Abstract

ELLIS, AMBER. Dry Detention Basin Optimization for Water Quality Treatment: Controlled Plot Trials. (Under the direction of Dr. William F. Hunt, III)

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 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 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 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 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) and highly controlled influent concentrations 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. Future research is needed to assess the hydrologic performance of IWS in DDBs.

Dry Detention Basin Optimization for Water Quality Treatment: Controlled Plot Trials

by
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Dedication

This thesis is dedicated to the relentless pursuit of making the world better, one small bit at a time.

"Often when you think you're at the end of something, you're at the beginning of something else."
-Fred Rogers

"When you do common things in life in an uncommon way, you will command the attention of the world."
– George Washington Carver

Biography

Amber Ellis grew up in the mountains of western North Carolina climbing apples trees, running through rhododendron thickets, splashing in cold creeks, and all together taking for granted the mundane magic of a childhood in the hills. Enamored with the natural world and the science that helps explain its wonder, she ventured to Durham, NC, graduating from the North Carolina School of Science and Mathematics before enrolling in Williams College for her undergraduate degree. At Williams she studied Geosciences and Africana Studies, and sometime between examining rock formations and critical race theory she realized that North Carolina was home for a reason.

She returned to the Old North State after graduation to serve with AmeriCorps in Brunswick County through a partnership with the county extension office and FoodCorps. Two years of service reconnected her with her love of natural resources and spurred her to pursue environmental engineering at N.C. State University. Under the hilariously entertaining and academically rigorous tutelage of Dr. Bill Hunt, she has discovered a passion for stormwater and water resource management. Upon graduation, she hopes to continue furthering stormwater research through N.C. Cooperative Extension.

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Thanks to Dr. Bill Hunt, my advisor, mentor, and friend, for the never-ending stream of encouragement, challenges, and laughs. He, along with the rest of the BAE stormwater team, made work feel like play and learning feel like growing.

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Finally, thanks to my mom and dad. I owe a great deal of who I am and what I have achieved to their generosity of love and confidence. I'm thankful that they cultivated the curiosity that fuels my nerdiness today.

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Chapter 1. A Literature Review on Dry Detention Basin Water Quality Performance and Potential Retrofit Options for Improving Pollutant Removal

1.1 Introduction

The population of the United States has increased more than three-fold over the past century, and nearly all that growth has been concentrated in urban centers (U.S. Census Bureau, 2016). As of 2010, over 80% of American residents live in urban areas (U.S. Census Bureau, 2016). As development and urbanization expand, more of the landscape transitions from natural, permeable surfaces to constructed, less-permeable ones. Precipitation that would have previously infiltrated into the soil is redirected by roads, parking lots, rooftops, and other urban infrastructure as runoff; this runoff transports various pollutants such as sediment, nutrients, and heavy metals into receiving waterways and bodies. The United States Environmental Protection Agency (EPA) has named this kind of nonpoint source pollution one of the leading causes of water quality impairment, and it has far reaching impacts including habitat destruction and human drinking water hazards (U.S. EPA, 2017).

Stormwater control measures (SCMs) are engineered systems designed to mitigate stormwater runoff rate, volume, and/or quality. Dry detention basins (DDBs) are common SCMs that have been employed since the 1970s, primarily to mitigate nuisance flooding and excessive erosion (Stanley, 1996). More recently, however, attention has turned to their limited ability to also improve water quality. The objectives of this chapter were to review the performance of DDBs as designed under standard guidance, as well as the growing body of research of optimizing DDB pollutant removal efficiency. This chapter identified and compiled research on design elements that have increased the pollutant removal efficiency of other stormwater practices as a means of creating a framework upon which DDB optimization research can build.

1.2 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, 2014). 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 (Figure 1-1). 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

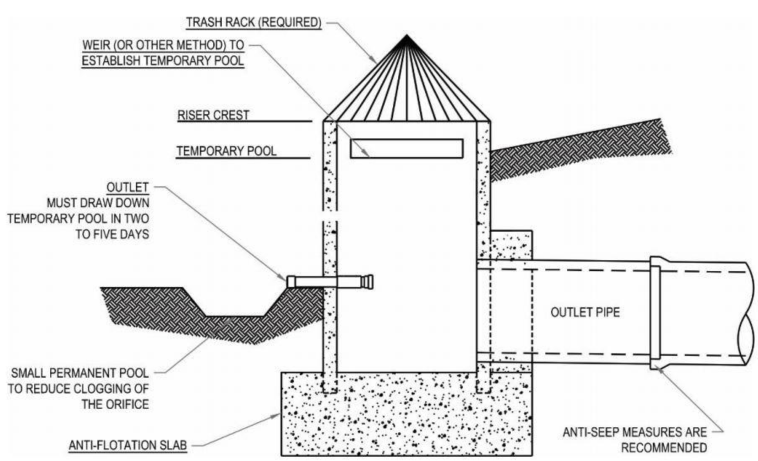

Figure 1-1. Standard DDB outlet structure in North Carolina (NCDEQ, 2017)

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 1-1). Certain pollutants, such as total nitrogen (TN), had similar removal efficiencies throughout the research; however, the removal of most pollutants was quite variable among DDBs and even significantly varied for a single basin when analyzed during different storm events (Stanley, 1996). The documented removal efficiency of Zn in one basin, for example, ranged from 2 to 79 % (Stanley, 1996). 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. For example, Stanley (1996) reported a 26 % reduction of total nitrogen, but an 8 % export of NO_X, a dissolved nitrogen species. This trend is consistent with research that showed that the primary pollutant removal mechanism in DDBs is sedimentation (Middleton & Barrett, 2008).

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

	DDB Study									
	Birch et al. (2006)	**Guo (1997)**	**Pope and 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)

1.3 Retrofitting Dry Detention Basins for Increased Sedimentation

1.3.1 Porous Baffles

Because the primary pollutant removal mechanism in DDBs is sedimentation, processes or retrofit configurations that increase sedimentation rates could increase DDB water quality treatment. 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 1-2). In a set of controlled field

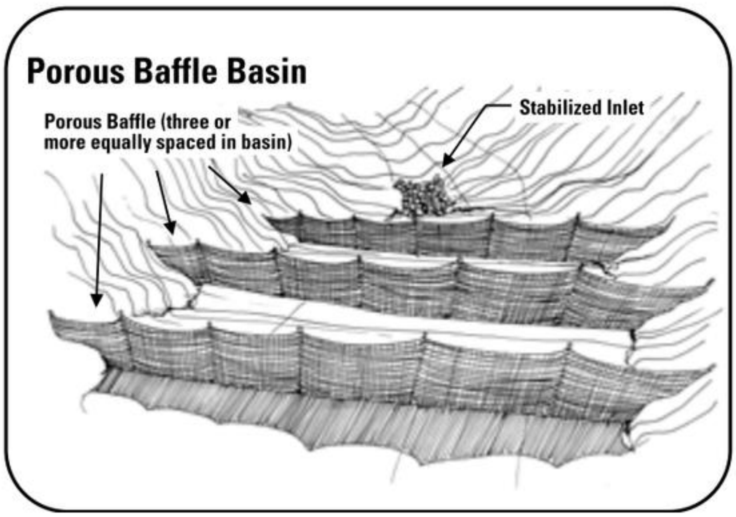

Figure 1-2. Typical sediment basin with baffles (McLaughlin, 2015)

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

The porous baffles distributed the flow energy across the entire width of the basin, thereby reducing preferential flow paths and increasing removal efficiency (Thaxton & McLaughlin, 2005). While the sediment capture rate was over 96% for all experiments, the jute/coir baffles captured the most sediment as well as a median grain size that was less than half of that when the basin had no baffles at all (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).

1.3.2 Increase Hydraulic Residence Time

In general, increasing the hydraulic residence time (HRT) increased sedimentation within DDBs (Bidelspach et al., 2004; Shammaa et al., 2002; Whipple & Randall, 1983). In a set of simulated storm events, delaying the outflow of a sedimentation basin for seven days increased TSS removal from 92 to 98 % (Bidelspach et al., 2004). In their study of two Canadian DDBs, Shammaa et al. (2002) reported HRT as the most important design factor when considering TSS removal in DDBs, but there was a limit to its impact. After 40 hours there was negligible additional improvement, suggesting an optimal HRT of 24 to 40 (Shammaa et al., 2002). A maximum HRT threshold is important for efficient water quality treatment as well as for public safety. DDBs' flood mitigation function remains a primary design consideration, and prolonging HRT such that complete inter-event dewatering is prevented can pose flooding risks during successive storm events (Papa et al., 1999).

Increasing total HRT for all storms may not be necessary to improve water quality performance, (Middleton & Barrett, 2008). Rather, specifically increasing HRT of the "first-flush" yielded higher pollutant removal efficiencies (Middleton & Barrett, 2008). The first-flush refers to the first portion of runoff generated by a storm event, which contains the highest pollutant concentrations (Hathaway & Hunt, 2011; Middleton & Barrett, 2008). Because typical DDB design includes a drawdown orifice at the bottom of the basin, the water with the highest proportion of contaminants also has the shortest HRT.

Modifying the outlet structure to create batch-treatment conditions improved DDBs' water quality treatment in Pennsylvania and Texas (Middleton & Barrett, 2008). In Middleton and Barrett's (2008) DDB field study, more sedimentation occurred by using a programmable outlet valve to store all the runoff within the basin for 12 hours before opening the drawdown orifice. The effluent concentrations of all studied pollutants were at least 50% lower in the modified DDB as compared with typical DDBs (Middleton & Barrett, 2008). The DDB performed particularly well in regard to TSS (91% removal efficiency, Middleton & Barrett, 2008). These studies suggested that water quality treatment could be improved by altering the outlet structure, rather than increasing HRT.

1.3.3 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 1-4). 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 modification increases sedimentation without requiring hydraulic residence time to increase (Jarrett, 2001; Pilon et al., 2016).

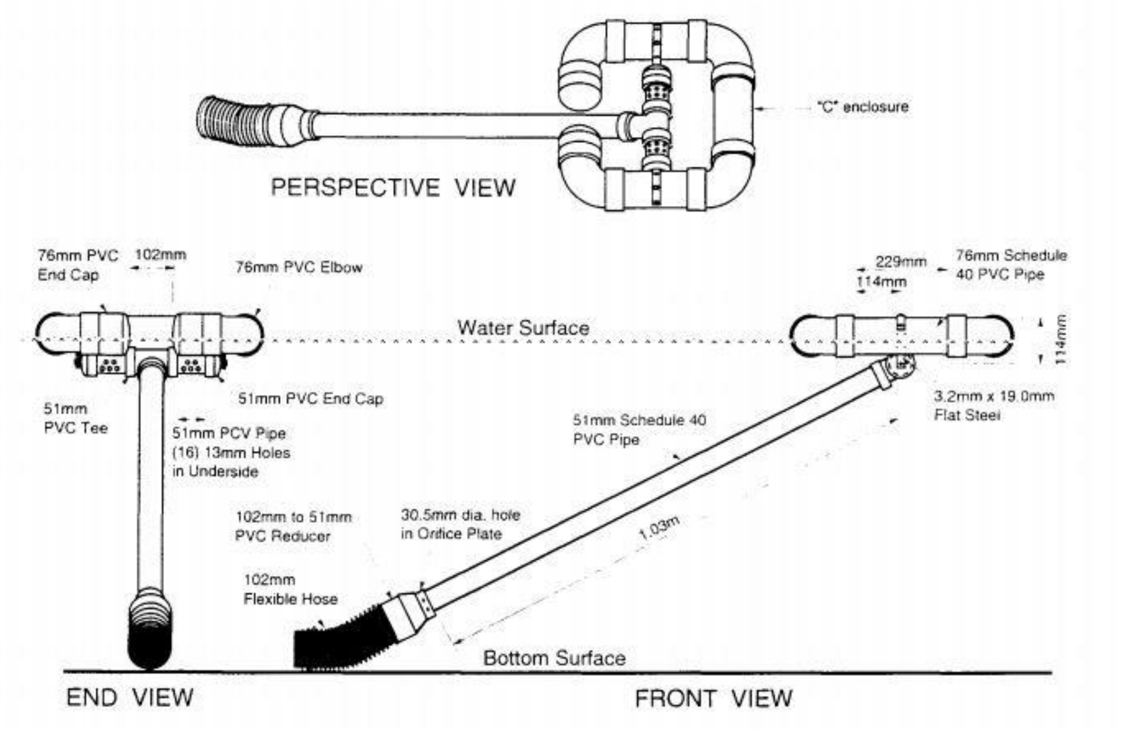

Figure 1-4. Typical Skimmer Outlet Device (Millen et al., 1997)

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).

Pilon et al. (2016) proposed a new skimmer design with no moving parts. The solid-state skimmer (SSS) is comprised of two nested, perforated risers and controls flow in such a way that the basin is dewatered from the top of the water column at a variable rate (Pilon et al., 2016). While no working prototypes have currently been produced or tested, the authors hypothesized that the benefits of the SSS are primarily related to maintenance and the ability of basins to successfully discharge larger storm events (Pilon et al., 2016).

1.3.4 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 1-5; 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, 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).

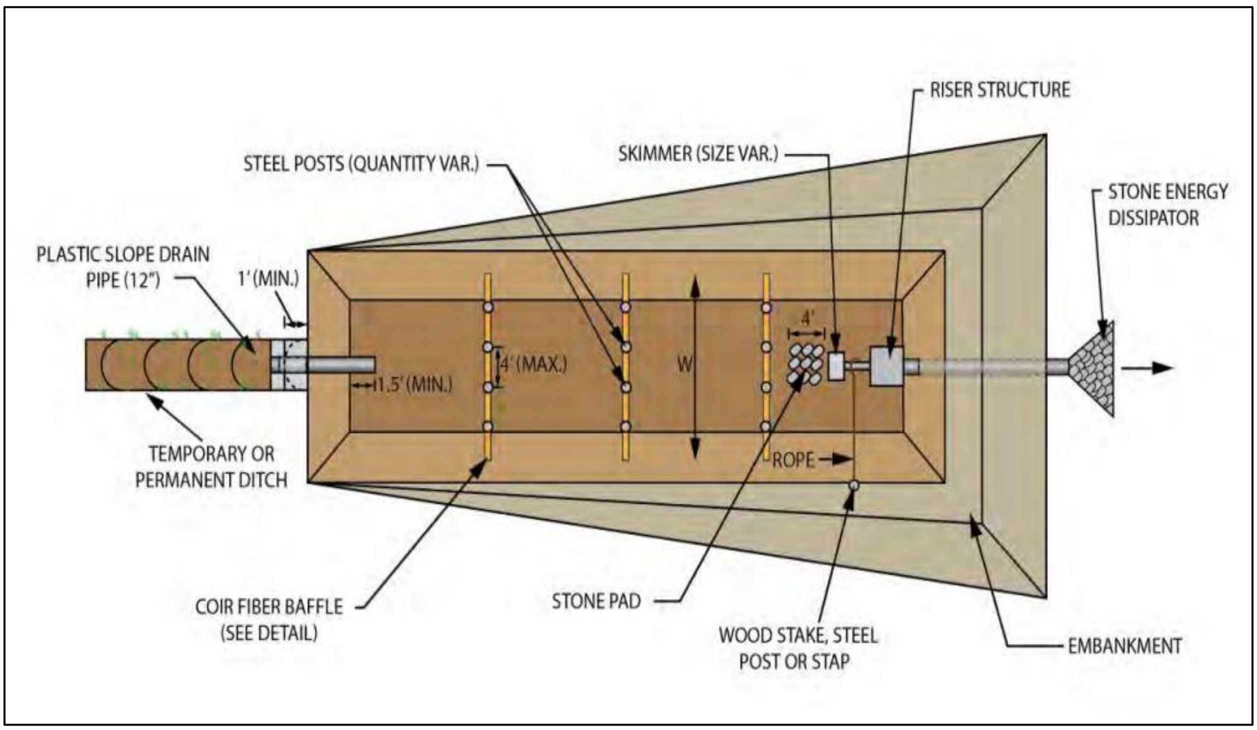

Figure 1-5. Typical sediment basin with porous baffles and a skimmer outlet (NCDOT, 2015)

1.4 Retrofitting Dry Detention Basins for Non-Particulate Pollutant Removal

1.4.1 Subsurface Saturation

Higher sedimentation increased particulate pollutant removal efficiencies, but retrofits aimed at sedimentation resulted in little improvement for dissolved pollutants such as NO_X (Middleton & Barrett, 2008). McPhillips and Walter (2015) examined whether hydrologic conditions drive denitrification in stormwater detention basins. Denitrification is the process by which excess NO_x is transformed into N_2 gas. They compared DDBs that maintained various levels of saturation and reported that denitrification potential was approximately three times higher in basins with saturated soils as compared to dry ones (McPhillips & Walter, 2015). This suggested that a DDB retrofitted with a subsurface saturated zone could more effectively remove dissolved nitrogen species (McPhillips & Walter, 2015).

1.4.2 Internal Water Storage (IWS)

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 1-6). 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 denitrification was limited (Hunt et al., 2012).

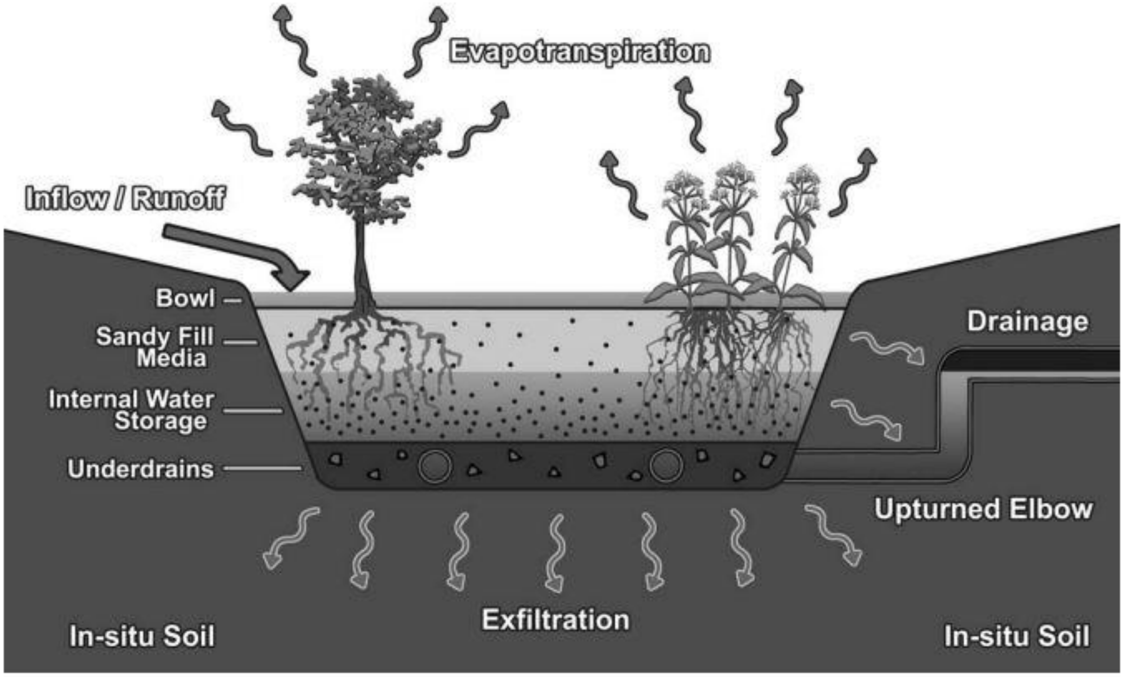

Figure 1-6. Bioretention cell schematic showing the location of IWS (Brown et al., 2009)

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).

1.4.3 Vegetative Retrofit Designs

1.4.3a Wetland Conversion

Mazer (2018) installed wetland plants and modified the outlet structure of a DDB to create permanent ponding and increased detention time in an effort to simulate constructed stormwater wetland (CSW) water quality treatment conditions (Figure 1-7). The retrofit increased effluent concentration reductions, by 58%, 65%, and 64% for TSS, total phosphorous, and total nitrogen, respectively, as compared to standard DDB removal rates. Retrofitted basins improved treatment via increased sedimentation, evapotranspiration, and nitrification (Mazer, 2018). NO_X concentrations were not reduced during storm events, however, high removal rates (99%) during inter-event baseflow suggested denitrification potential.

Figure 1-7. DDB before (left) and after (right) wetland conversion (Mazer, 2018)

Design regulations permit deeper ponding depths in DDBs than in CSW, which resulted in reduced storage capacity after conversion and an increase in bypass for storms 25mm and larger

(Mazer, 2018). In general, reductions in storage capacity can pose safety hazards as they increase flooding risks (Papa et al., 1997).

1.4.3b Naturalization

Typically, DDBs are mowed during routine maintenance (NCDOT, 2014), however, if left unmaintained, a "naturalization" process begins whereby the basin is recolonized by surrounding woody and herbaceous vegetation (Figure 1-8; Wissler, 2019). In a field monitoring study two such naturalized DDBs significantly reduced TSS, total nitrogen, and total phosphorous concentrations at rates consistent with standard DDB designs (Wissler et al., 2020). However, the woody vegetation increased infiltration, canopy capture, and evapotranspiration such that runoff volume reductions (41% and 61% for each basin) resulted in load reductions of total nitrogen and phosphorous that exceeded the credited values for DDBs (Wissler et al., 2020).

Figure 1-8. Naturalized DDB colonized with woody vegetation (Wissler, 2019)

Importantly, woody vegetation improved water quality treatment through increased evapotranspiration and infiltration via root channeling without significantly decreasing stormwater storage capacity within the DDBs. Therefore, while overgrown vegetation can increase safety risks associated with impeding sightlines (NCDOT, 2016), it did not increase basin bypass or associated flooding (Wissler et al., 2020).

1.5 Discussion and Future Work

With urbanization, negative impacts of stormwater runoff on water quality are expanding. For DDBs, however, the design guidance still focuses primarily on flood mitigation, with minimal regard for pollutant removal. This chapter identified key design elements that have improved the water quality performance of SCMs and suggested that these elements could yield improved water quality treatment of DDBs (Table 1-2).

Future research is needed to determine whether the water quality benefits associated with the use of porous baffles, skimmer outlets, and IWS systems demonstrated in other SCMs translate to DDBs. This future research will rely heavily on a combination of experimental trials and field monitoring. 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. For example, Birch et al. (2006), Stanley (1996), and McPhillips and Walter (2015) each had data sets of only six, eight, and seven points, respectively.

Table 1-2. Potential DDB retrofit design summary

Design Change	Function	Target Pollutants	Other Implementation Considerations for DDBs	SCM types studied	Citations
Porous Baffles	Distributes flow energy across the entire width of the basin, increasing sedimentation	Particulate	Additional maintenance	Sedimentation basin	Thaxton & McLaughlin, 2005 Vaze & Chiew, 2004
Increased HRT	More sedimentation and infiltration time	Particulate	Delayed de-watering increases flooding risks during successive storms	Sedimentation basin, DDB	Bidelspach et al., 2004 Shammaa et al,. 2002 Whipple & Randall, 1983
Increased HRT of first flush	More sedimentation time for the portion of runoff with highest pollutant concentrations	Particulate	Programmable outlet structure required	DDB	Middleton & Barrett, 2008
Skimmer Outlet	Dewaters basin from the top of the water column, increasing sedimentation	Particulate	Additional maintenance	Sedimentation basin	Jarrett, 2001 Millen et al., 1997
Skimmer Outlet + Porous Baffles	Same functions as skimmer outlet and porous baffles	Particulate	Additional maintenance	Sedimentation basin	McCaleb & McLaughlin, 2008
IWS	Retains a portion of runoff during	Particulate and dissolved	Decreased storage capacity increases flooding risks during successive storms	Bioretention, Permeable pavement	Brown & Hunt, 2011 Hunt et al., 2006 Braswell et al., 2018 Wardynski et al., 2013
Wetland conversion	Increases evapotranspiration, sedimentation, nitrification, and potentially denitrification	Particulate and dissolved	Decreased storage capacity	DDB	Mazer, 2018
Naturalization	Increases volume reduction through evapotranspiration, canopy interception and greater infiltration via root channeling	Particulate and dissolved	Increased safety risks associated with line-of-site and mosquito breeding	DDB	Wissler, 2019 Wissler et al., 2020

To directly analyze whether the retrofit options outlined in this paper will improve DDB water quality treatment, a plot study can be 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 would allow for a direct comparison of pollutant removal performance between basin designs and retrofit options.

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Chapter 2. Methods and Materials Used to Test the Water Quality Performance of Four Dry Detention Basin Retrofit Configurations in a Series of Controlled Plot Trials

2.1 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, and this chapter details the methods and materials used to conduct a set of controlled plot trials investigating that potential.

2.2 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 Raleigh, NC (Figure 2-1). SECREF is five miles from NCSU's campus and hosts educational workshops and research projects pertaining to stormwater management and sediment and erosion control.

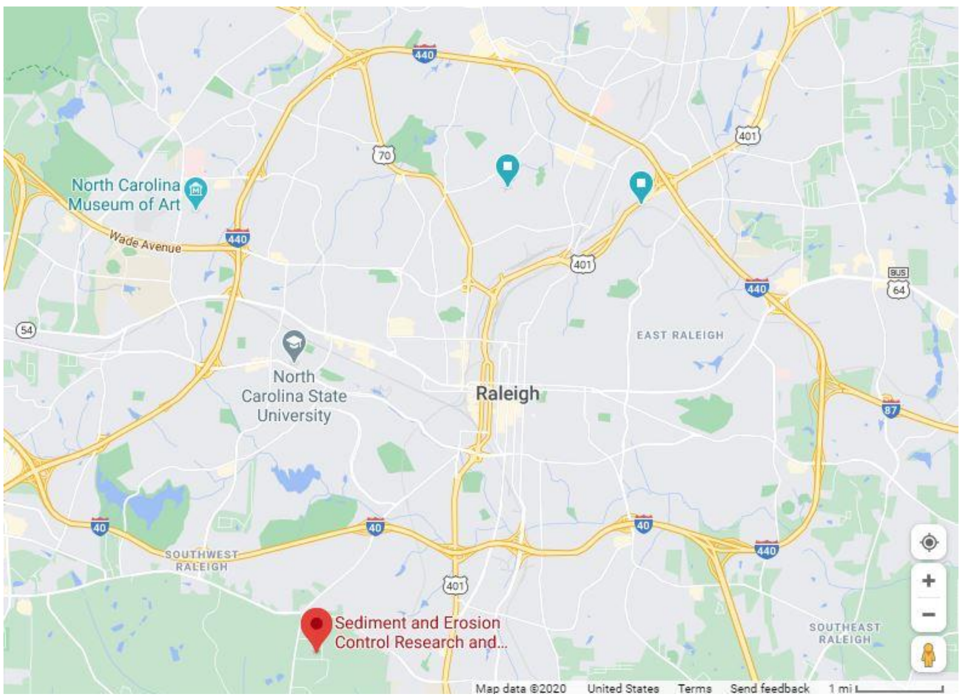

Figure 2-1. NCSU's Sediment and Erosion Control Research and Education Facility location (Google Maps, 2020)

2.2.1 DDB Characterization

A pond was converted into a DDB and retrofitted with each design configuration. The resulting DDB was approximately 9m long, 4.5m wide, and held a maximum volume of approximately 26m^3 (Figure 2-2, Table 2-1). 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.

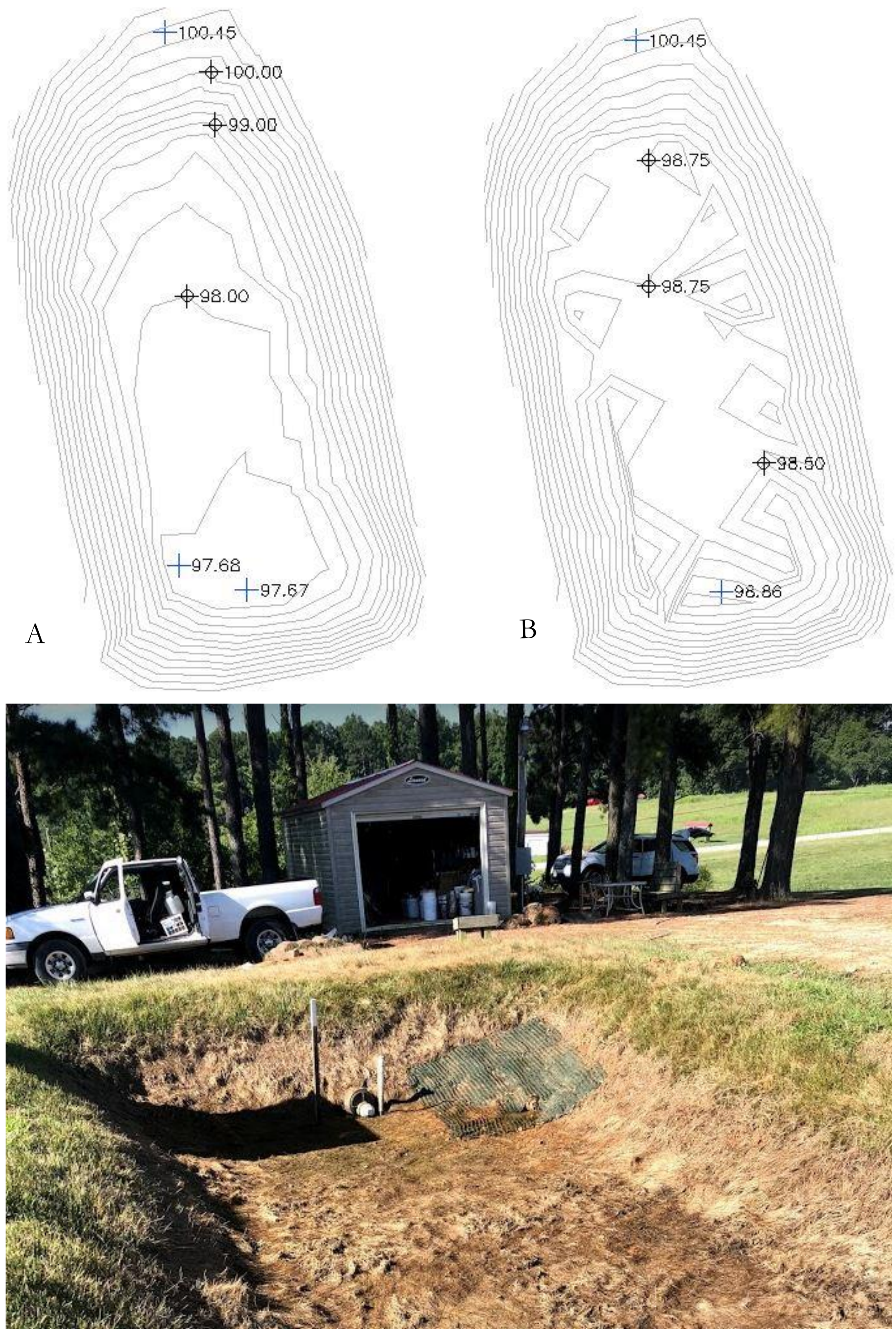

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Figure 2-2. Trial DDB topography with the inlet noted at the top (100.45'). A. Basin with skimmer connection (97.68') and control outlet (97.67') elevations noted B. Basin with IWS topography and outlet elevation noted C. Control basin drawdown position (figure is not representative of vegetation during trials)

Table 2-1. Control DDB stage-storage table

Contour Elevation (ft)	Contour Elevation (m)	Contour Area (m^2)	Incremental Depth (m)	Average End Method		Conic Method	
				Incremental Volume (m^3)	Cumulative Volume (m^3)	Incremental Volume (m^3)	Cumulative Volume (m^3)
97.75	29.8	4.29	N/A	N/A	0.00	N/A	0.00
98.00	29.89	12.80	0.076	0.65	0.65	0.62	0.62
98.25	29.97	19.01	0.076	1.21	1.86	1.20	1.82
98.50	30.04	23.78	0.076	1.63	3.49	1.62	3.45
98.75	30.12	28.09	0.076	1.97	5.46	1.97	5.42
99.00	30.20	31.35	0.076	2.26	7.72	2.26	7.68
99.25	30.27	34.24	0.076	2.49	10.22	2.49	10.17
99.50	30.35	37.15	0.076	2.72	12.93	2.71	12.89
99.75	30.42	40.17	0.076	2.94	15.87	2.94	15.83
100.00	30.50	43.45	0.076	3.18	19.05	3.18	19.01
100.25	30.58	46.89	0.076	3.44	22.49	3.44	22.44
100.50	30.65	50.12	0.076	3.69	26.18	3.69	26.13

2.2.2 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 12mm 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.

2.3 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.

2.3.1 Control

The control configuration was constructed in accordance with standard DDB guidance and requirements (NCDEQ, 2017). This included a 13mm drawdown orifice drilled into the PVC outlet pipe cap (Figure 2-3) positioned on the DDB's bottom (Figure 2-4). Fescue sod was installed during construction but prolonged inundation inhibited growth (Figure 2-2c). Volunteer vegetation was allowed to colonize the DDB and covered approximately 95% of the surface area at the time of trials (Figure 2-4). 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.

2.3.2 Porous Baffles

Two porous coir baffles with 13mm openings (700 g/m^2) (Figure 2-5), were installed across the width of the basin in the standard, double layer design achieved by folding over the baffle material. The baffles were 0.9m high, placed every 3m along the basin length (Figure 2-6, Figure 2-7), 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 (Section 2.3.1).

Figure 2-3. Baseline outlet orifice drilled into outlet pipe cap

Figure 2-4. Control DDB configuration with representative vegetation

Figure 2-5. Coir baffle material

Figure 2-6. DDB with porous baffles

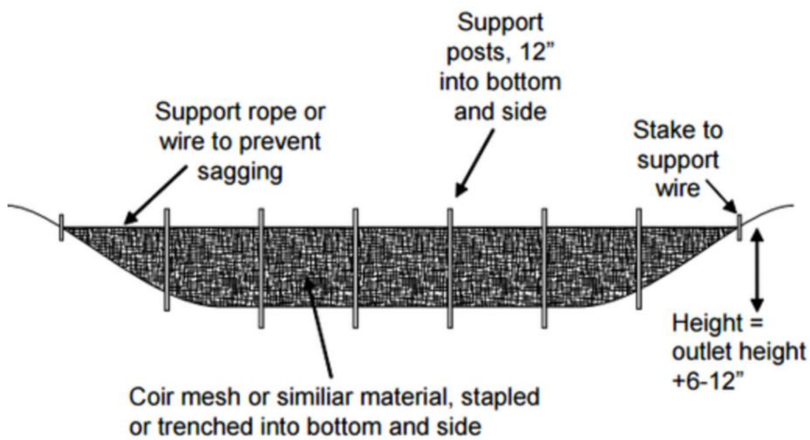

Figure 2-7. Baffle installation guidance (McLaughlin, 2015).
[Every 12" is equivalent to 30cm.]

2.3.3 Skimmer

A 2.0-inch (51mm) Faircloth Skimmer (J. W. Faircloth & Son, Inc., Hillsborough, NC) with a 13mm drawdown orifice (Figure 2-8) 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 (Section 2.4.2). 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 2-9). The control outlet pipe remained in the basin during the skimmer trials but was capped.

Figure 2-8. 2-inch skimmer with 13mm plug orifice

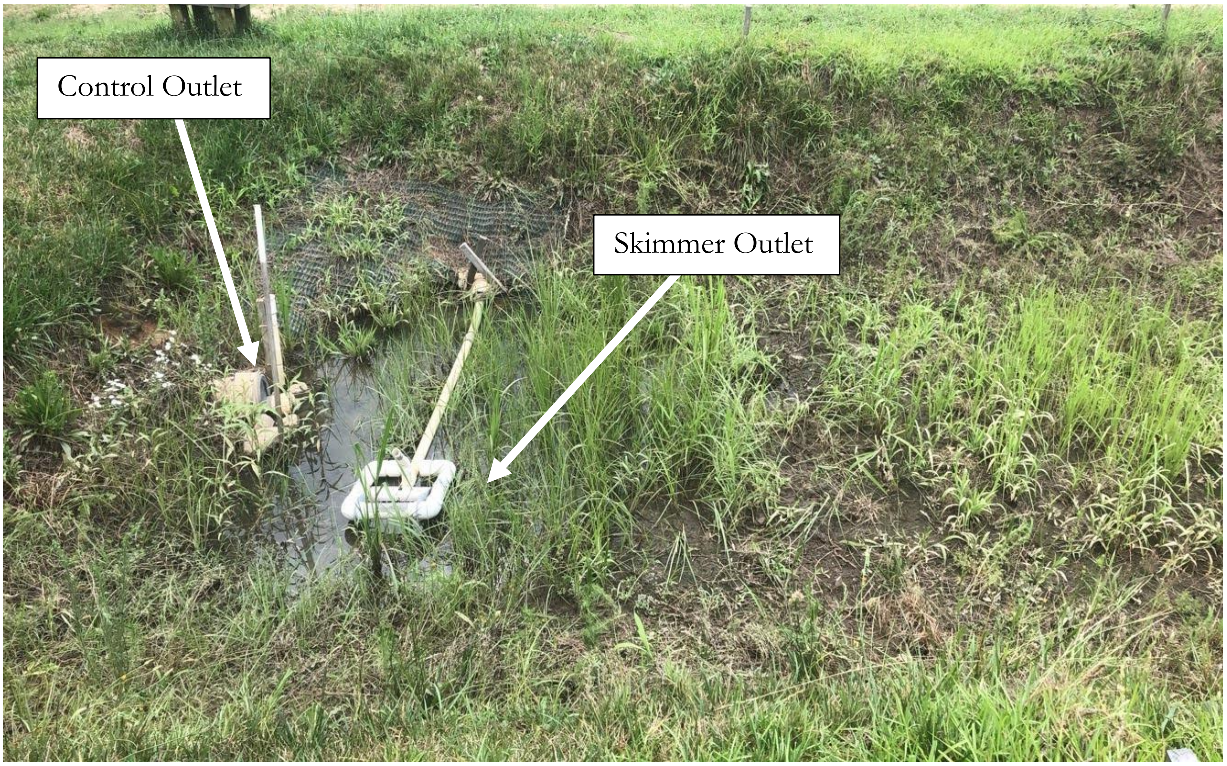

Figure 2-9. Skimmer outlet placement in relation to the control outlet (capped)

Figure 2-10. DDB configuration with porous baffles and skimmer in tandem (photo taken in 2019 before trials began

2.3.5 Internal Water Storage (IWS)

To install the IWS system, the control drawdown orifice was elevated approximately 0.3 m (Figure 2-11). 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 2-12). The skimmer outlet shown in Figure 2-11 was capped.

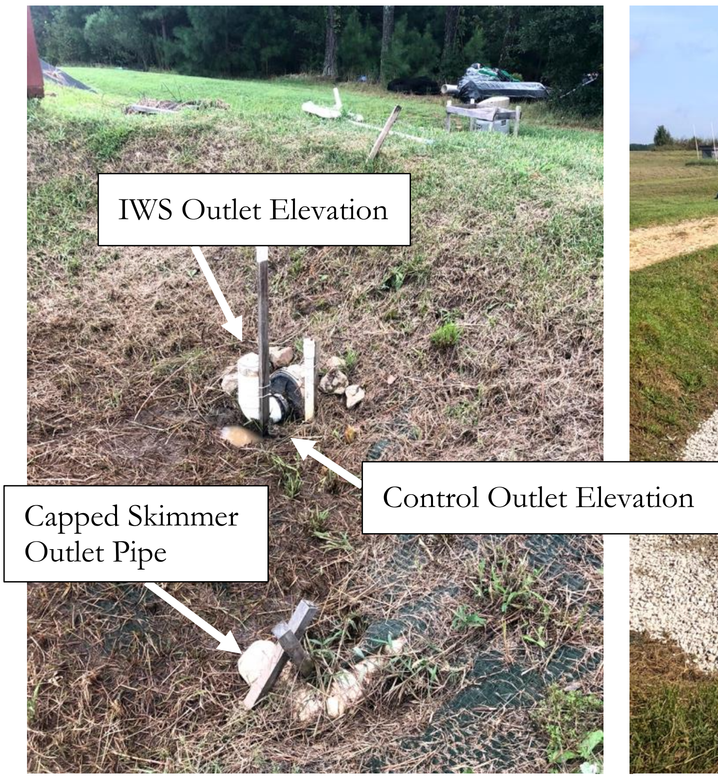

Figure 2-11. Elevated outlet orifice in IWS configuration pre-gravel installation

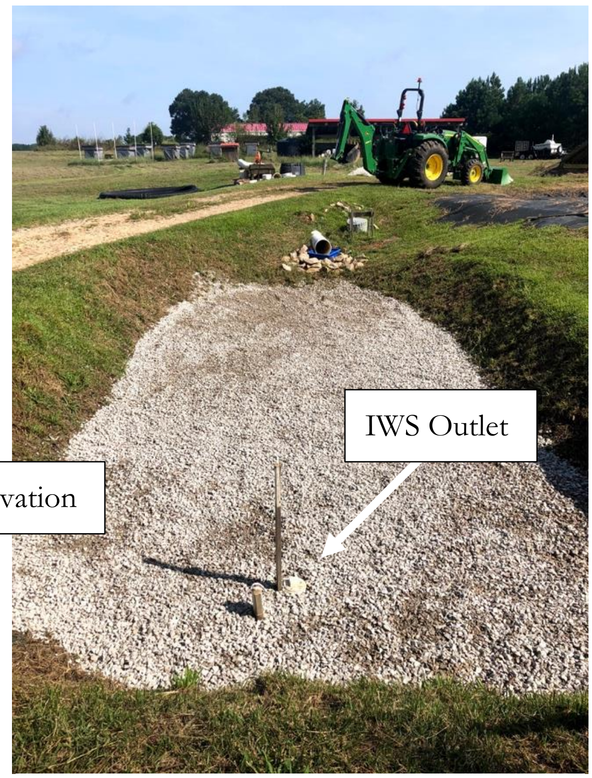

Figure 2-12. IWS basin configuration with #57 stone fill

2.4 Experimental Design and Set-Up

2.4.1 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 2-2).

Table 2-2. 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 in Section 2.8.

2.4.2 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 6, 12, and 24 m^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 2-4). 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 (see Section 2.5).

Table 2-4. Storm size details summary

Storm Size	Approximate Volume (m^3)	Inflow Time (mins)	Approximate Outflow Time (hrs)	Time Step (mins)
Small	6	20	12	5
Medium	12	30	18	5
Large	24	60	24	10

2.4.3 Temperature and Influent Concentration Controls

Trials were only conducted when the ambient air temperatures were above 10°C, 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 2-3; Wissler et al., 2020). Pollutant inputs were calculated by multiplying target concentrations (mg/L) by target storm volumes (L) (Table 2-3). 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. Section 2.5.2 details the matrix spike process.

Table 2-3. 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	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

2.5 Experimental Procedures

2.5.1 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 2-13). 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 2-14; Table 2-4).

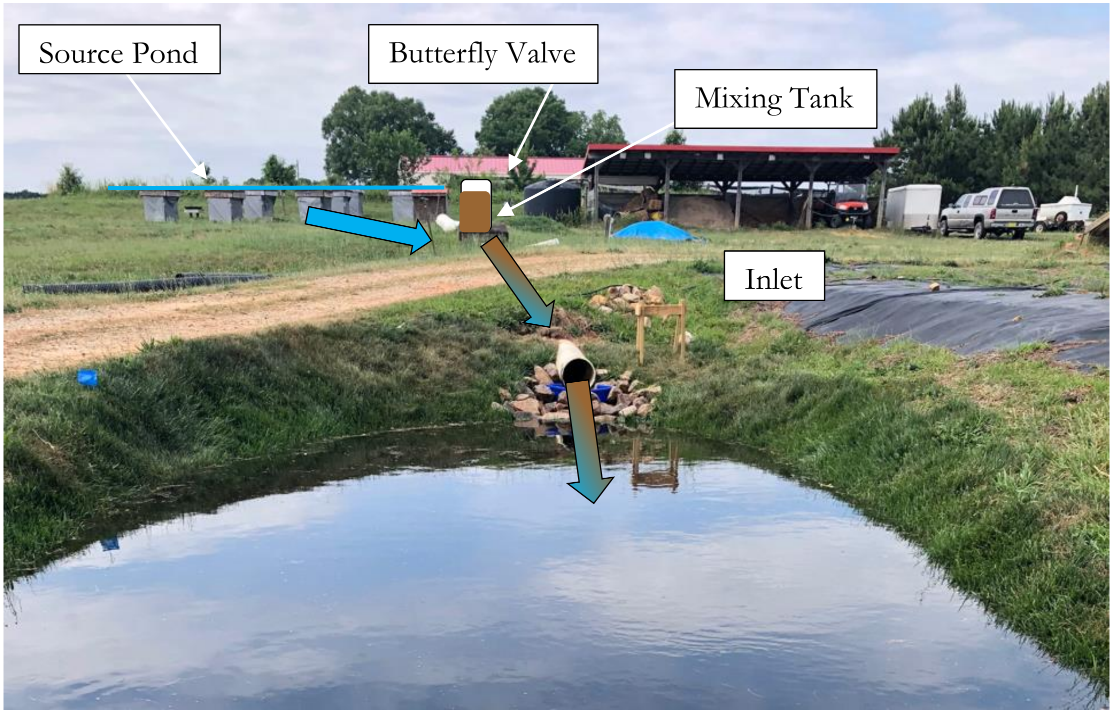

Figure 2-13. Trial DDB experimental set-up

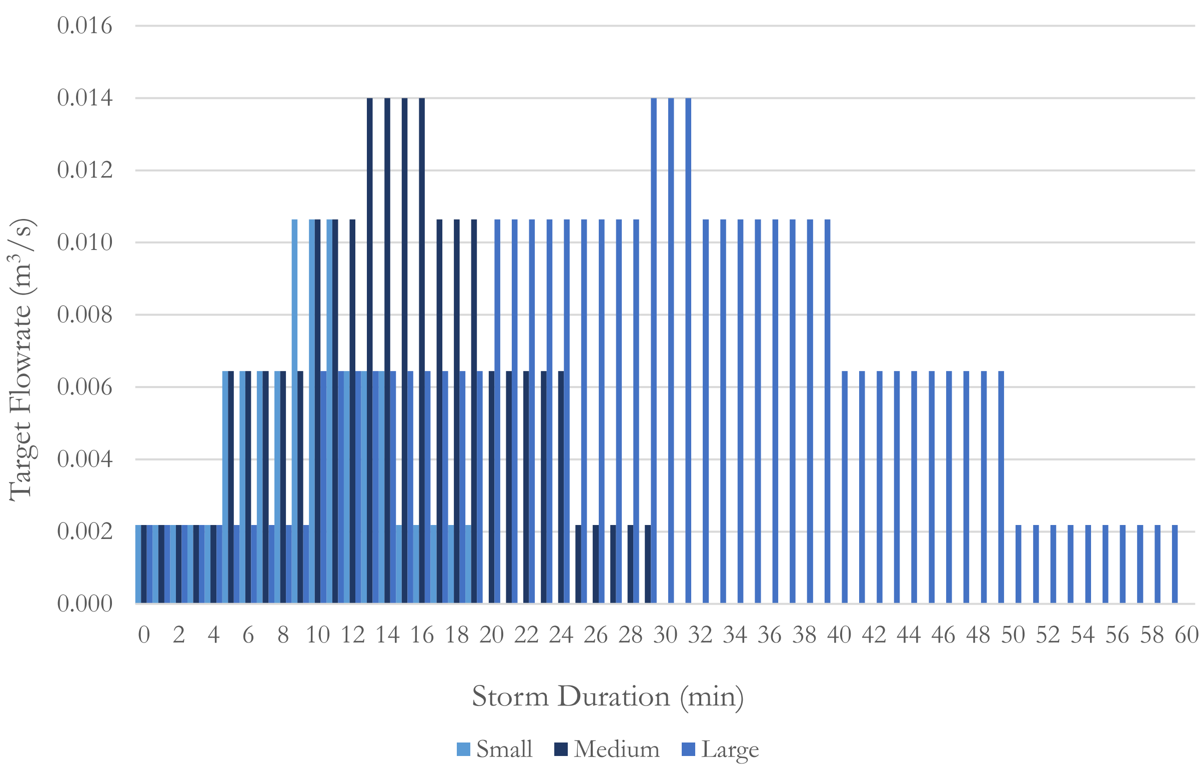

Figure 2-14. Idealized design storm hydrographs used in controlled plot trials

Table 2-4. Time-step duration, flow, and volume for each idealized storm size

Small			Medium			Large		
Time Step (minute)	Flow Rate (m^3/s)	Cumulative Volume (m^3)	Time Step (minute)	Flow Rate (m^3/s)	Cumulative Volume (m^3)	Time Step (minute)	Flow Rate (m^3/s)	Cumulative Volume (m^3)
0:00	0.002	0.00	0:00	0.002	0.00	0:00	0.002	0.00
0:05	0.006	0.66	0:05	0.006	0.66	0:10	0.006	1.31
0:09	0.011	2.20	0:10	0.011	2.59	0:20	0.011	5.17
0:12	0.006	4.12	0:13	0.014	4.50	0:29	0.014	10.92
0:15	0.002	5.28	0:17	0.011	7.86	0:32	0.011	13.44
0:20	0	5.93	0:20	0.006	9.78	0:40	0.006	18.55
			0:25	0.002	11.71	0:50	0.002	22.41
			0:30	0	12.36	0:60	0	23.72

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 0.002 m^3/s). 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 2-4 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.

2.5.2 Matrix Spikes

Premeasured pollutant masses (Table 2-3) 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 (2.00mm) and #35 (0.500mm) 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 $0.25m^3$ mixing tank and a $0.5m^3$ 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 2-15). 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 pond water in the pipe network to create the synthetic stormwater entering the DDB (Figure 2-13). When the water level of the mixing tank dropped to $0.1m^3$, 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 (Section 2.6.1). Therefore, the impacts of the pollutant input timing were assumed minimal.

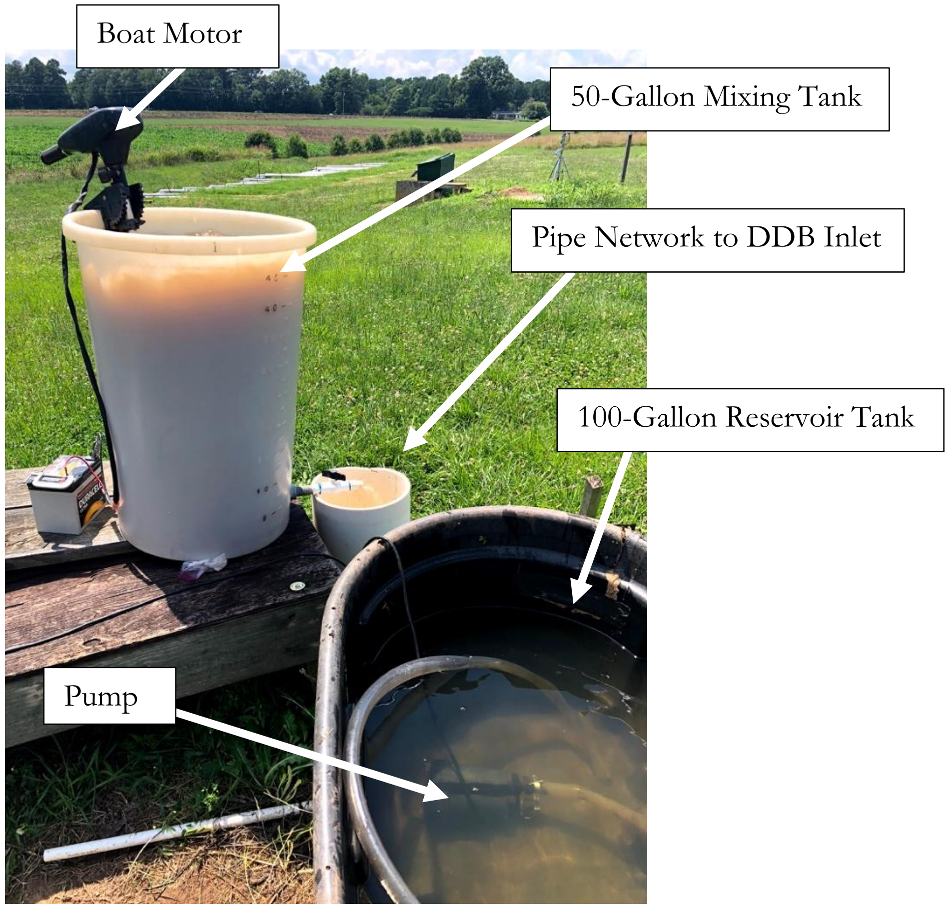

Figure 2-15. Matrix spike set-up

2.5.3 Antecedent and Concurrent Weather Conditions

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.

2.6 Data Collection

2.6.1 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 (Table 2-5). Both the inlet and outlet sampling were paced at the same flow increments. These composite samples represented each trial's event mean concentration (EMC).

Table 2-5. Composite sample flow-pacing for each storm size (m^3/subsample)

Small	Medium	Large
0.085	0.15	0.30

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 2-1) and flow (Eq 2-2) for the 300mm diameter PVC inlet pipe (Figure 2-16). 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).

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

$V = velocity\ \left(\frac{m}{s}\right)$
$n = roughness\ coefficient$
$R = Hydraulic\ Radius\ (m)$
$S = pipe\ slope\ \left(\frac{m}{m}\right)$

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

$Q = flowrate\ \left(\frac{m^3}{s}\right)$
$V = velocity\ \left(\frac{m}{s}\right)$
$A = flow\ area\ (m^2)$

Figure 2-16. Inlet pipe

Figure 2-17. 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 2-17). 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 2-3, Francis, 1883).

$$Q = C_d(H^{2.5}) \quad \text{Eq. 2-3}$$

$Q = flowrate\left(\frac{m^3}{s}\right)$
$C_d = V - notch\ weir\ coefficient\ (0.2744\ for\ 22.5º)$
$H = head\ above\ notch\ invert\ (m)$

Because both outlet weir boxes were open to ambient conditions (Figure 2-18), 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 2-18) that might have artificially inflated outlet nutrient concentrations.

Figure 2-18. Algae and organic debris removed from outlet weir box before sampling

2.6.2 Hydrologic monitoring

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.

2.7 Water Quality Analysis

Water quality performance was quantified using removal efficiency (RE) (Eq. 2-4) for all measured constituents (Table 2-6).

$$RE\ (\%) = 100 * \left(1 - \frac{EMC_{effluent}}{EMC_{influent}}\right) \qquad \text{Eq. 2-4}$$

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 as well as sample handling and preservation were used (Table 2-6).

Table 2-6. 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_3)	Std. Method 4500 NH3 H EPA 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 F EPA Method 353.3	11.2	125 mL plastic bottle	On ice
Total Nitrogen (TN)	TN = NO_X+TKN	-	-	-
Ortho-Phosphate (OP)	Std. Method 4500 P F EPA 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 F EPA Method 365.1	10	125 mL plastic bottle	On ice
Dissolved Cadmium (Cd)	EPA Method 200.8 EPA Method 200.9	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 200.7 EPA Method 200.8 EPA Method 200.9	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 200.7 EPA Method 200.8 EPA Method 200.9	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 200.7 EPA Method 200.8	10	500mL plastic bottle; filtered in field (0.45 micron vacuum)	1 + 1 HNO_3 to pH < 2[26]

2.8 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).

Influent concentration was used as a fixed, continuous, covariate variable, because influent concentration necessarily impacts removal efficiency, both mathematically and logically (Eq. 2-4). 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.

2.8.1 Statistical Implications of Non-Random Experimental Structure

The experiments were not conducted according to a completely randomized design (Section 2.4.1). 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.

2.9 References

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Chapter 3. Controlled Plot Trial Results and Dry Detention Basin Recommendations, Considerations, and Future Research Needs

3.1 Introduction

3.1.1 Background

Several design elements have had positive impacts on the water quality performance of various stormwater control measures and sediment and erosion control practices. The presence of baffles (B) and/or a skimmer outlet (S) increased sediment capture in sedimentation basins (Thaxton & McLaughlin, 2005; Jarret, 2001), and it is standard practice for them to be employed in tandem (S+B) for maximum pollutant removal (NCDOT, 2015). The addition of an internal water storage (IWS) system improved the water quality performance of permeable pavement systems and bioretention cells, both in terms of particulate and dissolved pollutants (Braswell et al., 2018; Hunt et al., 2012). This chapter details the data and conclusions resulting from a series of controlled plot trials designed to test the impact of these same design elements on the water quality treatment of a dry detention basin (DDB). Recommendations for DDB design, retrofit, and future research are also discussed.

3.1.2 Analysis Overview

Eleven pollutant parameters and their removal efficiencies were used to quantify the water quality performance for four retrofit basin configuration (B, IWS, S, S+B) and a control (C) basin designed according to current standards. Composite samples were collected at the inlet and outlet and analyzed for total suspended solids (TSS), total nitrogen (TN), total Kjeldahl nitrogen (TKN), nitrate/nitrite nitrogen (NO_X), ammonia nitrogen (NH_4^+), total phosphorous (TP), orthophosphate (OPO_4^-), dissolved cadmium (Cd), dissolved copper (Cu), dissolved lead (Pb), and dissolved zinc (Zn) (Appendix E). Event mean concentrations (EMCs), removal efficiencies (REs), and mean removal efficiencies (MREs) were then calculated for each and analyzed for statistical significance.

Each pollutant parameter was analyzed separately but discussed both independently as well as within the context of the entire body of data.

Each MRE was subjected to a two-sided t-test to determine if a statistically significant change in concentration occurred from inlet to outlet for each basin configuration (H_0: RE=0; H_A: RE≠0). The REs were then analyzed with a 2-factor analysis of covariance (ANCOVA) with basin configuration crossed with storm size and influent concentration as a covariate variable. Models were first fit with an interaction effect between basin configuration and influent concentration but were refit without an interaction if it was statistically insignificant. Each basin configuration pairwise difference in MRE was examined using a Tukey-Kramer adjusted multiple comparisons procedure. A statistical significance level of α=0.05 was used for all analysis.

3.2 Controlled Plot Trial Results and Discussion

3.2.1 Total Suspended Solids

Each basin configuration significantly reduced the amount of TSS from inlet to outlet (Figure 3-1, Table 3-1). 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 3-1. 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**

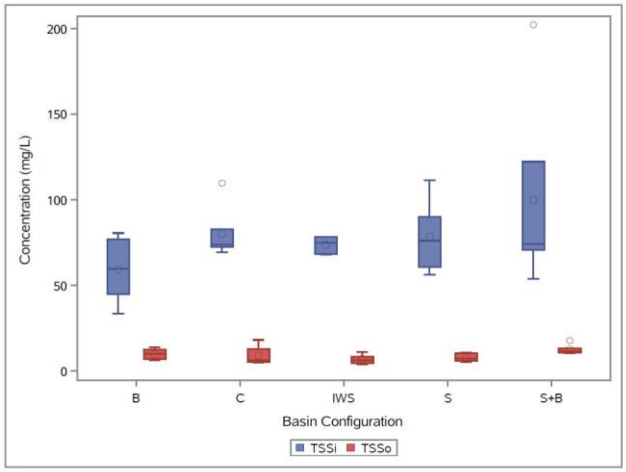

Figure 3-1. Influent (TSSi) and effluent (TSSo) TSS EMCs by basin configuration.

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 3-2).

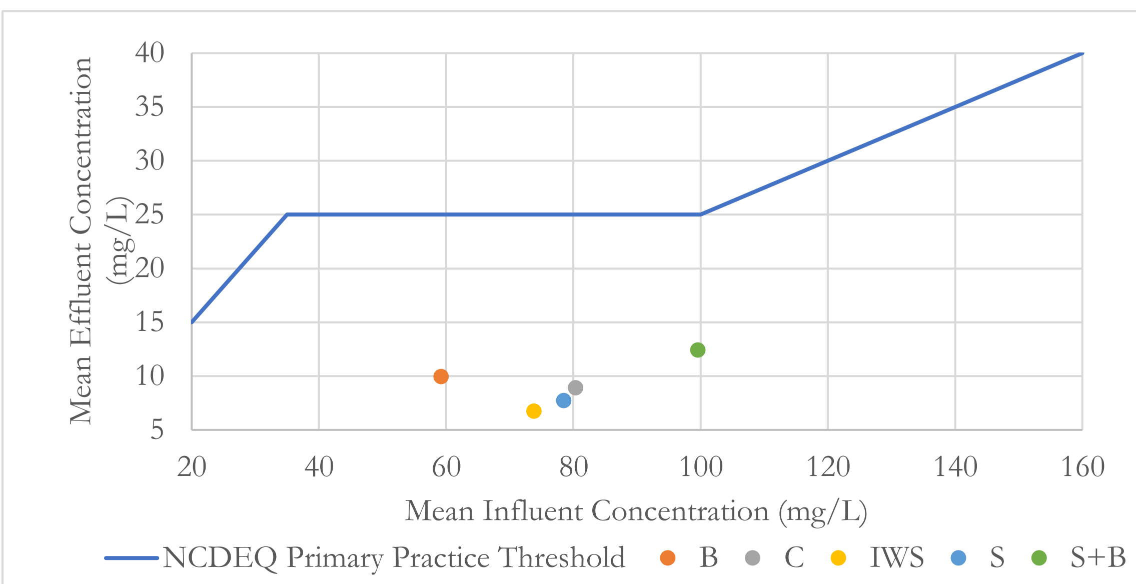

Figure 3-2. Mean effluent TSS EMCs for each basin configuration as compared to the primary practice threshold (NCDEQ, 2017a).

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 3-2). 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 3-3). 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.

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 3-2. 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

Table 3-3. 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

3.2.2 Nitrogen

All basin configurations except B significantly reduced both NH_4^+ and NO_X concentrations from inlet to outlet (Table 3-4). 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. 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.

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 3-4). 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). This 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 (Figure 3-4).

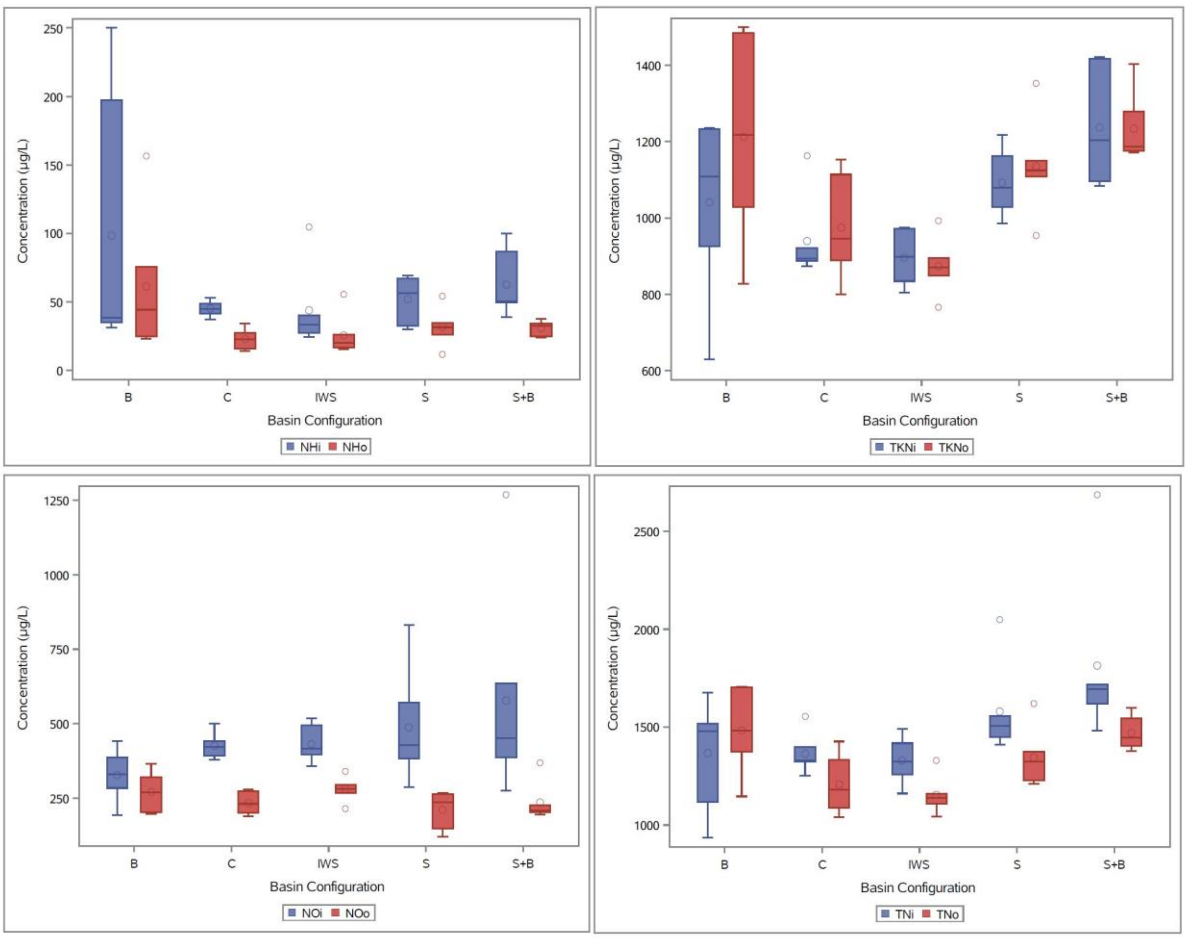

Figure 3-3. Influent and effluent nitrogen species EMCs by basin configuration.

Table 3-4. 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**

Table 3-5. 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 3-6. 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

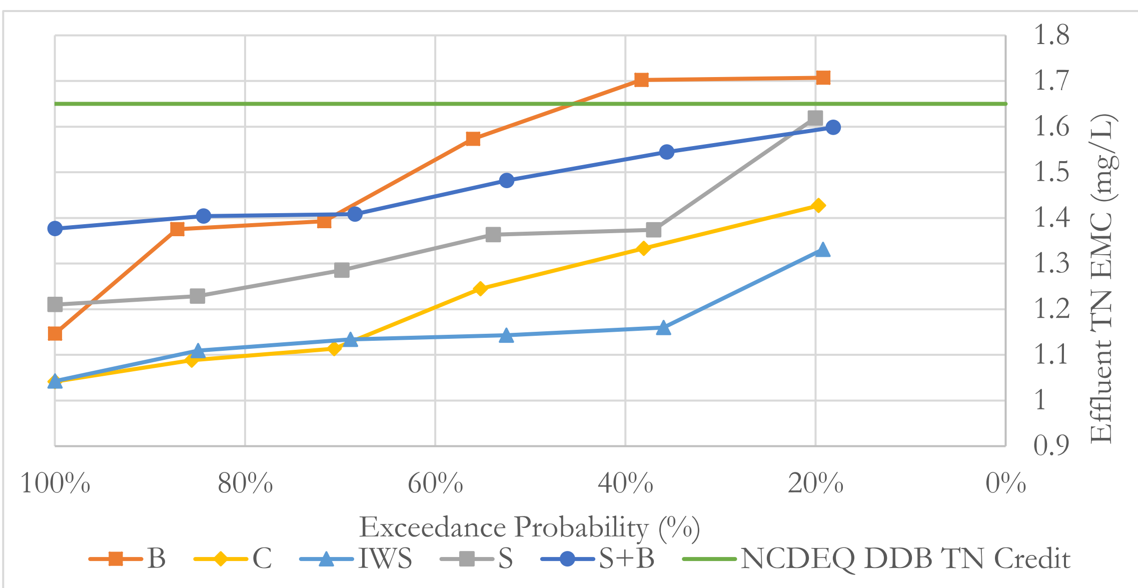

Figure 3-4. Exceedance probability of TN EMC for each basin configuration compared with the NCDEQ credit of 1.65 mg/L (NCDEQ, 2017a)

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. However, only TKN and TN exhibit any significant pairwise differences, all between the baffles configuration and others. These differences are likely due to the suspected organic nitrogen inputs previously discussed.

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 3-5). 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.

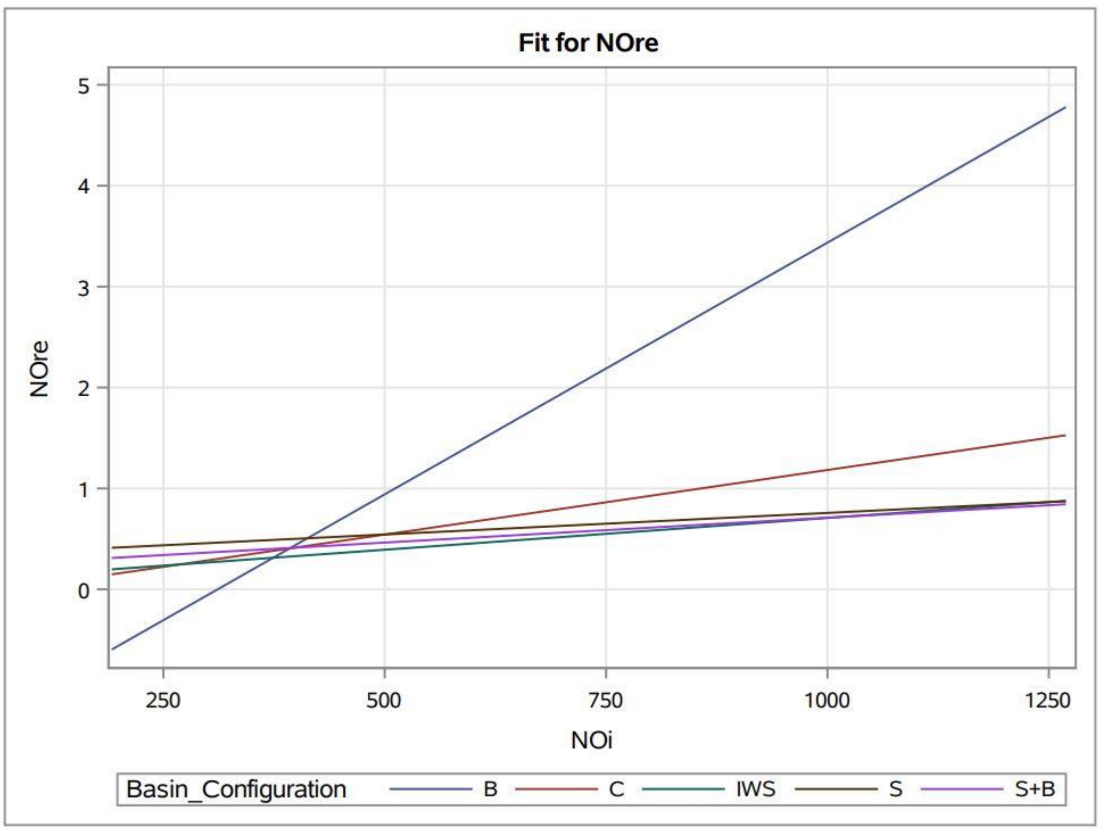

Figure 3-5. Interaction plot between the effects of influent NO_X concentration and basin configuration on NO_X removal efficiency, averaged over the effect of storm size

3.2.3 Phosphorus

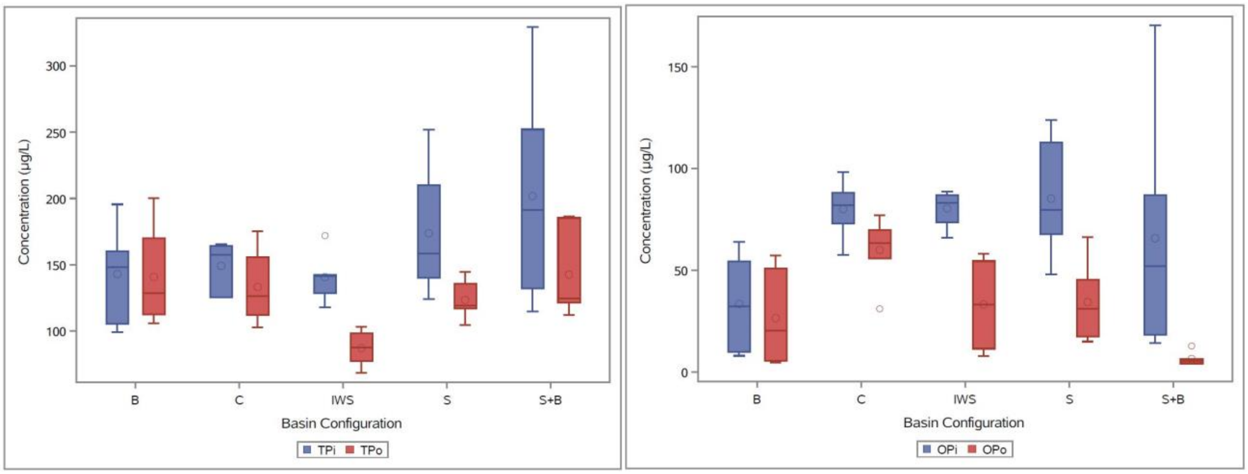

Figure 3-6. Influent and effluent phosphorus species EMCs by basin configuration.

While each retrofit design resulted in a reduction of TP from the inlet to the outlet (Figure 3-5), only the IWS basin produced a significant MRE (Table 3-7). Basin configuration did have a significant effect on TP (Table 3-8), with the IWS basin removing significantly more TP than the B, C, and S+B basins (Table 3-9). 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 3-1).

The C, IWS, S, and S+B basins significantly reduced OPO_4^- EMCs. Basin configuration did have a significant effect on OPO_4^- RE (Table 3-8), with the S+B removing significantly more OPO_4^- than the B and C basins (Table 3-9). OP 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 3-6).

Table 3-7. 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 3-8. 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 3-9. 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
B	IWS	**0.0002**	0.1701
B	S	0.1378	0.1820
B	S+B	0.9283	**0.0038**
C	IWS	**0.0053**	0.1167
C	S	0.8254	0.1133
C	S+B	0.9838	**0.0029**
IWS	S	0.0703	1.0000
IWS	S+B	**0.0040**	0.4499
S	S+B	0.5083	0.4715

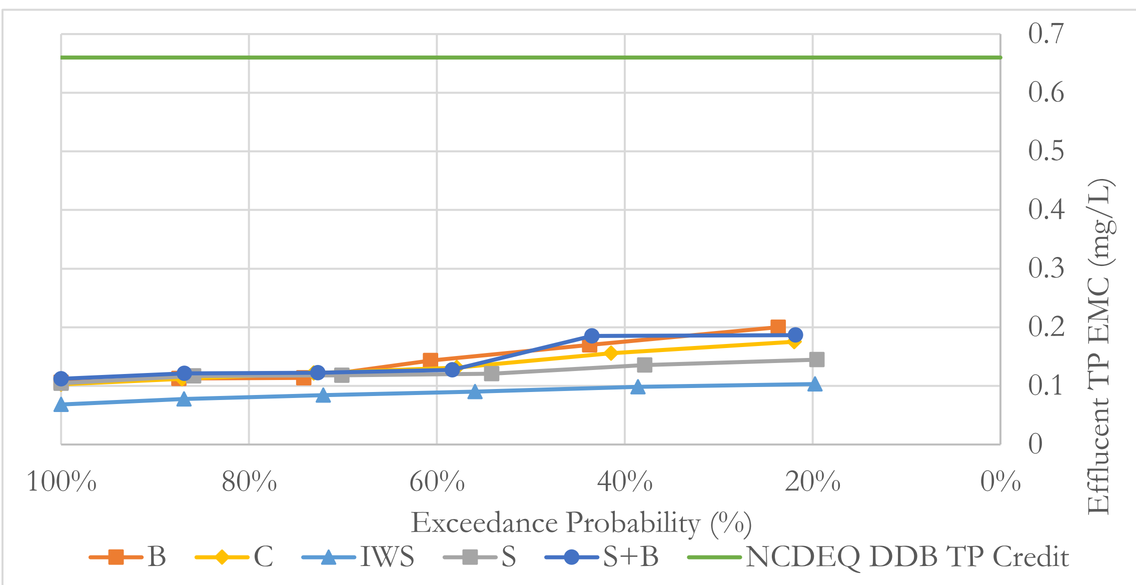

Figure 3-7. Exceedance probability of TP EMCs for each basin configuration as compared with the NCDEQ credit of 0.66 mg/L (NCDEQ, 2017a)

3.2.4 Heavy Metals

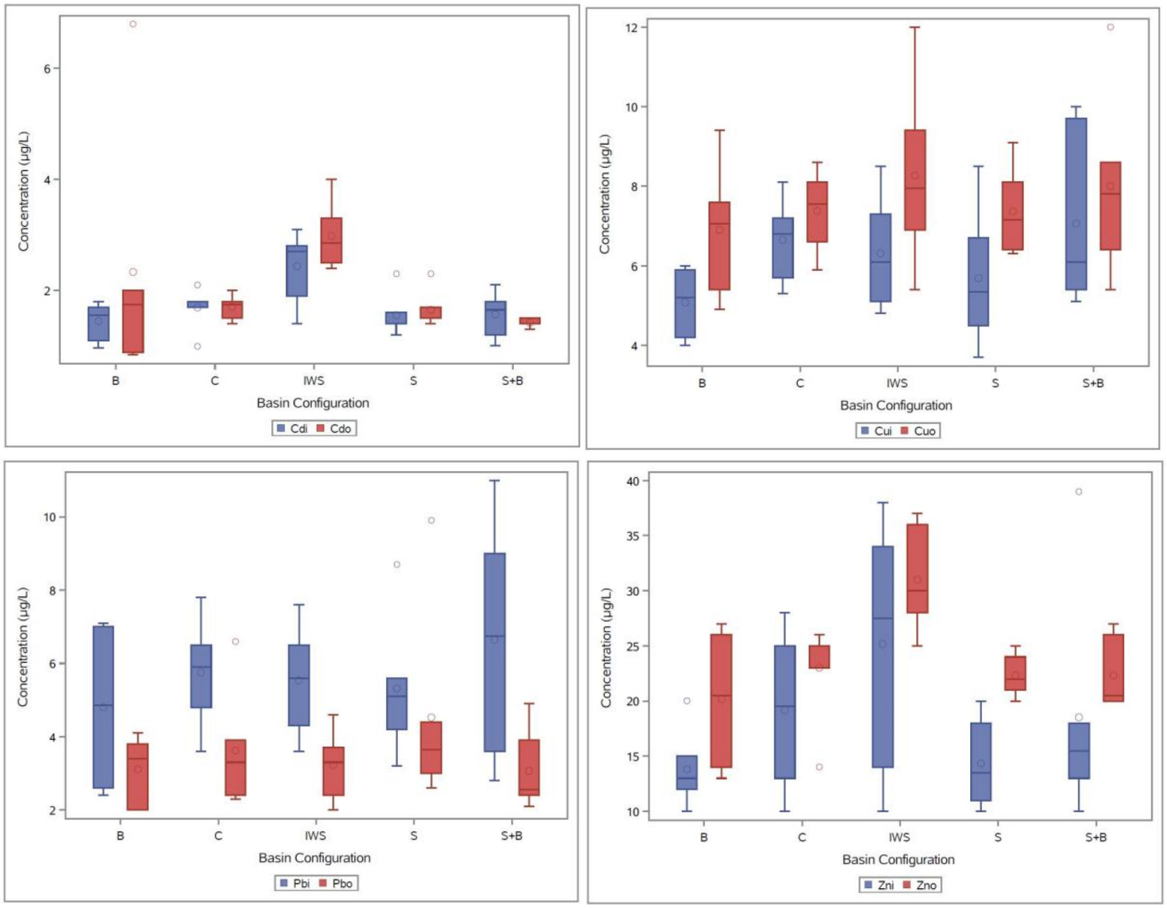

Figure 3-8. Influent (blue) and effluent (red) dissolved metal EMCs by basin configuration.

There was no significant CD EMC change from inlet to outlet in any basin configuration (Table 3-10). Every design exported Cu and Zn, and while only a few were statistically significant (Table 3-10), it reflected a trend consistent with DDB field studies (Wissler, 2019). Cd, Cu, and Zn readily bind to dissolved organic carbon (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 3-10. Dissolved heavy metals EMCs and REs for each basin configuration. Values in bold indicate a MRE that is significantly different than 0 ($p<0.05$).

Nitrogen Species	Basin Configuration	Mean Concentration (μg/L)		Mean Removal Efficiency (%)	p-value
		Influent	Effluent		
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
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
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**
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

Table 3-11. 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 3-12. 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 not have an impact on the RE of Cu, Pb, nor Zn. 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. This difference's significance is likely due to IWS's large spread of values (Figure 3-8), more so than a reflection of performance.

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 3-11, Figure 3-9). 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 3-10).

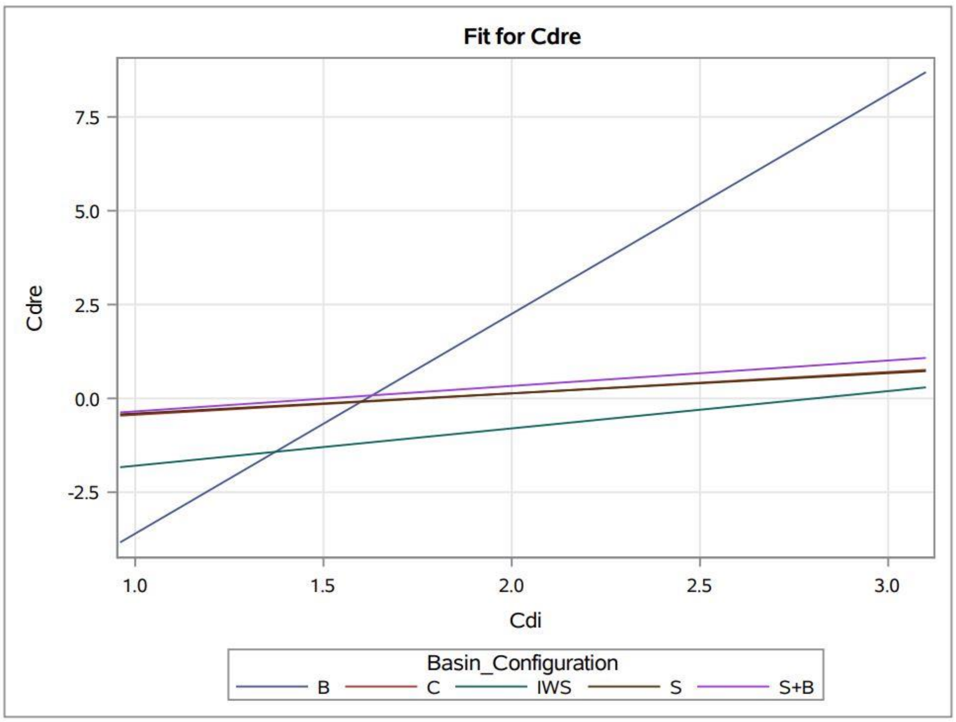

Figure 3-9. Interaction plot between the effects of influent dissolved Cd concentration and basin configuration on dissolved Cd RE, averaged over the effect of storm size

3.2.5 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 (Section 3.2.2).

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.

3.2.6 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 (Section 2.5.2), a value at the high end of the range of values reported in particle size distribution (PSD) field data collected along NC highways (Table 3-13.). 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 3-13. D90 values for NC highway runoff (mm)

	Study											
	Winston & Hunt (2017)								**Wissler (2019)**			
Location	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.

3.3 Future Research

3.3.1 Hydrology

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.

3.3.2 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, 2017). 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.

3.4 Retrofit 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).

3.4.1 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 exceeding that of DDBs 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 ON by 89, 60, 57, 71, 75, 69, and 75 %, 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.

3.5 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, 2017). 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 (2017).

- 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.

3.6 References

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APPENDICES

Appendix A: Representative Inflow Hydrographs

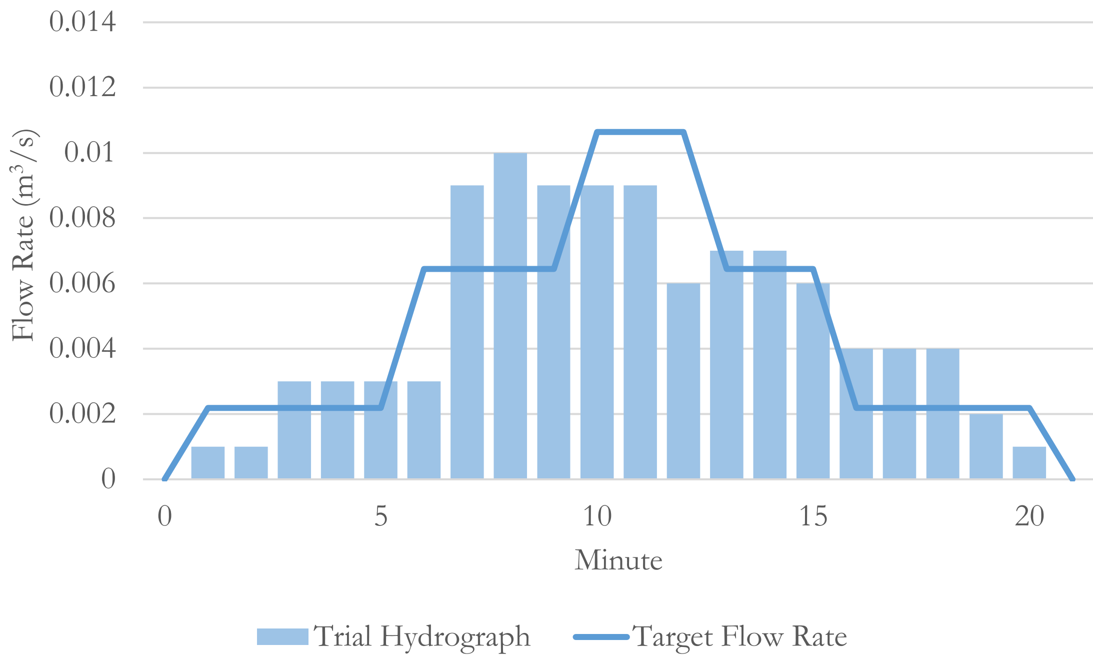


Figure A-1. Representative inflow hydrograph for a small storm, as compared to target flow rates

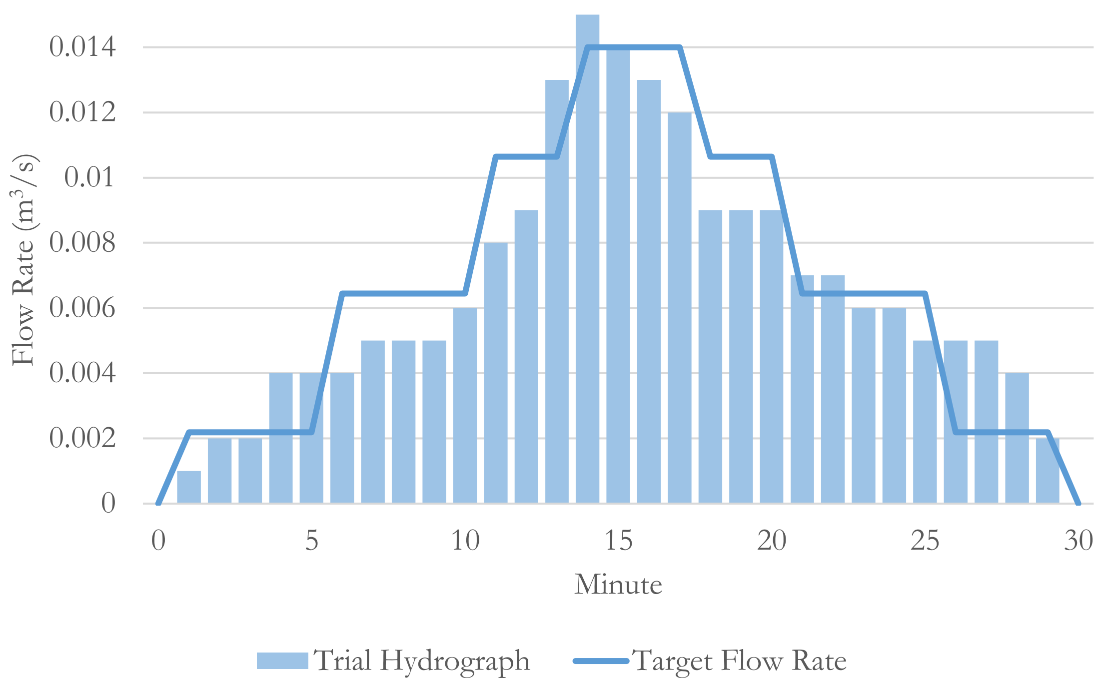


Figure A-2. Representative inflow hydrograph for a medium storm, as compared to target flow rates

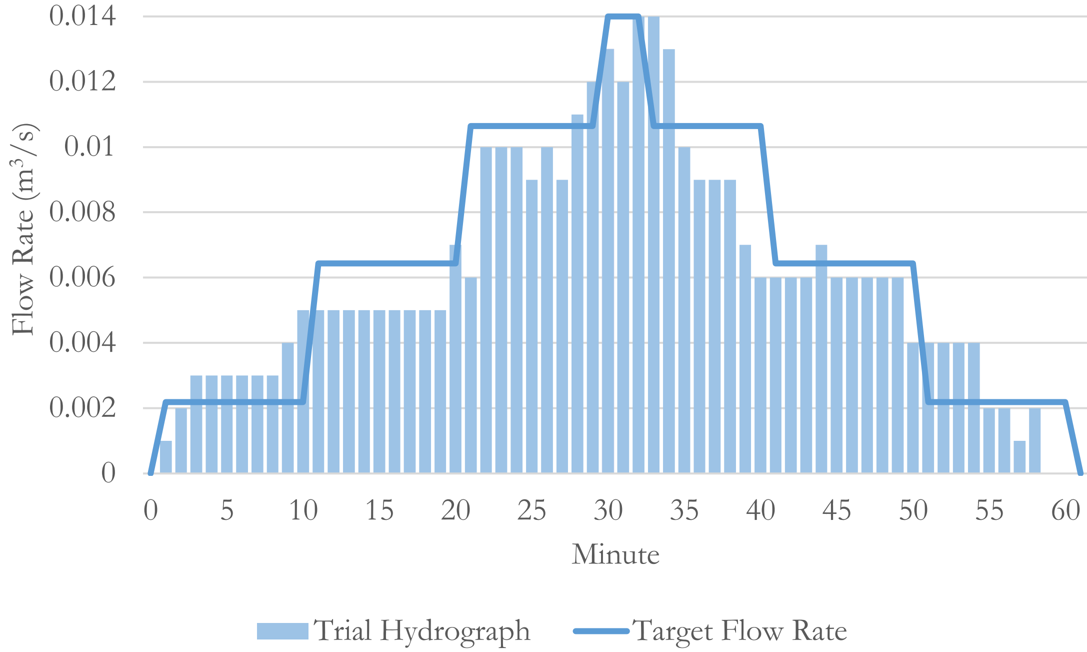


Figure A-3. Representative inflow hydrograph for a large storm, as compared to target flow rates

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;
```

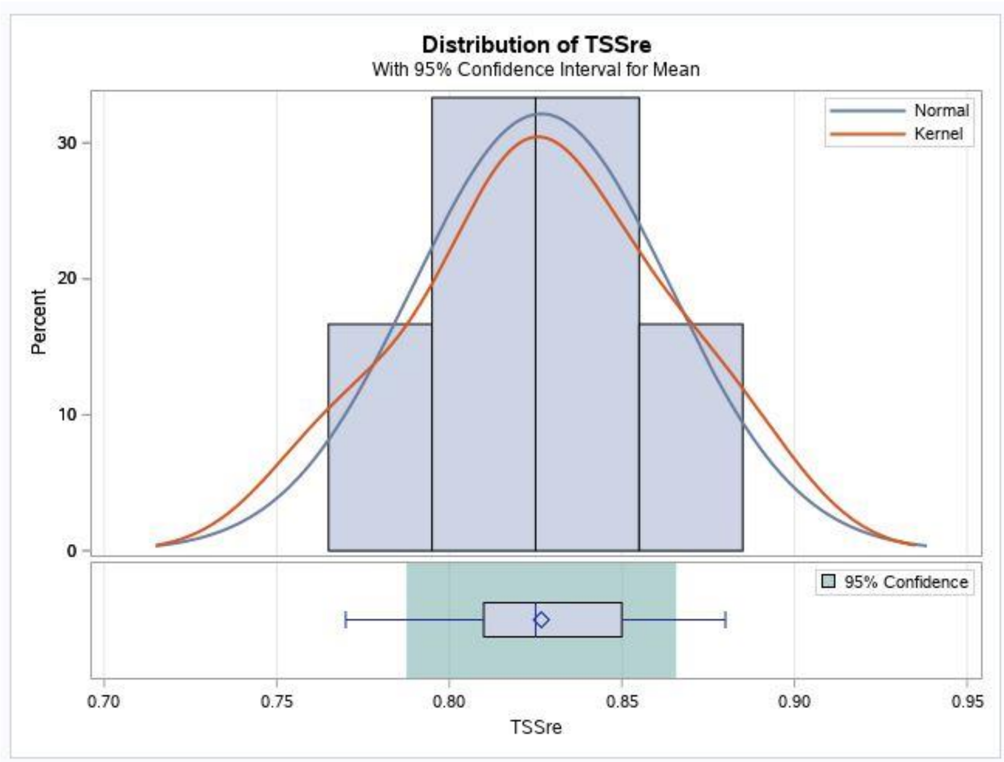
Step 2. Construct Boxplots

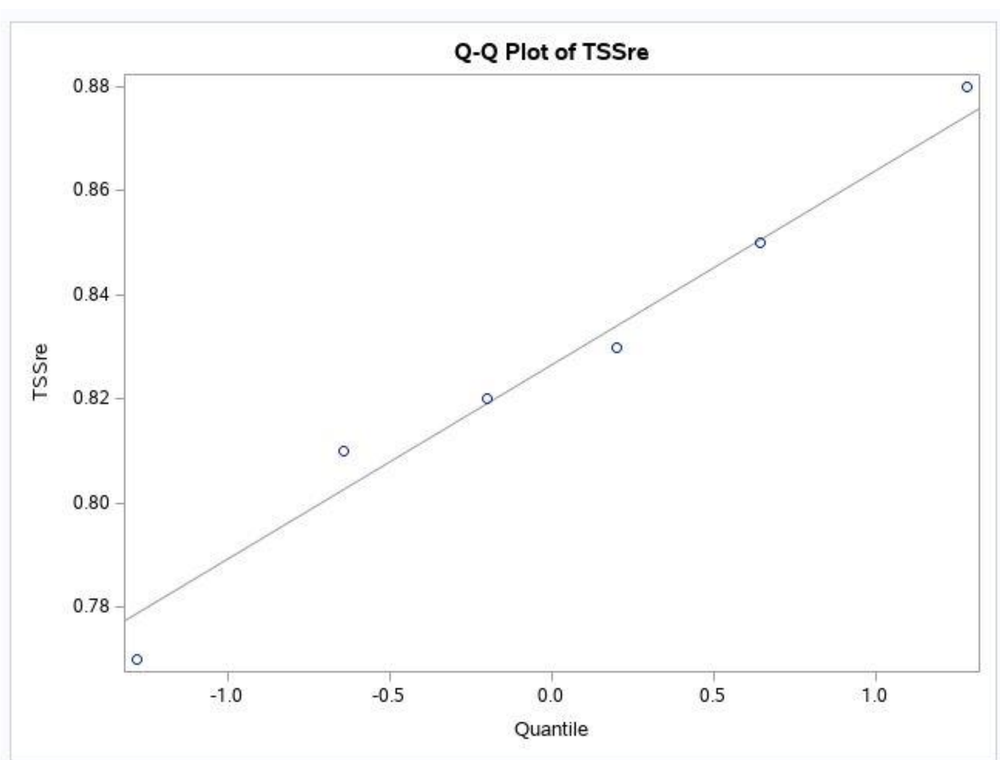
```
proc transpose data=data
    out=TSS(rename=(col1=Concentration)rename=(_Name_=Parameter));
    var TSSi TSSo;
    by trial basin_configuration notsorted;
run;


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)





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;
```

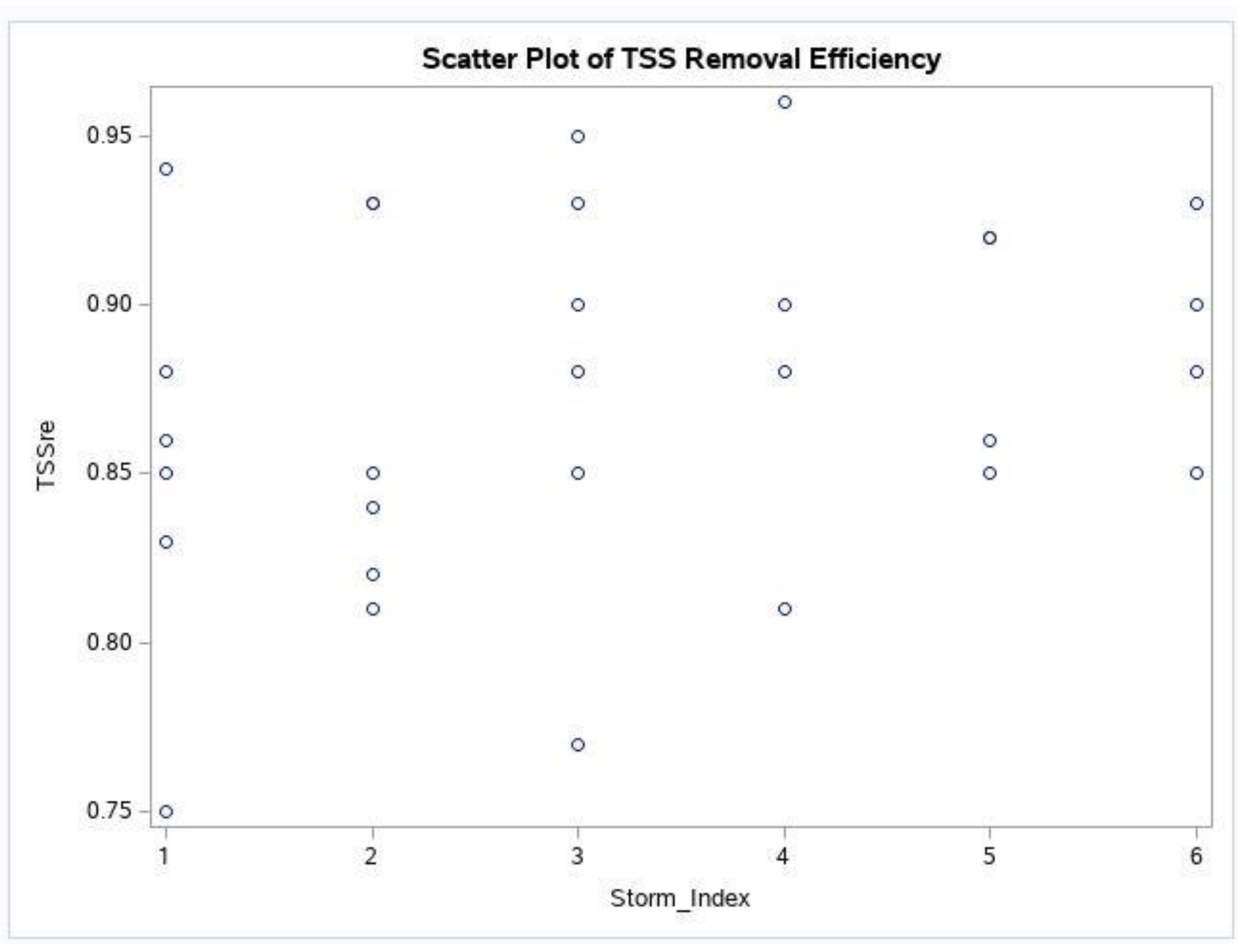


Figure D-1. Scatter plot of TSS removal efficiency by storm index

Basin Configuration Order

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

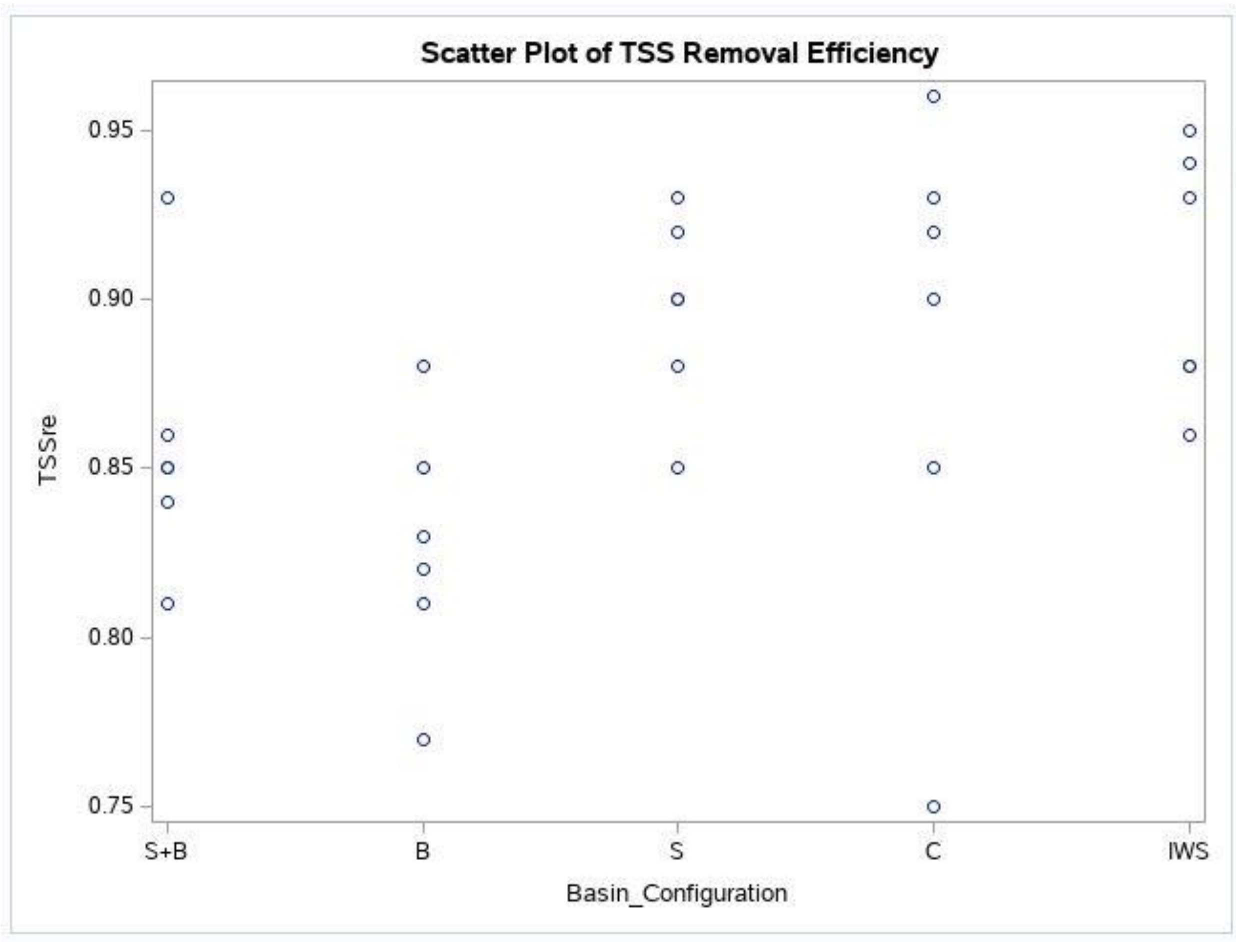


Figure D-2. Scatter plot of TSS removal efficiency by basin configuration order

Trial Order

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

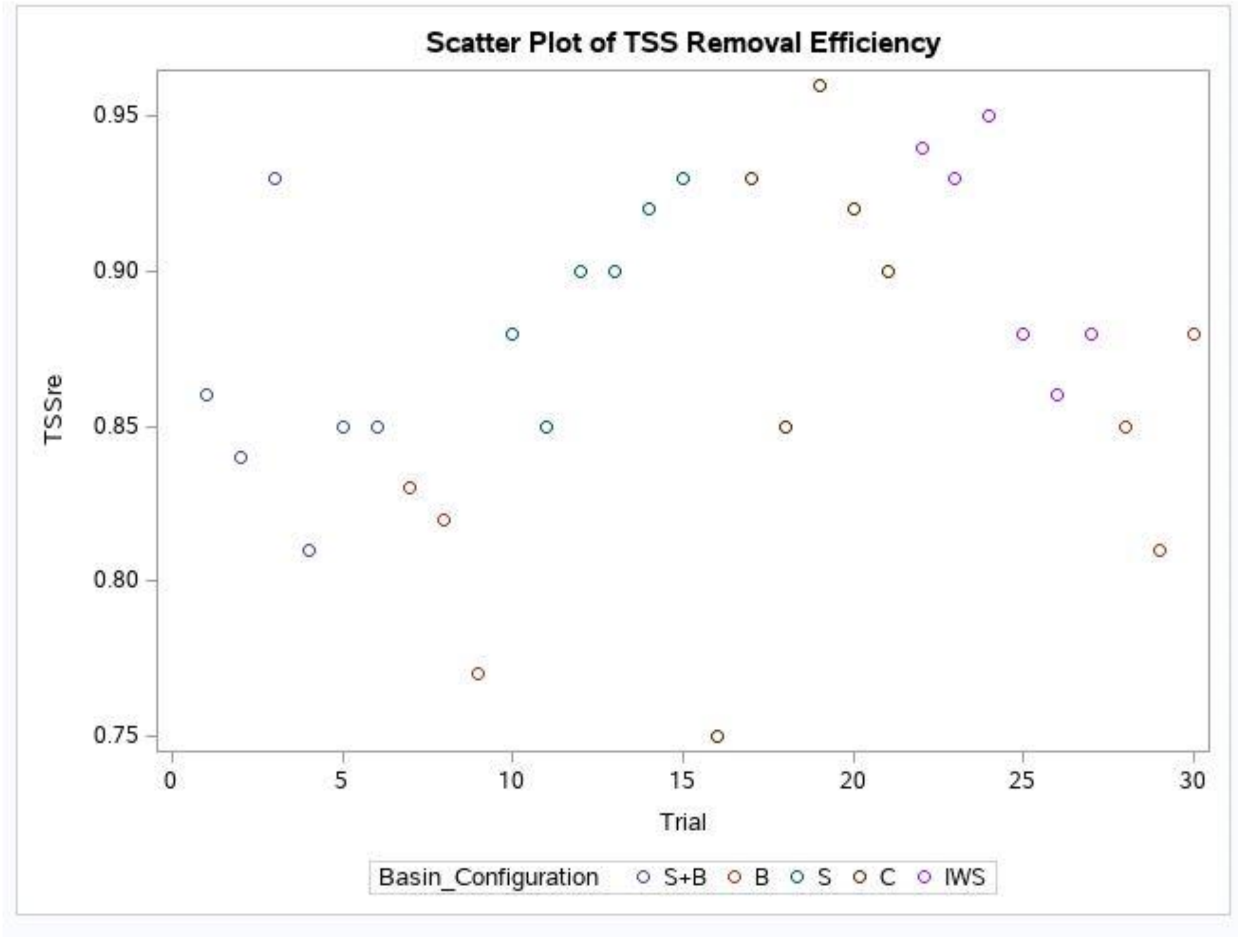


Figure D-3. Scatter plot of TSS removal efficiency by trial number

Appendix E: Water Quality Data

Table E-1. Inlet EMCs. TSS in mg/L all others µg/L

Storm Date	Basin Configuration	TKN	NO3	NH4	TN	TP	OP	TSS	Cd	Cu	Pb	Zn
6/3/2020	S+B	1176	514.46	49.8	1690.46	235.48	76.48	122.22	2.1	10	8.9	39
6/8/2020	S+B	1083.51	635.26	50.43	1718.77	252.13	86.93	75.37	1.2	5.4	9	13
6/21/2020	S+B	1416.98	1269.24	86.6	2686.22	329.61	170.35	202.1	1.6	9.7	11	15
6/22/2020	S+B	1421.02	274.94	38.74	1695.96	114.64	18.25	53.87	1	5.6	2.8	10
6/23/2020	S+B	1232.04	386.22	99.81	1618.26	131.99	**27.73**	73.13	1.8	6.6	4.6	18
6/24/2020	S+B	1096.85	385.88	50.06	1482.73	147.44	14.23	70.77	1.7	5.1	3.6	16
6/29/2020	B	1106.33	354.94	39.95	1461.27	137.69	8.04	64.52	1.6	5.6	6.5	13
7/1/2020	B	1235.96	440.98	34.99	1676.94	158.84	9.83	76.99	1.5	6	7	13
7/6/2020	B	1233.28	283.53	31.14	1516.81	195.58	28.7	54.9	1.1	4	2.4	10
7/13/2020	S	1102.33	398.44	29.92	1500.77	154.48	**69.86**	90.07	1.4	5.4	5	10
7/15/2020	S	1162.9	287.14	32.53	1450.04	124.12	47.96	56.38	1.2	5.3	5.2	11
7/20/2020	S	1217.33	831.48	61.37	2048.81	251.85	123.71	111.49	2.3	8.5	8.7	20
7/21/2020	S	1028.24	382.24	51.7	1410.48	140.09	67.68	60.81	1.4	3.7	4.2	13
7/22/2020	S	1057.17	455.88	67.11	1513.05	161.94	89.59	66.94	1.6	4.5	5.6	14
7/27/2020	S	985.92	570.2	69.1	1556.12	209.93	**112.85**	85.15	1.4	6.7	3.2	18
7/28/2020	C	1163.44	391.64	37.05	1555.08	163.13	57.62	73.24	2.1	8.1	3.6	28
8/11/2020	C	921.35	406.52	47.25	1327.87	151.82	**87.45**	74.36	1.8	5.7	7.8	13
8/17/2020	C	888.03	442.18	41.61	1330.21	165.65	**88.06**	82.7	1.8	6.5	4.8	25
8/19/2020	C	898.62	500.92	42.47	1399.54	164.28	98.28	109.85	0.99	5.3	6.1	10
8/24/2020	C	874.11	378.52	48.84	1252.63	125.48	72.94	72.57	1.8	7.1	6.5	18
8/26/2020	C	887.72	436.84	52.85	1324.56	125.23	76.26	69.3	1.7	7.2	5.7	21
9/3/2020	IWS	968.88	399.8	60.26	1368.68	116.39	73.74	61.64	1.6	7.6	3.2	31
9/14/2020	IWS	947.28	365.78	63.15	1313.06	131.39	73.62	71.18	1.3	6.7	5	15
9/15/2020	IWS	924.48	493.44	29.5	1417.92	142.14	**88.74**	78.3	1.9	4.8	6.5	14
9/21/2020	IWS	804.52	356.42	24.54	1160.94	117.7	**73.45**	68.29	1.4	5.1	3.6	10
9/23/2020	IWS	871.44	406.54	27.42	1277.98	128.69	84	78.29	2.8	7.3	5.3	38
9/27/2020	IWS	834.44	424.26	37.1	1258.7	142.15	82.27	68.12	2.7	6.4	4.3	34
9/28/2020	IWS	974.14	517.48	104.7	1491.62	172.11	86.85	76.96	2.7	8.5	7.6	31
9/30/2020	IWS	972.1	396.34	40.24	1368.44	140.97	65.93	72.88	3.1	5.8	5.9	24
8/26/2019	B	629.55	305.6	36.91	935.15	105.15	63.9	44.93	0.96	4.2	2.6	12
9/10/2019	B	925.45	191.8	197.26	1117.25	99.21	36.11	33.36	1.7	4.8	3.2	20
9/17/2019	B	1110.64	387.08	250.35	1497.72	160.3	54.31	80.52	1.8	5.9	7.1	15

Bold numbers analyzed outside of holding time. Underlined samples below PQL.

Table E-2. Outlet EMCs. TSS in mg/L all others µg/L

Storm Date	Basin Configuration	TKN	NO3	NH4	TN	TP	OP	TSS	Cd	Cu	Pb	Zn
6/3/2020	S+B	1178.9	225.36	24.18	1404.26	185.33	12.76	17.6	1.3	8.6	4.9	26
6/8/2020	S+B	1175.49	368.58	33.58	1544.07	186.53	6.17	11.74	1.4	12	3.9	27
6/21/2020	S+B	1403.88	194.34	34.34	1598.22	121.54	6.39	13.31	1.4	7.5	2.1	21
6/22/2020	S+B	1279.28	202.84	31.52	1482.12	122.18	4.15	10.33	1.4	8.1	2.4	20
6/23/2020	S+B	1171.33	205.04	37.48	1376.37	112.13	4.78	10.71	1.5	5.4	2.7	20
6/24/2020	S+B	1195.4	212.9	24.98	1408.3	127.1	4.27	10.91	1.5	6.4	2.4	20
6/29/2020	B	1376.54	196.82	24.86	1573.36	200.06	5.51	10.78	2	9.4	4.1	27
7/1/2020	B	1484.22	222.96	28.56	1707.18	169.8	7.48	13.94	1.9	7.6	3.8	26
7/6/2020	B	1500.7	201.49	23.13	1702.19	143.22	4.73	12.53	1.6	7.6	2	23
7/13/2020	S	1138.74	146.52	11.87	1285.26	120.75	17.36	10.47	1.5	8.1	3.8	20
7/15/2020	S	1109.17	119.57	29.72	1228.74	104.46	15.02	8.39	1.5	6.3	4.4	22
7/20/2020	S	1149.66	213.52	33.19	1363.18	144.67	24.89	10.7	1.7	9.1	2.6	22
7/21/2020	S	1110.54	263.52	34.82	1374.06	135.61	37.2	5.98	1.5	6.4	3	21
7/22/2020	S	953.29	256.76	26.31	1210.05	116.79	45.33	5.08	1.4	6.5	3.5	25
7/27/2020	S	1352.8	265.99	54	1618.79	117.84	66.23	5.89	2.3	7.8	9.9	24
7/28/2020	C	1113.98	219.18	34.33	1333.16	175.26	31.06	18.16	1.5	5.9	6.6	14
8/11/2020	C	925.88	187.72	22.73	1113.6	130.98	66.98	5.16	2	8.1	3.9	25
8/17/2020	C	888.66	199.73	27.3	1088.39	155.68	69.74	12.78	1.8	7.3	2.4	26
8/19/2020	C	799.46	242.03	14.25	1041.49	**102.67**	55.74	4.94	1.4	6.6	2.3	23
8/24/2020	C	1153.78	273.13	15.94	1426.91	121.68	77.02	5.5	1.8	8.6	3.5	25
8/26/2020	C	966.65	278.26	22.79	1244.91	111.92	59.75	7.01	1.7	7.8	3.1	25
9/15/2020	IWS	850.01	283.92	16.82	1133.93	98.32	54.52	4.41	2.4	8.9	4.6	25
9/21/2020	IWS	765.63	276.87	15.31	1042.5	77.4	40.77	4.52	4	12	2.4	32
9/23/2020	IWS	849.32	293.84	19.26	1143.16	90.43	58.07	3.95	2.8	9.4	3.7	36
9/27/2020	IWS	891.88	267.69	26.23	1159.57	68.28	25.73	8.21	3.3	7	2	37
9/28/2020	IWS	992.09	338.78	55.7	1330.87	103.11	11.53	10.96	2.5	6.9	3.7	28
9/30/2020	IWS	894.44	214.87	21.29	1109.31	84.29	8	8.45	2.9	5.4	2.9	28
8/26/2019	B	827.26	319.02	59.95	1146.28	105.98	57.2	6.95	6.8	4.9	2	13
9/10/2019	B	1028.41	364.3	156.39	1392.71	113.84	50.94	6.2	0.88	6.5	3.3	18
9/17/2019	B	1059.78	315.14	75.44	1374.92	112.43	33.2	9.48	0.84	5.4	3.5	14

Bold numbers analyzed outside of holding time. Underlined samples below PQL.