PREDICTING RESILIENCE AND REDUCING FAILURE OF SCMS TO EXTREME STORM EVENTS

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RESEARCH & DEVELOPMENT

Predicting Resilience and Reducing Failure of SCMs to Extreme Storm Events

FINAL REPORT

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16. Abstract

While stormwater Control Measures (SCMs) are designed to treat runoff, their principal focus has been treating moderately sized rainstorms. How these SCMs fare during larger events and the restorative maintenance efforts associated with SCM damage is a significant concern for the North Carolina Department of Transportation (NCDOT). This project created stormwater infrastructure models using the Personal Computer Storm Water Management Model (PCSWMM) software for four SCMs previously studied by NCDOT. Models for two bioretention cells (Mango Creek BRC and Wilmington BRC), a dry detention basin (DDB), and a regenerative stormwater conveyance (RSC) system were built, and simulations were run to determine the points of failure for each SCM. Failure was defined as a significant berm breach, and different simulation storms were constructed using two storm distribution types and two storm depth determination methods. Additionally, each set of simulations was run on the as-built design of the SCM as well as a hypothetical retrofit that increased storage volume, resulting in a total of eight different sets of simulations. Storm distributions were created using a standard National Resources Conservation Service (NRCS) unit hydrograph as well as natural distributions observed during Hurricane Florence in 2018. Standard storm depths from National Oceanic and Atmospheric Association (NOAA) Atlas 14 precipitation frequency tables were used, as well as depths with the application of a regional scale factor, a factor that accounts for local variations in changing precipitation patterns. All simulations were run at industry-standard return period intervals (10, 25, 50, 100 years).

Failure points ranged from the 10-100yr storms. The DDB and RSC had the lowest risk of failure, likely due to their larger storage and conveyance capacities. While the different storm depths and distributions resulted in some performance differences, the retrofitting of the SCMs proved to be the most significant factor in determining failure. This research supports maximizing available storage volumes to increase SCM resiliency to extreme events.

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Executive Summary

The state of North Carolina has been struck by several extreme rainfall events over the past few years, which have caused failures in stormwater infrastructure (including but not limited to Stormwater Control Measures (SCMs) regulated under the Department's NPDES stormwater permits (NCS000250)). While SCMs are designed to treat runoff, their principal focus has been treating moderately sized rain storms. How these SCMs fared during larger events, and the restorative maintenance efforts associated with SCM damage is a significant concern for the North Carolina Department of Transportation (NCDOT).

This project created stormwater infrastructure models using the Personal Computer Storm Water Management Model (PCSWMM) software for four SCMs previously studied by NCDOT. Models for two bioretention cells (Mango Creek BRC and Wilmington BRC), a dry detention basin (DDB), and a regenerative stormwater conveyance (RSC) system were built, and simulations were run to determine the points of failure for each SCM. Failure was defined as a significant berm breach, and different simulation storms were constructed using two storm distribution types and two storm depth determination methods. Additionally, each set of simulations was run on the as-built design of the SCM as well as a hypothetical retrofit that increased storage volume, resulting in a total of eight different sets of simulations. Storm distributions were created using a standard National Resources Conservation Service (NRCS) unit hydrograph as well as natural distributions observed during Hurricane Florence in 2018. Standard storm depths from National Oceanic and Atmospheric Association (NOAA) Atlas 14 precipitation frequency tables were used, as well as depths with the application of a regional scale factor, a factor that accounts for local variations in changing precipitation patterns. All simulations were run at industry-standard return period intervals (10, 25, 50, 100 years).

Failure points ranged from the 10-100yr storms. The DDB and RSC had the lowest risk of failure, likely due to their larger storage and conveyance capacities. However, model Nash-Sutcliffe Efficiency

values ranged from 0.19 (RSC) to 0.80 (Wilmington BRC), indicating a limited use for model predictions or comparisons between SCMs. Rather, models can be used to conceptualize relative performance of a single SCM under varying conditions. For example, storm depth and distribution type impacted failure occurrence for each SCM, but it was the retrofitted SCM simulations that resulted in the most significant changes to failure occurrence. Namely, retrofitted SCMs failed less frequently than their as-built counterparts. This points to the importance of maximizing available storage volumes as a means of increasing SCM resiliency to extreme events.

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List of Acronyms and Abbreviations

BRC – Bioretention Cell

DDB – Dry Detention Basin

EPA – Environmental Protection Agency

IWS – Internal Water Storage

LID – Low Impact Development

MDC – Minimum Design Criteria

NCDOT – North Carolina Department of Transportation

NCSCO – North Carolina State Climate Office

NOAA – National Oceanic and Atmospheric Association

NRCS – National Resources Conservation Service

NSE – Nash-Sutcliffe Efficiency

PCSWMM – Personal Computer Storm Water Management Model

RCP – Representative Concentration Pathway

RSC – Regenerative Stormwater Conveyance

RSF – Regional Scale Factor

SCM – Stormwater Control Measure

SRTC – Sensitivity-Based Radio Tuning Calibration

Introduction and Result of Literature Review

Stormwater Control Measures (SCMs) are commonly installed to mitigate deleterious impacts of urbanization and stormwater runoff. SCMs provide hydrologic benefits by detaining and delaying release of a designated volume and/or facilitating infiltration. While well-made SCMs are effective at managing runoff, they can and do fail during extreme weather events. A widespread loss of SCMs can result in the closure of essential transportation corridors that may be damaged during flooding, and any resulting damage can be expensive to repair. Several factors, such as severe weather and degradation due to aging, can contribute to SCM failure. Understanding the limits of SCMs and the factors that cause them to fail will enable design modifications to make them more resilient to these types of extreme weather events.

SCMs are structures designed to reduce the impact of stormwater runoff in urbanized areas. SCMs protect local waterways by attenuating runoff volumes and peak flows, as well as reducing pollutants. Common SCMs implemented in North Carolina include bioretention cells (BRCs) and dry detention basins (DDBs), while regenerative stormwater conveyance systems (RSCs) are a burgeoning technology in the state. DDBs are designed to capture the water quality event and drain completely within two to five days to prevent standing water (DEQ, 2020). DDBs reduce peak flow rates and settle suspended particles. BRCs are vegetated depressions in a landscape underlain with permeable media designed to increase infiltration and filter outflow. RSCs convert surface flow into subsurface flow via a series of terraced vegetated “pools” built atop high-flow media. They are used to stabilize eroded gullies, promote infiltration, and improve hypertrophic reactions. All three SCM systems are vulnerable to failure via erosion, embankment breaching, and/or clogging during extreme storm events. These failures can result in dangerous flooding conditions and expensive repair costs, for the SCMs as well as adjacent property and infrastructure.

The US Environmental Protection Agency (EPA) developed the Personal Computer Storm Water Management Model (PCSWMM) as a tool to model and achieve stormwater objectives (US EPA, 2022). Historical data can be used to calibrate a model of existing infrastructure and, subsequently, simulate its performance under various conditions (Shaneyfelt et al., 2021). Building a virtual model enables the evaluation of stormwater infrastructure performance in a cost-effective manner. Virtual watershed models aid in predicting the impact of urbanization and stormwater infrastructure on downstream environments (NRC, 2008).

This research aims to answer the following question. How resilient are current SCMs to large storm events, and how might their performance change under predicted future climate scenarios? The primary objectives of this investigation are to understand the current hydrologic capabilities of SCMs and to evaluate potential design alterations that can improve their resiliency to extreme storm events.

Model Development

General Model Information and Methods

PCSWMM models the movement of runoff through stormwater infrastructure with a series of nodes, conduits, subcatchments, and outfalls (Table 1). SCMs are modeled as "Low Impact Development (LID) controls," which are specialized subcatchments that treat the runoff produced in other subcatchments. Within a given model, an SCM's contributing drainage area is considered a subcatchment that is routed through the LID Control, itself an additional subcatchment as rain falls on both the watershed and the SCM. Therefore, each model includes a watershed, or contributing drainage area, subcatchment and an LID subcatchment that are both routed through the LID control, where water is treated before it reaches the ultimate outfall.

PCSWMM allows users to input parameters for each subcatchment and LID control, as well as choose from a variety of standardized methods for quantifying infiltration and flow routing. All models in this study use the modified Green-Ampt method for quantifying infiltration and the Dynamic Wave Routing method for flow routing (Rossman, 2016). Overall runoff volume, infiltration, and evaporation rates quantify the performance.

Table 1. PCSWMM Model Elements

Model Element	Role	Examples
Node	Points of converging or diverging flow	Junction boxes, storage tanks, non-terminal outfalls
Conduit	Conveyance paths	Pipes, channels
Subcatchment	Areas contributing runoff	Watersheds, drainage areas,
Outfalls	Point of final system discharge	Rivers, receiving waterbodies

Site Selection

Sites were selected for modeling based on the prevalence of a given SCM type within NCDOT's management assets, as well as the availability of robust datasets with which to calibrate the resulting models. To produce robust models of relevant practices, two bioretention cells (BRCs), a dry detention basin (DDB), and a regenerative stormwater conveyance (RSC) system were selected (Table 2). Three modeled SCMs were in the Piedmont Region, while one was in the Coastal Plain. At a minimum, each site had 10 months of monitoring data recorded, including influent flow, effluent flow, and rain gauge readings. Only storms with at least 0.1 inches of depth were considered per instrumentation accuracy (Teledyne ISCO, 1995).

Table 2. Site characteristics summary

	Mango Creek BRC	Wilmington BRC	DDB	RSC
SCM Type	Bioretention Cell	Bioretention Cell	Dry Detention Basin	Regenerative Stormwater Conveyance
Source	Luell, 2011	Tormey, 2021	Wissler, 2019	Cizek, 2014
Location	Knightdale (Piedmont)	Wilmington, (Coastal Plain)	Archdale (Piedmont)	Alamance County (Piedmont)
Volume Reduction*	30%	58%	78%	29%
Monitoring Period	October 2009 – December 2010	March 2017 – March 2021	February 2018 – January 2019	July 2013 – June 2014
Storm Events in Dataset	79	289	48	43
Notes on Performance	BRC significantly reduced runoff volumes and attenuated peak flow rates.	BRC achieved modest volume reductions despite being dramatically undersized.	Above-average rainfall fell during the monitoring period. Tests for soil Ksat in the basin revealed that infiltration is negligible.	Substantial hydrologic stormwater mitigation through surface volume reduction via conversion to subsurface seepage.

*Volume reduction values are as reported from previous research. See included citations for details.

Site Descriptions and Model Parameters

Mango Creek BRC

A 2011 study compared the hydrologic performance of an undersized BRC to that of a full-sized BRC in Knightdale, North Carolina (Luell, 2011). Both BRCs were installed in an easement near two I-540 bridge decks passing over Mango Creek (35°47’ 3.4” N, 78° 30’ 48.8”

W). The full-sized BRC was modeled as part of this study (Figure 1). The drainage area was 0.4 ha (0.98 ac) of 100% impervious concrete from the above bridge deck, routed via a series of thirty-two scuppers spaced 11 ft apart along the outer edge (Table 3).

Figure 1. Aerial views of Mango Creek BRC. Modeled BRC is the larger on the left (Luell, 2011)

Table 3. Contributing Watershed Characteristics – Mango Creek BRC

Area	0.98 ac
Flow Path Length	605 ft
Percent Impervious	100%

The Mango Creek BRC was designed to capture a 1" rain event, with centipede grass sod with class A riprap-lined forebays at the inlet. The soil media was separated from an underlying stone layer by a polypropylene woven monofilament geotextile fabric to prevent clogging of the stone. A 12-inch layer of washed No. 57 Stone surrounded two 6-inch underdrains. The underdrain had an upturned elbow, establishing an internal water storage zone to 2 ft, and it drained into a concrete outlet structure. Table 4 summarizes the relevant design features. Monitoring took place from October 2009 to October 2010, during which 79 inflow-producing events were collected. Equipment was installed to measure the rainfall, inflow, and outflow from the cell. For details on the monitoring scheme refer to Luell (2011).

Table 4. As-Built Characteristics - Mango Creek BRC

Length	102 ft
Average Width	20 ft
Surface Area	2018 ft^2
Ponding Volume	1210 ft^3
Average Ponding Depth	0.6 ft
Range of Ponding Depth	0.3 ft - 1.1 ft
Storage Layer (IWS)	2 ft
Stone Layer	12 in
Average Soil Media Depth	24 in
Underdrain Pipe Diameter	6 in
Outlet Pipe Diameter	12 in
Soil Media Composition	87% Sand 7% Organic Matter 3% Gravel 3% Clay

The Mango Creek BRC model includes a contributing drainage area subcatchment that routes to the LID control subcatchment. Parameters used to define each subcatchment are summarized in Tables 5 and 6, while LID control editor parameters are summarized in Table 7. Flow dividers are nodes used to divert inflows into specific conduits and were used to model the split between the larger and smaller cells (Figure 2).

Table 5. Contributing Drainage Area Subcatchment Parameters– Mango Creek BRC

Parameter	Value	Source
Watershed Area (ac)	0.98	Design plans and in-field measurements, Luell (2011)
Subcatchment Width (ft)	45	Design plans and in-field measurements, Luell (2011)
Subcatchment Slope (%)	0.5	Design plans and in-field measurements, Luell (2011)
Subcatchment Impervious Area (%)	100	Design plans and in-field measurements, Luell (2011)
Manning's n - Impervious	0.011	TR55
Depression Storage - Impervious (in)	0.05	Rawls et al. (1982)
Conductivity (in/hr)	1.2	Rawls et al. (1982)
Initial Deficit	0.339	Rawls et al. (1982)
Suction Head (in)	3.6	Rawls et al. (1982)

Table 6. LID Control Subcatchment Parameters– Mango Creek BRC

Parameter	Value	Source
Watershed Area (ft^2)	2018	Design plans and in-field measurements, Luell (2011)
Subcatchment Width (ft)	20	Design plans and in-field measurements, Luell (2011)
Subcatchment Slope (%)	Not Applicable	Design plans and in-field measurements, Luell (2011)
Manning's n	0.15	TR55
Depression Storage	2.54	Rawls et al. (1982)
Conductivity (in/hr)	1.2	Rawls et al. (1982)
Initial Deficit	0.339	Rawls et al. (1982)
Suction Head (in)	3.6	Rawls et al. (1982)

Table 7. LID Control Editor Parameters – Mango Creek BRC

Parameter	Value	Source
Berm height (in)	3	Design plans and in-field measurements, Luell (2011)
Vegetation volume (%)	0	SWMM Manual
Manning's n	0.41	Design plans and in-field measurements, Luell (2011)
Surface slope (%)	0.5	Design plans and in-field measurements, Luell (2011)
Thickness (in)	9	Design plans and in-field measurements, Luell (2011)
Porosity (volume fraction)	0.437	Rawls et al. (1982)
Field Capacity (volume fraction)	0.105	Rawls et al. (1982)
Wilting point (volume fraction)	0.047	Rawls et al. (1982)
Conductivity (in/hr)	1.2	Design plans and in-field measurements, Luell (2011)
Conductivity slope	43.789	Rawls et al. (1982)
Suction head (in)	2.4	Rawls et al. (1982)
Storage thickness (in)	12	Design plans and in-field measurements, Luell (2011)
Void ratio (voids/solids)	0.4	Rawls et al. (1982)
Seepage rate (in/hr)	0.05	Rawls et al. (1982)
Clogging factor	0.0	SWMM Manual
Drain coefficient (in/hr)	0.3	SWMM Manual
Drain exponent	0.5	SWMM Manual
Drain offset height (in)	14	Design plans and in-field measurements, Luell (2011)

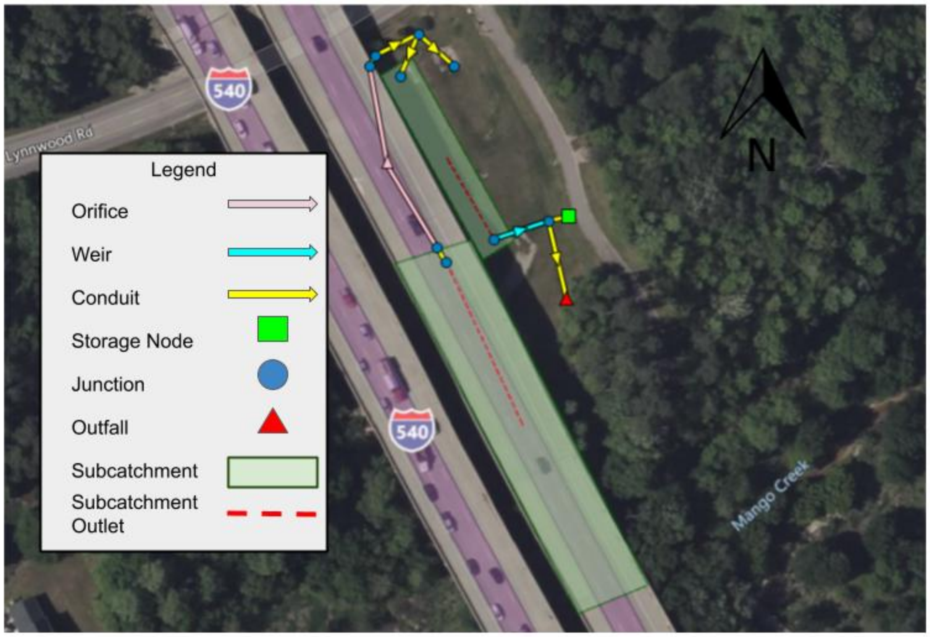

Figure 2. Mango Creek BRC PCSWMM schematic

Wilmington BRC

The second BRC modelling site is in Wilmington, North Carolina (34°11’52.2” N, 77° 53' 26.3” W). This BRC was installed in the parking lot of the Longleaf Mall as a retrofit during the summer of 2016 (Figure 3). 86% of the 3.11 acres contributing drainage area is impervious asphalt parking lot, with a few pervious landscaped islands (Table 8). As a retrofit, the cell is significantly undersized, by both surface area and media depth metrics. With surface area of 2,050 ft^2 and a total depth of 4 ft, the cell’s storage volume is only 7% of the required design storm (1.5”), and the bottom of the cell is within 1 ft of the seasonal high-water table (Table 9). Despite these design variations, the cell performed well due to the high infiltration rate of the underlying soils (Tormey, 2021). The media was composed of 87.4% sand, 7.3% silt, and 5.3% clay, and the cell was equipped with a 4 inch underdrain with an upturned elbow to allow for 1.2 ft of internal water storage (IWS). The outlet structure was 1.4 ft tall, and any overflow was calculated using a rectangular weir equation with the total length equaling the inside perimeter of the outlet structure grate.

Figure 3. Aerial view of bioretention cell at Longleaf Mall in Wilmington, NC

Table 8. Contributing Watershed Characteristics – Wilmington BRC

Area	3.11 acres
Flow Path Length	500 ft
Percent Impervious	86%

Table 9. As-Built SCM Characteristics – Wilmington BRC Compared to Minimum Design Criteria (MDC)

Parameter	NC MDCs	Wilmington BRC
Separation from Seasonal High-Water Table	> 2 ft	< 1 ft
Design Volume	100%	7%
Underdrain	Required w/ IWS when underlying soils have an infiltration rate 2 in/hr	15 in to IWS. Underlying soil Baymeade fine sand; Ksat 2 to 6 in/hr
Water Quality Ponding Depth	12 in	12 in (Captures 7% of the design storm)
Ponding to Overflow	18 in	17 in. (Captures 11% of the design storm)
Maximum Ponding	24 in	24 in
Media Depth	30 in	18 in
Internal Water Storage Zone	≥ 18 in from planting surface	10 in from planting surface

Hydrological data were recorded at 2-minute intervals between March 2017 and March 2021, resulting in the collection of 289 inflow-producing events. An ISCO 674 rain gauge and a manual rain gauge were installed to record the rainfall. Two ISCO 6712 automatic samplers were connected to the inlet and underdrain of the BRC. A pressure transducer was installed at the base of the cell to record the internal water storage. Flow within the underdrain and overflow were directly monitored, while influent volumes were calculated using on-site rain data. For each rainfall event exceeding 0.1 in, the volumes were calculated for the inflow, underdrain, and overflow of the cell and used to calculate the percent bypass. For monitoring details refer to Tormey (2021).

The site's resulting PCSWMM model included an impervious subcatchment for the parking lot (Table 10), a pervious subcatchment for the cumulative area of all landscaped islands (Table 11), and an LID control subcatchment for the BRC (Table 12). Runoff was directed from the pervious subcatchment, to the impervious subcatchment, and lastly to the LID control BRC subcatchment (Figure 4).

Table 10. Impervious Contributing Drainage Area Subcatchment Parameters – Wilmington BRC

Parameter	Value	Source
Watershed Area (ha)	1.08	Site Survey, Tormey (2021)
Subcatchment Width (ft)	380	Site Survey, Tormey (2021)
Subcatchment Slope (%)	0.80	Site Survey, Tormey (2021)
Subcatchment Impervious Area (%)	100	GIS, Tormey (2021)
Manning's n - Pervious	0.40	McCuen et al., (1996)
Manning's n - Impervious	0.011	McCuen et al., (1996)
Depression Storage - Impervious (in)	0.05	ASCE (1992)
Depression Storage - Pervious (in)	0.1	ASCE (1992)
Conductivity (in/hr)	4.7	Rawls et al. (1982), Soil Survey Staff (2021)
Initial Deficit	0.339	Rawls et al. (1982), Soil Survey Staff (2021)
Suction Head (in)	3.6	Rawls et al. (1982), Soil Survey Staff (2021)

Table 11. Pervious Contributing Drainage Area Subcatchment Parameters – Wilmington BRC

Parameter	Value	Source
Watershed Area (ha)	0.18	Site Survey, Tormey (2021)
Subcatchment Width (ft)	52.5	Site Survey, Tormey (2021)
Subcatchment Slope (%)	7.4	Site Survey, Tormey (2021)
Subcatchment Impervious Area (%)	0	GIS, Tormey (2021)
Manning's n - Pervious	0.40	McCuen et al., (1996)
Manning's n - Impervious	0.011	McCuen et al., (1996)
Depression Storage - Impervious (in)	0.05	ASCE (1992)
Depression Storage - Pervious (in)	0.1	ASCE (1992)
Conductivity (in/hr)	4.7	Rawls et al. (1982), Soil Survey Staff (2021)
Initial Deficit	0.413	Rawls et al. (1982), Soil Survey Staff (2021)
Suction Head (in)	3.6	Rawls et al. (1982), Soil Survey Staff (2021)

Table 12. LID Control Subcatchment Parameters – Wilmington BRC

Parameter	Value	Source
Watershed Area (ha)	0.0156	Site Survey, Tormey (2021)
Subcatchment Width (ft)	30	Site Survey, Tormey (2021)
Subcatchment Slope (%)	0.005	Site Survey, Tormey (2021)
Subcatchment Impervious Area (%)	0	GIS, Tormey (2021)
Manning's n - Pervious	0.40	McCuen et al., (1996)
Manning's n - Impervious	0.011	McCuen et al., (1996)
Depression Storage - Impervious (in)	0.05	ASCE (1992)
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Initial Deficit	0.413	Rawls et al. (1982), Soil Survey Staff (2021)
Suction Head (in)	3.6	Rawls et al. (1982), Soil Survey Staff (2021)

The bioretention option within the LID Control Editor was used to include the hydraulic parameters of the BRC (Table 13). A separate storage node was defined to model the overflow from the BRC. Ponding above the outlet structure was conveyed to a storage node. The curve of the storage node was defined by a survey of the cell geometry above the outlet structure conducted in December 2016. Two junctions were used to link the BRC to the existing stormwater drainage network. The first junction routed the overflow from the BRC, acting as the outlet structure. The rectangular grate on top of the outlet structure of the BRC was modeled with a transverse weir. A second junction combined the underdrain flow and the flow from the storage node. A conduit represented the concrete pipe that connected the BRC outlet structure to the final outfall.

Table 13. LID Editor Parameters – Wilmington BRC

Parameter	Value	Source
Berm height (in)	17	Design plans and in-field measurements
Vegetation volume	0	Grass provided negligible storage reduction
Manning's n	0.24	McCuen et al., (1996)
Surface slope (%)	0.5	Provide slope for overflow estimation.
Thickness (in)	18	Design plans
Porosity (volume fraction)	0.52	Rossman & Huber (2016)
Field Capacity (volume fraction)	0.15	Rossman & Huber (2016)
Wilting point (volume fraction)	0.08	Rossman & Huber (2016)
Conductivity (in/hr)	10	Design Plans. Soil Analysis.
Conductivity slope	46.7	Rossman & Huber (2016)
Suction head (in)	1.5	Rossman & Huber (2016)
Storage thickness (in)	6	Design Plans
Void ratio (voids/solids)	0.4	Rossman & Huber (2016)
Seepage rate (in/hr)	4.7	Ksat of in situ soil
Clogging factor	0.0	SWMM Manual
Drain coefficient (in/hr)	4.5	Rossman & Huber (2016)
Drain exponent	0.5	Rossman & Huber (2016)
Drain offset height (in)	14	Design plans, Tormey (2021)

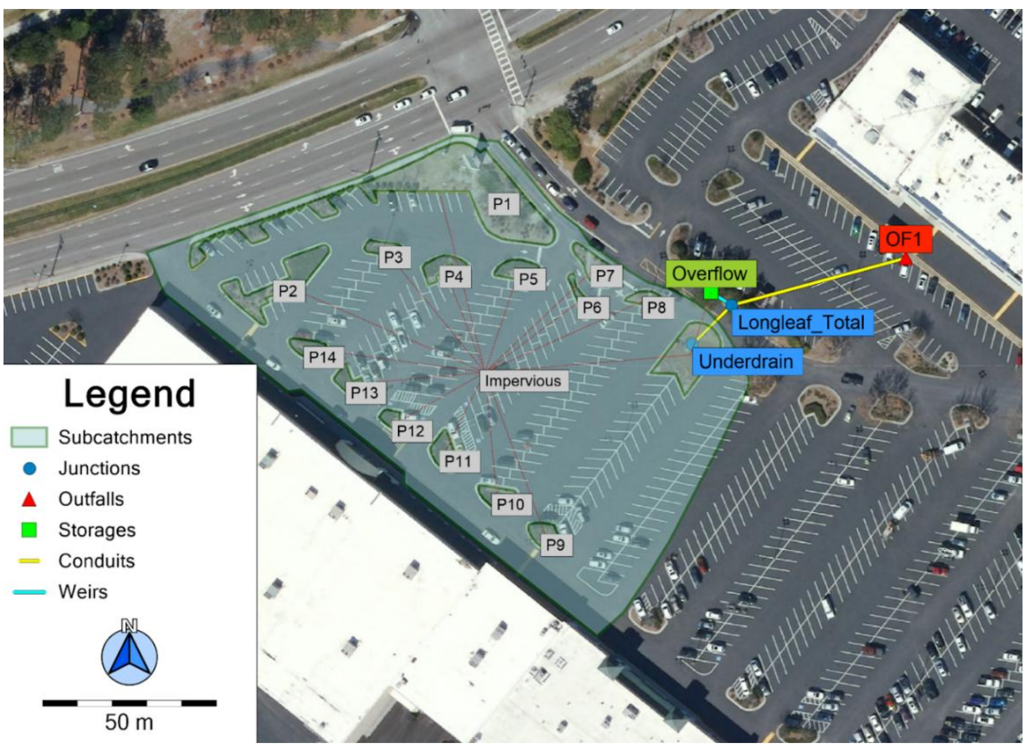

Figure 4. PCSWMM diagram of the DDB site

Dry Detention Basin

In 2010, a DDB was installed in Archdale, North Carolina (Figure 4) between I-74 and Hughes Farm Road (35°51' 39.744" N, 78° 53' 13.344" W). The DDB was lined with grass and routinely mowed for maintenance (Figure 5). The watershed was 9.81 acres with 3.06 acres of impervious surfaces (Table 14). A 2 ft reinforced concrete pipe collected runoff from four lanes of I-74, and runoff 250 feet of the adjacent road flowed directly into the basin (Figure 6). The site was within a predominantly agricultural region of the Piedmont and had loamy soils. The bottom area was 6,964.25 ft^2 (647 m^2) and was vegetated with herbaceous grasses. The basin could store up to $3{,}304.52^3$ ft (307 m^3) in volume. Riprap lined the forebay to provide some energy dissipation of the inlet flow. Tests for soil Ksat in the basin revealed negligible infiltration. The outlet structure consisted of a rectangular riser, with a 2 in drawdown orifice. DDB characteristics are summarized in Table 15.

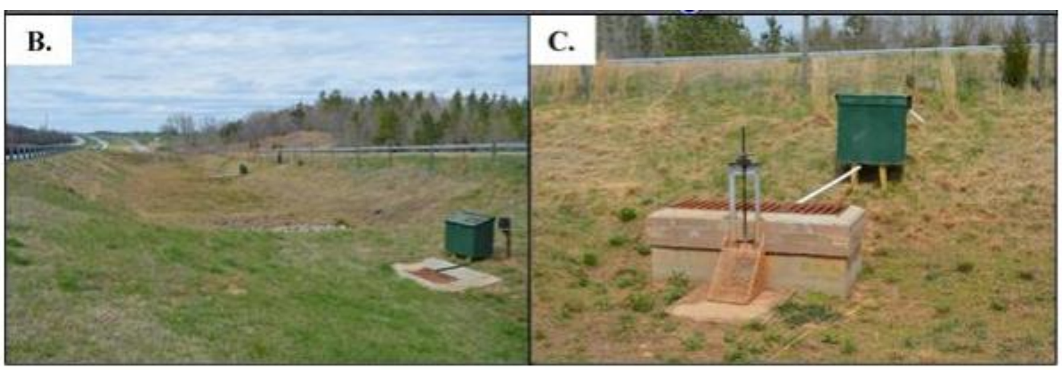

Figure 5. DDB is long and narrow (B) with an outlet structure in the center (C)

Table 14. Drainage Area Characteristics - DDB

Area	3.97 ha
Percent Impervious	31 %
Flow Path Length	250 ft

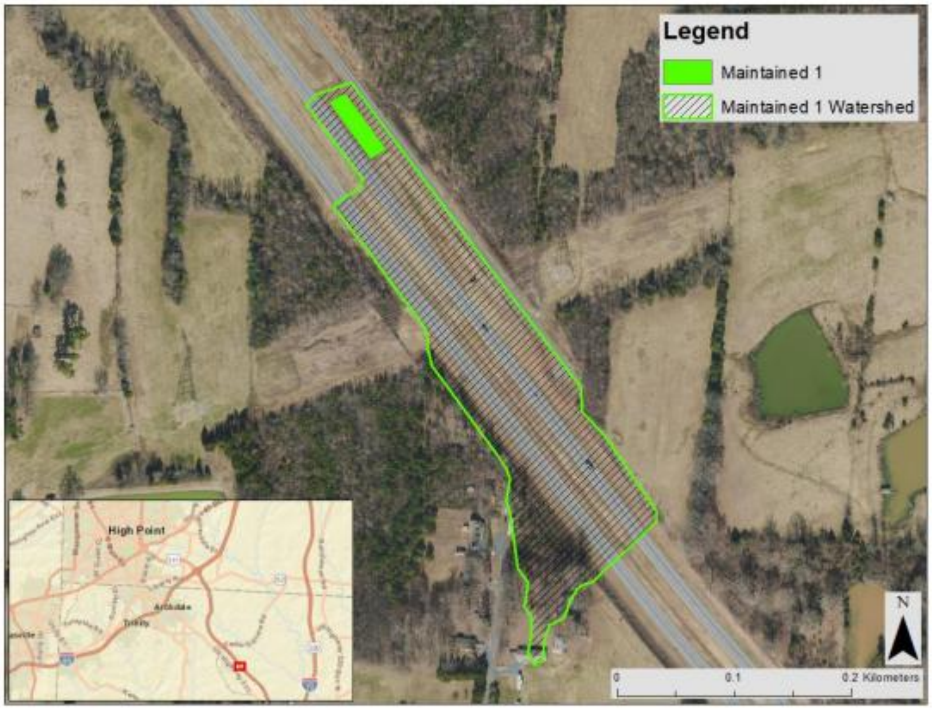

Figure 6. Aerial view of DDB (referred in figure as "Maintained 1") illustrating the watershed area and area occupied by the DDB (Wissler, 2019)

Table 15. As-Built Characteristics - DDB

Characteristic	Value
Inlet Pipe Diameter	2 ft
Length	121 ft
Surface Area	6964 ft^2
Volume	3305 ft^3
Ponding Depth	2 ft
Soil Composition	42% Sand 39% Silt 19% Clay
Orifice	6 in

Hydrologic data was collected from March 2018 to February 2019, capturing 48 discrete storm events. Rainfall accumulation and intensity were measured with an ISCO 674 automatic tipping bucket rain gauge. In the catch basin directly upstream from the inlet pipe, a 90-degree sharp crested v-notch weir measured inflow volume. An identical V-notch weir was placed inside the outlet structure to measure the outflow volume. Additionally, a 6712 ISCO automatic sampler and a HOBO pressure transducer were installed to quantify the volume at the inlet and outlet. A 730 bubbler flow module was connected to automated samplers at the inlet and outlet to measure stage discharging over sharp-crested weirs. Descriptions of the monitoring methods are detailed in Wissler, 2019.

The resulting PCSWMM model included one contributing drainage area subcatchment (Table 16) and one LID control subcatchment (Table 17), routed through an LID control (Table 18). The vegetated swale option within the LID control editor was used to include the DDB's hydrologic parameters, given that PCSWMM does not include a dry detention LID control option. Ponding above the outlet structure was simulated with a storage node assigned with elevation data from survey data. The outlet structure limited ponding to 2 feet and had a 2-inch drawdown orifice. The outlet structure of the dry detention basin was modeled, featuring a junction that leads to a V-notch weir before ultimately reaching the outfall (Figure 7).

Table 16. Contributing Drainage Area Subcatchment Parameters - DDB

Parameter	Value	Source
Watershed Area (ha)	3.97	Design Plans, Wissler (2019)
Subcatchment Width (ft)	1709	Auto-calculated by PCSWMM
Subcatchment Slope (%)	0.80	Determined from survey (2023)
Subcatchment Impervious %	31	Design Plans, Wissler (2019)
Manning's n - Pervious	0.15	TR55
Manning's n - Impervious	0.011	TR55
Depression Storage - Impervious (in)	0.05	ASCE (1992)
Depression Storage - Pervious (in)	0.1	ASCE (1992)
Conductivity (in/hr)	1.1	Infiltration Test, Wissler (2019)
Initial Deficit	0.339	Rawls et al. (1982)
Suction Head (in)	0.33	SWMM Manual

Table 17. LID Control Subcatchment Parameters - DDB

Parameter	Value	Source
Watershed Area (ha)	0.29	Design Plans, Wissler (2019)
Subcatchment Width (ft)	121	Auto-calculated by PCSWMM
Subcatchment Slope (%)	0.5	Determined from survey (2023)
Subcatchment Impervious Area (%)	0	Design Plans, Wissler (2019)
Manning's n - Pervious	0.15	TR55
Manning's n - Impervious	0.011	TR55
Depression Storage - Impervious (in)	0.05	ASCE (1992)
Depression Storage - Pervious (in)	0.1	ASCE (1992)
Conductivity (in/hr)	4.7	Infiltration Test, Wissler (2019)
Initial Deficit	0.25	Rawls et al. (1982)
Suction Head (in)	4	SWMM Manual

Table 18. LID Control Editor Parameters - DDB

Parameter	Value	Source
Berm height (in)	24	Design Plans, Wissler (2019)
Vegetation volume %	0	Grass provided a negligible reduction in storage
Manning's n	0.3	McCuen et al., (1996)
Surface slope (%)	1	Design Plans
Conductivity (in/hr)	1.1	Soil Infiltration Test, Wissler (2019)
Suction head (in)	8	PCSWMM 5 User Guide
Seepage rate (in/hr)	0.47	Wissler (2019)

Figure 7. PCSWMM diagram of the DDB site

Regenerative Stormwater Conveyance

A regenerative stormwater conveyance system was installed along an exit ramp from a rest area in Alamance, North Carolina (36°03'52.8"N 79°32'06.0" W) in the summer of 2013 (Figure 8). The RSC received runoff from a 3.95-acre watershed with 63% impervious surfaces

(Table 19). Runoff was received from the paved lot and rooftop of the rest stop facilities and directly connected to the inlet via a sewer grate and a 24 in concrete pipe.

(a) (b)

Figure 8. Alamance County RSC watershed (a) and photo with monitoring weir visible (b) (Cizek, 2014)

Table 19. Contributing Drainage Area Characteristics - RSC

Area	3.95 ac
Percent Impervious	63%
Flow Path Length	109.9 ft

The Regenerative Stormwater Conveyance system was 110 ft long, designed to convey the 100-year 24-hour storm via non-erosive surface flow. The design consisted of three terraced sand media beds (Table 20). The media beds were 2 ft deep and lined with Class A riprap for stabilization. The sand had a porosity of approximately 30%, and the riprap had a porosity of 25% (Stephens et al., 1998). A rifle with a 2.5% slope connected each media bed, with the final pool releasing surface flow to a 9.5 ft drop and into a series of three wetland pools. To provide further stabilization, approximately 6 inches of hardwood mulch covered the entirety of the system. The RSC did not have any substantial vegetation during the monitoring period.

Table 20. As-Built Characteristics - RSC

Infiltration Rate (in/hr)			0.01	
Sand Media Drainage Porosity			30%	
Sand Media Depth (ft)			2	
Riprap Depth (ft)			1.5	
Ponding Depth (ft)			1.5	
	Pool 1	Pool 2	Pool 3	Final Wetland Pool
Length (ft)	19	20	23	48
Width (ft)	16	16	16	16
Surface Area (ft^2)	304	320	368	768
Contributing Run-On Area (ft^2)	3,605	710	988	2,734
Average Slope (%)	1.3	3.75	2.3	8.33
Sand Media Storage (ft^3)	198	286	230	537
Riprap Storage (ft^3)	105	78	130	318
Pond Storage (ft^3)	120	173	215	283

Hydrologic data was collected between July 2013 and June 2014, collecting 43 inflow-producing rainfall events. Rainfall was measured with a tipping bucket rain gauge and a manual rain gauge for further calibration. The flow exiting the system was measured as surface flow, seepage, evapotranspiration, or exfiltration. Runoff entering the system was monitored with an ISCO 750 area velocity meter located 3 ft inside the 24 in concrete inlet pipe. An ISCO 730 bubbler was used to collect water depth measurements at the inlet and outlet monitoring weirs of the following RSC cells. An exfiltration trench installed underneath Cell 4 was used to estimate exfiltration rates. Because vegetation within the system was not established during the monitoring period, evaporation rates were considered only when water ponded on the RSC.

Seepage was calculated using a water balance based on the previously determined inflow and outflows. For monitoring details refer to Cizek, 2014.

Data collected from Cizek in the project outlined above were used to design a PCSWMM model to evaluate the site's hydrological performance. The model included a contributing drainage area subcatchment (Table 21) routed through a series of pervious cells that make up the RSC LID Control (Table 22).

Table 21. Contributing Drainage Area Subcatchment Parameters - RSC

Parameter	Value	Source
Watershed Area (ha)	1.6	Design Plans, Cizek (2014)
Subcatchment Width (ft)	16	Design Plans, Cizek (2014)
Subcatchment Slope (%)	0.80	Design Plans, Cizek (2014)
Subcatchment Impervious (%)	63	Design Plans, Cizek (2014)
Manning's n - Pervious	0.011	McCuen, R. et al. (1996)
Manning's n - Impervious	0.40	McCuen, R. et al. (1996)
Depression Storage - Impervious (in)	0.05	ASCE, (1992). Design & Construction of Urban Stormwater Management Systems, New York, NY.
Depression Storage - Pervious (in)	0.1	ASCE, (1992). Design & Construction of Urban Stormwater Management Systems, New York, NY.
Conductivity (in/hr)	4.7	Infiltration Test, Wissler (2019)
Initial Deficit	0.339	Rawls et al. (1982)
Suction Head (in)	3.6	SWMM Manual

Table 22. LID Control Subcatchment Parameters - RSC

Parameter	Value	Source
Watershed Area (ac)	3.7	Design Plans, Cizek (2014)
Subcatchment Width (ft)	150	Auto-calculated by PCSWMM
Subcatchment Slope (%)	0.5	Determined from survey (2023)
Subcatchment Impervious Area (%)	63	Design Plans, Cizek (2014)
Manning's n - Pervious	0.15	TR55
Manning's n - Impervious	0.011	TR55
Depression Storage - Impervious (in)	0.05	ASCE (1992)
Depression Storage - Pervious (in)	0.1	ASCE (1992)
Conductivity (in/hr)	0.5	USGS Web Soil Survey
Initial Deficit	0.25	Rawls et al. (1982), Soil Survey Staff (2021)
Suction Head (in)	3.5	USEPA (2022)

The bioretention option within the LID control Editor was utilized to model the site, in the absence of an RSC LID control option. Runoff was directed from the parking lot via a sewer grate and a concrete pipe, modeled as a conduit. Runoff entered the first cell through a V-notch weir. Following the inlet, there were three modeled bioretention cells in series, each with an associated storage node, connected by conduits that modeled the RSC pools. These bioretention cells had identical LID parameters (Table 23) with varying surface areas (Table 20). After exiting the series of pools, any flow that was not converted to seepage, exfiltrated, or evapotranspiration exited over a weir, into the final pool that was modeled as a single bioretention LID control (Table 23, Figure 9).

Table 23. LID Editor Parameters - RSC

Parameter	Value
Berm height (in)	18
Vegetation volume (fraction)	0
Surface roughness (Manning's n)	0.1
Surface slope (%)	1
Thickness (in)	24
Porosity (volume fraction)	0.52
Field Capacity (volume fraction)	0.2
Wilting point (volume fraction)	0.1
Conductivity (in/hr)	0.5
Conductivity slope	10
Suction head (in)	3.5
Storage thickness (in)	18
Void ratio (voids/solids)	0.75
Seepage rate (in/hr)	0.5
Clogging factor	0.0
Drain coefficient (in/hr)	0
Drain exponent	0.5
Drain offset height (in)	6

Figure 9. PCSWMM diagram of the RSC site

Model Calibration

Preparation of Historical Data

Data were prescreened by their original authors for anomalies, and any unreliable outliers were removed from the dataset. For details regarding data anomalies, refer to the original publications (Table 2). Extreme peaks in flow rate indicate a clog or error in the monitoring equipment and were excluded from analysis. Additionally, the data may experience "drizzle," a phenomenon where the model predicts numerous small storms. This can be mitigated through bias correction scripts designed to smooth the data.

CSV. files of rainfall and outflow data at 2-minute intervals were used to complete the calibration process for each site. The units of the rainfall data were provided as depths in inches and were converted into rates of intensity within the PCSWMM graph panel. The outflow file was saved as a binary time series file (.tsb) to ensure compatibility with the Sensitivity-Based Radio Tuning Calibration (SRTC) Tool.

Calibrating with the SRTC Tool

Uncalibrated models were first run for the sake of comparison. Afterward, one node was selected for the calibration process. The data associated with the node were split, with 80% allocated for calibration and 20% for validation. PCSWMM's SRTC tool enables the model to be calibrated against observed data. The first step in calibrating a model, after obtaining observed flow data, is to select parameters for calibration and estimate the uncertainty associated with these parameters. The uncertainty parameters dictate the acceptable range over which the model may adjust the parameter to increase accuracy. This range is expressed as an absolute value percentage deviation from its current value. Uncertainty Parameters are a range recommended by the Storm Water Management Model User's Manual Version 5.1 (Rossman, L. A., 2015) (Table 24).

Table 24. SRTC Tool Uncertainty Parameter Values

Parameter	Uncertainty (%)
Width	200
Slope	25
Imperviousness	20
N Imperv	10
N Perv	50
Depression Storage Imperv	20
Depression Storage Perv	50
Suction Head	50
Hydraulic Conductivity	50
Initial Deficit	25

The historic outflow time series was imported into the graph panel, and the model was calibrated to the Nash Sutcliffe Efficiency (NSE) using the SRTC tool. Models with an NSE greater than 0.5 are typically considered acceptable in hydrology (David & Mota, 2022). Once calibrated, the new model parameters can override the current project or be saved as a new scenario. The calibrated model was saved as a new scenario, allowing the original, uncalibrated model to serve as a reference point. The calibration process is visualized in the SRTC radio tuning window, which displays a plot of the observed, current, and calibrated data, along with the model's error (Figure 10).

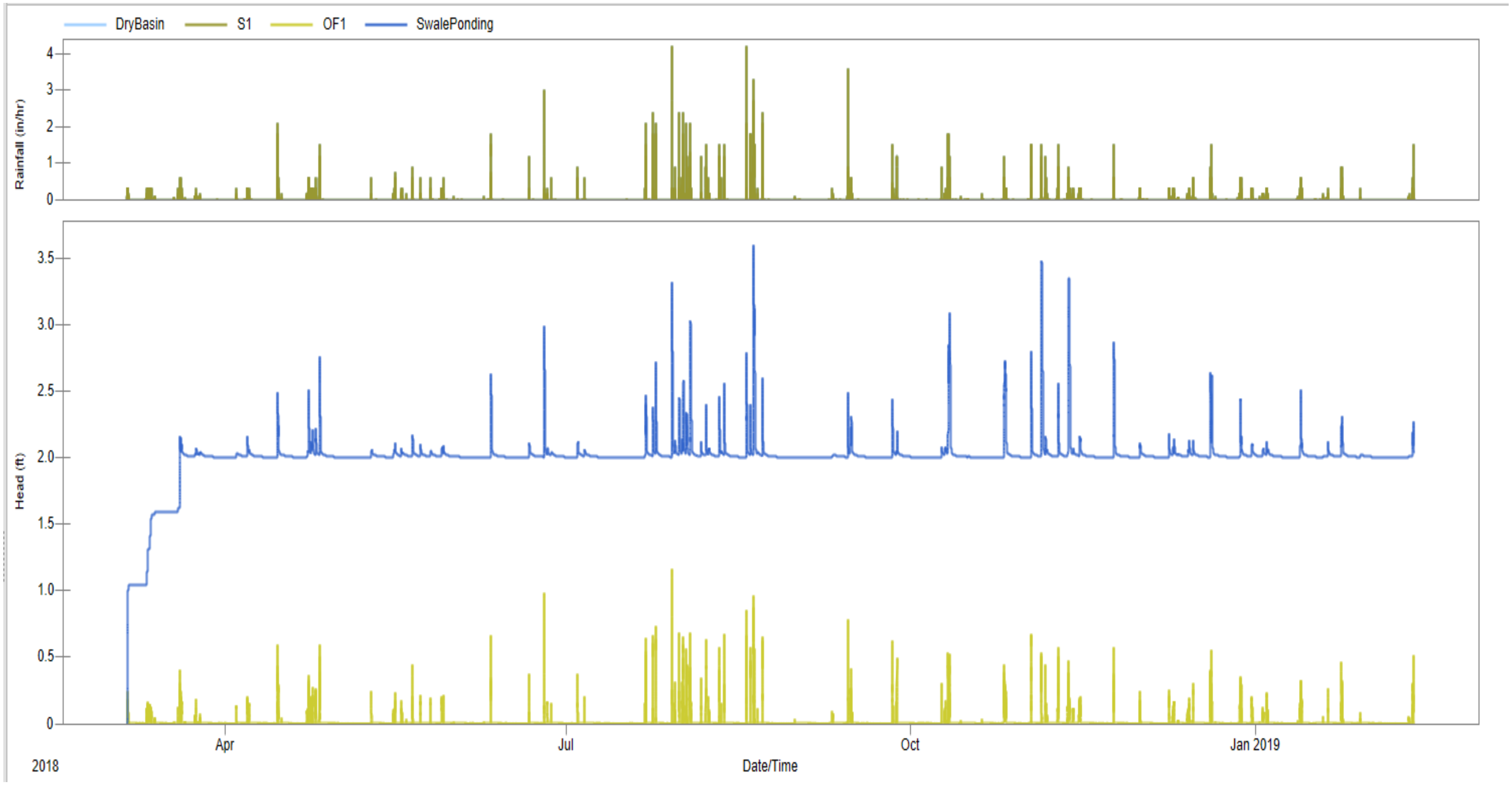

Figure 10. Example PCSWMM calibration results from DDB

This calibration process was completed for each site, resulting in four stormwater models with NSEs ranging from 0.80 to 0.19 (Table 25). The Wilmington BRC had the best fit (NSE 0.80) of the four models, partially due to the SCM being the best maintained and having the most reliable historical data. The Mango Creek BRC, DDB, and RSC models all had relatively poor performance (NSE < 0.5). When the data was refined to filter out unreliable data points, the performance improved slightly. Major storms during the monitoring period overwhelmed the measurement devices, causing unreliable readings. This is likely responsible for the model results not calibrating well, considering the PCSWMM software assumes ideal monitoring conditions for the run output.

Table 25. NSE Values for each calibrated and uncalibrated model

SCM	Uncalibrated NSE	Calibrated NSE
Mango Creek BRC	-0.19	0.21
Wilmington BRC	0.54	0.80
DDB	0.12	0.27
RSC	-0.15	0.19

Only the Wilmington BRC produced a model with an NSE value meeting the industry standard for acceptable predictions. Therefore, the results presented should be considered useful in conceptualizing relative changes to individual SCM performance under varying conditions, rather than as absolute metrics that can be compared between SCMs. When developing PCSWMM models, the proper collection and refinement of flow data are crucial for accurate results.

SCM Stress Tests

Once the calibrated models were completed for each site, “stress tests” were conducted to determine the failure points of each SCM. Failure is defined as the overtopping of the berm, which occurs when the depth of water stored exceeds the berm’s capacity to contain it, risking erosion, structural damage, or a complete structural breach. Overtopping is considered a critical failure mode because it indicates that the berm can no longer function as a protective barrier. Understanding and preventing overtopping is essential in the design and maintenance of berms, as it directly influences their effectiveness in managing stormwater and protecting surrounding areas from flooding.

To determine the storm characteristics that contribute to failure, the SCMs were tested using both synthetic and natural storm distributions. Synthetic distributions were center-weighted design storms, while natural storm distributions were derived from rainfall patterns observed during Hurricane Florence in 2018.

Both storm distribution types were considered at storm depths currently used in design guidance, as well as at scaled depths representative of recent shifts in local rainfall patterns. Storm depths and return periods varied per the location of the SCMs. Simulations were run at increasing return periods until failure occurred. Once the return period that induced failure was determined, an annual failure risk was calculated.

Rainfall Depths

Current Scenarios

The Precipitation Frequency Data Server is a platform developed by the National Oceanic and Atmospheric Association (NOAA) to share nationwide rainfall data. The website delivers NOAA Atlas 14 precipitation frequency estimates that can be used to develop synthetic unit hydrographs. Two sets of storm depths were used, one from the piedmont region (Mango Creek, RSC, DDB analyses) and one from the coastal plain region (Wilmington RSC, Table 26). The hydrographs include rainfall depths for a given return period, distributed over 24 hours, which is the standard duration used for modeling stormwater control measures.

Scaled Scenarios

A second set of simulations were run using the synthetic storm distributions at scaled storm depths. The scaled shifts in rainfall patterns used in this study were calculated using the regional scale factors (RSF) produced by the North Carolina State Climate Office (NCSCO) (personal communication, Jared Bowden). The NCSCO developed these scale factors based on the Representative Concentration Pathway (RCP) 4.5 climate model, and they can be applied as multipliers to current NOAA Atlas 14 storm depth estimates for accurate representations of recent changes to local weather patterns (Table 26).

Table 26. Current and Scaled Rainfall Depths

Return Period – Duration	Depth (in)	RSF	Scaled Depth (in)
Piedmont Region			
10 yr - 24 hr	5.06	1.22	6.17
25 yr - 24 hr	5.95	1.27	7.56
50 yr - 24 hr	6.72	1.30	8.74
100 yr - 24 hr	7.44	1.34	9.97
Coastal Region			
10 yr - 24 hr	7.25	1.33	9.64
25 yr - 24 hr	9.19	1.42	13.05
50 yr - 24 hr	10.87	1.50	16.31
100 yr - 24 hr	12.77	1.60	20.43

Rainfall Distributions

Synthetic Storms

Synthetic storms were constructed using the unit hydrograph method. The unit hydrograph theory states that hydrographs for storms of the same duration will have the same shape, provided a linear relationship exists, with values proportional to the runoff depth. Various methods for developing hydrographs are available, but the NRCS is considered the standard within engineering practice for basins less than 10 square miles (USDA, 1984). The rainfall distribution type used to create the synthetic storms was type II.

Natural Distributions

Several assumptions are made to maintain the principles of the unit hydrograph theory. The primary assumptions are that the storm is evenly distributed spatially and temporally and that the characteristics of the watershed are homogeneous. However, the durations and distributions of real storms may deviate substantially. For this reason, storm data recorded by the NCSCO was used to create more realistic storm hydrographs for model analysis.

To model natural distributions, historical data from Hurricane Florence were used. The target depth of the storm with a specified return frequency was identified within NOAA Atlas 14 (Table 25). A city that experienced the target rainfall depth during Hurricane Florence was then identified. Rainfall data for the identified city during the corresponding storm period were then acquired from NCSCO. The result was a rainfall dataset that was the target depth in a natural, observed hurricane distribution (Table 27).

Table 27. Hurricane Florence September 14 - 17

Region	Frequency	Target Depth (in)	Observed Florence Depth (in)	Observed City
Piedmont	10 yr - 24 hr	5.06	5.00	North Wilkesboro
	25 yr - 24 hr	5.95	6.06	Gastonia
	50 yr - 24 hr	6.72	6.71	Washington
	100 yr - 24 hr	7.44	7.62	Concord
Coastal	10 yr - 24 hr	7.25	7.29	Aho
	25 yr - 24 hr	9.19	9.18	Chapel Hill
	50 yr - 24 hr	10.87	10.67	Asheboro
	100 yr - 24 hr	12.77	13.29	Fort Bragg

SCM Retrofits

A set of simulations was conducted with altered models to simulate retrofit designs within each SCM. Retrofit options were determined iteratively, based on feasibility and performance impacts. Table 28 summarizes the retrofit design elements for each SCM. While the scale of change varies, the most effective retrofit for each SCM was to increase the storage capacity.

Table 28. Retrofit Design Elements for each SCM

SCM	Parameter	As-Built Value	Retrofit Value	% Increase in Storage
Mango Creek BRC	Avg Ponding Depth	0.6 ft	0.9 ft	50
Wilmington BRC	Ponding Depth	12 in	28 in	133
DDB	Ponding Depth	2 ft	3 ft	50
RSC	Pool 1 Area	.0070 ac	.009 ac	29
	Pool 2 Area	.00736 ac	.01 ac	36
	Pool 3 Area	.0081 ac	.01 ac	23
	Final Pool Area	.0018 ac	.0023 ac	28

Performance Results and Discussion

SCM Performance

Annual percent chances of failure ranged from <1% to 10%, depending on the site and simulation (Table 29, Figures 11 - 14). The RSC generally performed the best, experiencing failure at the 100 year storm under all conditions, however, the DDB was able to safely route the 100 year storm without failure in 3 of the 8 simulations, all post-retrofit. The DDB's low chance of failure is likely due to its high storage volume capacity, particularly post-retrofit. While storage was more limited in the RSC, it has multiple flow pathways and was specifically designed as a conveyance system. These factors likely facilitated the safe routing of extreme events.

In contrast, both BRCs had relatively high chances of failure, likely due to limited storage and conveyance capability. The filter media that is key to the water quality performance of BRCs also constricts and limits flow, risking failure. While both BRCs were equipped with overflow outlet structures that activate during such extreme events, they were insufficient to accommodate the resulting volumes.

Table 29. Annual failure risk* for each SCM (%)

SCM Site	Current Storm Depths				Scaled Storm Depths			
	Synthetic Storm		Natural Storm		Synthetic Storm		Natural Storm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Mango Creek BRC	4	2	4	2	10	4	10	10
Wilmington BRC	4	2	4	2	4	2	2	2
DDB	2	<1	2	<1	2	2	2	<1
RSC	1	1	1	1	1	1	1	1

* Annual Failure Risk = 1/Induced Failure Return Period * 100

Importantly, the Wilmington BRC outperformed the Mango Creek BRC during the scaled rainfall depth simulations, despite being severely undersized (7% of design storage volume). This highlights the important role of in-situ soils as a flow pathway that can reduce the risks of failure. Both BRCs had sandy, high-flow media, but the Wilmington BRC was underlain with HSG A soils, while the Mango Creek BRC was atop C soils. This likely contributed to the overall rates and volumes able to route through the cell without failure.

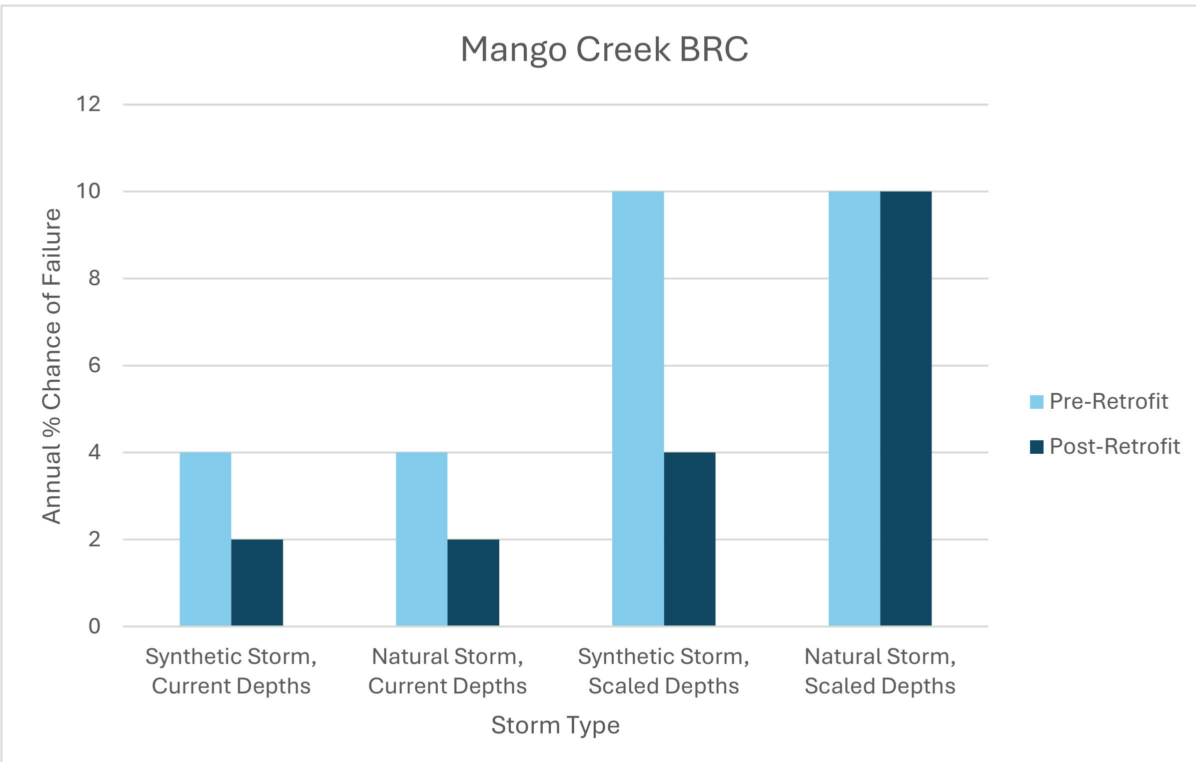

Figure 11. Mango Creek BRC annual percent chance of failure by simulation type

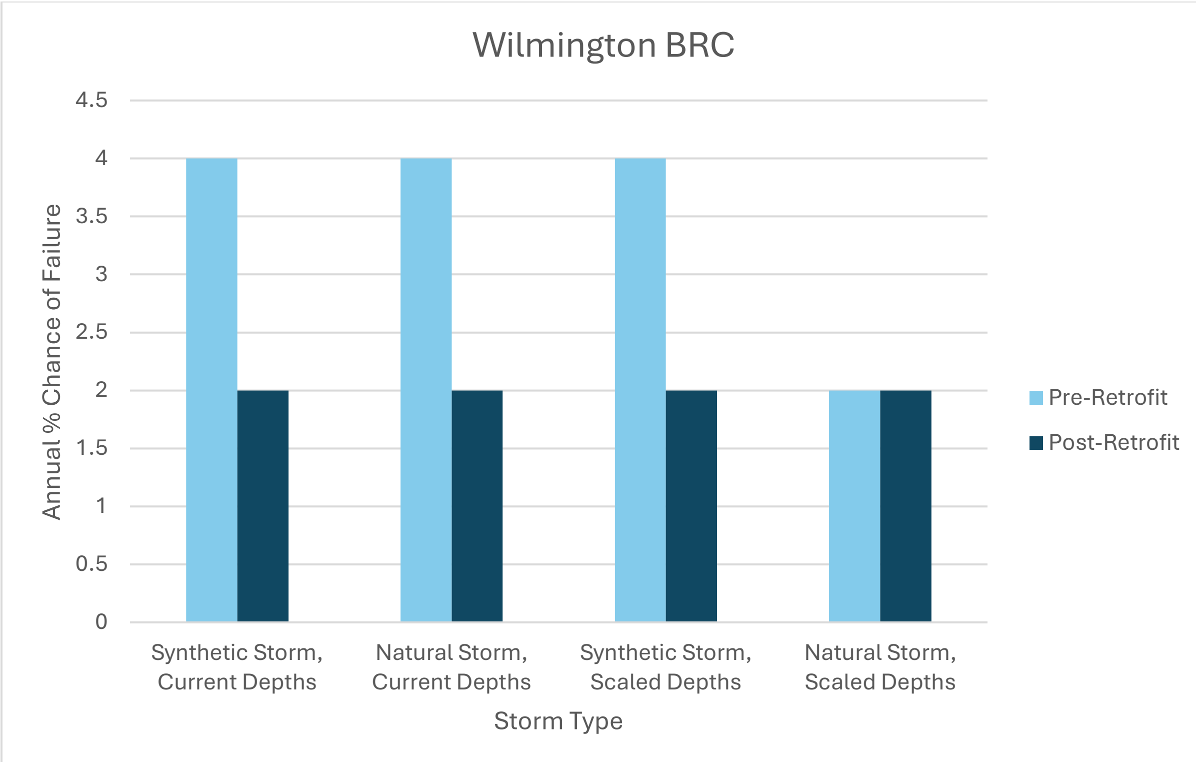

Figure 12. Wilmington BRC annual percent chance of failure by simulation type

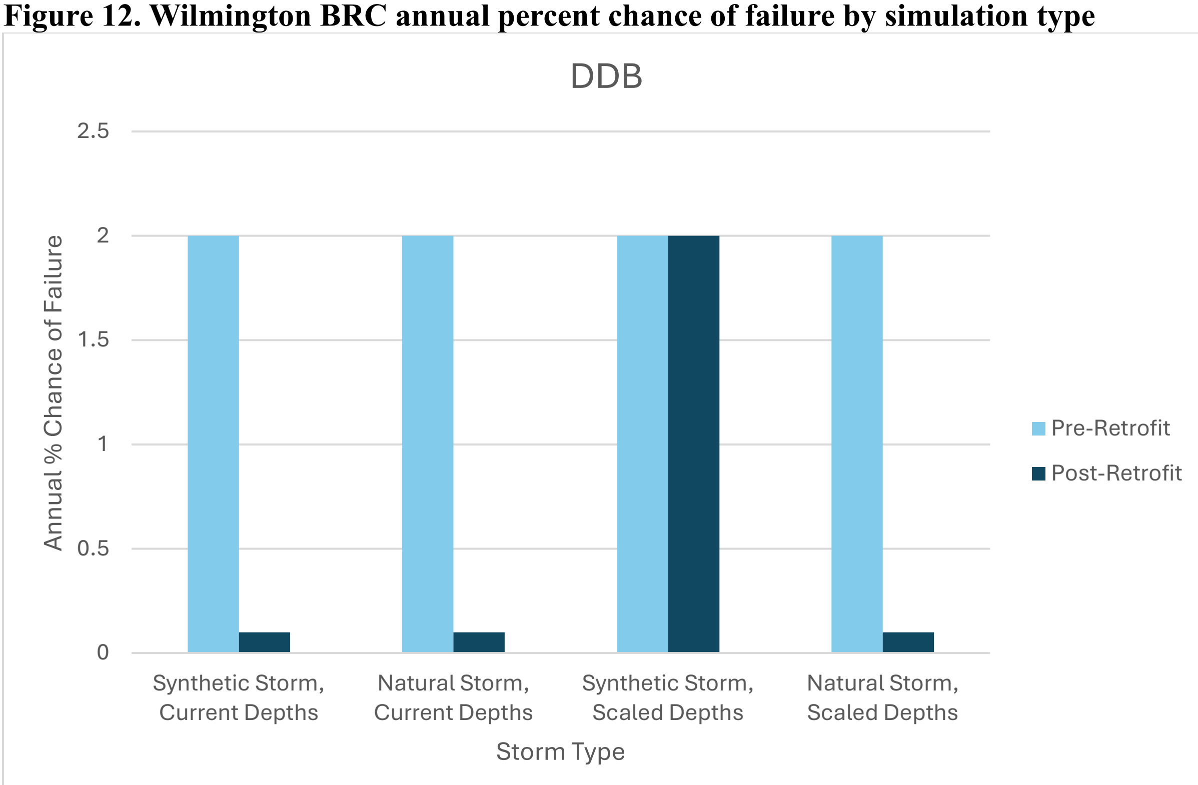

Figure 13. DDB annual percent chance of failure by simulation type

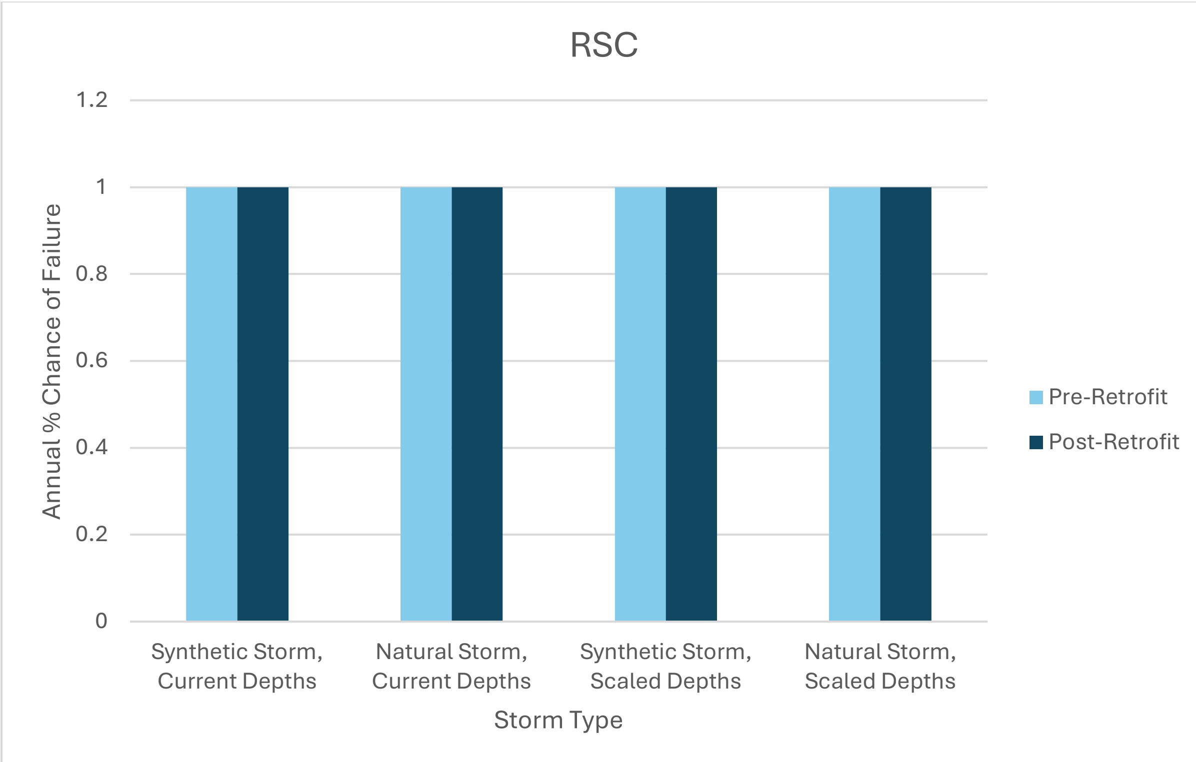

Figure 14. RSC annual percent chance of failure by simulation type

Impact of Storm Distribution

The storm distribution had limited impact on performance in terms of total failure. Compared to the natural distribution, the synthetic storm is a conservative method, as it concentrates the majority of the rainfall to a shorter period. Therefore, it often resulted in failure more quickly during the storm, as compared to the natural distribution. However, storm distribution type had very little impact on the annual percent chance of failure. While the synthetic distributions tended to induce failure sooner within the storm, it rarely changed the return period that ultimately resulted in SCM failure. An important topic of future research is to investigate this difference in failure timing within the same storm and the impacts it could have on downstream flooding and erosion.

Impact of Depths

The Mango Creek BRC was the only SCM to experience consistent increases in failure risk associated with the scaled rainfall depths. The risk of failure at least doubled in each simulation, as compared to the same storm simulation run with current design storm depths. This is consistent with the project hypothesis that as the weather patterns shift, SCMs will be at great risk, because the scaled storms are larger than the current design storms.

Unexpectedly, the Wilmington BRC, DDB, and RSC generally experienced little to no increased risk of failure with scaled rainfall depths, as compared to the current design storm depths. For the DDB and RSC this is likely attributable to their high performance and low risk across all simulations. The Wilmington BRC likely saw no increased risk due to the coarse nature of the return period intervals. If smaller intervals of return periods were investigated, a finer and more complete model of risk could be observed.

Retrofit Effectiveness and Design Implications

Of all the simulation variations, retrofitting the SCM had the most significant impact on failure risk. Apart from the RSC, which was consistently resilient across simulations, the risk of failure for all SCMs in nearly all simulation circumstances decreased substantially with retrofit implementation. Importantly, all retrofits were designed to increase storage volume.

The feasibility of increasing storage volume on both existing infrastructure as well as on new builds is both fiscally and physically limited. Increasing an SCM's surface area, whether during construction or as a retrofit is costly, and increasing the allowable ponding depths is often limited by the ground surface elevation and the seasonal high-water table (such as for the Wilmington BRC). Regardless, maximizing the storage volume to the greatest reasonable extent on any given project makes the practice more resilient to extreme events.

Findings, Conclusions, and Recommendations

The goal of this study was to evaluate the resiliency of various stormwater control measures (SCMs) in North Carolina using PCSWMM modeling. By analyzing four distinct SCM types across different geographic locations, the study aimed to identify the storm characteristics most likely to cause failure, understand the mechanisms behind those failures, and assess how targeted retrofits could improve performance. Despite calibration challenges, the modeling results offer meaningful insights into design improvements and broader planning strategies. The following five points summarize the key findings and implications of this research.

1 **Designing for Extremes Is Essential but Must Be Informed by Local Risk**

The PCSWMM analysis of storm events revealed that traditional SCMs often fail under high-intensity, short-duration storms that exceed their design capacity. This highlights the need for designing stormwater systems with greater storage volumes, higher infiltration rates, and overflow safeguards. However, how much larger they should be depends on localized storm characteristics and watershed constraints.

2 **Financial Trade-Offs Support Proactive Investment in Resilience**

While increasing the size or complexity of SCMs results in higher upfront costs, model simulations suggest that these costs may be justified when weighed against long-term maintenance and damage expenses. Retrofitting during the construction phase, as opposed to repairing after repeated failure, offers financial advantages and prevents service disruptions.

3 **Modeling Identifies Failure Mechanisms Even with Imperfect Calibration**

Despite poor calibration fits across the four sites—due to data limitations, unmodeled complexity, or assumptions about infiltration—PCSWMM simulations still yielded valuable insights. Namely, larger SCMs are more resilient to a wider variety of storms, as evidenced by the retrofitted SCM simulations failing less frequently than those in the as-built simulations.

4 Retrofit Simulations Show Measurable Performance Gains

While the exact performance impacts varied, the trend across models was that design modifications led to reduced surface overflow and improved volume capture, especially during moderate to severe storm events. These retrofits also suggest that robust conveyance of storms larger than that of the design storm can improve a practice's resiliency to extreme events.

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