	Cd	Cu	Pb	Zn
Basin Configuration	**0.0070**	0.5421	0.5293	0.0550
Influent Concentration	**0.0003**	**<0.0001**	**0.0124**	**<0.0001**
Basin Configuration * Influent Concentration	**0.0117**	N/A	N/A	N/A
Storm Size	0.3437	**0.0350**	0.4037	0.1090

Table 20. Pairwise basin configuration comparisons of RE of dissolved heavy metals. Values in bold indicate that RE least squares means for the pair are significantly different after the Tukey-Kramer adjustment (p<0.05).

Comparison Pair		p-value			
		Cd	Cu	Pb	Zn
B	C	0.7498	0.9951	0.9919	0.8941
B	IWS	0.0842	0.6118	0.9999	**0.0400**
B	S	0.7539	0.9854	0.5863	0.9725
B	S+B	0.9281	0.6821	0.9992	0.9175
C	IWS	0.3193	0.8132	0.9790	0.1422
C	S	1.0000	1.0000	0.8348	0.9978
C	S+B	0.9922	0.8344	0.9997	1.0000
IWS	S	0.3701	0.8668	0.5101	0.1142
IWS	S+B	0.2153	1.0000	0.9958	0.1292
S	S+B	0.9901	0.8971	0.7510	0.9992

Basin configuration did have an effect on Cd RE, but interpreting it is complicated by the interaction effect between basin configuration and influent concentration (Table 19, Figure 27). The small sample size, tightly clustered data set, and fact that no basin had a Cd RE significantly different than 0, make it imprudent to draw definitive conclusions (see a similar discussion for NO_X in Section 3.2.2). Additionally, while statistically significant, basin configuration was unsubstantial in regards to Cd MRE, as no basin had a MRE significantly different than zero (Table 18).

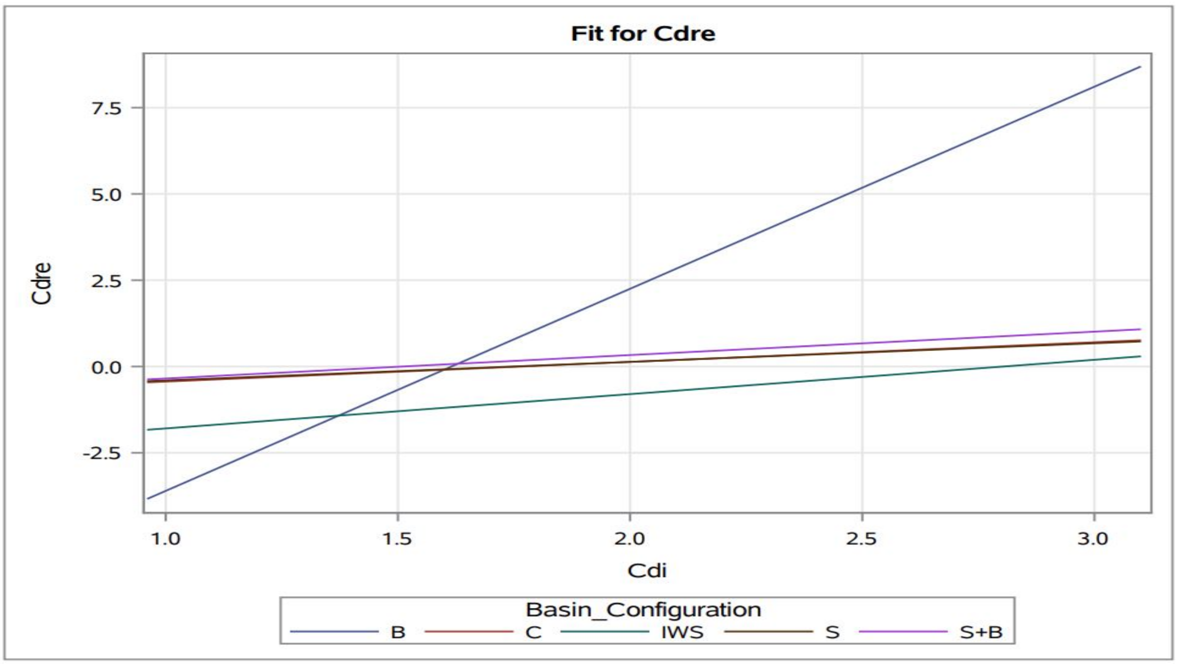

Figure 27. Interaction plot between the effects of influent dissolved Cd (Cdi) concentration and basin configuration on dissolved Cd RE (Cdre), averaged over the effect of storm size

Influent Concentration and Storm Size

As expected, influent concentration had a statistically significant effect on most pollutant REs. Only TKN and OPO_4^- REs were not impacted by influent concentration. For TKN, this is consistent with the idea that the significant exports in the B configuration were likely due to external organic nitrogen inputs (such as decomposing vegetation), independent of the controlled influent concentrations.

Importantly, OPO_4^- samples have the shortest holding time of the measured analytes (48hrs). Due to the Covid-19 pandemic, the analysis lab was functioning at decreased capacity and 7 (23%) samples were thus analyzed outside of the proper holding time. Because filtered orthophosphate samples that are stored under different conditions produce significantly different concentration measurements (Moore & Locke, 2013), the delay in analysis could have impacted statistical analysis.

Storm size, a proxy for HRT, had a significant effect only on TP and Cu removal. In past studies, increasing hydraulic retention time increased sedimentation and RE for its associated pollutants (Whipple & Randall, 1983; Bidelspach, et al., 2004); however, the lack of a significant storm size effect supports the proposal by Shammaa et al. (2002) that there is an optimal drawdown period, beyond which water quality benefits are minimal. They suggest an optimal HRT of 12-40 hours, a range within which all three storm sizes fall.

While not entirely outside of the range of recorded water quality performance in the field (Stanley, 1996), the TSS and nutrient REs reported herein do not reflect average DDB performance (Birch et al., 2006; Stanley, 1996). The optimal HRT, coupled with the highly controlled influent concentrations, could partially explain why every basin configuration, including the control, performed better than average DDB performance documented in the literature (Birch et al., 2006; NCDEQ, 2017a). This study controlled influent concentrations, and while the resulting mean influent EMCs reflected average values reported elsewhere in North Carolina field studies (Wissler, 2019; Schueler, 1996), they did not exhibit the same variability. Because influent concentration had a significant impact on nearly all REs, a wider range of influent concentrations would likely result in a wider range of REs and, therefore, a different average removal.

Temperature, Particle Size, and Performance

The temperature and particle size distribution of stormwater also impact performance, particularly in SCMs, such as DDBs, that utilize sedimentation as the primary pollutant removal mechanism (Roseen et al., 2009; Charters et al., 2015). Higher temperatures result in lower water viscosities, thereby increasing sedimentation rates (Roseen et al., 2009), and performance variation due to temperature was evident in the data (Table D-3). Sedimentation rates were greatest during the months of July and August, when temperatures were highest. However, because all trials were conducted when temperatures were above 10°C, sedimentation conditions were favorable during the trials in ways that are not reflective of field conditions year-round.

Additionally, the sediment inputs may not have been reflective of field conditions. Sediment was dried and sieved to a final d100 of 0.500mm, a value at the high end of the range of values reported in particle size distribution (PSD) field data collected along NC highways (Table 21). Because differences in PSD can result in treatment uncertainty and variability (Charters et al., 2015), if the influent particles during trials were generally larger than those in the field, it would be expected that the trial DDBs would capture more sediment.

Table 21. D90 values for NC highway runoff (mm)

	Study											
	Winston & Hunt (2017)								Wissler (2019)			
Locale	Black Mountain	Brevard	Jack Bennett	Hanks Chapel	Faison	Benson	Wilson	Goldsboro	Knightdale		Archdale	
d90	0.426	0.594	0.113	0.591	0.522	0.131	0.506	0.072	11.2	0.092	0.088	0.076

While relating the d90 values of past studies and the and d100 value produced here is an indirect and limited means of comparison, it does indicate that the PSD of the influent stormwater could be largely responsible for the high water quality performances observed in this study in all basin configurations. Future controlled plot trials should include PSD analyses to investigate this possibility.

<u>Future Research</u>

<u>Hydrology</u>

While not always by a statistically significant margin, the IWS basin had the highest TSS and TP REs and reduced TN concentrations substantially, results consistent with its performance in other SCMs (Hunt et al., 2006; Brown & Hunt, 2011; Braswell et al., 2018). One of the primary pollutant removal mechanisms enhanced by IWS additions is infiltration, a mechanism that was not monitored during this study due to site constraints (Hunt et al., 2012). Infiltration can be a primary pollutant removal mechanism in some DDB's even without retrofit (Bidelspach, 2004), and IWS' demonstrated ability to improve infiltration rates even among clay soils with low conductivity (Hunt et al., 2006; Wardynski et al., 2013; Braswell et al., 2018) bodes well for future possibilities in DDB enhancement. Future research should integrate hydrologic monitoring to investigate if the data trends observed in this study are confirmed when analyzed in the context of retrofit impacts on DDB hydrology and total load reductions of pollutants.

Increasing statistical power

For several pollutants (TSS, NO_X, OPO_4^-, Cd) basin configuration had a significant impact on RE, but few, if any, significant differences existed between the retrofit designs. Practically, this indicates that while there is more variation among configurations than within them, there is not enough evidence to confidently differentiate between the performances of any two configurations. Statistically, this is a function of different levels of power for the different procedures (ANCOVA vs Multiple Comparisons). For example, according to power analyses conducted in SAS (Version 3.8, SAS Institute Inc., Cary, NC), the ANCOVA procedure's power associated with detecting the effects of basin configuration on TSS RE was 0.608. For comparison, the power associated with the process of detecting a difference in the least-squares-means of the IWS basin's TSS RE versus the C basin was only 0.138. (Sample SAS code is included in Appendix C.)

Typically there are three ways to increase statistical power: (1) increase the magnitude of the effect in question (2) decrease the amount of variation within like-groups (3) increase sample size (McClelland, 2000). The magnitude of the effects is the subject of study and therefore cannot be purposefully manipulated. Importantly, the magnitude of the effects for most of the studied pollutant parameters is small. All basin configurations, including the control, provided better water quality treatment than is reported in the literature (Stanley, 1996; Birch et al., 2006) and credit documents (NCDEQ, 2017c). Comparing retrofits against a high-performing control, makes any effect more difficult to ascertain. The amount of variation within like-groups was already minimized to the extent that was logistically possible by controlling for temperature and quantifying the effects of storm size and influent concentration within the model. Therefore, to improve these trials future research should increase the sample size.

Originally this study was designed such that each trial was run in triplicate (n=9 for each basin). The Covid-19 pandemic shortened the available timeframe in which trials could occur, requiring each to be run in duplicate (n=6). While larger sample size would have increased statistical power, the degree of increase varies from test to test. For example, the comparison of least-squares-means of the IWS basin's TSS RE with that of the C basin was 0.138, but if the sample size were increased to n=9 (assuming the same means, standard deviation, and α), power only increases to 0.194. Alternatively, comparisons of least-squares-means of the IWS basin's TSS RE with that of the S+B basin produces powers of 0.625 and 0.827 for n=6 and n=9, respectively. Increasing the sample size in future studies will increase the analysis' associated statistical power; however, it is uncertain if this increase will lead to different conclusions.

Conclusions

This study examined 5 DDB configurations to examine the potential for water quality treatment improvements through retrofit designs. The following conclusions were made.

- Each retrofit basin configuration and the control significantly and substantially reduced TSS from the inlet to the outlet at rates higher than those in the literature and in crediting documents (NCDEQ, 2017a). There was no evidence for TSS RE performance differences among basin configurations.

- There is no significant evidence that indicates a particular basin configuration provided better nitrogen removal. However, data suggest that retrofits causing prolonged saturation (IWS, S, S+B) could improve denitrification potential. The baffle configuration significantly exported TN, likely the result of external organic nitrogen inputs.

- The IWS basin captured TP at significantly higher rates than the other basin configurations, but all effluent concentrations were substantially lower than the TP effluent concentration credit assigned by NCDEQ (2017a).

- Though the baffles basin significantly exported Cd, none of the basin configurations had a substantial effect on the removal efficiencies of dissolved Cd, Cu, Pb, or Zn.

- The results of this study do not provide evidence that any of the analyzed basin configurations improve water quality treatment of DDBs in both significant and substantial ways. However, data trends suggest that the IWS basin could improve cumulative load reductions. Future research is needed to assess the hydrologic performance of IWS in DDBs.

Recommendations

The capacity for the research presented herein to recommend implementing DDB retrofit designs at scale is limited. However, evidence exists for watersheds with a particular interest in limiting effluent phosphorus that an IWS retrofit offers significant benefit. This could have specific application in DDBs receiving high TP concentrations from agricultural areas and/or in nutrient-sensitive waters such as the Neuse River watershed (NCDEQ, 2020).

Field-Vetted Retrofits

The experimental trials of this study yielded limited retrofit recommendations, but wetland conversion and basin naturalization are field-vetted DDB retrofit designs that improved water quality treatment. Constructed stormwater wetlands (CSW) are primary SCMs that provide pollutant removal through enhanced sedimentation, chemical process such as sorption and denitrification, and biochemical processes including evapotranspiration, microbial degradation, and nitrogen assimilation (Bavor et al., 2001; Haarstad et al., 2011). By elevating the drawdown orifice and planting wetland vegetation, many of the same pollutant removal processes can occur within DDBs (Mazer, 2018). Mazer (2018) studied one such retrofit, and, compared to the pre-retrofit DDB, the wetland conversion reduced annual effluent loads of TSS, TP, OP, TN, TKN, $NH_{3,}$ and by 89, 60, 57, 71, 75, and 69%, respectively. While not on par with CSWs, these reductions were substantial improvements from typical DDB performance (Mazer, 2018).

Because DDBs allow for greater ponding depths than CSWs (NCDEQ, 2017b), wetland conversion can lead to a decrease in storage capacity. While this decrease can pose safety risks associated with flooding during successive storm events (Papa et al., 1999), research suggests that they still contribute positively to water quality treatment, despite being undersized (Hathaway & Hunt, 2009).

For sites where flood mitigation is a high priority and storage capacity must be preserved, basin naturalization is a water-quality enhancing option (Wissler, 2019). Simply neglecting routine vegetative maintenance (i.e., no mowing) and allowing local vegetation to colonize the DDB improved pollutant load reductions (Wissler, 2019). In North Carolina, two naturalized DDBs had volume reduction rates of 39 and 54%, resulting in significant pollutant load reductions for every constituent (Wissler, 2020). Specifically, the presence of trees and woody vegetation enhanced volume reduction through uptake, canopy interception, and increased infiltration due to root channeling without significantly decreasing storage capacity (Wissler, 2020). This retrofit not only improves the water quality treatment of the DDB but also reduces maintenance costs.

Implementation and Technology Transfer plan

This report is the first/primary step toward transferring the synthesized results of project 2018-03. A current webinar targeted to the technical design community that includes this and other research is scheduled for February 23, 2021. The webinar is to be offered via NC State Biological and Agricultural Engineering. A future NCDOT-specific seminar/webinar is available upon request.

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Appendix A: Representative Inflow Hydrographs

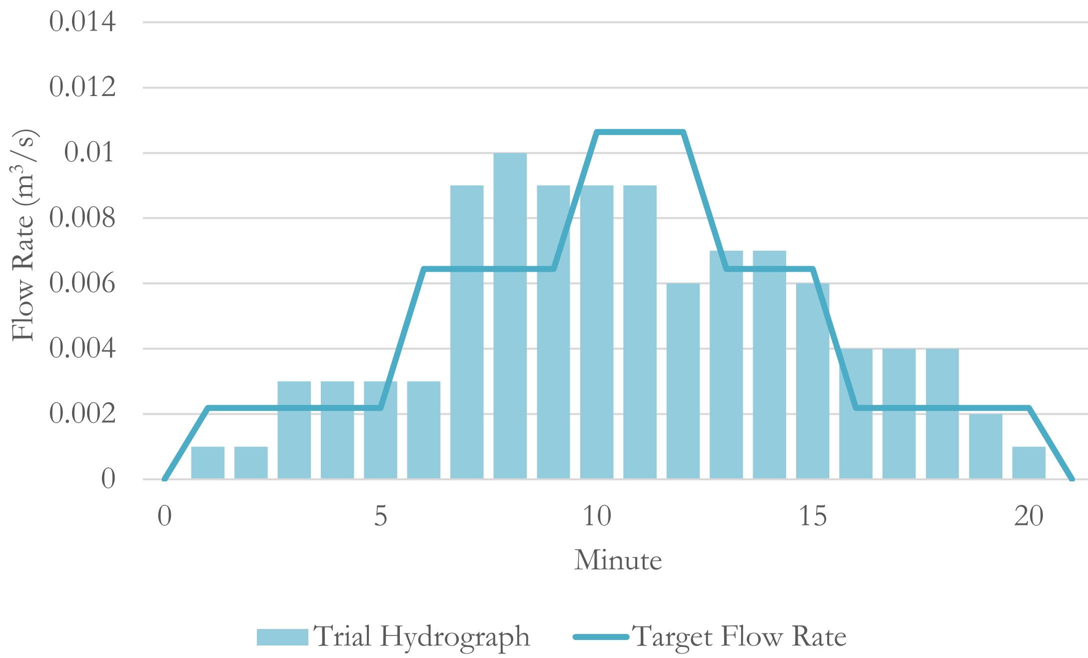


Figure A-1. Representative inflow hydrograph for a small storm, as compared to target flow rates

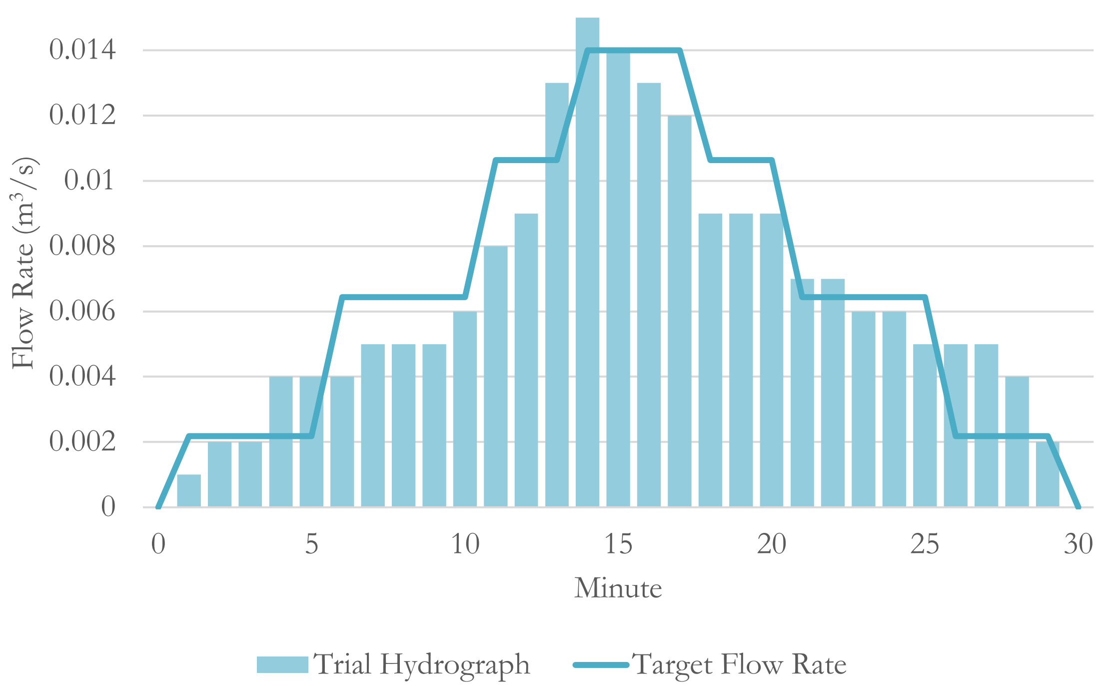


Figure A-2. Representative inflow hydrograph for a medium storm, as compared to target flow rates

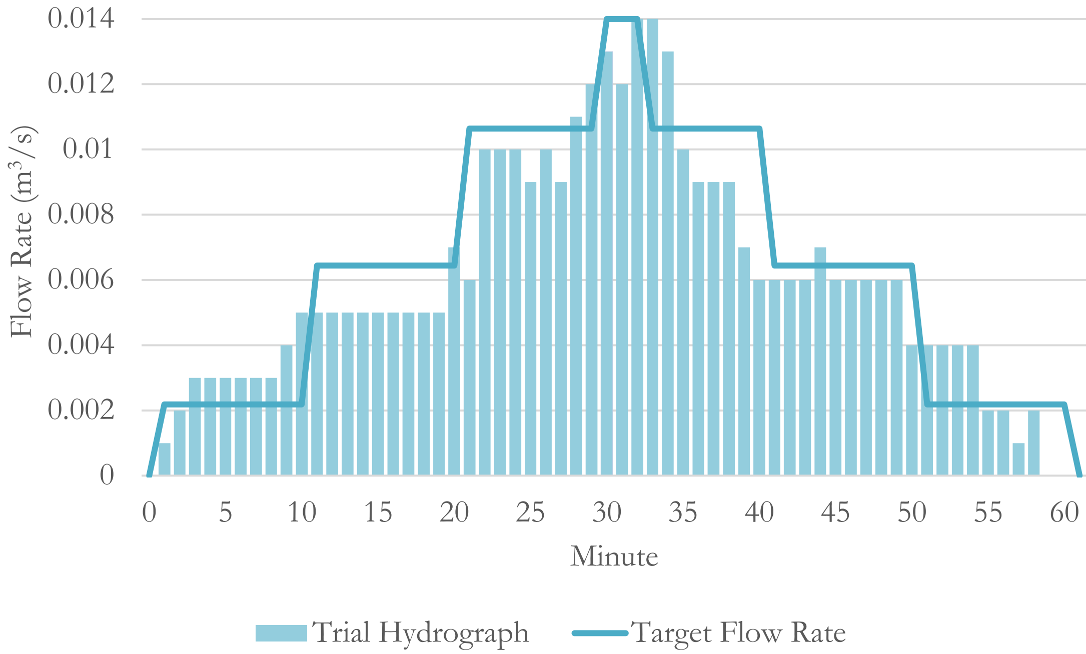


Figure A-3. Representative inflow hydrograph for a large storm, as compared to target flow rates

Appendix B: Simulated Storm Log

Table B-1. Simulated Storm Log

Storm Date	Storm Size	Basin Configuration	Relevant Field Notes
6/3/2020	LARGE	S+B	
6/8/2020	LARGE	S+B	
6/21/2020	MEDIUM	S+B	
6/22/2020	MEDIUM	S+B	Surrounding area was being mowed during trial, no visible impacts
6/23/2020	SMALL	S+B	
6/24/2020	SMALL	S+B	
6/29/2020	LARGE	B	
7/1/2020	LARGE	B	
7/6/2020	MEDIUM	B	
7/13/2020	LARGE	S	
7/15/2020	LARGE	S	
7/20/2020	MEDIUM	S	
7/21/2020	MEDIUM	S	
7/22/2020	SMALL	S	
7/27/2020	SMALL	S	
7/28/2020	LARGE	C	
8/11/2020	LARGE	C	
8/17/2020	MEDIUM	C	
8/19/2020	MEDIUM	C	~50mm rain event during drawdown, adding ~2m3 of water (17% of storm volume)
8/24/2020	SMALL	C	
8/26/2020	SMALL	C	
9/15/2020	LARGE	IWS	
9/21/2020	MEDIUM	IWS	
9/23/2020	LARGE	IWS	
9/27/2020	SMALL	IWS	
9/28/2020	MEDIUM	IWS	Battery died mid-trial, missing ~2 minutes (minutes 12 & 13) and an estimated 0.4m3 (~3% of storm volume)
9/30/2020	SMALL	IWS	
8/26/2019	SMALL	B	
9/10/2019	SMALL	B	
9/16/2019	MEDIUM	B	

Appendix C: Example SAS Code for Data Analysis

All sample code uses TSS data as the example, but code was written for each pollutant parameter.

Step 1. Load data set.

```
PROC IMPORT DATAFILE= "/folders/myfolders/Data.txt"
    OUT= data
    DBMS=dlm
    REPLACE;
    delimiter='09'x;
RUN;
```

Step 2. Construct Boxplots

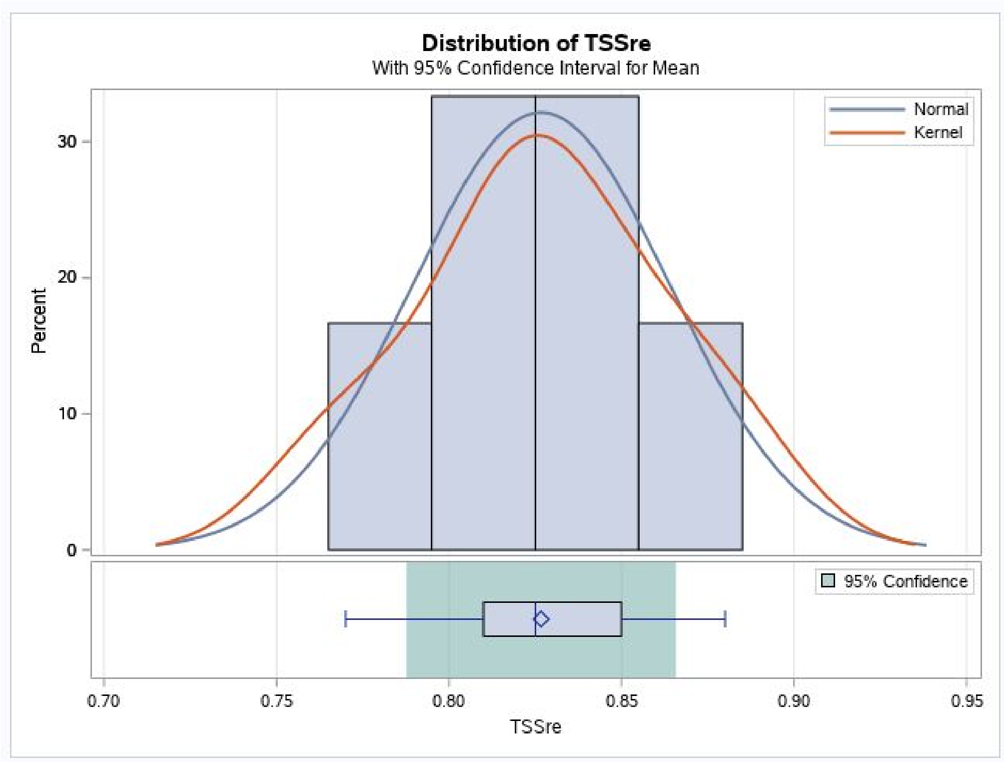
```
proc transpose data=data
    out=TSS(rename=(col1=Concentration)rename=(_Name_=Parameter));
    var TSSi TSSo;
    by trial basin_configuration notsorted;
run;
```

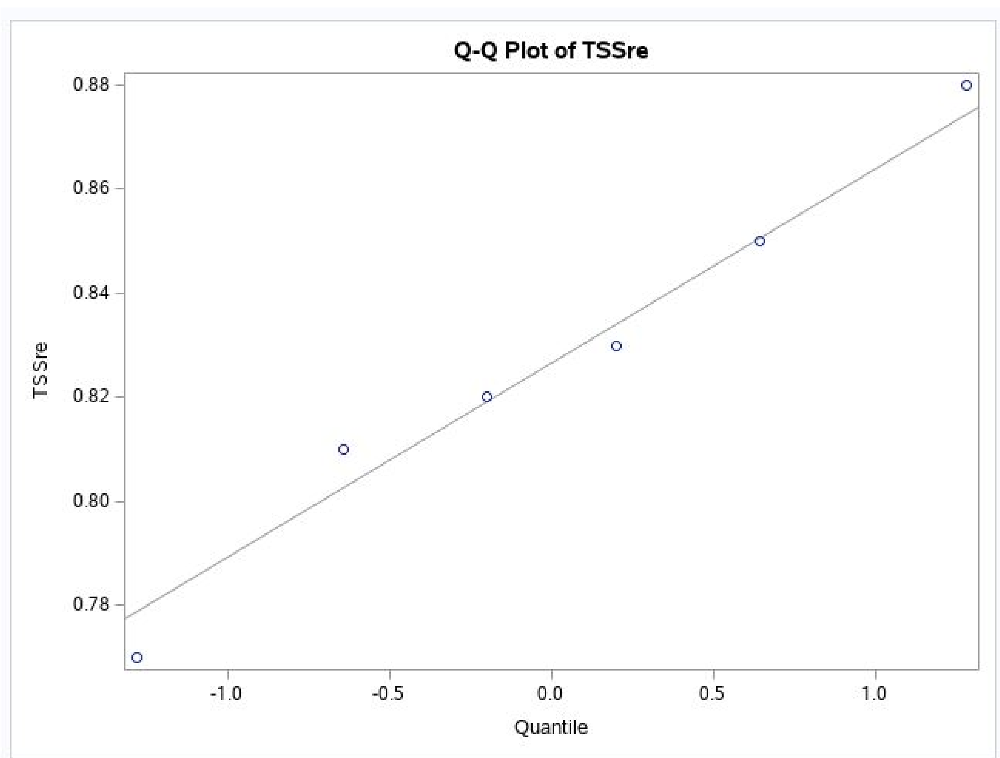
```
proc sgplot data=TSS;
    vbox Concentration / category=basin_configuration group=Parameter;
    keylegend/title="";
    xaxis label = "Basin Configuration";
    yaxis label = "Concentration (mg/L)";
run;
```

Step 3. Two-tailed T-test for H_0: RE=0; H_A: RE≠0 and visual inspection for normality

```
proc ttest data=data H0=0;
    var TSSre;
    by basin_configuration;
run;
```

Example SAS Output used to visually inspect for normality (Configuration B)


Distribution of TSSre
With 95% Confidence Interval for Mean
Normal
Kernel
Percent
30
20
10
0
95% Confidence
0.70
0.75
0.80
0.85
0.90
0.95
TSSre


Q-Q Plot of TSSre
TSSre
0.88
0.86
0.84
0.82
0.80
0.78
-1.0
-0.5
0.0
0.5
1.0
Quantile

Step 4. ANCOVA and Tukey's multiple comparisons procedure

```
proc glm data=data plots=residuals;
    class Basin_Configuration storm_size;
    model TSSre = basin_configuration TSSi storm_size;
    lsmeans basin_configuration / adjust=tukey pdiff;
run;
```

Appendix D: Data Trend Inspection Plots

All sample plots are of TSS, but plots were created for each pollutant parameter.

Sample SAS code and plot outputs

Storm Size Order

```
title "Scatter Plot of TSS Removal Efficiency";
proc sgplot data=data;
    scatter x=storm_index y=TSSre ;
run;
title;
```

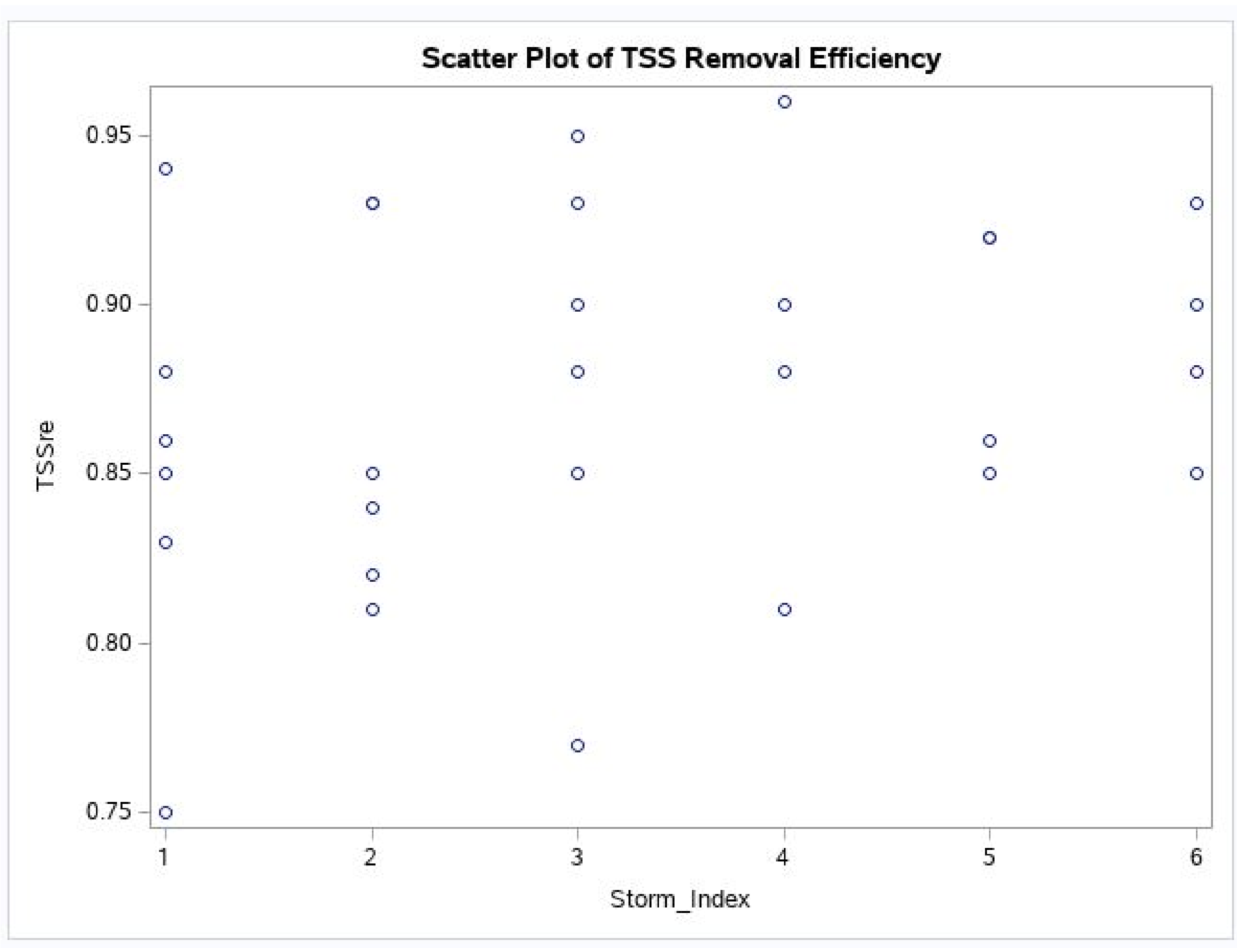


Figure D-1. Scatter plot of TSS removal efficiency by storm index

Basin Configuration Order

```
title "Scatter Plot of TSS Removal Efficiency";
proc sgplot data=data;
    scatter x=basin_configuration y=TSSre ;
run;
title;
```

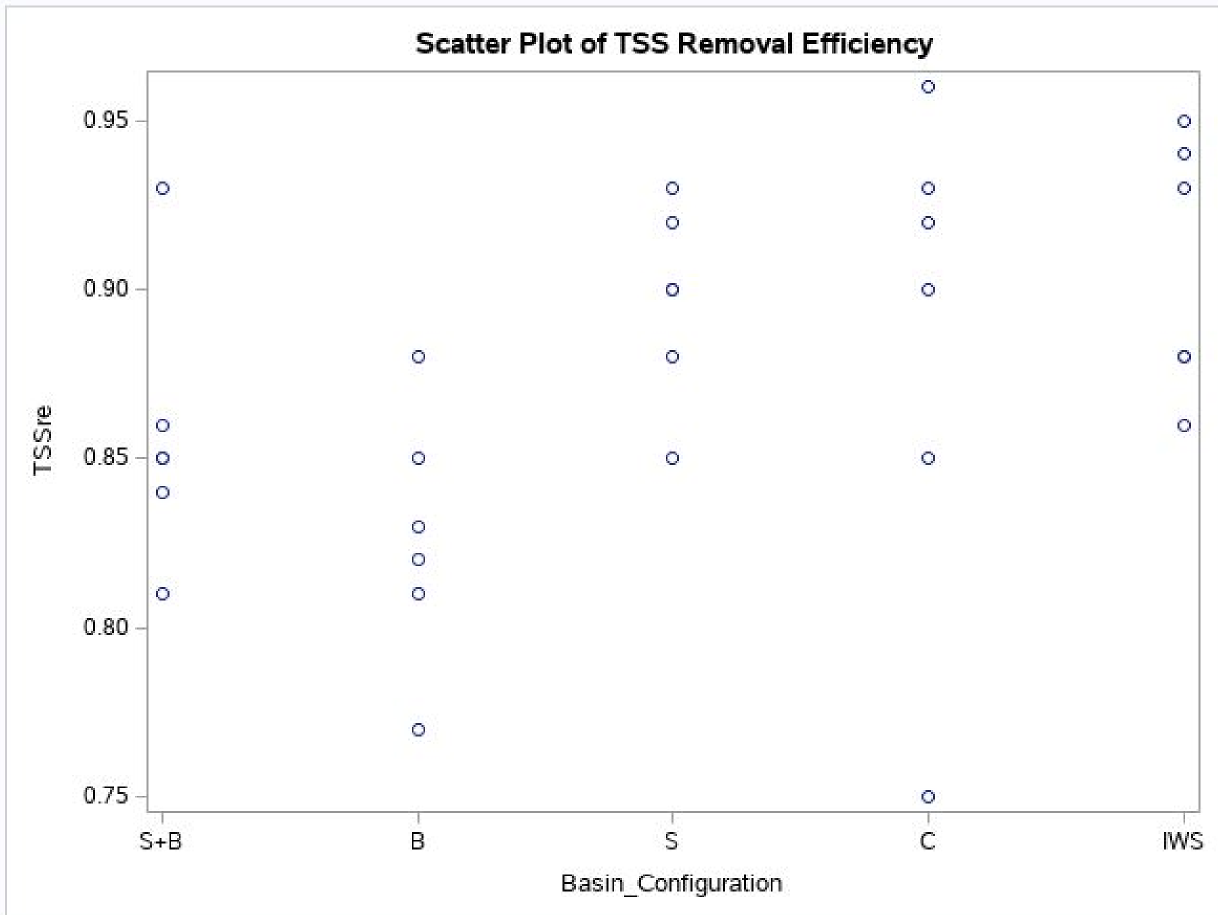


Figure D-2. Scatter plot of TSS removal efficiency by basin configuration order

Trial Order

```
title "Scatter Plot of TSS Removal Efficiency";
proc sgplot data=data;
    scatter x=trial y=TSSre / group=Basin_Configuration;
run;
title;
```

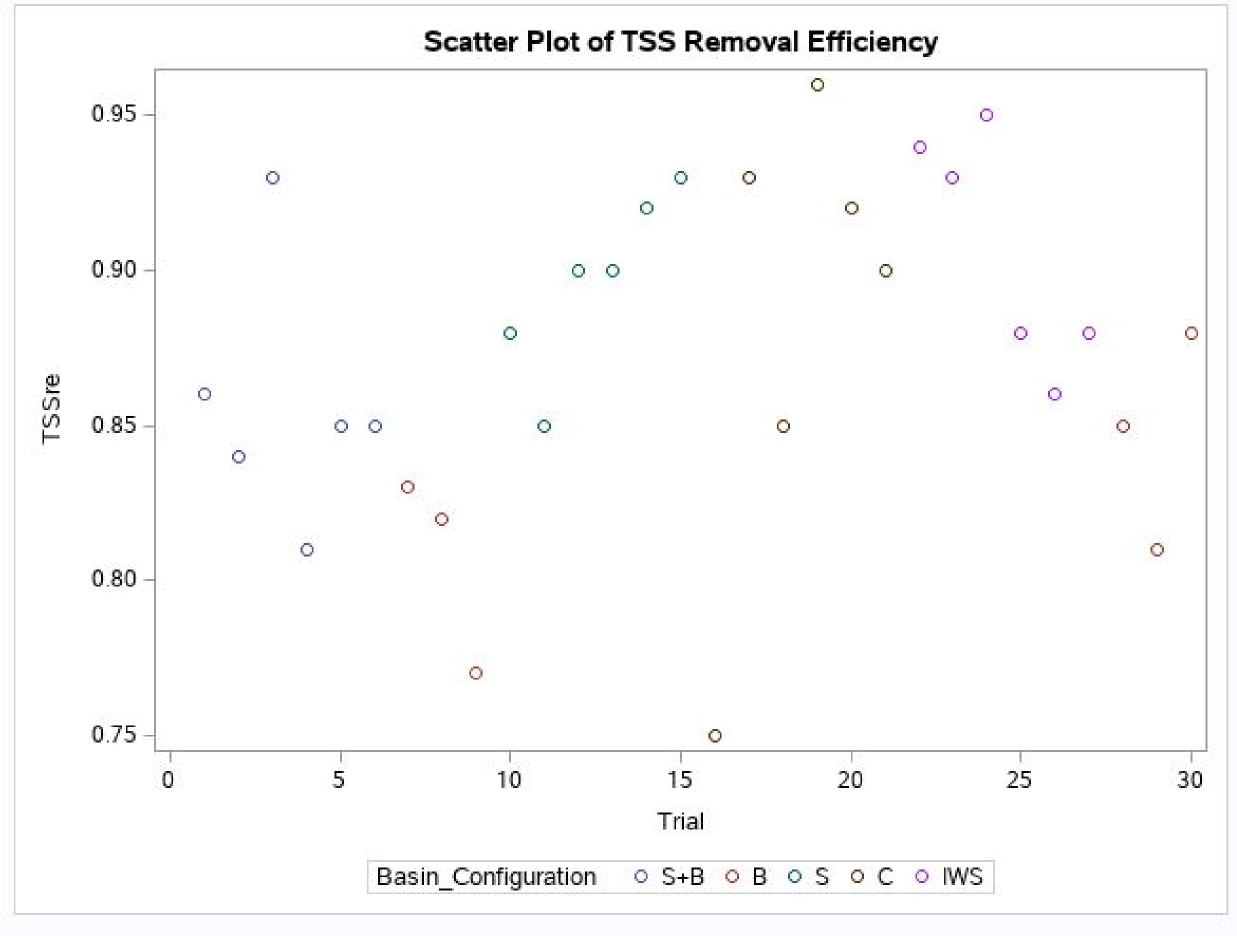


Figure D-3. Scatter plot of TSS removal efficiency by trial number