ABSTRACT

TILLETT, BREANNA. Characterization of Coastal Plain Parking Lot Runoff and Effects of Retrofitting with Infiltrating Stormwater Control Measures. (Under the direction of Dr. William Hunt).

Parking lots are a major component of the urban landscape. As impervious surfaces, they decrease infiltration and evapotranspiration and increase surface runoff. This leads to downstream issues such as stream erosion, flooding, reduced stream base flow, and aquatic health deterioration. Parking lots contribute nutrients, sediment, heavy metals, and polycyclic aromatic hydrocarbons (PAHs) to surrounding surface waters. Stormwater control measures (SCMs) are employed by engineers to capture and treat runoff. Infiltrating SCMs, such as bioretention cells and bioswales, are commonly used to treat parking lot runoff. This study sought to first characterize parking lot runoff in the Coastal Plain of North Carolina, then assess the effect of retrofitting this parking lot with infiltrating SCMs. The asphalt parking lot was built in 1954, is 0.65 ha, and was divided into two sub-catchments. Monitoring for hydrologic and water quality variables occurred February-June 2014 for pre-retrofit and September 2014-December 2015 for post-retrofit. Flow-weighted, composite samples were tested for nitrogen species, phosphorous species, total suspended sediment (TSS), copper (Cu), lead (Pb), zinc (Zn), and PAHs.

Runoff volume and peak discharge from this parking lot, normalized by watershed area, were less than those found by other studies, while the runoff coefficient (ROC) was similar. It appears that the aging parking lot has greater surface storage for runoff than newer parking lots. TSS concentrations (53.8 mg/L) were greater than those of other parking lots apparently due to the ‘leaching’ of sediment from the pavement surface. Cu and Zn concentrations (5 µg/L and 36 µg/L, respectively) were less than concentrations found by

other studies presumably due to low frequency usage of this lot. In general, these and other parking lot pollutant concentrations are lower than highway concentrations.

Multiple linear regression models were used to explain the variation in parking lot hydrology and water quality. Runoff volume, ROC, and peak discharge were best explained by rainfall depth, peak hourly rainfall intensity, and temperature. Pollutant event mean concentrations (EMCs) were negatively correlated with duration, indicating a dilution effect. Pollutant loads are best explained by a combination of rainfall depth, peak hourly rainfall intensity, and temperature. First flush analyses showed that pollutant loads, normalized by runoff depth, were greatest in the first 13 mm of rainfall. In a retrofit situation, smaller SCMs may be utilized to capture this first flush volume.

Ability of the bioretention and bioswale retrofit to capture runoff was analyzed for the full post-retrofit dataset as well as a smaller sub-dataset that matched the season of the pre-retrofit data. The addition of the SCMs in the parking lot decreased the ROC from 0.45 to 0.29. Despite the lack of change in pollutant EMCs, all pollutant loads but nitrate/nitrite and total ammoniacal nitrogen were reduced (48-84%) when the pre-retrofit data was compared to the ‘Like-Season’ data. More than 50% of total phosphorus, TSS, Cu, and Zn event mean concentrations exceeded ambient water quality criteria for freshwater aquatic life.

These results indicate that age and condition of a parking lot have a large impact on parking lot runoff. Older lots contribute more sediment but less metals than newer lots, so retrofit designs should focus on TSS removal in old parking lots.

Characterization of Coastal Plain Parking Lot Runoff and Effects of Retrofitting with Infiltrating Stormwater Control Measures

by
Breanna Tillett

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Biological and Agricultural Engineering

Raleigh, North Carolina

2016

APPROVED BY:

Dr. William Hunt
Committee Chair

Dr. Eban Bean

Dr. Ryan Emanuel

DEDICATION

For the generations who worked these waters before me and all those to come. May there be red skies at night, calm seas, and a plentiful catch.

BIOGRAPHY

Breanna Tillett was born on September 12, 1992 to Darnell and Dawn Tillett of Manteo, North Carolina. Growing up on the Outer Banks of NC instilled a passion for the coastal waters that make the area unique. To this day Bree enjoys nothing more than a day at the beach with a good book. After graduating from high school, Bree attended North Carolina State University where she graduated in 2014 with a Bachelor's degree in Environmental Science. An internship with the NC Coastal Federation during this period introduced her to stormwater best management practices and the work of Dr. William F. Hunt, III at NC State. This led Bree to the pursuit of a Master of Science in Biological and Agricultural Engineering under the direction of Dr. Hunt and the stormwater engineering team. She believes her biological background can improve stormwater practice design to create more natural systems. Bree thoroughly enjoyed her years at NC State and is excited to begin her professional career back on the coast of NC.

ACKNOWLEDGMENTS

I want to sincerely thank all the individuals who have made my graduate career so amazing. First, I would like to offer my gratitude to Dr. Bill Hunt for the opportunity to work for him and the NCSU Stormwater Engineering Group. Your enthusiasm for your work is contagious, and I hope to find that passion in my own career. I would like to thank Dr. Ryan Emanuel for serving on my committee as well as his consistent advice since undergrad. I would also like to thank Dr. Eban Bean for serving on my committee and providing helpful insight. Thank you to Jon Page for providing guidance on monitoring and experimental design; Shawn Kennedy for working in tight spaces and answering all my equipment questions; Jenny James, Linda McKenzie, and Zach Thomas at the North Carolina Center for Applied Aquatic Ecology for performing water quality analyses and accepting samples at a moment's notice. This work was performed in partnership with the Water Resources Research Institute (WRRI). I am beyond thankful to have been funded as a National Science Foundation Graduate Research Fellow.

Next I want to thank all the wonderful people on the Stormwater Team for the laughs, encouragement, and constant support. You guys rock and I will miss you more than you know. Charlie Stillwell and Kevin Koryto, thanks for letting me bombard you with questions and ideas about my research and for being my bros for two years.

Thank you to my parents for all the love and support during my time in Raleigh. Thank you for always being my cheerleaders in all of life's endeavors. To Paul, thank you for being my rock and believing in me when I find it hard to believe in myself.

TABLE OF CONTENTS

LIST OF TABLES viii

LIST OF FIGURES xii

CHAPTER 1: LITERATURE REVIEW OF PARKING LOT STORMWATER MANAGEMENT 1

1.1 Urban Stormwater Impacts 1

1.2 Stormwater Regulations 2

1.3 Parking Lot Runoff 3

1.4 Stormwater Control Measures 7

1.5 Bioretention Cells 7

1.6 Bioswales 14

1.7 SCM Retrofits 17

1.8 References 18

CHAPTER 2: CHARACTERIZATION OF ASPHALT PARKING LOT RUNOFF IN THE COASTAL PLAIN OF NORTH CAROLINA 26

2.1 Abstract 26

2.2 Introduction 27

2.3 Site Description 30

2.4 Materials and Methods 33

Monitoring Scheme 33

Monitoring Challenges 37

Data Analysis 38

Statistical Analyses 40

2.5 Hydrology Results 41

Precipitation 41

Descriptive Statistics 44

Seasonal Variation 46

Correlation 47

Multiple Linear Regression 49

2.6 Water Quality Results 51

Descriptive Statistics 51

Comparison of EMCs 53

Seasonal Variation 56

Correlation 58
Multiple Linear Regression 60
2.7 First Flush Analysis 64
2.8 Summary and Conclusions 67
2.9 References 70
CHAPTER 3: HYDROLOGIC AND WATER QUALITY EFFECTS OF RETROFITTING A PARKING LOT WITH INFILTRATING STORWATER CONTROL MEASURES 75
3.1 Abstract 75
3.2 Introduction 76
3.3 Site Description 78
3.4 Materials and Methods 82
SCM Retrofit 82
Monitoring Scheme 85
Monitoring Challenges 88
Data Analysis 91
Statistical Analysis 92
3.5 Results 93
Precipitation 93
Hydrology 94
Water Quality 98
Load Analysis 103
Ambient Water Quality Comparison 108
Discussion 112
3.6 Summary and Conclusions 114
3.7 References 116
CHAPTER 4: SUMMARY, RECOMMENDATIONS, AND FURTHER RESEARCH 120
4.1 Summary of Studies 120
4.2 Recommendations for Design and Monitoring 121
4.3 Future Research 122
4.4 References 123
APPENDICES 124

Appendix A. Example MLR SAS Code 125
Appendix B. Example Retrofit SAS Code 128
Appendix C. Raw Pollutant Data 131
Appendix D. Photos of Parking Lot 134

LIST OF TABLES

Table 1-1: Summary of average nutrient and TSS concentrations in asphalt parking lot runoff studies in NC, MD, and FL. 5

Table 1-2: Summary of average heavy metal concentrations in asphalt parking lot studies. .. 6

Table 1-3: Summary of TSS and nutrient removal percentages for several bioretention studies. 11

Table 1-4: Summary of metal reduction percentages from several bioretetion studies. 13

Table 1-5: Summary of pollutant removal percentages for several swale studies. 16

Table 2-1: Description of the two sub-watersheds pre-retrofit. 33

Table 2-2: Summary of watershed characteristics and monitoring periods. 34

Table 2-3: Summary of equipment installed for water quality and hydrology monitoring. ... 35

Table 2-4: Laboratory methods and reporting limits for pollutants. 36

Table 2-5: Summary of precipitation during the two monitoring periods. 42

Table 2-6: Summary statistics of total monitored precipitation (n=79). 42

Table 2-7: Descriptive statistics for the seasonal breakdown of hydrologic variables. 43

Table 2-8: Comparison of monitoring period rainfall to 30-year normal rainfall. 44

Table 2-9: Summary hydrologic statistics for the four watersheds. 45

Table 2-10: Summary hydrologic statistics for the study. 46

Table 2-11: Summary hydrological statisticcs for the seasons during the study. 47

Table 2-12:Seasonal variation for the hydrological variables in the study. Seasons with a different letter are significallty different from the others. 47

Table 2-13: Pearson correlation coefficients between the proposed MLR factors. 48

Table 2-14: Pearson correlation coefficients between the log-transformed hydrological variables and MLR factors. 49

Table 2-15: MLR model coefficients for the three hydrologic variables and the associated R^2. 51

Table 2-16: Descriptive statistics of concentrations and loads for the four watersheds during the monitoring period. 52

Table 2-17: Descriptive statistics of concentrations and loads for the full dataset. 53

Table 2-18: Cumulative loads (kg/ha/yr) for the four watersheds and combined loads for the parking lot during the two monitoring periods 53

Table 2-19: Summary of average EMCs from this study and previous parking lot and highway studies. Ambient water quality criteria provided for comparison. 56

Table 2-20: Means and medians of concentrations and loads for seasons. 57

Table 2-21: REGWQ seasonal groupings for pollutant concentrations and loads. Seasons with different letters are significantly different (α=0.10). 58

Table 2-22: Pearson correlation coefficients between predictive factors. 59

Table 2-23: Pearson correlation coefficents between pollutant variables and predictive factors. 60

Table 2-24: MLR coefficients for pollutant EMCs. 62

Table 2-25: MLR coefficients for pollutant loads. 63

Table 3-1: Description of the two sub-watersheds pre-retrofit. 81

Table 3-2: Summary of equipment installed for water quality and hydrology monitoring. 86

Table 3-3: Laboratory methods and reporting limits for pollutants. 87

Table 3-4: Summary of watershed characteristics during the two monitoring periods. 89

Table 3-5: Summary of rainfall during the monitoring periods. 93

Table 3-6: Number of rainfall events per season during monitoring periods. 94

Table 3-7: Summary of hydrologic variables and reductions between the Calibration and Treatment periods. 95

Table 3-8: Summary of statistical analyses on reductions between the Calibration and Treatment periods. *95*

Table 3-9: Summary of hydrologic variables and reductions between the Calibration and Like-Season Treatment data. *96*

Table 3-10: Summary of statistical analyses on reductions between the Calibration and Like-Season periods. *96*

Table 3-11: Summary of rainfall events that were sampled for water quality analysis. *98*

Table 3-12: Breakdown of water quality sampling events per season. *98*

Table 3-13: Mean and median reductions of pollutants between the Calibration and Treatment periods. *99*

Table 3-14: Summary of statistical analyses for the pollutant reductions between the Calibration and Treatment periods. *99*

Table 3-15: Mean and median reductions of pollutants between the Calibration and Like-Season periods. *100*

Table 3-16: Summary of statistical analyses for the pollutant reductions between the Calibration and Like-Season periods. *100*

Table 3-17: Mean and median reductions in pollutant loads between the Calibration and Treatment periods. *104*

Table 3-18: Summary of statistical analyses on pollutant reductions between the Calibration and Treatment periods. *104*

Table 3-19: Mean and median reductions of pollutants between the Calibration and Like-Season periods. *105*

Table 3-20: Summary of statistical analyses on pollutant reductions between the Calibration and Like-Season periods. *105*

Table 3-21: Mean and median concentrations for selected pollutants for the three periods in comparison to water quality thresholds set by various sources. *109*

Table C-1: Raw nitrogen pollutant concentrations for both watersheds. *131*

Table C-2: Raw phosphorous and total suspended sediment concentrations for both watersheds.. 132

Table C-3: Raw metals concentrations for both watersheds.. 133

LIST OF FIGURES

Figure 1-1: Effect of increasing imperviousness on watershed water balance. Modified from Paul and Meyer (2001). *1*

Figure 1-2: Cross-section of a typical bioretention cell with underdrains (Photo credit: Shawn Kennedy, NCSU). *8*

Figure 1-3: Bioswale with concrete check dams and planted with Muhly Grass. *14*

Figure 2-1: Map of North Carolina with ecoregions and project location. *30*

Figure 2-2: NHHS parking lot pre-retrofit. Note large amounts of sediment. *31*

Figure 2-3: An aerial view of the parking lot at NHHS pre-retrofit. The black line delineates the two sub-watersheds within the lot. *32*

Figure 2-4: An aerial view of the parking lot at NHHS post-retrofit. The black line delineates the two sub-watersheds within the lot. Note the extension of the Control Watershed into the Retrofit watershed. *34*

Figure 2-5: (Left) Tipping bucket and manual rain gauges; (Right) Weir box installed within catch basin. *35*

Figure 2-6: (Left) Broken bubbler tubing due to friction from speed bump; (Right) Large amounts of organic litter clogging hidden catch basin. *38*

Figure 2-7: Average nutrient mass per millimeter of runoff over three rainfall intervals (n=44). *65*

Figure 2-8: Average metal mass per millimeter of runoff over three rainfall intervals (n=44). *66*

Figure 2-9: Average TSS mass per millimeter of runoff over three rainfall intervals (n=44). *67*

Figure 3-1: Map of North Carolina with ecoregions and project location. *79*

Figure 3-2: NHHS parking lot pre-retrofit. Note parking lot islands, space between parking stops, and large amounts of sediment. *80*

Figure 3-3: An aerial view of the parking lot at NHHS pre-retrofit. The black line delineates the two sub-watersheds within the lot. *81*

Figure 3-4: This aerial photograph shows the parking lot after SCM establishment with new watershed delineations. Note the linear systems between parking stops................................ 82

Figure 3-5: Phases of construction of the SCMs. Clockwise from Top Left: curb installed and systems dug out; check dams installed in swales with mulch; Muhly Grass planted within swales; resulting system with swales and bioretention areas... 83

Figure 3-6: Post-construction amendments made to the systems as issues arose. (Left) Pipe installed through tree island; (Right) Sand cores installed to promote infiltration in BRC... 84

Figure 3-7: (Left) Tipping bucket and manual rain gauges; (Right) Weir box installed within catch basin. 86

Figure 3-8: Stormwater flows from Retrofit watershed on right, across the swale, and exits to Control watershed on the left... 89

Figure 3-9: (Left) Broken bubbler tubing due to friction from speed bump; (Right) Large amounts of organic litter clogging hidden catch basin. 90

Figure 3-10: Boxplots of the runoff depth for the Calibration, Like-Season, and Treatment periods.. 96

Figure 3-11: Boxplots of runoff coefficient for the Calibration, Like-Season, and Treatment periods.. 97

Figure 3-12: Boxplots of peak discharge for the Calibration, Like-Season, and Treatment periods.. 97

Figure 3-13: Boxplots comparing the distributions of nitrogen species concentrations for the Calibration, Like-Season, and Treatment data.. 101

Figure 3-14: Boxplots comparing the distributions of phosphorous species concentrations for the Calibration, Like-Season, and Treatment data.. 102

Figure 3-15: Boxplots comparing the distributions of heavy metal concentrations for the Calibration, Like-Season, and Treatment data.. 102

Figure 3-16: Boxplot comparing the distributions of TSS concentrations for the Calibration, Like-Season, and Treatment data. 103

Figure 3-17: Boxplots comparing the distributions of nitrogen species loads for the Calibration, Like-Season, and Treatment data.. 106

Figure 3-18: Boxplots comparing the distributions of phosphorous species loads for the Calibration, Like-Season, and Treatment data. 107

Figure 3-19: Boxplots comparing the distributions of heavy metal loads for the Calibration, Like-Season, and Treatment data. 107

Figure 3-20: Boxplot comparing the distribution of TSS loads for the Calibration, Like-Season, and Treatment data. 108

Figure 3-21: Cumulative probability plot of TP concentrations for the Calibration, Treatment, and Like-Season data in relation to the TP water quality threshold of 0.09 mg/L (McNett et al., 2010). 110

Figure 3-22: Cumulative probability plot of TSS concentrations for the Calibration, Treatment, and Like-Season data in relation to the TSS water quality threshold of 20 mg/L (NCDEQ, 2016). 110

Figure 3-23: Cumulative probability plot of Cu concentrations for the Calibration, Treatment, and Like-Season data in relation to the Cu water quality threshold of 3.6 µg/L (NCDDEQ, 2016). 111

Figure 3-24: Cumulative probability plot of Pb concentrations for the Calibration, Treatment, and Like-Season data in relation to the Pb water quality threshold of 14 µg/L (NCDEQ, 2016). 111

Figure 3-25: Cumulative probability plot of Zn concentrations for the Calibration, Treatment, and Like-Season data in relation to the Zn water quality threshold of 36 µg/L (NCDEQ, 2016). 112

Figure D-1: Clockwise from Top Left 1) Erosional features near Retrofit watershed catch basin 2) Cracks and sediment accumulation in the Control watershed 3&4) Surface runoff storage in Control watershed 134

Figure D-2: Left: Surface storage and channelization of flow in Retrofit watershed Right: Accumulation of sediment in bioswale 135

CHAPTER 1: LITERATURE REVIEW OF PARKING LOT STORMWATER MANAGEMENT

1.1 Urban Stormwater Impacts

Urbanization leads to the conversion of large tracts of natural areas into impervious cover. This changes the hydrology of a watershed, potentially harming the receiving aquatic environment. In a natural watershed, infiltration and evapotranspiration play the major roles in the water balance (Paul & Meyer, 2001). Impervious surfaces such as buildings, roads, and parking lots decrease infiltration and evapotranspiration, increasing the portion of rainfall that becomes runoff (Paul & Meyer, 2001, Figure 1-1). This leads to a multitude of issues downstream: reduced groundwater recharge and stream baseflow (DeBusk et al., 2011; Line & White, 2007; Paul & Meyer, 2001), stream incision and erosion (Bledsoe & Watson, 2001), downstream flooding (Jennings & Jarnagin, 2002; Line & White, 2007; Leopold, 1968), and deteriorating aquatic ecosystems (Walsh et al., 2001).

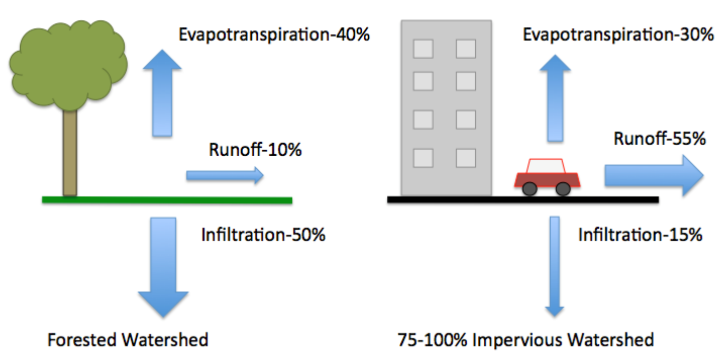


Figure 1-1: Effect of increasing imperviousness on watershed water balance. Modified from Paul and Meyer (2001).

Impervious surfaces accumulate pollutants that are then swept away with runoff in what is known as the ‘first flush’ (Lee et al., 2002; National Research Council, 2008). Line and White (2007) showed that development leads to greater export of pollutants including sediment, nutrients, heavy metals, oils and grease, and pathogens (Bannerman et al., 1993; Line & White, 2007). The accumulation of these pollutants leads to eutrophication, fish kills, and human health risks.

1.2 Stormwater Regulations

The first U.S. federal water quality regulation was the Federal Water Pollution Control Act of 1948. In 1972 the legislation was amended to become the Clean Water Act (CWA), which set forth guidelines for the protection of the nation’s waters (US EPA, 2015a). The CWA initially targeted point sources of pollution such as industry and water treatment plants utilizing National Pollutant Discharge Elimination System (NPDES) permitting. By 1990, stormwater and other nonpoint sources of water pollution were acknowledged as an issue to the environment and the EPA stormwater program began. Phase 1 of the NPDES Stormwater Program, enacted in 1990, regulates municipalities with populations greater than 100,000 with municipal separate storm sewer systems (MS4s). Phase 2, passed in 1995, increased the reach of the system to smaller MS4 communities (National Research Council, 2008). These entities are required to develop a stormwater management plan that documents efforts being made to reduce stormwater leaving jurisdictional boundaries.

Within North Carolina, the Department of Environmental Quality (NCDEQ) is required to uphold the CWA and administer permits for the NPDES. Critical watersheds such as those in coastal areas, Falls Lake reservoir, and the Neuse River Basin, have more stringent stormwater regulations on new development, often focusing on nutrient management or pathogen sequestration (NCDEQ, 2016b).

1.3 Parking Lot Runoff

Roads and parking lots constitute 70-80% of impervious coverage in urban areas, and are assumed to produce similar stormwater runoff (National Research Council, 2008). Traditionally, parking lot stormwater "management" has been to quickly remove water by channelizing flow to prevent ponding, thereby increasing flow rates of water leaving the site. Parking lots are typically directly connected impervious area (DCIA), which is a better indicator of stormwater impacts than total impervious area (Lee & Heaney, 2003).

Organic and inorganic particulates such as sediment, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), pathogens, and gross solids accumulate on parking lot surfaces. The main sources of these pollutants include atmospheric deposition, vehicular traffic, and organic litter (Bannerman et al., 1993; Brinkmann, 1985; Passeport & Hunt, 2009; Pitt et al., 1995). The export of particulates during a rainfall event is dependent on storm characteristics such as antecedent dry period, rainfall intensity, and duration as well as parking lot characteristics (Pitt et al., 1995; Sartor et al., 1974). Pavement type and pavement condition influences pollutant loading in parking lot runoff (Drapper et al., 2000; Hope et al., 2004; Rushton, 2001). Pavement in poor condition will export more solids than a newly paved site (Hope et al., 2004). Fine particulates are highly associated with pollutants and more readily exported during a storm (Sartor et al., 1974).

Nutrients, including organic and inorganic forms of nitrogen (N) and phosphorous (P), are found in parking lot stormwater (Hope et al., 2004; Knight et al., 2013; Line & White, 2007; Passeport & Hunt, 2009). The most common sources are atmospheric deposition, organic material, animal waste, and fertilizer (Brinkmann, 1985; Davis et al., 2006). Nitrate/nitrite (NO_x-N) and orthophosphate (O-PO_4^{3-}), dissolved components of N and P, respectively, are of particular concern because they can lead to algal blooms and eutrophication in the downstream environment (National Resource Council, 2008). Parking lots often integrate landscaped areas, such as a tree island, which may contribute nutrients through organic litter or washed-off fertilizer (Pitt et al., 1995). Total phosphorous (TP) loads from parking lots have been shown to be similar to those of roads and highways, with total nitrogen (TN) loads are slightly lower (Passeport & Hunt, 2009).

Nutrient concentrations leaving a parking lot vary greatly (Table 1-1). TN concentrations from these lots range 0.55-1.68 mg/L. Atmospheric deposition was the leading source of nitrogen for these sites, so climatic variation may play a large role in nitrogen loading. The cause of TP concentration variation (0.05-0.41 mg/L) is more difficult to discern. Passeport and Hunt (2009) found that TP concentrations were correlated with watershed size and percent natural area within the watershed. Phosphorous is often particulate-bound, so TP concentrations may be related to TSS concentrations (Li & Davis, 2015). TSS concentrations (11-66 mg/L) may vary due to parking lot conditions or surrounding landscaping (Rushton, 2001).

Table 1-1: Summary of average nutrient and TSS concentrations in asphalt parking lot runoff studies in NC, MD, and FL.

Study	Site	Pollutant Concentration (mg/L)							
		TSS	NO_x-N	TAN	TKN	TN	ON	TP	$O\text{-}PO_4^{3-}$
Brown et al. (2012)	NC (CP)	28.8	0.18	0.17	0.49	0.67	0.32	0.05	<RL
Knight et al. (2013)*	NC (CP)	33	0.18	0.16	0.98	1.21	0.83	0.14	0.06
Li & Davis (2009) CP*	MD (CP)	66	0.36	-	1.20	1.6	-	0.10	-
Li & Davis (2009) SS*	MD (CP)	17	0.34	-	0.50	1.0	-	<RL	-
Passeport & Hunt (2009)+	NC (CP,P)	-	0.36	0.32	1.24	1.63	-	0.21	0.07
Rushton (2001) F1	FL (CP)	11.2	0.27	0.13	-	0.56	-	0.11	0.04
Rushton (2001) F2	FL (CP)	13.5	0.28	0.12	-	0.55	-	0.11	0.06
Mean		28.2	0.28	0.18	0.88	1.03	0.58	0.12	0.06
Median		22.9	0.31	0.16	0.98	1.11	0.58	0.11	0.06

*Median concentrations used +Average of six different sites in NC RL=Reporting Limit
CP=Coastal Plain P=Piedmont

Heavy metal accumulation is a major issue within parking lots due to vehicular presence. Copper (Cu) and zinc (Zn) originate from brakes and tires as well as atmospheric deposition (Grebel et al., 2013; Pitt & Bannerman, 2005). Studies of asphalt parking lots (Table 1-2) found Cu concentrations ranging 3.5-19 µg/L, which are generally greater than US EPA limits for aquatic biota health (3.6 µg/L) (NCDEQ, 2016a). A wide range of Zn concentrations were reported by these studies (15-72 µg/L). Zn concentration variation has been attributed to differences in average daily traffic in watersheds (Drapper et al., 2000). Lead (Pb) is associated with vehicle exhaust deposition (Brinkmann, 1985; Davis et al., 2001). Pb concentrations in the parking lot studies were similar (4-6 µg/L), well below acute toxicity levels for NC (NCDEQ, 2016a). Asphalt pavement produces greater Cu and Zn concentrations than concrete surfaces (Murphy et al., 2015). Additionally, building siding and roofs surrounding the parking lot may contribute some heavy metals (Davis et al., 2001; Pitt et al., 1995). Heavy metals are normally bound to particles (LeFevre et al., 2015). Toxicity due to the accumulation of metal-rich sediment can impact aquatic life (Grebel et al., 2013). Ingesting water with high Pb concentrations can be detrimental to human health (US EPA, 2015b).

Table 1-2: Summary of average heavy metal concentrations in asphalt parking lot studies.

Study	Site	Pollutant Concentration (μg/L)		
		Cu	Pb	Zn
Hunt et al. (2008)	NC (P)	12.8	4.85	72
Knight et al. (2013)	NC (CP)	3.5	-	72
Li & Davis (2009) CP*	MD (CP)	19	6	71
Li & Davis (2009) SS*	MD (CP)	13	<RL	15
Rushton (2001) F1	FL (CP)	10.64	4.00	45.7
Rushton (2001) F2	FL (CP)	9.99	4.20	43.8
Mean		11.5	4.7	53.3
Median		11.7	4.4	58.4
NC WQ Standard+		3.6	14	36

*Median concentrations +Freshwater acute toxicity concentrations (NCDEQ, 2016a) RL=Reporting Limit
CP=Coastal Plain P=Piedmont

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds found in many vehicular by-products such as oil/grease, tire particles, and exhaust (Davis, 2005; Ngabe et al., 2000; Pitt et al., 1995). Additionally, the sealcoat used in many asphalt parking lots can contribute PAHs to runoff as it erodes (Mahler et al., 2005). Coal-tar sealant is used primarily in the eastern US, and several aquatic species show acute toxicity to PAHs from degrading coal-tar sealant (McIntyre et al., 2016). James et al. (2010) found that PAH concentrations in stormwater runoff ranged 5 to 277 mg/L. Fluoranthene and pyrene, heavy PAHs, are known to occur in stormwater runoff, and are associated with toxicant effects in aquatic sediments

(James et al., 2010). Like heavy metals, PAHs accumulate in stream and reservoir sediment and become toxic to aquatic life over time (Ngabe et al., 2000).

1.4 Stormwater Control Measures

Low Impact Development (LID) is a land management strategy that seeks to mimic pre-development hydrology and water quality (Ahiablame et al., 2012; Coffman et al., 1999; Davis, 2005). Stormwater Control Measures (SCMs) are part of this design approach. The main goal of an SCM is to capture and treat runoff leaving a site. SCMs can employ ecological elements, potentially providing an aesthetic benefit as well (Moore & Hunt, 2012). SCMs utilize detention, filtration, evapotranspiration (ET), infiltration, and microbiological processes to remove pollutants from runoff (Ahiablame et al., 2012; Grebel et al., 2013; National Research Council, 2008). Primary examples of SCMs include: bioretention, grass lined swales, wet ponds, constructed wetlands, permeable pavement, and green roofs. SCMs may be required as part of an NPDES stormwater permit. North Carolina and other states have produced manuals for the design of these structures (NCDEQ, 2009; MDE, 2009).

1.5 Bioretention Cells

Bioretention cells (BRCs) are engineered shallow depressions in the landscape designed to temporarily pool, then filter runoff. They consist of a vegetated surface, engineered soil media, and may include underdrains to the storm sewer network (Figure 1-2). Hunt et al. (2012) laid out several design guidelines based on current research. BRCs can be grassed or planted with drought resistant trees and shrubs. Healthy, mature plants are required in BRCs for pollutant treatment (Lucas & Greenway, 2009). Due to the dependence on vegetation, BRCs are more successful during warm, dry months when ET is at its peak (Braga et al., 2007; Emerson & Traver, 2008; Hunt et al., 2006). A 5-10 cm mulch layer overlaying 0.9 m of media will encourage nutrient, metals, and PAH removal (Brown & Hunt, 2011b; Dietz & Clausen, 2006; Hong et al., 2006; Hunt et al., 2012). Engineered media is recommended to maintain low P-index, 8-12% fine material, and low organic matter content to reduce nutrient leaching (Hunt et al., 2012; Hunt et al., 2006; Li & Davis, 2014). Underdrains may be needed if underlying soils are impermeable, but are not a requirement. The addition of an Internal Water Storage (IWS) zone is also recommended to enhance infiltration and create anoxic conditions for nutrient transformation (Brown & Hunt, 2011a; Kim et al., 2003; Passeport et al., 2009)

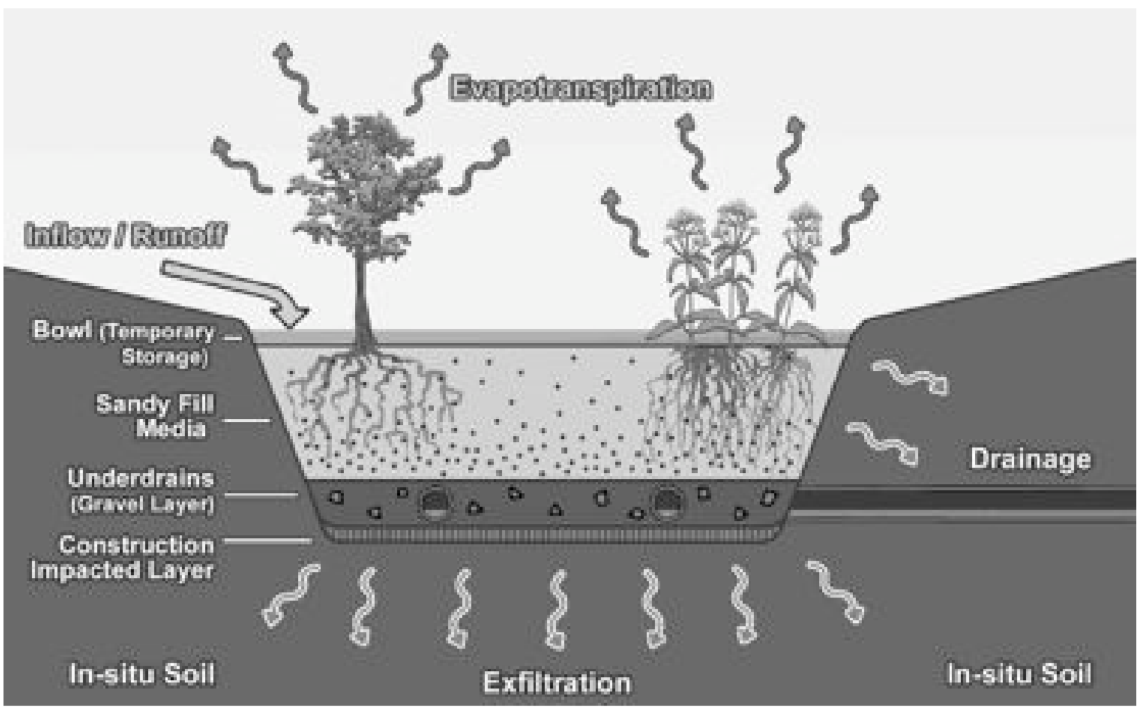


Figure 1-2: Cross-section of a typical bioretention cell with underdrains (Image credit: Shawn Kennedy, NCSU).

BRC hydrologic performance is dependent upon rainfall and cell design (Davis et al., 2012). Peak flow attenuation and delay has been recorded for many cells (Davis, 2008; Davis et al., 2012; Hatt et al., 2009; Hunt et al., 2006; Li et al., 2009), with reductions as high as 99% for storms under 42 mm (Hunt et al., 2008). Additionally, runoff volumes are reduced with evidence of complete elimination for small storms (Davis, 2008; Hatt et al., 2009; Hunt et al., 2006; Li et al., 2009). Cells with deeper media and greater surface area perform better at reducing peak flows and runoff volumes (Brown & Hunt, 2011b; Davis et al., 2012; Li et al., 2009). One means of assessing hydrologic treatment provided by BRCs, the Bioretention Abstraction Volume (BAV), is the combination of bowl volume and media pore space that stores runoff without discharge to surface waters (Davis et al., 2012; Hunt et al., 2012).

Previous studies show variable nutrient removal efficiencies by BRCs (Table 1-3). In fact, most mass removal can be attributed to runoff volume reduction rather than a significant change in concentration (Li & Davis, 2009). It may be ideal to perform several evaluation metrics to determine the effect of a BRC or any SCM (Lenhart & Hunt, 2011). Table 1-3 presents concentration and load reductions. Nitrogen (N) retention is dependent upon speciation within runoff as well as media composition, depth, and moisture condition (Brown & Hunt, 2011b; Hunt et al., 2012; LeFevre et al., 2015; Li & Davis, 2014). Dissolved N forms include nitrate (NO_3^-), nitrite (NO_2^{2-}), ammonia (NH_3), ammonium (NH_4^+), and organic N (ON). ON may also be found in particulate form. While particle-bound N is easily captured through filtration and sedimentation, dissolved N removal utilizes adsorption, precipitation, ion exchange, and biological processes (LeFevre et al., 2015; Li & Davis, 2014). Influent ON and NH_4^+ are aerobically converted to NO_3^- through ammonification and nitrification between storms, contributing to reductions in total Kjedahl N (TKN) (Davis et al., 2006; LeFevre et al., 2015; Li & Davis, 2014). NO_x-N has proven difficult to retain in BRCs due to leaching and lack of saturation for anaerobic transformation (Dietz & Clausen, 2006). An IWS will increase residence time and potentially create an anaerobic zone that allows for denitrification (Kim et al., 2003; Passeport et al., 2009). Dissolved ON represents a significant portion of leached N from BRCs and can affect the TN removal rates, therefore media should have low organic matter content when nutrients are targeted (Hunt et al., 2012; LeFevre et al., 2015; Li & Davis, 2014). While plant uptake does play an important role for removal of dissolved N (Lucas & Greenway 2009), plant decay can re-release N to the system (Davis et al., 2006; Li & Davis, 2009).

Influent phosphorous (P) is found in dissolved (organic P and orthophosphate) and particulate-bound forms. Particle-bound P is removed in conjunction with TSS through filtration and sedimentation (Li & Davis, 2015). Dissolved P reductions are reliant upon chemical adsorption and some vegetative uptake (Grebel et al., 2013; Hunt et al., 2012; LeFevre et al., 2015; Li & Davis, 2015). Orthophosphate adsorbs to iron and aluminum oxides within the media in fast, reversible processes during events as well as slower, less reversible processes between events (LeFevre et al., 2015; Li & Davis, 2015). Media composition is extremely important for P removal; media with a low P-index, a measure of P content in soil, and higher cation exchange capacity will sequester more P (Hunt et al., 2006; LeFevre et al., 2015; Li & Davis, 2015). Deeper media (Brown & Hunt, 2011b), amended with a Fe/Al source is recommended for greatest P removal (Hunt et al., 2012; LeFevre et al., 2015; Li & Davis, 2015). When the proper media is utilized, BRCs can remove P from runoff (Hatt et al., 2009; Hunt et al., 2008; Table 1-3)

BRCs remove TSS from stormwater runoff (Table 1-3) via filtration and sedimentation. This potentially leads to clogging (Fears, 2014); but proper maintenance should sustain function (Hunt & Lord, 2006). Reduction of suspended solids is correlated with reduction of other constituents such as phosphorous, certain metals, and PAHs (DiBlasi et al., 2009; LeFevre et al., 2015).

Table 1-3: Summary of TSS and nutrient removal percentages for several bioretention studies.

Study	ID	Pollutant Removal (%)						
		TSS	NO_x-N	TAN	TKN	TN	TP	O-PO_4^{3-}
Brown & Hunt (2011)[1]	0.6m	71	-81	78	39	12	5	-37
	0.9m	84	-142	79	58	13	44	-5
Chapman & Hormer (2010)[1]	A	87	-	-	-	63	67	-44
	B	93	-	-	-	82	83	28
Dietz & Clausen (2006)[1]	RG1	-	36	84	29	31	-104	-
	RG2	-	36	86	34	34	-117	-
Hatt et al. (2009)[2]	Mon	76	-13	64	-	-7	-398	-1271
	McD	93	-17	96	-	37	86	81
Hunt et al. (2006)[1]	G2	-	75	-1	-5	40	-240	-9
	C1	-	13	86	45	40	65	69
Hunt et al. (2008)[2]	HM	60	-5	72	44	32	31	-
Li & Davis (2009)[2]	CP	88	-170	-	-11	-53	-200	-
	SS	88	86	-	-80	-10	0	-
Mean[1]		84	-11	69	33	39	-25	0
Median[1]		86	25	82	37	37	25	-7
Mean[2]		81	-24	77	-16	0	-96	-595
Median[2]		88	-13	72	-11	-7	0	-595

1-Calculated using mass loading
2-Calculated using concentrations

Significant heavy metal removal, especially for copper (Cu), lead (Pb), and zinc (Zn), is well documented for bioretention cells. Pb is more commonly found attached to soil particles than Cu and Zn; therefore, its removal heavily relates to that of TSS (Li & Davis, 2009).

Dietz and Clausen (2006) found that a surface mulch layer will accumulate metals. Copper and zinc often exist in aqueous solution as positively charged cations, and are removed by sorption to soil particles, normally within the first 45 cm of media (Grebel et al., 2013; Hatt et al., 2009). Metals cations, Cu in particular, have a high affinity for organic matter (LeFevre et al., 2015). Precipitation from aqueous form will also immobilize metals at the pH commonly found for stormwater (6-8) (LeFevre et al., 2015). Plant uptake plays a small role in metals removal, however Cu is an important nutrient in plant leaves for photosynthesis, so its uptake may be accelerated by vegetation (Grebel et al., 2013; LeFevre et al., 2015). Core samples of bioretention media indicate that adsorption is successful below the surface and dissolved metals are captured (Jones & Davis, 2013; Li & Davis, 2008). Jones and Davis (2013) found that a hotspot of metal accumulation exists at the inlet of BRCs, and any maintenance should focus on this point. A submerged anoxic zone prevents metals from mobilizing (Blecken et al., 2009).

Table 1-4: Summary of metal reduction percentages from several bioretetion studies.

Study	ID	Pollutant Reduction* (%) Cu	Pb	Zn
Chapman & Hormer (2010)[1]	A	58	-	72
	B	79	-	86
Davis et al. (2003)[2]	Green	97	95	95
	Largo	43	70	64
Hatt et al. (2009)[2]	Mon	67	80	84
	McD	98	98	99
Hunt et al. (2006)[1]	G2	99	81	98
Hunt et al. (2008)[2]	HM	54	31	77
Li & Davis (2009)[2]	CP	31	55	78
	SS	0	0	80
Mean[1]		79	81	85
Median[1]		79	81	86
Mean[2]		56	61	82
Median[2]		54	70	80

1-Calculated using mass loading
2-Calculated using concentrations
*Total Metals

PAHs can be found in stormwater with a large range of molecular weights. Generally, heavier PAHs (fluoranthene and pyrene) are more hydrophobic and particulate-bound (James et al., 2010; LeFevre et al., 2015). Heavier PAHs are pyrogenic compounds originating from combustion, and may be the greater concern in parking lots due to vehicular usage (David et al., 2014). BRCs are highly capable of reducing the PAH load of stormwater and reduction is associated with TSS removal within a cell (DiBlasi et al., 2009; Hong et al., 2006; LeFevre et al., 2015). Sorption is the main removal mechanism of dissolved PAHs during filtration (LeFevre et al., 2015). Additionally, hydrophobic PAHs will partition into the hydrophobic portions of organic matter (Grebel et al., 2013; Hunt et al., 2012). David et al. (2014) found that ratio of light to heavy PAHs in effluent increased after treatment by a BRC, indicating that the cell was less capable of removing lighter aqueous species.

1.6 Bioswales

Bioswales are another SCM that can be used within a parking lot. A bioswale combines the concepts of bioretention and vegetated swales to increase pollutant reduction. A bioswale is a vegetated linear depression in the landscape, with an underlying engineered media, that is designed to convey and partially filter stormwater (Figure 1-3). Swales and bioswales replace traditional curb and gutter systems. Bioswales may be designed with check dams to promote infiltration before water leaves the system (Davis et al., 2012; Stagge et al., 2012; Yu et al., 2001). If in-situ soils have low hydraulic conductivity, an underdrain may be installed at the bottom (NRCS, 2005). While traditional swales are grass-lined, bioswales may be planted with deep-rooted native vegetation (NRCS, 2005).

Figure 1-3: Bioswale with concrete check dams and planted with Muhly Grass.

While grassed swales are designed to slow flow velocity, they do not treat water quality as well as other practices due to a lack of necessary pollutant removal mechanisms (NCDEQ, 2009). Bioswales have not been studied to the extent of BRCs or grassed swales, but runoff treatment is expected to be similar to or exceed treatment by conveyance swales (Xiao & Mcpherson, 2011). Grassed swales have been shown to reduce total runoff volume from parking lots and roadways for small storms (<30 mm) (Bäckström, 2002; Barrett, 2005; Davis et al., 2012). Volume reduction is due to infiltration during conveyance of runoff. Grass blades act as barriers to flow when flow is below the height of grass (Bäckström, 2003; Barrett et al., 1998). For this reason grass within swales should be kept higher relative to that of landscaped areas.

Grassed swales have variable effects on pollutant concentrations in stormwater runoff (Table 1-5). Sedimentation and straining due to vegetation is the primary pollutant removal mechanism within swales, therefore TSS reductions have been recorded (Barrett et al., 1998; Knight et al., 2013; Stagge et al., 2012). Sedimentation increases with the length of the swale, with larger particles falling out first and particle size decreasing along the length (Bäckström, 2002; Deletic, 2005). Additionally, higher infiltration rates increase particle trapping (Bäckström, 2002).

Nutrient treatment by grassed swales is variable, with exports recorded during some studies. Nutrient removal utilizes sedimentation, filtration, and requires infiltration for transformation of dissolved forms. P reduction depends on the particle size the solid is bound too, as well as underlying soils' adsorption potential (Bäckström, 2002; Deletic & Fletcher, 2006). Nitrogen, primarily found in dissolved form, requires a higher hydraulic residence time for improved infiltration to mediate biological transformation (Deletic & Fletcher, 2006). The addition of check dams increases infiltration and contact time with soil (Davis et al., 2012; Yu et al., 2001). Stagge et al. (2012) found check dams improved swale performance for nitrate removal.

Reductions in sediment-bound pollutants are expected from grassed swales including charged metallic ions like Cu, Pb, and Zn. Dissolved forms of these metals require infiltration for adsorption to take place. Zn shows greatest removal potential in grassed swales, but this may be due to high influent concentrations (Stagge et al., 2012). Cu has high affinity for colloidal fractions, so it can be exported from a swale if attached to organic material or colloids (Bäckström, 2003). Metals are generally adsorbed to the smaller particle fraction, so reductions are reliant on sediment particle size removal (Zanders, 2005).

Table 1-5: Summary of pollutant removal percentages for several swale studies.

Study	ID	Pollutant Removal (%)					
		TSS	TN	TP	Cu	Pb	Zn
Barrett et al. (1998)[1]	US183	87	-	44	-	41	91
	MoPac	85	-	34	-	17	75
Knight et al. (2013)[1]	Swale	81	24	-21	-147	-	72
Stagge et al. (2012)[2*]	No-FS	44	-6	-28	42	37	53
	No-FS-CD	83	77	15	75	62	88
Yousef et al. (1987)[1]	Maitland	-	11	25	17	0	86
	EPCOT	-	-7	3	8	57	62
Yu et al. (2001)[2+]	TC	48	20	50	-	-	-
	TD	67	14	29	-	-	-
Mean[1]		84	9	17	-41	29	77
Median[1]		85	11	25	8	29	75
Mean[2]		61	26	17	59	50	71
Median[2]		58	17	22	59	50	71

1: Calculated using concentrations 2: Calculated using mass loading
*Study compares swales with and without check dams
+Study varies flow rates

Bioswales utilize engineered media to increase the reductions in TN, TP, and dissolved species as described in section 1.5. Bioswales have not been studied to the extent of vegetated swales, however one study reported reductions in nutrients, metals, and TSS of 95%, 87%, and 95% respectively, which exceed typical conveyance swale performance from Table 1-5 (Xiao & Mcpherson, 2011). The engineered soil media and tree system allowed for greater treatment of runoff volumes.

1.7 SCM Retrofits

To conform to pollutant loading reduction requirements in certain watersheds in NC (NCDEQ, 2016b), retrofitting already developed land may be necessary. Roadsides, medians, and parking lots offer an opportunity for retrofitting with SCMs, including utilizing existing pervious area without impacting traffic flow. Right-of-way LID retrofits have been shown to improve watershed-scale stormwater runoff quality (Page et al., 2015).

To integrate treatment systems in a parking lot or the right-of-way, design criteria may need to be relaxed. Infiltrating SCMs such as bioretention and bioswales may need "undersized" surface areas. Several studies have examined undersized bioretention cell efficiency. Luell et al. (2011) directly compared a 50% undersized BRC to a regulation-sized BRC which were both treating highway bridge deck runoff. The smaller BRC load reductions were 60-90% of those achieved by the larger BRC. Brown and Hunt (2011b) examined pollutant removal and hydrologic function of two undersized BRCs. While the cells could not store a full design storm, they still significantly removed TSS and most nutrient species (Table 1-3). Line et al. (2012) found that a site in the Piedmont of NC with poorly constructed SCMs that did not meet state regulations had better water quality than a site with no treatment.

This study evaluates (1) runoff water quality from a deteriorating asphalt parking lot in the NC Coastal Plain and (2) the impact of an undersized infiltrating SCM retrofit on this parking lot's hydrology and water quality.

1.8 References

Ahiablame, L. M., Engel, B., & Chaubey, I. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. *Water, Air, & Soil Pollution, 223*(7), 4253–4273.

Bäckström, M. (2002). Sediment transport in grassed swales during simulated runoff events. *Water Science and Technology, 45*(7), 41–49.

Bäckström, M. (2003). Grassed swales for stormwater pollution control during rain and snowmelt. *Water Science and Technology, 48*(9), 123–132.

Bannerman, R., Owens, D., Dodds, R., & Homewer, N. (1993). Sources of Pollutants in Wisconsin Stormwater. *Water Science and Technology, 28*(3-5), 241–259.

Barrett, M. E. (2005). Performance Comparison of Structural Stormwater Best Management Practices. *Water Environment Research, 77*(1), 78–86.

Barrett, M. E., Walsh, P. M., Malina, J. F., & Charbeneau, R. J. (1998). Performance of Vegetative Controls for Treating Highway Runoff. *Journal of Environmental Engineering, 124*(11), 1121–1128.

Blecken, G. T., Zinger, Y., Deletic, A., Fletcher, T. D., & Viklander, M. (2009). Impact of a submerged zone and a carbon source on heavy metal removal in stormwater biofilters. *Ecological Engineering, 35*(5), 769–778.

Bledsoe, B. P. (2002). Stream Erosion Potential and Stormwater Management Strategies. *Journal of Water Resources Planning and Management, 128*(6), 451–455.

Bledsoe, B. P., & Watson, C. C. (2001). Effects of urbanization on channel instability. *Journal of the American Water Resources Association, 37*(2), 255–270.

Braga, A., Horst, M., & Traver, R. (2007). Temperature Effects on the Infiltration Rate through an Infiltration Basin BMP. *Journal of Irrigation and Drainage Engineering, 133*, 593–601.

Brinkmann, W. (1985). Urban Stormwater Pollutants: Sources and Loadings. *GeoJournal, 11*(3), 277–283.

Brown, R., & Hunt, W. F. (2011a). Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads. *Journal of Environmental Engineering, 137*(11), 1082–1091.

Brown, R., Line, D. E., & Hunt, W. F. (2012). LID Treatment Train: Pervious Concrete with Subsurface Storage in Series with Bioretention and Care with Seasonal High Water Tables. *Journal of Environmental Engineering, 138*(6), 689–697.

Brown, R., & Hunt, W. (2011b). Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. *Journal of Irrigation and Drainage Engineering, 137*, 132–143.

Chapman, C. & Horner, R. (2010). Performance Assessment of a Street-Drainage Bioretention System. *Water Environment Research, 82*(2), 109-119.

Coffman, L., Goo, R., & Frederick, R. (1999). Low-Impact Development An Innovative Alternative Approach to Stormwater Management. In Water Resources Planning and Management Conference (pp. 1–10).

David, N., Leatherbarrow, J. E., Yee, D., & McKee, L. J. (2014). Removal Efficiencies of a Bioretention System for Trace Metals, PCBs, PAHs, and Dioxins in a Semiarid Environment. *Journal of Environmental Engineering, 141*(6), 4014092.

Davis, A. (2005). Green Engineering Principles Promote Low-Impact Development. *Environmental Science & Technology, 6*(8), 338A–344A.

Davis, A. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering, 13*(2), 90–95.

Davis, A., Shokouhian, M., Ni, S. (2001). Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere, 44*, 997-1009.

Davis, A. P., Stagge, J. H., Jamil, E., & Kim, H. (2012). Hydraulic performance of grass swales for managing highway runoff. *Water Research, 46*(20), 6775–6786.

Davis, A. P., Traver, R. G., Hunt, W. F., Lee, R., Brown, R. A., & Olszewski, J. M. (2012). Hydrologic Performance of Bioretention Storm-Water Control Measures. *Journal of Hydrologic Engineering*, *17*(5), 604–614.

Davis, A., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water Quality Improvement through Bioretention Media : Nitrogen and Phosphorus Removal. *Water Environment Research*, *78*(3), 284–293.

Davis, A., Shokouhian, M., Sharma, H., Minami, C., & Winogradoff, D. (2003). Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal. *Water Environment Research*, *75*(1), 73–82.

DeBusk, K. M., Hunt, W. F., & Line, D. E. (2011). Bioretention Outflow : Does It Mimic Nonurban Watershed Shallow Interflow? *Journal of Hydrologic Engineering*, *16*, 274–279.

Deletic, A. (2005). Sediment transport in urban runoff over grassed areas. *Journal of Hydrology*, *301*(1-4), 108–122.

Deletic, A., & Fletcher, T. D. (2006). Performance of grass filters used for stormwater treatment - A field and modelling study. *Journal of Hydrology*, *317*(3-4), 261–275.

DiBlasi, C., Li, H., Davis, A., & Ghosh, U. (2009). Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility. *Environmental Science & Technology*, *43*(2), 494–502.

Dietz, M., & Clausen, J. (2005). A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air, and Soil Pollution*, *167*(1-4), 123–138.

Dietz, M., & Clausen, J. (2006). Saturation to Improve Pollutant Retention in a Rain Garden. *Environmental Science & Technology*, *40*(4), 1335–1340.

Drapper, D., Tomlinson, R., & Williams, P. (2000). Pollutant Concentrations in Road Runoff: Southeast Queensland Case Study. *Journal of Environmental Engineering*, *126*(4), 313–320.

Emerson, C., & Traver, R. (2008). Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices. *Journal of Irrigation and Drainage Engineering*, *134*(5), 598–605.

Fears, J. (2014). Evaluating Water Quality and Hydrologic Performance of a Poorly Draining Bioretention Cell at a Military Installation in North Carolina. MS Thesis. Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina.

Grebel, J., Mohanty, S., Torkelson, A., Boehm, A., Higgins, C., Maxwell, R., Sedlak, D. (2013). Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environmental Engineering Science*, *30*(8), 437–454.

Hatt, B., Fletcher, T., & Deletic, A. (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology*, *365*(3-4), 310–321.

Hong, E., Seagren, E. a, & Davis, A. P. (2006). Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. Water Environment Research : A Research Publication of the Water Environment Federation, 78(2), 141–155.

Hope, D., Naegeli, M. W., Chan, A. H., & Grimm, N. B. (2004). Nutrients on asphalt parking surfaces in an urban environment. *Water, Air, and Soil Pollution: Focus*, *4*(2-3), 371–390.

Hunt, W. F., Davis, A. P., & Traver, R. G. (2012). Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *Journal of Environmental Engineering*, *138*(6), 698–707.

Hunt, W., James, A., Smith, J., & Sharkey, L. (2006). Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, *132*(6), 600–608.

Hunt, W. & Lord, W. (2006). Bioretention Performance, Design, Construction, and Maintenance. NC Cooperative Extension, Raleigh, NC.

Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *Journal of Environmental Engineering*, *134*(5), 403–408.

James, R. R., Wilbon, P., & Divincenzo, J. P. (2010). Pervious and impervious urban stormwater runoff in a rapidly urbanizing region: Occurrence of fluoranthene and pyrene. *Bulletin of Environmental Contamination and Toxicology*, *85*(1), 32–36.

Jennings, D., & Jarnagin, S. (2002). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology*, *17*, 471–489.

Jones, P. & Davis, A. (2013). Spatial Accumulation and Strength of Affiliation of Heavy Metals in Bioretention Media. *Journal of Environmental Engineering, 139*(4), 479-487.

Kim, H., Seagren, E., & Davis, A. (2003). Engineered Bioretention for Removal of Nitrate from Stormwater Runoff. *Water Environment Research, 75*(4), 355–367.

Knight, E. M. P., Hunt, W. F., & Winston, R. J. (2013). Side-by-side evaluation of four level spreader-vegetated filter strips and a swale in eastern North Carolina. *Journal of Soil and Water Conservation, 68*(1), 60–72.

Lee, J. H., Bang, K. W., Ketchum, L. H., Choe, J. S., & Yu, M. J. (2002). First flush analysis of urban storm runoff. *The Science of the Total Environment, 293*(1-3), 163–175.

Lee, J., & Heaney, J. (2003). Estimation of Urban Imperviousness and its Impacts on Storm Water Systems. *Journal of Water Resources Planning and Management, 129*, 419–426.

LeFevre, G. H., Paus, K. H., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering, 141*(1).

LeFevre, G., Novak, P., & Hozalski, R. (2015). Effect of Vegetation on the Fate of Petroleum Hydrocarbons in Laboratory-Scale Raingardens. Low Impact Development Technology: Design Methods and Case Studies, 37–42.

Leopold, L. (1968). Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. United States Department of the Interior, Washington, DC.

Li, H. & Davis, A. (2008). Heavy Metal Capture and Accumulation in Bioretention Media. *Environmental Science and Technology, 42*, 5247-5253.

Li, H. & Davis, A. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *Journal of Environmental Engineering, 135*, 567–576.

Li, H., Sharkey, L., Hunt, W., & Davis, A. (2009). Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. *Journal of Hydrologic Engineering, 14*, 407–415.

Li, J., & Davis, A. P. (2015). A unified look at phosphorus treatment using bioretention. *Water Research, 90*, 141–155.

Li, L., & Davis, A. P. (2014). Urban stormwater runoff nitrogen composition and fate in bioretention systems. *Environmental Science and Technology, 48*(6), 3403–3410.

Line, D., Brown, R., Hunt, W., & Lord, W. (2012). Effectiveness of LID for Commercial Development in North Carolina. *Journal of Environmental Engineering, 138*, 680–688.

Line, D., & White, N. (2007). Effects of Development on Runoff and Pollutant Export. *Water Environment Research, 79*(2), 185–190.

Lucas, W., & Greenway, M. (2009). Nutrient Retention in Vegetated and Nonvegetated Bioretention Mesocosms. *Journal of Irrigation and Drainage Engineering, 134*, 613–623.

Mahler, B., Van Metre, P., Bashara, T., Wilson, J., & Johns, D. (2005). Parking Lot Sealcoat: An Unrecognized Source of Urban Polycyclic Aromatic Hydrocarbons. *Environmental Science & Technology, 39*(15), 5560–5566.

McIntyre, J. K., Edmunds, R. C., Anulacion, B. F., Davis, J. W., Incardona, J. P., Stark, J. D., & Scholz, N. L. (2016). Severe Coal Tar Sealcoat Runoff Toxicity to Fish Is Prevented by Bioretention Filtration. *Environmental Science & Technology*, *50*(3), 1570–1578.

McNett, J. K., Hunt, W. F., & Osborne, J. A. (2010). Establishing Storm-Water BMP Evaluation Metrics Based upon Ambient Water Quality Associated with Benthic Macroinvertebrate Populations. *Journal of Environmental Engineering, 136*(5), 535–541.

MDE. (2009). Maryland Stormwater Design Manual, Volumes I and II. Maryland Department of the Environment, Baltimore, Maryland.

Moore, T. & Hunt, W. (2012). Ecosystem service provision by stormwater wetlands and ponds-A means for evaluation? *Water Research, 46*, 6811-6823.

Murphy, L., Cochrane, T., & O'Sullivan, A. (2015). The Influence of Different Pavement Surfaces on Atmospheric Copper, Lead, Zinc, and Suspended Solids Attenuation and Wash-Off. *Water, Air, and Soil Pollution*, 226, 232.

National Research Council. (2008). Urban Stormwater Management in the United States. National Academy of Sciences, Washington, DC.

NC DEQ. (2009). Stormwater BMP Manual. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

NC DEQ. (2016a). North Carolina Surface Water Standards and Protective Values. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

NC DEQ. (2016b). North Carolina Total Maximum Daily Load Program. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

Ngabe, B., Bidleman, T., & Scott, G. (2000). Polycyclic aromatic hydrocarbons in storm runoff from urban and coastal South Carolina. *The Science of the Total Environment, 255*, 1–9.

NRCS. (2005). Bioswales. National Resources Conservation Service, Washington, DC.

Page, J. L., Winston, R. J., Mayes, D. B., Perrin, C. A., & Hunt, W. F. (2015). Retrofitting Residential Streets with Stormwater Control Measures over Sandy Soils for Water Quality Improvement at the Catchment Scale. *Journal of Environmental Engineering, 141*(4).

Passeport, E., & Hunt, W. (2009). Asphalt Parking Lot Runoff Nutrient Characterization for Eight Sites in North Carolina, USA. *Journal of Hydrologic Engineering, 14*(4), 352–361.

Passeport, E., Hunt, W. F., Line, D. E., Smith, R.., & Brown, R. (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. *Journal of Irrigation and Drainage Engineering, 135*(4), 505–510.

Paul, M., & Meyer, J. (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics, 32*(1), 333–365.

Pitt, R., & Bannerman, R. (2005). Sources of pollutants in urban areas (Part 1)–Older monitoring projects. *Effective Modeling of Urban Water Systems*, 1–20.

Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability. *Water Environment Research, 67*(3), 260–275.

Rushton, B. (2001). Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management, 127*, 172–179.

Sartor, J. D., Boyd, G. B., & Agardy, F. J. (1974). Water pollution of street surface contaminants. *Journal (Water Pollution Control Federation), 46*(3), 458–467.

Stagge, J. H., Davis, A. P., Jamil, E., & Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research, 46*(20), 6731–6742.

US EPA. (2015a). History of the Clean Water Act. Laws, Regulations, Guidance, and Dockets. United States Environmental Protection Agency. Accessed 11 January 2016.

US EPA. (2015b). Learn About Lead. United States Environmental Protection Agency. Accessed 9 March 2016.

Walsh, C., Sharpe, A., Breen, P., & Sonneman, J. (2001). Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities. *Freshwater Biology, 46*, 535–551.

Xiao, Q., & Mcpherson, E. (2011). Performance of engineered soil and trees in a parking lot bioswale. *Urban Water Journal*, *8*(4), 241–253.

Yu, S. L., Kuo, J.-T., Fassman, E. A., & Pan, H. (2001). Field Test of Grassed-Swale Performance in Removing Runoff Pollution. *Journal of Water Resources Planning and Management, 127*(3), 168–171.

Zanders, J. M. (2005). Road sediment: Characterization and implications for the performance of vegetated strips for treating road run-off. *Science of the Total Environment, 339*(1-3), 41–47.

CHAPTER 2: CHARACTERIZATION OF ASPHALT PARKING LOT RUNOFF IN THE COASTAL PLAIN OF NORTH CAROLINA

2.1 Abstract

Parking lots occupy a substantial fraction of the urban landscape. They are a major source of stormwater runoff, discharging a suite of pollutants including sediment, nutrients, heavy metals, oils and grease, and pathogens. In this study, two catchments of an aging asphalt parking lot were monitored in the Coastal Plain of North Carolina for hydrology and water quality (total suspended solids (TSS), nutrients, heavy metals, and polycyclic aromatic hydrocarbons (PAC)). Runoff volume, runoff coefficient, and peak discharge were also analyzed. Runoff volume and peak discharge, normalized by watershed area, were less than those found in other parking lot studies. The mean runoff coefficient was 0.31, lower than expected for such highly impervious catchments. Average total phosphorous and TSS event mean concentrations (EMCs) were higher than those found in other parking lot studies, while heavy metals EMCs were less than those of other parking lots. Total phosphorous, TSS, Cu, and Zn EMCs are above ambient water quality criteria for coastal NC. Overall, parking lot EMCs were less than average highway EMCs. Only pollutant loads showed seasonal variation, with summer producing the highest loads. Multiple linear regression models were created to explain variation in the hydrologic variables, pollutant EMCs, and pollutant loads. The main factors found to influence these variables were rainfall depth, rainfall intensity, storm duration, impervious fraction, and temperature. The strongest correlations occurred between pollutant loads and predictive factors. All pollutants, except lead, showed a first

flush effect, with the average load per millimeter of runoff greatest during the first 13 mm of rainfall

2.2 Introduction

Increasing impervious surface coverage in a watershed increases urban stormwater runoff and decreases the ability of the watershed to infiltrate and evapotranspirate rainfall (Jennings & Jarnigan, 2002; Paul & Meyer, 2001). Stormwater runoff impacts the downstream environment through reduced groundwater recharge and stream baseflow (DeBusk et al., 2011; Line & White, 2007; Paul & Meyer, 2001), stream incision and erosion (Bledsoe & Watson, 2001), flooding (Jennings & Jarnagin, 2002; Line & White, 2007; Leopold, 1968), and deteriorating aquatic ecosystems (Walsh et al., 2001). Additionally, stormwater runoff carries a multitude of pollutants and pathogens that can lead to eutrophication, fish kills, aquatic toxicity, and human health risks.

Roads and parking lots constitute 70-80% of impervious coverage in urban areas, and are expected to produce similar stormwater runoff (National Research Council, 2008). These impervious surfaces eliminate infiltration, producing a much larger volume of runoff than a vegetated watershed. Traditionally, parking lots have been designed with curb and gutters to remove runoff as quickly as possible, amplifying stormwater impacts (Davis, 2005).

Organic and inorganic particulates such as sediment, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), pathogens, and gross solids accumulate on parking lot surfaces during dry periods. In a phenomenon known as the “first flush”, the greatest mass load of these pollutants occurs during the first portions of the storm (Deletic, 1998; Flint & Davis, 2007; Hathaway et al., 2012). The main sources of these pollutants include atmospheric deposition, vehicular traffic, and organic litter (Bannerman et al., 1993; Brinkmann, 1985; Passeport & Hunt, 2009; Pitt et al., 1995). Rainfall may be a source of dissolved pollutants such as ammonium and nitrate (NADP, 2014). The export of particulates during a rainfall event is dependent on storm characteristics such as antecedent dry period, rainfall intensity, and duration as well as pavement type and condition (Pitt et al., 1995; Sartor et al., 1974; Drapper et al., 2000; Hope et al., 2004; Rushton, 2001).

Nutrients, including organic and inorganic forms of nitrogen (N) and phosphorous (P), are found in parking lot stormwater (Hope et al., 2004; Knight et al., 2013; Line & White, 2007; Passeport & Hunt, 2009). The most common sources are atmospheric deposition, organic material, animal waste, and fertilizer (Brinkmann, 1985; Davis et al., 2006; Pitt et al., 1995). Nitrate/nitrite (NO_x-N) and orthophosphate (O-PO_4^{3-}), dissolved components of N and P respectively, are of particular concern because they can lead to algal blooms and eutrophication in the downstream environment. Total phosphorous (TP) and total nitrogen (TN) concentrations range 0.05-0.21 mg/L and 0.55-1.63 mg/L respectively (Brown et al., 2012; Knight et al., 2013; Li & Davis, 2009; Passeport & Hunt, 2009; Rushton, 2001). Passeport & Hunt (2009) found that TP loads from parking lots are similar to those of roads and highways, but TN loads are slightly lower.

Heavy metal accumulation is a major issue within parking lots due to vehicular presence and impacts of metals. Toxicity due to the accumulation of metal-rich sediment can impact aquatic life (Grebel et al., 2013), and ingesting water with high lead concentrations is detrimental to human health (US EPA, 2015b). Copper (Cu) and zinc (Zn) originate from brakes and tires as well as atmospheric deposition, while lead (Pb) is associated with vehicle exhaust deposition (Brinkmann, 1985; Davis et al., 2001; Grebel et al., 2013; Pitt & Bannerman, 2005). Additionally, building siding and roofs surrounding the parking lot may contribute some heavy metals (Davis et al., 2001; Pitt et al., 1995). Zn concentration variation has been attributed to differences in average daily traffic in watersheds (Drapper et al., 2000). Asphalt pavement produces greater Cu and Zn concentrations than concrete surfaces (Murphy et al., 2015).

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds found in many vehicular by-products such as oil/grease, tire particles, and exhaust as well as coal-tar sealant (Davis, 2005; Ngabe et al., 2000;Pitt et al., 1995; Mahler et al., 2005). Coal-tar sealant is used primarily in the eastern US, and several aquatic species show acute toxicity to PAHs from degrading coal-tar sealant (McIntyre et al., 2016). James et al. (2010) found that PAH concentrations in stormwater runoff ranged 5 to 277 mg/L. Fluoranthene and pyrene, heavy molecular weight PAHs, are known to occur in stormwater runoff, and are associated with toxicant effects in aquatic sediments (James et al., 2010). Like heavy metals, PAHs accumulate in stream and reservoir sediment and cause chronic toxicity issues (Ngabe et al., 2000).

Due to assumed similarities, parking lot runoff is often assigned water quality characteristics of highway runoff. Few studies have been completed with the express goal of analyzing parking lot runoff. Passeport and Hunt (2009) studied nutrients in runoff from eight parking lots in NC and found differences between parking lot concentrations and highway concentrations. Additionally, Coastal Plain parking lots have different underlying soils and climate than parking lots in other ecoregions, so runoff possibly varies among ecoregions. The objective of this study was to characterize parking lot runoff for the Coastal Plain of North Carolina through the monitoring of one site. Nutrient, TSS, heavy metal, and PAH concentrations were analyzed to provide a comprehensive diagnosis of parking lot runoff water quality. Multiple linear regression models were used to explain variation of hydrology and water quality.

2.3 Site Description

The project site is located at New Hanover High School (NHHS) in Wilmington, North Carolina. Wilmington lies near the mouth of the Cape Fear River within the Coastal Plain ecoregion (Figure 2-1). The city population is 113,000, a NPDES Phase II jurisdiction (US Census Bureau, 2014). Wilmington has a moderate climate, with normal temperatures ranging from 7.8°C in January to 27.3°C in July (State Climate Office of NC, 2016). Average annual rainfall is 1448 mm; July is on average the wettest month (194 mm) and April is the driest (75 mm) (State Climate Office of NC, 2016).

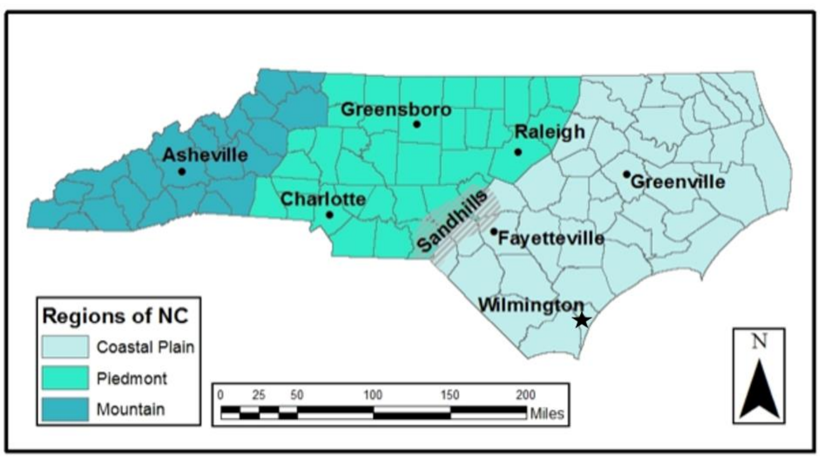


Figure 2-1: Map of North Carolina with ecoregions and project location.

The NHHS parking lot lies within the Burnt Mill Creek watershed, which drains to the Cape Fear River and has been on the North Carolina 303(d) impaired waters list since 2004 due to turbidity, benthic health, and toxicity (NCDEQ, 2014).

The asphalt parking lot was created in 1954 and is in relatively fair condition, with potholes forming and large amounts of sediment accumulation due to erosion (Figure 2-2, Appendix D). It has not been resurfaced in at least 15 years, based on aerial photography. The site originally had five parking lot islands, two with large trees established and the others with crepe myrtle shrubs. There are three traffic lanes, six rows of parking, and a large open space for school bus drop-offs (Figure 2-3). The lot is primarily used by students during the school year (September-June), but is also used by churchgoers at the adjacent St. Andrews-Covenant Presbyterian Church on Sundays. The parking lot was observed to fill to capacity during school hours.

Figure 2-2: NHHS parking lot pre-retrofit. Note large amounts of sediment.

The site is 0.65 ha overall, split into two sub-watersheds that drain into individual conventional catch basins at the eastern end of the lot (Figure 2-3). The southern sub-watershed (0.20 ha) will hereby be referred to as the “Control” and the northern sub-watershed (0.45 ha) will be referred to as “Retrofit”. The sub-watersheds consist of the parking lot and a bordering sidewalk. A particle size analysis, using the hydrometer method, confirmed the New Hanover County Soil Survey classification of sandy underlying soils (USDA, 1977). The average longitudinal slope is 2%. Table 2-1 lists the watershed characteristics.

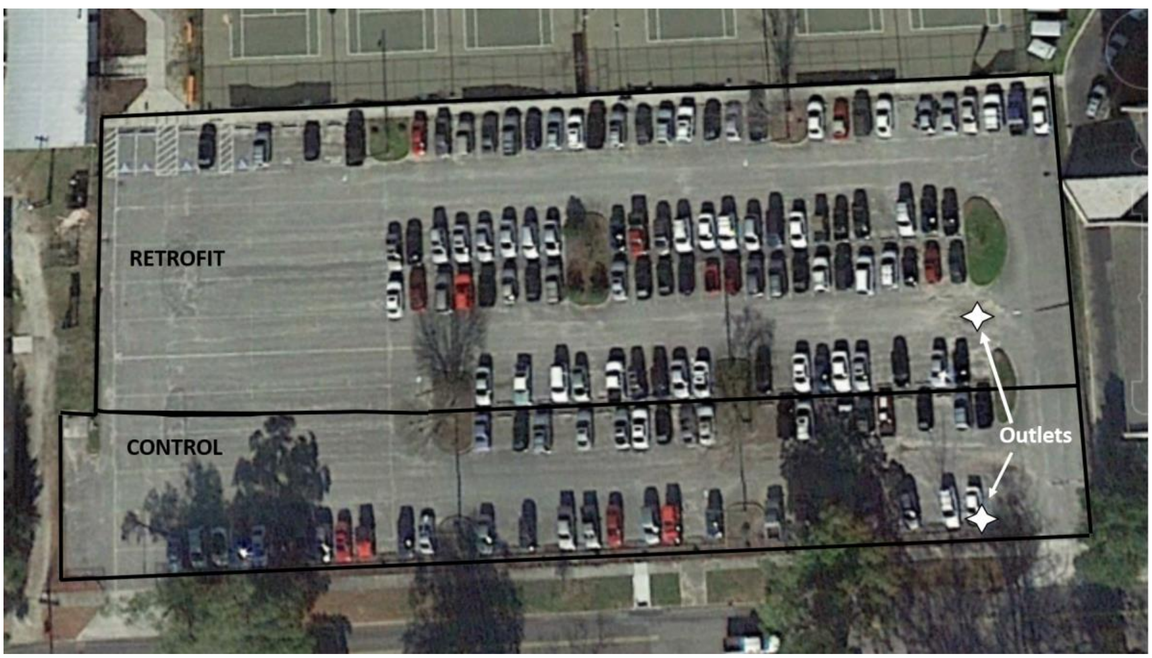


Figure 2-3: An aerial view of the parking lot at NHHS pre-retrofit. The black line delineates the two sub-watersheds within the lot.

Table 2-1: Description of the two sub-watersheds pre-retrofit.

Parameter	Watershed	
	Control	Retrofit
Drainage Area (m^2)	2015	4485
Length (m)	122	122
Width (m)	18	40
Impervious Fraction	0.97	0.95
Slope (%)	2	2
Soil Series	Leon Urban Land Complex	Leon Urban Land Complex
USDA Soil Class	Sand	Sand
Outlet Location	34.235754, -77.931037	34.235972, -77.931064
Receiving Water Body	Burnt Mill Creek	Burnt Mill Creek
River Basin	Cape Fear	Cape Fear

2.4 Materials and Methods

Monitoring Scheme

As part of another study, the parking lot was retrofitted with infiltrating SCMs to treat Retrofit watershed runoff. The initial monitoring scheme for this project was a paired watershed design to evaluate hydrology and water quality of the parking lot (Clausen & Spooner, 1993). This approach requires two watersheds (Control and Retrofit) in a close vicinity and two monitoring periods (Calibration and Treatment). During the Calibration period, conditions within the watersheds remained unchanged. After the Calibration period, the retrofit was applied to one of the watersheds. The Treatment period monitoring then commenced. Due to preferential flow, runoff from the Retrofit watershed overtopped the SCM and exited the site via the Control catch basin. In effect, two new watershed areas were formed (Table 2-2, Figure 2-4).

Table 2-2: Summary of watershed characteristics and monitoring periods.

Watershed	Dates	Drainage Area (m^2)	Impervious Fraction
CAL-Control	(February 2014-	2015	0.972
CAL-Retrofit	July 2014)	4485	0.950
TREAT-Control	(September 2014-	2507	0.966
TREAT-Retrofit	December 2015)	3996	0.916

Figure 2-4: An aerial view of the parking lot at NHHS post-retrofit. The black line delineates the two sub-watersheds within the lot. Note the extension of the Control Watershed into the Retrofit watershed.

Monitoring equipment was installed in the Control and Retrofit watershed catch basins in March 2014. ISCO 6712™ portable automated samplers were installed near the catch basins. Ninety degree V-notch weirs and weir boxes were mounted within the catch basins to accurately measure discharge and volume from the parking lot (Figure 2-5). ISCO 730™ bubbler flow modules were used in concert with the ISCO 6712™ to measure stage above the weirs at two-minute intervals. Bubbler and sampler tubing were run under protective plastic speed bumps across the drive aisles into the catch basins. Samplers were powered by 12-volt batteries and an attached solar panel. Rainfall was monitored utilizing an automated gauge and manual gauge. An ISCO 674™ tipping bucket rain gauge was installed alongside a cylinder gauge on a wooden post in a clear area (Figure 2-5). The tipping bucket was connected to the Retrofit ISCO 6712™ sampler and recorded rainfall in 0.25 mm increments on two-minute intervals.

Table 2-3: Summary of equipment installed for water quality and hydrology monitoring.

Equipment	Type	Interval
Weir	90° V-notch	N/A
Flow Monitoring Device	ISCO 730™ Bubbler Module	2-minute
Sampling Device	ISCO 6712™ Automated Sampler	Flow-paced
Power Source	12-volt Battery with 20-watt solar panel	N/A
Rainfall Monitoring Device	ISCO 674™ Tipping Bucket and Manual Rain Gauge	0.25 mm increments 2-minute

Figure 2-5: (Left) Tipping bucket and manual rain gauges; (Right) Weir box installed within catch basin.

The ISCO 6712™ samplers collected flow-weighted samples (200 mL) during storm events that were deposited in 1 of 24 1-L bottles. Flow weighting was adjusted based on expected intensities of incoming storms to capture at least 70% of the hydrograph. Samples were suctioned from the bottom of the weir box in an area of well-mixed flow.

Water quality samples were tested for total suspend solids (TSS), total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrate-nitrite-nitrogen (NO_x-N), total phosphorous (TP), ortho-phosphate (O-PO_4^{3-}), copper (Cu), lead (Pb), zinc (Zn), and polycyclic aromatic hydrocarbons (PAHs). TSS and nutrient species were analyzed by the North Carolina Center for Applied Aquatic Ecology (CAAE) at NCSU in Raleigh, NC. PAHs and metals were analyzed by NCDEQ Environmental Chemistry Lab in Raleigh, NC. The labs are located 210 km from the study site. Laboratory methods and calculations are listed in Table 2-4.

Table 2-4: Laboratory methods and reporting limits for pollutants.

Pollutant	Name	Analytical Method	Reporting Limit (µg/L)
TKN[a]	Total Kjeldahl Nitrogen	EPA Method 351.2	280
NO_x-N[a]	Nitrate/Nitrite Nitrogen	SM 4500 NO3 F	5.6
TAN[a]	Total Ammoniacal Nitrogen	SM 4500 NH3 G	7
TN	Total Nitrogen	=TKN + NO_x-N	NA
ON	Organic Nitrogen	=TKN – TAN	NA
TP[a]	Total Phosphorous	SM 4500 P F	10
O-PO_4^{3-}[a]	Ortho-Phosphate	SM 4500 P F	6
TSS[a]	Total Suspended Solids	SM 2540 D	2.5
Cu[b]	Copper	EPA 200.8	2
Pb[b]	Lead	EPA 200.8	2
Zn[b]	Zinc	EPA 200.7	10
PAH[b]	Polycyclic Aromatic Hydrocarbons	EPA 625/8270/3510	10-50

a- CAAE
b- NC DEQ

Water quality samples were collected within 24 hours following a rain event. Only storms producing 2.5 mm to 51 mm of rain were sampled as long as at least 70% of the hydrograph was accounted for. Upon arrival, the flow-weighted samples were composited into one 24-L bottle and thoroughly mixed in order to re-suspend particles. At least 2 L was needed to fill all bottles for TSS, nutrient, and metal analyses. Five total liters were needed to add on PAH analysis. A 1-L clear plastic bottle for TSS analysis was filled from the larger mixing bottle. From this smaller vessel a 30-mL sample was filtered through a 0.45-μm filter into a dark glass bottle for O-PO_4^{3-} testing. A 125-mL pre-acidified plastic bottle was filled for other nutrients. A 500-mL clear plastic bottle was filled and then preserved with nitric acid for metals analysis. On the occasions enough water was available for PAH samples, a 3-L dark glass bottle was also filled. The large mixing bottle was re-agitated any time extra water was needed to fill the variety of bottles. Gloves were worn while sampling and the samples were immediately placed on ice.

Monitoring Challenges

The primary monitoring challenges were due to equipment malfunctions. Tubing had to be run across a drive aisle in the Retrofit watershed. Although it had a protective speed bump, continual wear and tear from speed bump movement caused tubing to break twice (Figure 2-6). The Control watershed tubing ran through a parking spot which led to an eventual break due to weight of vehicles. Loss of power due to battery outage was an issue during colder months.

Figure 2-6: (Left) Broken bubbler tubing due to friction from speed bump; (Right) Large amounts of organic litter clogging hidden catch basin.

The Control watershed contains two large deciduous tree and many flowering bushes, leading to large amounts of organic material clogging the catch basin during leaf fall and flowering seasons (Figure 2-6). In addition to removing this material from the catch basin grate, the weir box had to be continually cleaned out to keep flow unimpeded.

During installation of monitoring equipment for the Calibration period a mistake was made with the automated rain gauge. This resulted in missing rainfall data for the first nine storms (February 26 – June 9, 2014). The project site is located 5.6 km from the Wilmington International Airport, site of a National Weather Service (NWS) weather station from which hourly rainfall data were acquired for missing storms (NWS, 2016).

Data Analysis

Hydrologic data were first reviewed within FLOWLINK Version 5.12 for any abnormalities (ISCO, 2005). Rainfall amounts were adjusted by a scaling factor calculated by comparing the tipping bucket totals to manual gauge totals. Rainfall events were separated for storms with at least 2.54 mm of rain and a six hour antecedent dry period. The data were then exported from FLOWLINK for further analysis and transformation. Five-minute and hourly intensities were calculated from transformed two-minute rainfall data. For the missing rainfall events in the Calibration period only hourly intensities could be computed. Flow was calculated from the recorded two-minute stage data using the stage-discharge weir equation provided by ISCO (Equation 2-1). From the two-minute flow data cumulative volume, runoff coefficient (ROC), and peak discharge could be calculated for each storm. The ROC represents the fraction of rainfall that becomes runoff.

$$Q = 2.5H^{2.5} \qquad \text{Equation 2-1}$$

Where,

Q = Discharge (cfs)

H = Head on Weir (ft)

Water quality data from the labs were event mean concentrations (EMCs). Sampling for PAHs was ended several months into the Treatment period (July 2015) because all concentrations were below practical reporting limits. For other constituents, any concentrations less than the reporting limit were assigned a concentration one-half the reporting limit. Concentrations were converted to pollutant loads for each storm using the equation below (Equation 2-2). Annual loads were then calculated using Equation 2-3.

$$L = \frac{V \times C}{A \times 1000} \qquad \text{Equation 2-2}$$

Where,

L = Pollutant Load (g/ha)

V = Runoff Volume (L)

C = Event Mean Concentration (mg/L)

A = Area of Watershed (ha)

$$L_{Annual} = \Sigma L_{Measured} * \frac{P_{Annual}}{\Sigma P_{Measured}} \qquad \text{Equation 2-3}$$

Where,

L_{Annual} = Estimated Annual Load (g/ha·yr)

$L_{Measured}$ = Pollutant Load Measured (g/ha)

P_{Annual} = Long Term Average Annual Rainfall (mm)

$P_{Measured}$ = Rainfall Measured During Monitoring (mm)

Statistical Analyses

SAS Version 9.3™ was used for all statistical analyses (SAS Institute, 2012; Appendix A). Descriptive statistics were produced for runoff coefficient, peak discharge, pollutant concentrations, and pollutant loads. The results were then compared to previous parking lot and highway runoff studies. Seasonal variation in the variable distributions was analyzed using multi-comparison tests including REGWQ.

Next the effect of select factors on parking lot hydrology and water quality variables was assessed through multiple linear regression development. The first step in the MLR process was an analysis of factor and variable distributions. Pearson correlation tests were performed on the factors as well as between the factors and variables. To assess the linearity assumption, the variables were plotted by the factors. Factor selection for the model was performed using stepwise, backward, and forward selection techniques with p-value (α=0.1) and adjusted R^2 criteria. Ninety-percent confidence was used rather than 95% confidence to decrease the probability of a Type II error; not rejecting the null hypothesis when it is actually false. The models produced by these methods was compared to a model with all possible factors to assess fit. The BoxCox method was used to discern if any transformation was required to maintain normality of residuals. Finally, the variance inflation factors (VIF) were calculated for the factors. The VIF and Pearson correlation coefficients were analyzed to determine which factors would remain in the model to reduce multicollinearity.

2.5 Hydrology Results

Precipitation

Monitoring during the Calibration period occurred February 26, 2014, through July 3, 2014. In this time 16 hydrologic events were recorded, but three were eliminated due to technical difficulties. Rainfall for remaining storms to be analyzed ranged from 4.06 mm to 91.69 mm. The Treatment period lasted from September 6, 2014, to December 21, 2015. Seventy-seven events were recorded and 12 were removed due to equipment error. Rainfall for the events used in analyses for the Treatment period ranged from 2.54 mm to 64.01 mm. During the two monitoring periods (Calibration and Treatment), 78 storms were successfully recorded and analyzed (Table 2-6). Shorter duration storms were usually more intense. Not all storms were accurately captured by the samplers or were otherwise missed. Fifty-eight and 81% of rainfall was captured and consequently used in analyses for the Calibration and Treatment periods, respectively.

Table 2-5: Summary of precipitation events during the two monitoring periods.

Monitoring Period	Dates	Mean (mm)	Median (mm)	Range (mm)	Percent of Rainfall
Calibration (n=13)	02/26/2014-07/03/2014	18.87	10.67	4.06-91.69	58
Treatment (n=65)	09/06/2014-12/21/2015	19.54	13.21	2.54-64.01	81

Table 2-6: Summary statistics of total monitored precipitation (n=79).

Constituent	Mean	Median	SD	Minimum	Maximum
Rainfall (mm)	19.43	12.19	17.90	2.54	91.69
Peak Hourly Intensity (mm/hr)	8.14	6.22	6.69	0.76	34.04
Duration (hr)	7.62	5.39	7.45	0.20	33.13
Antecedent Dry Period (hr)	79.46	50.30	81.42	6.00	348.50

The number of events was relatively similar seasonally, except winter which had approximately one-half of the storms. Rainfall depths and intensities were greatest in the fall, which is abnormal for Wilmington, NC (NC State Climate Office, 2016). Storms in the summer were short and intense (Table 2-7).

Table 2-7: Descriptive statistics for the seasonal breakdown of hydrologic variables.

Season	Variable	Rainfall (mm)	Peak Hourly Intensity (mm/hr)	Duration (hr)	ADP (hr)
SPRING (n=22)	Mean	20.2	8.4	8.3	94.8
	Median	12.1	7.1	6.2	56.6
	Range	4.1-91.7	0.76-19.6	0.3-30.0	11.0-282.6
SUMMER (n=22)	Mean	16.3	8.3	3.9	74.7
	Median	11.1	6.6	3.1	48.0
	Range	3.8-41.7	2.3-30.2	0.2-9.9	7.9-229.7
FALL (n=21)	Mean	22.3	9.1	10.2	71.4
	Median	14.5	6.4	5.4	39.3
	Range	2.5-64.0	1.5-34.0	0.3-33.1	6.0-348.5
WINTER (n=13)	Mean	18.6	5.9	8.7	74.3
	Median	11.9	4.3	8.2	55.9
	Range	3.8-62.2	1.5-18.3	0.4-19.9	10.0-201.4

The 30-year average rainfall for Wilmington is 1448 mm (Table 2-8). Overall, 2014 was an average year for rainfall (1518 mm). However, the end of the Calibration period was significantly drier than normal. The Treatment period had above average rainfall. In fact, rainfall in 2015 (1957 mm) was 35% greater than the normal. Fall 2015 was one of the wettest on record, with rainfall in October and November being a cumulative 390 mm above normal.

Table 2-8: Comparison of monitoring period rainfall to 30-year normal rainfall.

Month	Rainfall (mm)	30-year Normal Rainfall (mm)
March 2014*	162	107
April 2014*	124	75
May 2014*	63	112
June2014*	70	136
September 2014	123	172
October 2014	27	82
November 2014	125	83
December 2014	179	96
January 2015	136	115
February 2015	115	93
March 2015	94	107
April 2015	68	75
May 2015	131	112
June 2015	173	136
July 2015	141	194
August 2015	217	186
September 2015	139	172
October 2015	404	82
November 2015	199	83
December 2015	140	96
Annual	1518[a] 1957[b]	1448

*Calibration period
a: 2014 b:2015

Descriptive Statistics

Table 2-9 shows the mean, median, and range for the three hydrologic variables analyzed: runoff volume, ROC, and peak discharge. As the Control watershed is smaller than the Retrofit watershed, the volume of water and discharge leaving the Control is less than that of the Retrofit for both periods. Additionally, the Retrofit watershed has more pervious surface and depressional area so the ROC is expected to be less than the ROC of the Control (Table 2-2). The ROC of both watersheds decreased after the retrofit. This may be due to the decreasing impervious fraction within both watersheds. While peak flow varied between the Control and Retrofit watersheds, there was no change in peak flow between monitoring periods.

Table 2-9: Summary hydrologic statistics for the four watersheds.

Watershed	Variable	Mean	Median	SD	Minimum	Maximum
CAL-Control	Volume (L)	28605	12119	40421	3313	147984
	ROC	0.61	0.66	0.22	0.19	0.88
	Peak Flow (L/s)	8.11	8.38	6.33	1.44	17.22
CAL-Retrofit	Volume (L)	40831	24296	54504	4446	201644
	ROC	0.45	0.45	0.14	0.13	0.73
	Peak Flow (L/s)	24.60	23.76	25.39	1.93	97.81
TREAT-Control	Volume (L)	11750	5956	14369	473	76005
	ROC	0.22	0.19	0.17	0.03	0.86
	Peak Flow (L/s)	11.26	6.14	15.60	0.54	91.69
TREAT-Retrofit	Volume (L)	28764	13505	35137	303	144499
	ROC	0.29	0.29	0.16	0.03	0.82
	Peak Flow (L/s)	33.41	12.83	41.42	0.34	169.19

The average normalized runoff volume for this parking lot is 69119 L/ha (0.007 m^3/m^2) (Table 2-10). This is much lower than median parking lot volumes (0.021-0.122 m^3/m^2) reported by Li et al. (2009). The mean reported in this study includes the effect of infiltrating SCMs, which decreases the volume of runoff leaving the Retrofit watershed. However, the averages for the CAL-Control and CAL-Retrofit watersheds are 0.014 and 0.009 m^3/m^2 respectively, which are still lower than values from the other studies. Volumes may be lower because the parking lot is old and eroded, storing some runoff on the surface itself. Some infiltration may be expected through pores and cracks in the surface.

The mean ROC (0.30) of this parking lot is lower than projected (Table 2-10). The parking lot is 95% impervious, so runoff coefficients were expected to be at least above 0.70

(ASCE, 1992). However, other parking lot studies have reported runoff coefficients as low as 0.51 for an undisturbed lot (Rushton, 2001). This study also tested the parking lot with swales installed and the runoff coefficient dropped to 0.16. The drop in ROC is similar to what was seen in this experiment. These studies show that design practices may actually overestimate the amount of rainfall becoming runoff.

The average peak flow, normalized by watershed area, is 61.8 L/s·ha (0.006 L/s·m^2); less than peak discharge from another asphalt parking lot (0.012-0.38 L/s·m^2) (Davis, 2008). As with runoff volumes, normalized peak flows for the Calibration period are also below the range in Davis (2008). Differences in peak flows may also be attributed to the condition of the parking lot.

Table 2-10: Summary hydrologic statistics for the study.

Variable	Mean	Median	SD	Minimum	Maximum
Volume (L)	23011	11841	32441	303	201644
Normalized Volume (L/ha)	69119	33625	97555	757	739918
ROC	0.30	0.25	0.22	0.03	0.88
Peak Flow (L/s)	21.5	8.8	31.3	0.34	169.2
Normalized Peak Flow (L/s·ha)	61.8	29.5	81.9	0.9	423

Seasonal Variation

For all three variables, the mean in winter appears to be less than the other seasons (Table 2-11). The peak discharge in winter (7.19 L/s) is one fourth the peak discharge in summer (28.82 L/s). A multi-comparison test using REGWQ showed that the winter peak discharge was significantly different than other seasons at the 90% confidence level (Table 2-12).This is most likely due to lower intensity storms occurring in winter (Table 2-7). The winter ROC is also significantly different than that of the other seasons. The ROC in winter

(0.17) is one-half that of the spring (0.38), which may also be attributable to differences in rainfall intensities. Runoff volumes do not show seasonal variation.

Table 2-11: Summary hydrologic statistics for the seasons during the study.

Season	Variable	Mean	Median	SD	Minimum	Maximum
SPRING	Volume (L)	27031	15034	40406	525	201644
	ROC	0.35	0.28	0.22	0.03	0.88
	Peak Flow (L/s)	20.21	12.73	24.08	0.68	107.75
SUMMER	Volume (L)	21873	11368	28747	1560	135767
	ROC	0.35	0.29	0.22	0.10	0.86
	Peak Flow (L/s)	28.82	13.25	34.99	2.63	152.15
FALL	Volume (L)	26247	11862	34272	303	144499
	ROC	0.28	0.25	0.15	0.03	0.73
	Peak Flow (L/s)	24.01	7.69	39.65	0.34	169.19
WINTER	Volume (L)	13222	7063	18783	473	87094
	ROC	0.17	0.15	0.11	0.03	0.38
	Peak Flow (L/s)	7.19	3.36	10.29	0.54	49.41

Table 2-12:Seasonal variation for the hydrological variables in the study. Seasons with a different letter are significallty different from the others.

Season	Volume Grouping	ROC Grouping	Peak Flow Grouping
Spring	A	A	A
Summer	A	A	A
Fall	A	A	A
Winter	A	B	B

Correlation

Pearson correlation coefficients show the extent to which a factor is positively or negatively related to another factor (Table 2-13). Coefficients closer to one are more highly correlated. Factor-factor correlation analysis helps determine which factors should be considered for MLR. The highest coefficient found for the potential MLR factors was between Impervious Fraction and Watershed Area (-0.86). Since area is used to calculate Impervious Fraction, it may be beneficial to omit one of these factors from the MLR.

Correlations between rainfall intensity factors were significant and greater than 0.50. Hourly intensity and 5-minute intensity factors are correlated at 0.79. Hourly intensity will be used for the MLR because some 5-minute intensity data points are missing. Intensities and rainfall duration are all significantly correlated with total rainfall. Correlations under 0.50, regardless of significance, are considered weak and do not indicate multicollinearity. Further multicollinearity testing was performed after model creation using the variance inflation factor (VIF).

Table 2-13: Pearson correlation coefficients between the proposed MLR factors.

Factor	Rain	5-Min Int[1]	Hourly Int[1]	Avg Int[1]	Dur[2]	ADP	Temp	Imp[3] Frac	Area
Rain	1	0.49*	0.73*	0.34*	0.70*	0.04	0.02	0.00	0.00
5-Min Int	0.49*	1	0.79*	0.70*	0.06	-0.09	0.41*	0.00	0.00
Hourly Int	0.73*	0.79*	1	0.53*	0.35*	0.04	0.22*	-0.01	0.00
Avg Int	0.34*	0.70*	0.53*	1	-0.15*	-0.10	0.40*	0.02	0.00
Dur	0.70*	0.06	0.35*	-0.15*	1	0.12	-0.28*	-0.02	0.00
ADP	0.04	-0.09	0.04	-0.10	0.12	1	0.14*	0.01	0.00
Temp	0.02	0.41*	0.22*	0.40*	-0.28*	0.14*	1	0.06	0.00
Imp Frac	0.00	0.00	-0.01	0.02	-0.02	0.01	0.06	1	-0.86*
Area	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.86*	1

* denotes significant coefficients (α=0.10) 1: Intensity 2: Duration 3: Impervious Fraction

Table 2-14 shows Pearson correlation coefficients for the hydrologic variables and predictive factors. These coefficients show how well a single factor explains variation in the variable. Runoff volume is positively correlated with rainfall depth (0.74) and peak hourly intensity (0.64). It is significantly correlated with all factors except ADP (-0.05). All correlations are positive except for impervious fraction (-0.20). Correlations between ROC and predictive factors are weak. The highest correlation is for peak hourly intensity (0.33). Coefficients for duration, ADP, impervious fraction, and area with ROC are not significant. Peak flow is most correlated with peak 5-minute intensity (0.69) and peak hourly intensity (0.67). Coefficients are not significant for duration or ADP. Like for runoff volume, the correlation between peak discharge and impervious fraction is negative (-0.27). Negative correlations between runoff volume and peak discharge with impervious fraction indicates multicollinearity due to the sign, therefore area will be used in the MLR.

Table 2-14: Pearson correlation coefficients between the log-transformed hydrological variables and MLR factors.

Factor	Rain	5-Min Int[1]	Hourly Int[1]	Average Intensity	Dur[2]	ADP	Temp	Imp Frac[3]	Area
Volume	0.75*	0.48*	0.64*	0.41*	0.46*	-0.05	0.19*	-0.21*	0.26*
ROC	0.32*	0.30*	0.34*	0.26*	0.14	-0.11	0.28*	-0.01	0.13
Peak Flow	0.51*	0.69*	0.67*	0.59*	0.11	-0.05	0.49*	-0.28*	0.30*

* denotes significant coefficients (α=0.10) 1: Intensity 2: Duration 3: Impervious Fraction

Multiple Linear Regression

Multiple linear regression pinpoints the factors that combine to most greatly influence a variable. After consideration of Pearson correlation coefficients it was determined that the main factors to be evaluated within the MLR analysis were rainfall depth, area, temperature, and hourly peak intensity (Equation 2-4). Variables were log transformed in order to meet residual normality conditions. Factors that showed greatest multicollinearity were eliminated from the analysis. The high temperature was recorded for the day of each storm. This value serves as a continuous factor that is a surrogate for seasonal variation. These models would not serve well for predictive use at other sites because they do not have a significant watershed factor.

Equation 2-4

$$\text{Log(Hydrology Variable)} = \beta_0 + \beta_1\text{*(RF depth)} + \beta_2\text{*(RF intensity)} + \beta_3\text{*(temp)}$$

Factor selection for runoff volume found rainfall depth, temperature, and peak hourly intensity to be significant at the 90% confidence level (α=0.10) (Table 2-15). Volume is expected to increase with an increase in rainfall depth and intensity. These factors both increase during warmer months, so an increase in temperature should lead to greater runoff volumes. The MLR model for runoff volume fit well (R^2=59%) with the chosen factors, with climatic factors having more effect than watershed characteristics.

The runoff coefficient MLR model does not explain ROC variation as well as the other models (R^2=16%). The largest expected factor to impact ROC would have been impervious fraction of the parking lot, however the selection process did not show this as being significant. Seasonal analysis for ROC showed that winter months had a significantly lower ROC, so it is no surprise that temperature was one of the only significant factors.

The peak flow model is similar to the runoff volume model. However, *ceteris paribus*, changes in hourly intensity has greater effect on the variable in the peak flow model. This accurately describes conditions of impervious surfaces; greater intensities lead to larger volumes of water flowing faster across the surface. Temperature plays an important role due to changing rainfall characterization during different seasons. This model strongly explains variation in peak flow leaving this parking lot, even with the area factor remaining so small (R^2=59%).

Table 2-15: MLR model coefficients for the three hydrologic variables and the associated R^2.

Log(Variable)	Intercept	Rainfall Depth (mm)	Hourly Intensity (mm/hr)	Temperature (°C)	Area (ha)	R^2
Runoff Volume	2.60	0.02[1]	0.01[1]	0.01[1]	1.88[1]	0.67
ROC	-1.16	0.01[1]	-	0.01[1]	0.48[1]	0.18
Peak Flow	-0.82	0.01[1]	0.04[1]	0.03[1]	2.04[1]	0.67

1-denotes significance at α=0.10

2.6 Water Quality Results

Descriptive Statistics

Table 2-16 provides descriptive statistics of pollutant concentrations and loads for the four watersheds. These data include outliers from one large storm during the Calibration period and one abnormally high TP reading in the TREAT-Control watershed. These readings are removed from later MLR analysis due to the high leverage they show in model creation. Pollutant concentrations do not vary among the watersheds. Means and medians are consistently different, pointing to the need to transform the data. TSS concentrations varied greatly within each watershed.

Average pollutant loads in the Retrofit watershed decrease between monitoring periods. Although not expected, the same was true for the Control watershed for all pollutants except TP. This could point to a dependency on climatic factors. The MLR process will determine what factors cause these differences. Estimated cumulative loads (kg/ha/yr) were greater during the Calibration period than during the Treatment period.

Table 2-16: Descriptive statistics of concentrations and loads for the four watersheds during the monitoring period.

WS[1]	Var[2]	TN	TP	TSS	Cu	Pb	Zn
EMC		*mg/L*	*mg/L*	*mg/L*	*µg/L*	*µg/L*	*µg/L*
CAL Control	Mean	1.30	0.18	51.1	6	4	39
	Med	1.26	0.16	44.7	6	2	23
	Range	0.54-2.44	0.08-0.31	21.2-120.3	1-10	1-10	12-86
CAL Retrofit	Mean	1.02	0.12	67.8	6	4	36
	Med	1.12	0.14	80.9	5	3	31
	Range	0.35-1.74	0.04-0.19	11.4-127.7	1-9	1-8	11-70
TREAT Control	Mean	0.99	0.15	52.4	5	3	34
	Med	0.79	0.13	41.6	5	3	30
	Range	0.30-2.17	0.04-0.32	11.7-156.3	2-9	1-10	5-79
TREAT Retrofit	Mean	0.85	0.10	51.9	6	4	38
	Med	0.75	0.10	42.4	5	4	37
	Range	0.37-1.68	0.07-0.21	14.3-174.2	3-10	1-8	17-63
Load		*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*
CAL Control	Mean	190	27	7057	0.71	0.47	5.1
	Med	156	20	5604	0.71	0.64	5.5
	Range	54-397	8-56	2709-15593	0.28-1.25	0.11-0.73	1.6-8.8
CAL Retrofit	Mean	87	10	4770	0.41	0.31	2.9
	Med	69	9	4985	0.44	0.28	2.4
	Range	53-159	4-19	2570-6918	0.30-0.50	0.18-0.45	1.8-5.0
TREAT Control	Mean	67	33	1972	0.29	0.17	1.5
	Med	21	4	1313	0.15	0.08	1.0
	Range	7-658	1-425	183-8984	0.04-2.70	0.01-0.91	0.2-11.2
TREAT Retrofit	Mean	56	6	2351	0.36	0.26	2.0
	Med	32	5	1774	0.23	0.14	1.8
	Range	3-275	1-20	299-5538	0.04-1.26	0.02-0.73	0.3-5.6

1: Watershed 2: Variable (Med=Median)

Table 2-17: Descriptive statistics of concentrations and loads for the full dataset.

Variable	TN	TP	TSS	Cu	Pb	Zn
EMC	*mg/L*	*mg/L*	*mg/L*	*µg/L*	*µg/L*	*µg/L*
Mean	0.98	0.13	53.81	5	4	36
Median	0.80	0.10	42.38	5	3	32
Range	0.30-2.44	0.04-0.32	11.39-174.17	1-10	1-10	5-86
Load	*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*
Mean	78.9	19.2	3014	0.38	0.25	2.27
Median	37.0	5.6	2195	0.25	0.16	1.56
Range	3.1-658.4	0.8-424.7	183-15593	0.04-2.70	0.01-0.91	0.24-11.22

Table 2-18: Cumulative loads (kg/ha/yr) for the four watersheds and combined loads for the parking lot during the two monitoring periods

Period	TN	TP	TSS	Cu	Pb	Zn
CAL Control	9.86	1.40	366.4	0.037	0.025	0.265
CAL Retrofit	4.50	0.51	247.7	0.021	0.016	0.151
TREAT Control	5.32	0.64	155.9	0.023	0.013	0.121
TREAT Retrofit	4.40	0.46	185.9	0.028	0.020	0.157
Calibration	14.36	1.91	614.1	0.058	0.041	0.416
Treatment	9.71	1.09	341.7	0.051	0.033	0.279

Comparison of EMCs

The average TN EMC of this study is lower than that of parking lots in the Coastal Plain and Piedmont of North Carolina (Hunt et al., 2008; Passeport et al., 2009), but greater than EMCs found a parking lot in Florida (Rushton, 2001; Table 2-19) Parking lot TN concentrations (0.55-1.68 mg/L) are lower than highway TN concentrations (3.67-5.53 mg/L) presented herein. Passeport and Hunt (2009) also found TN concentrations below average highway runoff TN concentrations during a study of eight NC parking lots.

TP concentrations are similar to other reported TP concentrations including those from the Coastal Plain parking lots. However these are lower than the average concentration from the national study of 28 highway sites (US EPA, 1983).

Parking lot runoff TSS concentrations vary (11.24-66 mg/L). This parking lot's TSS was second highest in this list and observations confirm that the parking lot surface is sandy. Parking lot TSS concentrations are generally lower than highway TSS concentrations. The NC Highway produced the largest TSS concentrations (283 mg/L).

Cu concentrations for this parking lot were lower than all other parking lot concentrations presented, by more than one-half in most cases. Similar to Cu, the average Zn concentration found herein (36 µg/L) is generally lower than other parking lot concentrations. This could be due to frequency of parking lot usage. Because it serves a school, most vehicles only drive onto and from the parking lot twice a day. There is less total traffic during the day, therefore less wear on tires and breaks that would contribute Cu and Zn to the pavement. A study done on residential streets in the same watershed reported stormwater Cu concentration of 13 µg/L, indicating that low traffic volumes effect Cu concentrations (Page et al., 2015). Parking lot Cu and Zn concentrations are substantially less than highway runoff concentrations (Table 2-19).

The parking lot Pb concentrations vary from below detection limits to 6 µg/L. The mean Pb concentration for this parking lot is 4 µg/L, similar to that of other studies. Highway Pb concentrations can be very large, up to 182 µg/L in the national study due to gasoline lead content (US EPA, 1983). Parking lot concentrations are consistently less than the lowest highway Pb concentration (Table 2-19).

To evaluate parking lot runoff in an ecological context, pollutant EMCs are also compared to ambient water quality criteria. McNett et al. (2010) developed water quality concentrations for TN and TP for the ecoregions of NC based on macroinvertebrate health. In the Coastal Plain, the TP threshold is 0.09 mg/L (McNett et al., 2010). NC DEQ established a maximum TSS concentration of 20 mg/L for high quality waters (NCDEQ, 2016). NC DEQ metals criteria presented herein are limits for acute toxicity for freshwater aquatic species. Acute toxicity levels are used rather than chronic because stormwater is flashy. Pollutant concentrations for this parking lot are greater than or equal to water quality criteria for TP, TSS, Cu, and Zn, similar to results from the other parking lots. TP concentrations in several of the parking lot studies were closer to the water quality criteria than the concentration produced in this study. The Li and Davis (2009) SS site average Zn concentration was actually below the water quality limit. Highway pollutant concentrations are substantially greater than these criteria.

It appears from this synthesis of results that parking lot and highway runoff are considerably different and thus should not be grouped together for design purposes. Pollutant concentrations for parking lots are typically much lower than those of highways. This may be attributed to heavier vehicular traffic on highways than in parking lots (Kayhanian et al., 2003; Passeport & Hunt, 2009). Additionally, while highway concentrations far exceed ambient water quality conditions, concentrations from parking lot runoff are similar to these targets. Therefore, less treatment may be necessary to reduce parking lot concentrations than previously thought. The deteriorating condition of this parking lot resulted in greater concentrations of TSS and TP than those of other parking lots, indicating the need to target particulate-bound pollutants in aging parking lots.

Table 2-19: Summary of average EMCs from this study and previous parking lot and highway studies. Ambient water quality criteria provided for comparison.

Study	Type[c]	EMC					
		TN	TP	TSS	Cu	Pb	Zn
		mg/L	*mg/L*	*mg/L*	*µg/L*	*µg/L*	*µg/L*
This Study	PL	0.98	0.13	53.8	5	4	36
Hunt et al. (2008)	PL	1.68	0.19	49.5	12.8	4.85	72
Li & Davis (2009) CP*	PL	1.6	0.1	66	19	6	71
Li & Davis (2009) SS*	PL	1.0	<0.1	17	13	<2	15
Passeport et al. (2009) Kin1	PL	1.13	0.10	-	-	-	-
Passeport et al. (2009) Kin2	PL	1.14	0.07	-	-	-	-
Rushton (2001) F1	PL	0.56	0.11	11.2	10.6	4	46
Rushton (2001) F2	PL	0.55	0.11	13.5	10.0	4.2	44
Wu et al. (1998) 1	HW	3.67+	0.43	283	24.2	21	-
Stagge et al. (2012)	HW	5.53	0.55	98	56	24	440
Kayhanian et al. (2007)*	HW	-	0.18	59.1	21.1	12.7	111
NURP (1983)*	HW	-	0.42	180	43	182	202
Ambient WQ	-	-	0.09[a]	20[b]	3.6[b]	14[b]	36[b]

*Medians reported +Calculated by combining TKN and $NO_{2,3}$-N concentrations
a: Good Coastal water quality limits as reported in McNett et al. (2010)
b: NC DEQ surface water quality acute aquatic life criteria (NCDEQ, 2016)
c: Refers to type of urban area; PL=parking lot, HW=highway

Seasonal Variation

Seasonal variation demonstrates how climatic factors effect runoff variables. If there is a significant difference among seasons, then a seasonal factor may improve MLR models. Average nutrient and TSS EMCs were greatest in the spring while average Zn EMCs were greatest in the winter (Table 2-20). Cu and Pb average concentrations were very similar throughout the seasons. All pollutant concentrations had the greatest range in spring except for TP, which was greatest in fall. The smallest range for all pollutants occurred in the winter. REGWQ (α=0.1) multi-comparison tests were performed on the seasonal means

(Table 2-21). Only Zn EMCs showed any significant difference between the seasons. The average winter Zn concentration was significantly greater than the fall Zn concentration.

Pollutant loads were greatest in the summer, in correlation with greatest rainfall amounts (Table 2-19 & Table 2-20). The range of nutrient, Cu, and Zn loads were greatest in the summer, while TSS and Pb loads had greatest range in spring. All pollutant loads in the summer were significantly greater than loads in the fall and winter, except Zn which was only showed significant difference in the summer and fall loads. The difference in summer and fall average rainfall was greatest, explaining the change in load.

Table 2-20: Means and medians of concentrations and loads for seasons.

Season	Variable	TN	TP	TSS	Cu	Pb	Zn
EMC		*mg/L*	*mg/L*	*mg/L*	*µg/L*	*µg/L*	*µg/L*
Spring	Mean	1.16	0.14	62.06	6	3	35
(n=22)	Median	1.24	0.13	42.38	5	3	29
Summer	Mean	1.02	0.12	41.79	6	5	32
(n=6)	Median	0.82	0.09	38.59	6	5	29
Fall	Mean	0.69	0.13	39.88	5	4	31
(n=8)	Median	0.55	0.10	32.39	5	3	22
Winter	Mean	0.71	0.10	54.05	4	5	49
(n=8)	Median	0.65	0.10	49.87	4	4	48
Loads		*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*	*g/ha*
Spring	Mean	85	11	3556	0.36	0.22	2.36
(n=22)	Median	57	7	2639	0.29	0.13	1.66
Summer	Mean	189	20	4514	0.87	0.54	4.22
(n=6)	Median	76	9	4232	0.41	0.50	2.68
Fall	Mean	35	5	1635	0.28	0.19	1.10
(n=8)	Median	24	4	1175	0.14	0.10	0.72
Winter	Mean	24	3	1780	0.16	0.20	1.75
(n=8)	Median	17	3	1628	0.12	0.15	1.27

Table 2-21: REGWQ seasonal groupings for pollutant concentrations and loads. Seasons with different letters are significantly different (α=0.10).

Season	TN	TP	TSS	Cu	Pb	Zn
EMC						
Spring	A	A	A	A	A	AB
Summer	A	A	A	A	A	AB
Fall	A	A	A	A	A	B
Winter	A	A	A	A	A	A
Loads						
Spring	AB	AB	AB	AB	B	AB
Summer	A	A	A	A	A	A
Fall	B	B	B	B	B	B
Winter	B	B	B	B	B	AB

Correlation

Table 2-22 provides Pearson correlation coefficients for multicollinearity analysis between predictive factors. Rainfall depth is significantly and positively correlated with both intensity factors (α=0.10). Average hourly intensity is highly correlated with peak hourly intensity (0.82), indicating that only one of these variables should be used in MLR analysis. The other highly correlated factors are area and impervious fraction (-0.82). Temperature also shows significant correlations, which could be due to seasonal variation in rainfall patterns. Correlations below 0.50 are weak, and do not indicate multicollinearity. VIFs will be used during MLR creation to ensure multicollinearity does not occur.

Table 2-22: Pearson correlation coefficients between predictive factors.

Factor	Rain	Hourly Int[1]	Average Int[1]	Duration	ADP	Temp	Imp[2] Fraction	Area
Rain	1	0.69*	0.50*	-0.06	0.18	0.40*	-0.09	0.00
Hourly Int	0.70*	1	0.82*	-0.50*	-0.18	0.32*	-0.02	0.00
Average Int	0.50*	0.82*	1	-0.60*	-0.10	0.45*	0.03	0.00
Duration	-0.06	-0.50*	-0.60*	1	0.23	-0.31*	-0.13	0.00
ADP	0.18	-0.18	-0.10	0.23	1	0.13	-0.02	0.00
Temp	0.40*	0.32*	0.45*	-0.31*	0.13	1	0.07	0.00
Impervious Fraction	-0.09	-0.02	0.03	-0.13	-0.02	0.07	1	-0.85*
Area	0.00	0.00	0.00	0.00	0.00	0.00	-0.85*	1

* denotes significant coefficients (α=0.10) 1: Intensity 2: Impervious

None of the pollutant EMCs show strong correlations with the predictive factors. This shows that more factors may be needed to explain variations in pollutant EMCs. Nutrient, TSS, and Pb EMCs are significantly, negatively correlated with storm duration. This could point to a dilution effect as the total accumulated pollutants are swept away with the first flush and any subsequent rainfall only increases volume (Brezonik & Stadelmann, 2002; Passeport & Hunt, 2009). However, concentrations were not correlated with antecedent dry period which would be expected due to pollutant build up between rainfall events (Brezonik & Stadelmann, 2002). The Zn EMC is the only pollutant correlated with rainfall depth, rainfall intensity, and temperature.

All pollutant loads were significantly, positively correlated with rainfall depth (0.43-0.54), peak hourly intensity (0.41-0.70), and average hourly intensity (0.33-0.56). This is expected as greater rainfall leads to greater volume of runoff which is used to calculate loads.

These coefficients were greater than those for EMCs, pointing to greater correlation. Like EMCs, the pollutant loads are negatively correlated with duration, reemphasizing a dilution effect. All pollutant loads except Zn were also significantly correlated with temperature, which is in line with seasonal variation described before. Watershed factors and ADP were not significantly correlated with pollutant loads.

Table 2-23: Pearson correlation coefficents between pollutant variables and predictive factors.

Factor	Rain	Hourly Int[1]	Average Int[1]	Duration	ADP	Temp	Impervious Fraction	Area
Log(EMC)								
TN	-0.11	-0.15	-0.05	-0.33*	0.08	0.25	0.23	-0.14
TP	-0.19	-0.01	-0.02	-0.31*	0.00	0.11	0.38*	-0.34*
TSS	-0.29	-0.03	-0.17	-0.30*	-0.07	-0.05	-0.01	0.12
Cu	-0.25	-0.02	-0.01	-0.25	-0.04	0.12	-0.12	0.17
Pb	-0.05	0.33	0.14	-0.31*	-0.05	-0.10	-0.23	0.26*
Zn	-0.31*	-0.19	-0.36*	-0.18	0.10	-0.33*	-0.10	0.13
Log(Load)								
TN	0.50*	0.41*	0.43*	-0.33*	-0.00	0.50*	0.11	-0.04
TP	0.49*	0.49*	0.50*	-0.31*	-0.02	0.45*	0.17	-0.12
TSS	0.43*	0.53*	0.41*	-0.42*	-0.09	0.41*	0.00	0.12
Cu	0.49*	0.48*	0.47*	-0.27*	-0.04	0.44*	-0.05	0.10
Pb	0.54*	0.70*	0.56*	-0.38*	-0.06	0.32*	-0.13	0.18
Zn	0.47*	0.45*	0.33*	-0.32*	0.02	0.25	-0.06	0.11

* denotes significant coefficients (α=0.10) 1: Intensity

Multiple Linear Regression

Analysis of Pearson correlation coefficients determined that the main factors to be considered for MLR models were rainfall depth, hourly intensity, rainfall duration, temperature, and impervious fraction. MLR models will determine how these factors combine to affect the pollutant EMCs and loads. After step function factor selection methods, other factors were eliminated due to multicollinearity. As before, temperature was used as a continuous variable to represent seasonal variation. While it was originally hypothesized that parking lot usage would impact pollutant concentrations, specifically heavy metals, analysis disproved this for all constituents except Pb load. Therefore, this categorical factor was not included in MLR creation.

Table 2-24 shows MLR coefficients and their significance for all pollutant EMCs. All models have at least two significant coefficients and were chosen based on the overall model fit and R^2. As discussed in earlier sections, there was little seasonal variation in the EMCs so temperature was only added if it created a more descriptive model. Duration was the only factor included in all models. An example model is provided below:

Equation 2-5

$$\text{Log(TN EMC)} = \beta_0 + \beta_1(\text{Average Hourly Intensity}) + \beta_2(\text{Duration}) + \beta_3(\text{Temp})$$

According to the models, *ceteris paribus* an increase in rainfall duration leads to a decrease in EMC. For all models including average hourly intensity, EMCs decrease with increasing intensity. This points to a possible dilution effect as volume of runoff increases. Only TP and Pb EMCs showed any relationship to watershed characteristics. A greater area of impervious surface was expected to increase pollutant EMCs. Impervious fraction had a large effect on TP concentrations.

Overall these models have relatively low R^2 values, illustrating that more descriptive factors are needed to accurately describe parking lot runoff pollutant concentrations. These results are similar to those found by Passeport and Hunt (2009) and Brezonik and Stadelmann (2002). Both studies created MLR models for urban runoff and found a dilution effect for pollutant EMCs. However, the study herein did not find a consistent relationship between watershed area or impervious fraction with pollutant EMCs as the others did. For this parking lot, precipitation duration is the most important factor in determining pollutant EMCs, pointing to a first flush effect.

Table 2-24: MLR coefficients for pollutant EMCs.

Variable	Intercept	Rainfall (mm)	Hourly Intensity (mm/hr)	Duration (hr)	Temp (˚C)	Impervious Fraction	Area (ha)	R^2
Log(TN)	-0.003	-	-0.03*	-0.02*	0.01*	-	-	0.28
Log(TP)	-3.68	-	-	-0.01*	-	3.01*	-	0.22
Log(TSS)	2.10	-	-0.05*	-0.03*	-	-	-	0.29
Log(Cu)	-2.14	-0.01*	-	-0.01*	-	-	-	0.13
Log(Pb)	-2.63	-	-	-0.02*	-	-	0.88*	0.16
Log(Zn)	-0.88	-	-0.05*	-0.03*	-0.01*	-	-	0.42

* denotes significant coefficient (α=0.10)

Pollutant load MLR models will vary from EMC models. Pearson correlation analysis shows greater correlation between pollutant loads and factors than between EMCs and factors, so MLR models are expected to be stronger. These models will indicate what factors influence pollutant loads the most, and therefore should be the focus of management strategies. Stepwise factor selection methods produced variable results for pollutant load models. To create comprehensive models, climatic and watershed factors were added and removed until the best fitting model was found. Watershed area was not included because pollutant loads are normalized by area. The models in Table 2-25 were selected based on overall model fit statistics and the significance of individual coefficients. An example pollutant load model is below:

Equation 2-6

$$\text{Log(TN load)} = \beta_0 + \beta_1(\text{Rainfall Depth}) + \beta_2(\text{Temperature})$$

Pearson correlation coefficients between pollutant loads and rainfall depth showed a positive relationship. All MLR models except TSS and Pb load include a significant, positive coefficient for rainfall depth. For the TSS and Pb models, peak hourly intensity was significant and positive as the Pearson correlation analysis showed. Pollutant load increases as rainfall depth increases due to increasing volume of runoff. Additionally, higher intensities are correlated with larger runoff volumes in this dataset, so pollutant loads also increase with intensity.

Temperature was included in models because pollutant loads varied with seasons. Pb and Zn models were tested with temperature as a factor, but the final model was stronger without it. Impervious fraction was tested in the models, but did not benefit the models overall.

While R^2 values were greater for pollutant loads than for pollutant EMCs, they were still low for all models, indicating that the models do not explain all the variance in pollutant loads.

Table 2-25: MLR coefficients for pollutant loads.

Variable	Intercept	Rainfall (mm)	Hourly Intensity (mm/hr)	Duration (hr)	Temperature (°C)	R^2
Log(TN)	0.64	0.02*	-	-	0.02*	0.36
Log(TP)	-0.11	0.02*	-	-	0.02*	0.32
Log(TSS)	2.60	-	0.03*	-	0.02*	0.35
Log(Cu)	-1.46	0.02*	-	-	0.02*	0.31
Log(Pb)	-1.37	-	0.06*	-	-	0.49
Log(Zn)	-0.04	0.02*	-	-0.02*	-	0.22

* denotes significant coefficient (α=0.10)

2.7 First Flush Analysis

Due to the apparent dilution effect discovered in the MLR models, a first flush analysis was conducted. In the first flush, a disproportionately high fraction of pollutants are washed off impervious surfaces in the first portions of a storm. Several studies have indicated that the first flush exists by comparing cumulative load to cumulative runoff volume (Deletic, 1998; Hathaway & Hunt, 2011; Hathaway et al., 2012). In a different type of analysis examining rainfall depth rather than runoff volume, Flint and Davis (2007) found that more than 80% of pollutant mass of metals, nutrients, and TSS could be treated by capturing the first 13 mm of a storm.

To measure the first flush effect, the load for each storm was normalized by runoff depth to determine the mass of pollutant that leaves the surface with each millimeter of runoff (g/ha·mm) (Equation 3-4). These loads were then averaged for 12.7 mm rainfall intervals to determine if a trend existed (Figures 2-7 and 2-8).

$$\text{Normalized Load} = \frac{L}{R_D}$$

Where,

Normalized Load = Load per mm of runoff (g/ha·mm)

L = Pollutant Load (g/ha)

R_D = Runoff Depth (mm)

All pollutants, except Pb, have largest normalized loads in rainfall under 12.7 mm. TP, TSS, and Zn show a negative trend in load as rainfall increases. Average Pb loads are largest between 12.7 and 25.5 mm, but decrease after 25.4 mm. Taken together these figures show that a large portion of the pollutant load can be captured in the first 12.7 mm of rainfall, just as Flint and Davis (2007) found. Hathaway et al. (2012) show a stronger first flush for nitrogen species than phosphorous, but this study shows a stronger first flush for phosphorous than nitrogen. Wilmington, NC lies in an area of higher nitrogen atmospheric deposition than other portions of the state, which may explain the weak TN first flush effect.

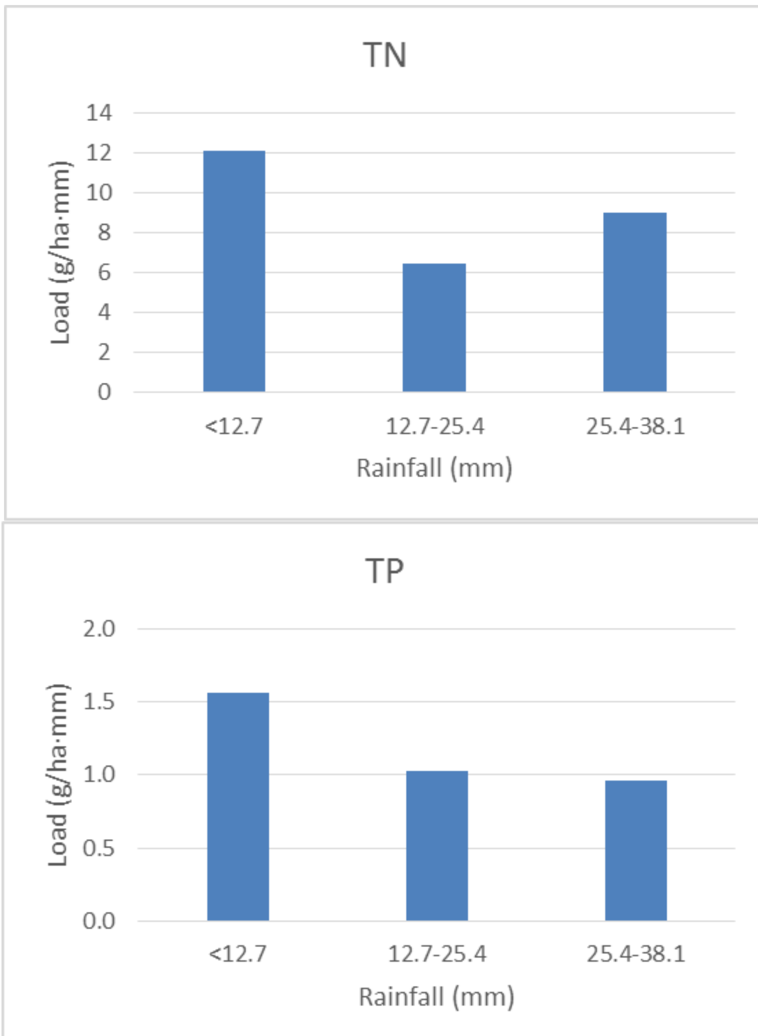


Figure 2-7: Average nutrient mass per millimeter of runoff over three rainfall intervals (n=44).

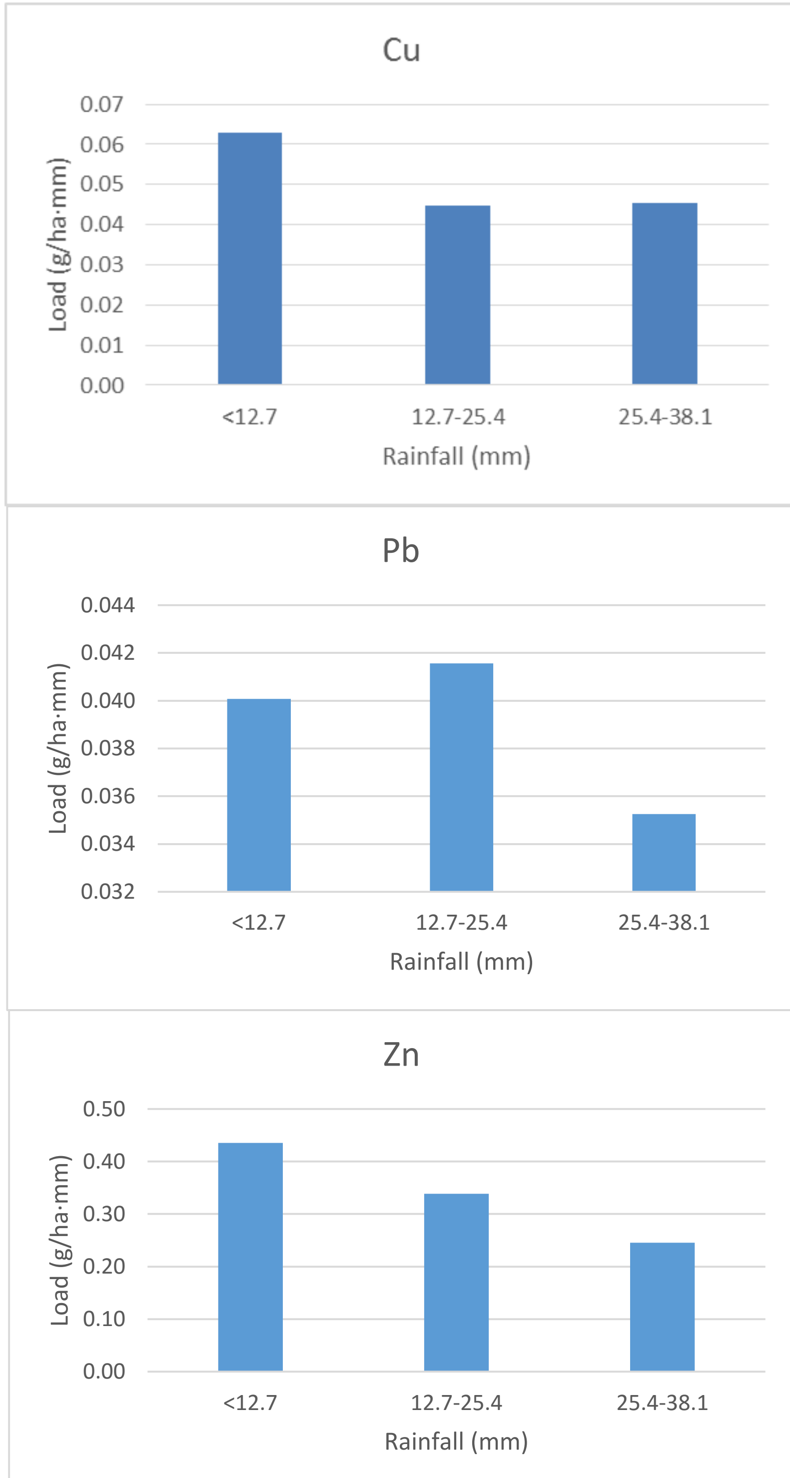


Figure 2-8: Average metal mass per millimeter of runoff over three rainfall intervals (n=44).

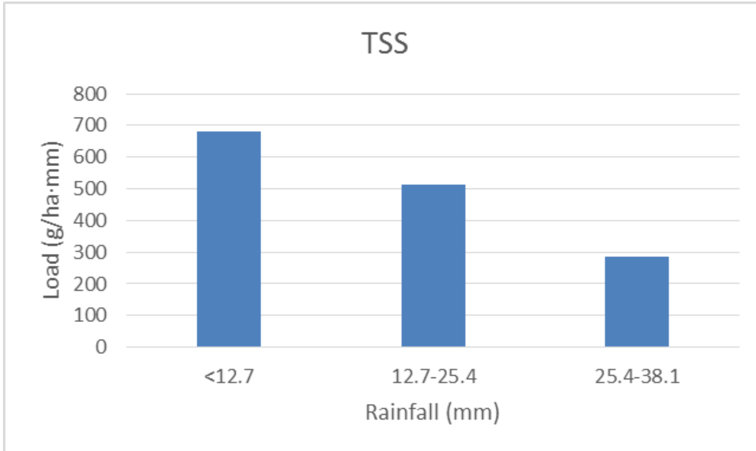


Figure 2-9: Average TSS mass per millimeter of runoff over three rainfall intervals (n=44).

2.8 Summary and Conclusions

This study sought to characterize aging parking lot runoff hydrology and water quality in the Coastal Plain of North Carolina. The parking lot runoff was compared to data from previous parking lot and highway studies. Statistical models were created to explain variation in hydrology, pollutant EMCs, and pollutant loads. The following conclusions were drawn:

1) Runoff volume (0.007 m^3/m^2) and peak flow (0.006 $L/s \cdot m^2$) from this parking lot were lower than those found in other parking lot studies (Davis, 2008; Li et al., 2009). This may be due to the ageing condition of the parking lot, which has surface storage due to erosional features.
2) The average ROC of the parking lot was 0.30, lower than expected for a highly impervious area. This number is lower than the ROC (0.51) found for a parking lot in Florida (Rushton, 2001).

3) MLR models predict that rainfall depth, temperature, peak hourly rainfall intensity, and watershed area are the most important factors for explaining variation in runoff volume, ROC, and peak discharge.
4) Overall, parking lot runoff EMCs are less than those for highways for TN, TP, TSS, Cu, Pb, and Zn (Hunt et al., 2008; Kayhanian et al., 2007; Li & Davis, 2009; US EPA, 1983; Passeport et al., 2009; Rushton, 2001; Stagge et al., 2012; Wu et al., 1998). This can generally be attributed to greater traffic on highways than in parking lots. Pollutant loading models should consider parking lot and highway area separately.
5) Daily traffic has an effect on metals accumulation (Kayhanian et al., 2003). This parking lot has lower Cu (5 µg/L) and Zn (36 µg/L) EMCs than other parking lots (Hunt et al., 2008; Li & Davis, 2009; Rushton, 2001). This may be due to intermittent use of parking lot, because it serves a high school. Vehicles only enter and leave two times a day, providing less opportunity for tire and break wear.
6) This parking lot has greater TSS (53.8 mg/L) EMCs than other parking lots reported (Hunt et al., 2008; Li & Davis, 2009; Passeport et al., 2009; Rushton, 2001). This is due to underlying sandy soils and condition of the parking lot exporting sediment and associated pollutants.
7) The TN (0.98 mg/L) EMC in this parking lot is lower than that of lots in both the Piedmont (Hunt et al., 2008) and Coastal Plain (Passeport et al., 2009) of NC. The TP EMC is similar to that of the other NC lots. Lower TN amounts may be due to a lack of heavy landscaping in the lot.

8) TP, TSS, and Cu EMCs are greater than ambient water quality criteria for coastal NC (McNett et al., 2010; NCDEQ, 2016). Other parking lots are generally above this criteria for Zn as well, but this parking lot's EMC is equal to the water quality criteria. Parking lots generally come closer to ambient water quality targets than highways.

9) Pollutant EMCs showed no seasonal variation, while loads were greatest in the summer. This is due to higher amounts and intensities in the warmer months producing higher runoff volumes. This indicates that designers may need to target management of summer average intensities rather than the full year to best treat pollutants in runoff.

10) All pollutant EMCs were significantly, negatively correlated with storm duration. This points to a dilution effect as accumulated pollutants are swept away with the first flush of runoff (Brezonik & Stadelmann, 2002; Passeport & Hunt, 2009).

11) MLR models for pollutant EMCs indicate that rainfall depth, rainfall intensity, storm duration, temperature, impervious fraction, and watershed area are all important factors that explain variation in EMCs. Duration was a significant factor for all EMCs.

12) Pollutant loads are significantly correlated with rainfall depth, intensity, duration, and temperature. Loads increase with depth and intensity due to increasing volume, but decrease with duration pointing to a dilution effect again. Correlation with temperature indicates that loads vary with the seasons.

13) MLR models for pollutant loads indicate that rainfall depth, rainfall intensity, storm duration, and temperature as the most important factors for explaining variation in loads.

14) All pollutants, except Pb, show a first flush effect, with greatest load per millimeter of runoff occurring in the first 12.7 mm of rainfall. Management of the first portions of the storm may be the most important for pollutant treatment.

15) Overall, this study indicates the need for further study of parking lot age and condition. This deteriorating parking lot can store runoff on its surface while generating sediment due to erosion.

2.9 References

ASCE. (1992). Design and construction of urban stormwater management systems. WEF Manual of Practice FD-20, New York, 91-92.

Bannerman, R., Owens, D., Dodds, R., & Homewer, N. (1993). Sources of Pollutants in Wisconsin Stormwater. *Water Science and Technology, 28*(3-5), 241–259.

Bledsoe, B. P., & Watson, C. C. (2001). Effects of urbanization on channel instability. *Journal of the American Water Resources Association, 37*(2), 255–270.

Brezonik, P. & Stadelmann, T. (2001). Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA. *Water Research*, *36*, 1743-1757.

Brinkmann, W. (1985). Urban Stormwater Pollutants: Sources and Loadings. *GeoJournal, 11(*3), 277–283.

Brown, R., Line, D. E., & Hunt, W. F. (2012). LID Treatment Train: Pervious Concrete with Subsurface Storage in Series with Bioretention and Care with Seasonal High Water Tables. *Journal of Environmental Engineering, 138*(6), 689–697.

Clausen, J. & Spooner, J. (1993). Paired Watershed Study Design. United States Environmental Protection Agency, Washington, DC.

Davis, A. (2005). Green Engineering Principles Promote Low-Impact Development. *Environmental Science & Technology, 6*(8), 338A–344A.

Davis, A. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering, 13*(2), 90–95.

Davis, A., Shokouhian, M., Ni, S. (2001). Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere, 44*, 997-1009.

Davis, A., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water Quality Improvement through Bioretention Media : Nitrogen and Phosphorus Removal. *Water Environment Research*, *78*(3), 284–293.

DeBusk, K. M., Hunt, W. F., & Line, D. E. (2011). Bioretention Outflow : Does It Mimic Nonurban Watershed Shallow Interflow? *Journal of Hydrologic Engineering, 16*, 274–279.

Deletic, A. (1998). The First Flush Load of Urban Surface Runoff. *Water Research, 32*(8), 2462-2470.

Drapper, D., Tomlinson, R., & Williams, P. (2000). Pollutant Concentrations in Road Runoff: Southeast Queensland Case Study. *Journal of Environmental Engineering, 126*(4), 313–320.

Flint, K. & Davis, A. (2007). Pollutant Mass Flushing Characterization of Highway Stormwater Runoff from an Ultra-Urban Area. *Journal of Environmental Engineering, 133*(6), 616-626.

Grebel, J., Mohanty, S., Torkelson, A., Boehm, A., Higgins, C., Maxwell, R., Sedlak, D. (2013). Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environmental Engineering Science, 30*(8), 437–454.

Hathaway, J. & Hunt, W. (2011). Evaluation of First Flush for Indicator Bacteria and Total Suspended Solids in Urban Stormwater Runoff. *Water, Air, and Soil Pollution, 217*, 135-147.

Hathaway, J., Tucker, R., Spooner, J., & Hunt, W. (2012). A Traditional Analysis of the First Flush Effect for Nutrients in Stormwater Runoff from Two Small Urban Catchments. *Water, Air, and Soil Pollution, 223*, 5903-5915.

Hope, D., Naegeli, M. W., Chan, A. H., & Grimm, N. B. (2004). Nutrients on asphalt parking surfaces in an urban environment. *Water, Air, and Soil Pollution, 4*(2-3), 371–390.

Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *Journal of Environmental Engineering, 134*(5), 403–408.

ISCO Flowlink Software V 5.11.206. (2005). Teledyne ISCO, Inc. Lincoln, Nebraska.

James, R. R., Wilbon, P., & Divincenzo, J. P. (2010). Pervious and impervious urban stormwater runoff in a rapidly urbanizing region: Occurrence of fluoranthene and pyrene. *Bulletin of Environmental Contamination and Toxicology, 85*(1), 32–36.

Jennings, D., & Jarnagin, S. (2002). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology, 17,* 471–489.

Kayhanian, M., Singh, A., Suverkropp, C., & Borroum, S. (2003). Impact of Annual Average Daily Traffic on Highway Runoff Pollutant Concentrations. *Journal of Environmental Engineering, 129*(11), 975-990.

Kayhanian, M., Suverkropp, C., Ruby, A., & Tsay, K. (2007). Characterization and prediction of highway runoff constituent event mean concentration. *Journal of Environmental Management, 85*, 279-295.

Knight, E. M. P., Hunt, W. F., & Winston, R. J. (2013). Side-by-side evaluation of four level spreader-vegetated filter strips and a swale in eastern North Carolina. *Journal of Soil and Water Conservation, 68*(1), 60–72.

Leopold, L. (1968). Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. United States Department of the Interior, Washington, DC.

Li, H., & Davis, A. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *Journal of Environmental Engineering, 135*, 567–576.

Li, H., Sharkey, L., Hunt, W., & Davis, A. (2009). Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. *Journal of Hydrologic Engineering, 14*, 407–415.

Line, D., & White, N. (2007). Effects of Development on Runoff and Pollutant Export. *Water Environment Research, 79*(2), 185–190.

Mahler, B., Van Metre, P., Bashara, T., Wilson, J., & Johns, D. (2005). Parking Lot Sealcoat: An Unrecognized Source of Urban Polycyclic Aromatic Hydrocarbons. *Environmental Science & Technology, 39*(15), 5560–5566.

McIntyre, J. K., Edmunds, R. C., Anulacion, B. F., Davis, J. W., Incardona, J. P., Stark, J. D., & Scholz, N. L. (2016). Severe Coal Tar Sealcoat Runoff Toxicity to Fish Is Prevented by Bioretention Filtration. *Environmental Science & Technology, 50*(3), 1570–1578.

McNett, J. K., Hunt, W. F., & Osborne, J. A. (2010). Establishing Storm-Water BMP Evaluation Metrics Based upon Ambient Water Quality Associated with Benthic Macroinvertebrate Populations, *Journal of Environmental Engineering, 136*(5), 535–541.

Murphy, L., Cochrane, T., & O'Sullivan, A. (2015). The Influence of Different Pavement Surfaces on Atmospheric Copper, Lead, Zinc, and Suspended Solids Attenuation and Wash-Off. *Water, Air, and Soil Pollution, 226*, 232.

National Research Council. (2008). Urban Stormwater Management in the United States. National Academy of Sciences, Washington, DC.

NC DEQ. (2014). 303d List of Impaired Waters. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

NC DEQ. (2016). North Carolina Surface Water Standards and Protective Values. North Carolina Department of Environmental Quality, Raleigh, North Carolina

Ngabe, B., Bidleman, T., & Scott, G. (2000). Polycyclic aromatic hydrocarbons in storm runoff from urban and coastal South Carolina. *The Science of the Total Environment, 255*, 1–9.

NWS. (2016). Regional Climate Report. National Weather Service Wilmington International Airport.

Page, J. L., Winston, R. J., Mayes, D. B., Perrin, C. A., & Hunt, W. F. (2015). Retrofitting Residential Streets with Stormwater Control Measures over Sandy Soils for Water Quality Improvement at the Catchment Scale. *Journal of Environmental Engineering, 141*(4).

Passeport, E., & Hunt, W. (2009). Asphalt Parking Lot Runoff Nutrient Characterization for Eight Sites in North Carolina, USA. *Journal of Hydrologic Engineering, 14*(4), 352–361.

Passeport, E., Hunt, W. F., Line, D. E., Smith, R.., & Brown, R. (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. *Journal of Irrigation and Drainage Engineering, 135*(4), 505–510.

Paul, M., & Meyer, J. (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics*, *32*(1), 333–365.

Pitt, R., & Bannerman, R. (2005). Sources of pollutants in urban areas (Part 1)–Older monitoring projects. *Effective Modeling of Urban Water Systems*, 1–20.

Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability. *Water Environment Research, 67*(3), 260–275.

Rushton, B. (2001). Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management, 127*, 172–179.

Sartor, J. D., Boyd, G. B., & Agardy, F. J. (1974). Water pollution of street surface contaminants. *Journal (Water Pollution Control Federation), 46*(3), 458–467.

SAS Institute Inc. (Version 9.2) [Software]. (2008). The SAS system for Windows.

Stagge, J. H., Davis, A. P., Jamil, E., & Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research, 46*(20), 6731–6742.

State Climate Office of NC. (2016). 1971-2000 Climate Normals. Accessed March 1, 2016.

US Census Bureau. (2014). QuickFacts Wilmington, North Carolina. United States Department of Commerce, Washington, DC.

USDA. (1977). Soil Survey of New Hanover County, North Carolina. United States Department of Agriculture Soil Conservation Service.

US EPA. (1983). Results of the Nationwide Urban Runoff Program, Volume 1-Final Report. National Technical Information Service (NTIS), Washington, DC.

US EPA. (2015b). Learn About Lead. United States Environmental Protection Agency. Accessed 9 March 2016.

Walsh, C., Sharpe, A., Breen, P., & Sonneman, J. (2001). Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities. *Freshwater Biology, 46,* 535–551.

Wu, J., Allan, C., Saunders, W., & Evett, J. (1998). Characterization and Pollutant Loading Estimation for Highway Runoff. *Journal of Environmental Engineering, 124*(7), 584-592.

CHAPTER 3: HYDROLOGIC AND WATER QUALITY EFFECTS OF RETROFITTING A PARKING LOT WITH INFILTRATING STORMWATER CONTROL MEASURES

3.1 Abstract

Stormwater regulations often focus on new development while pre-existing sites continue to produce runoff unchecked. In an effort to mitigate this continuing stormwater pollution, it may be necessary to retrofit pre-existing development. Parking lots are a major source of stormwater and offer the opportunity for retrofitting with stormwater control measures (SCMs) without disrupting traffic flow. In this study an undersized pair of infiltrating SCMs was installed in a parking lot in Wilmington, North Carolina. The loading ratio of impervious area to infiltrating area for these systems is 18:1. Monitoring occurred pre- and post-retrofit for hydrologic and water quality variables. Pre-retrofit monitoring occurred February-June 2014, the SCMs were constructed July-August 2014, and monitoring continued post-retrofit September 2014-December 2015. The retrofit reduced the runoff coefficient (ROC) by 36%, but did not significantly impact the runoff depth or peak discharge leaving the site. Pollutant event mean concentrations (EMCs) did not change after the retrofit. Total suspended solids (TSS) and organic nitrogen loads decreased post-retrofit. All pollutant loads but nitrate-nitrite and total ammoniacal nitrogen were reduced when pre-season data was compared to a ‘Like-Season’ post-retrofit dataset. Greater than fifty percent of total phosphorous, TSS, copper, and zinc concentrations exceeded ambient water quality thresholds for freshwater aquatic life in coastal NC.

3.2 Introduction

Urbanization increases impervious surface coverage, leading to greater amounts of stormwater runoff and pollutant loads entering nearby waters (Jennings & Jarnagin, 2002). Impervious surfaces decrease the ability of a watershed to store rainfall through infiltration and evapotranspiration, increasing surface runoff by up to 45% (Paul & Meyer, 2001). This in turn leads to stream incision, erosion, downstream flooding, and a decrease in groundwater discharge (Bledsoe, 2002; DeBusk et al., 2011; Jennings & Jarnagin, 2002; Leopold, 1968; Line & White, 2007). Urban stormwater pollutants include nutrients, sediment, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and pathogens.

Parking lots are a common source of stormwater runoff in the urban landscape. Traditionally, parking lots have been designed with curb and gutters to remove runoff as quickly as possible, amplifying stormwater impacts (Davis, 2005). Organic and inorganic particulates accumulate on parking lot surfaces from atmospheric deposition, vehicular fluids, and organic litter (Brinkmann, 1985; Passeport & Hunt, 2009; Pitt & Bannerman, 2005). The pollutant loading of a parking lot depends on its age, pavement type, antecedent dry period, and rainfall intensity (Drapper et al., 2000; Hope et al., 2004; Pitt et al., 1995; Rushton, 2001).

Nutrients in parking lot runoff originate from atmospheric deposition, organic litter, and fertilizers used in landscaping (Brinkmann, 1985; Davis et al., 2006; Pitt et al., 1995). Nitrogen and phosphorous in runoff exist in solid and aqueous forms. The dissolved forms are of particular concern because they can lead to eutrophication downstream.

Vehicles are a main source of heavy metals such as copper, lead, and zinc (Bannerman et al., 1993; Davis et al., 2001; Grebel et al., 2013). Cu and Zn originate from brake and tire wear, while vehicular exhaust deposition is the main source of Pb (Brinkmann, 1985; Grebel et al., 2013; Pitt & Bannerman, 2005). Heavy metals accumulate in the aquatic environment, and can cause toxicity issues for aquatic species (Grebel et al., 2013). PAHs, oils and grease, also come from vehicular fluids (Davis, 2005; Mahler et al., 2005; Pitt et al., 1995). Coal-tar sealcoat, used in many asphalt parking lots, contributes PAHs to runoff as it erodes (Mahler et al., 2005; McIntyre et al., 2016). Like metals, accumulation in the aquatic environment has toxicant effects (James et al., 2010; Ngabe et al., 2010).

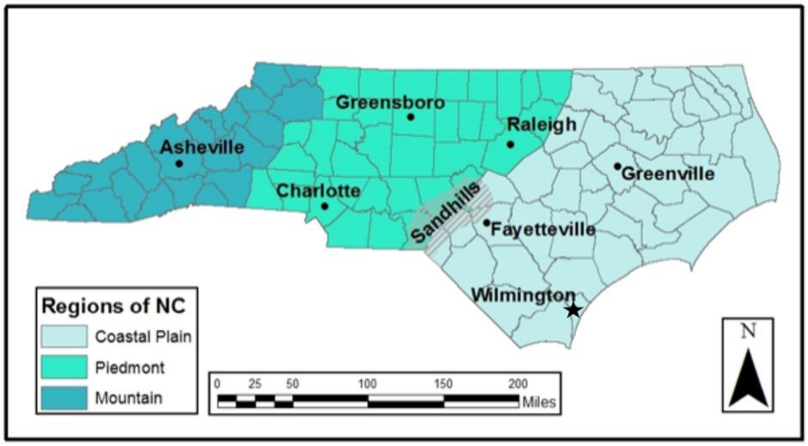
Stormwater management is regulated at the state and federal level. The National Pollutant Discharge Elimination System (NPDES) has two phases that require municipalities of various size to construct Stormwater Control Measures (SCMs) to combat stormwater pollution. SCMs include bioretention cells, green roofs, permeable pavement, constructed wetlands, and others.

Infiltrating SCMs such as bioretention and bioswales significantly reduce urban runoff and decrease pollutant concentrations in effluent. Bioretention cells can eliminate runoff from small storm (Davis, 2008; Hunt et al., 2008). The main pollutant removal mechanisms within infiltrating SCMs are filtration, sedimentation, infiltration, vegetative uptake, adsorption, and biogeochemical processes (Hunt et al., 2012; LeFevre et al, 2015). Infiltrating SCMs significantly reduce total suspended solids (TSS) in runoff and other pollutants bound to sediment such as phosphorous, heavy metals, and PAHs (DiBlasi et al., 2009; Li & Davis, 2009; Li & Davis, 2015). Water quality evaluations show variable reduction efficiency for pollutants with significant dissolved components (Brown & Hunt, 2011b; Dietz & Clausen, 2005; Li & Davis, 2009). In some cases pollutant load reductions can be attributed to runoff volume decreases rather than change in concentration (Li & Davis, 2009).

Pre-existing development is not required to manage stormwater to comply with regulations. However, new local regulations on pollutant loads may require these sites to retrofit with SCMs. Parking lots offer an opportunity for retrofitting existing pervious area without impacting traffic flow. When retrofitting, it may be necessary to produce undersized SCMs in order to fit within available land area. This study examined the effect of an undersized SCM retrofit on parking lot runoff in the Coastal Plain of North Carolina.

3.3 Site Description

The project site is located at New Hanover High School (NHHS) in Wilmington, North Carolina. Wilmington lies near the mouth of the Cape Fear River within the Coastal Plain ecoregion (Figure 3-1). The city population is 113,000, a NPDES Phase II jurisdiction (US Census Bureau, 2014). Wilmington has a moderate climate, with normal temperatures ranging from 7.8°C in January to 27.3°C in July (State Climate Office of NC, 2016). Average annual rainfall is 1448 mm; July is on average the wettest month (194 mm) and April is the driest (75 mm) (State Climate Office of NC, 2016).



Data from NC DOT and ArcGIS Online

Figure 3-1: Map of North Carolina with ecoregions and project location.

The NHHS parking lot lies within the Burnt Mill Creek watershed, which drains to the Cape Fear River and has been on the North Carolina 303(d) impaired waters list since 2004 due to turbidity, benthic health, and toxicity (NCDEQ, 2014). Watershed scale stormwater projects have been ongoing since 2010.

The asphalt parking lot was created in 1954 and is in relatively fair condition, with potholes forming and large amounts of sediment accumulation due to erosion (Figure 3-2). It has not been resurfaced in at least 10 years. The site originally had five parking lot islands, two with large trees established and the others with crepe myrtle shrubs. There are three traffic lanes, six rows of parking, and a large open space for school bus drop-offs (Figure 3-3). The lot is primarily used by students during the school year (September-June), but is also used by churchgoers at the adjacent St. Andrews-Covenant Presbyterian Church on Sundays. The parking lot was observed to fill to capacity during school hours.

Figure 3-2: NHHS parking lot pre-retrofit. Note parking lot islands, space between parking stops, and large amounts of sediment.

The site is 0.65 ha overall, split into two sub-watersheds that drain into individual conventional catch basins at the eastern end of the lot (Figure 3-3). The southern sub-watershed (0.2 ha) will hereby be referred to as the “Control” and the northern sub-watershed (0.45 ha) will be referred to as “Retrofit”. The sub-watersheds consist of the parking lot and a bordering sidewalk. A particle size analysis, using the hydrometer method, confirmed the New Hanover County Soil Survey classification of sandy underlying soils. The average longitudinal slope is 2%. Table 3-1 lists the watershed characteristics.

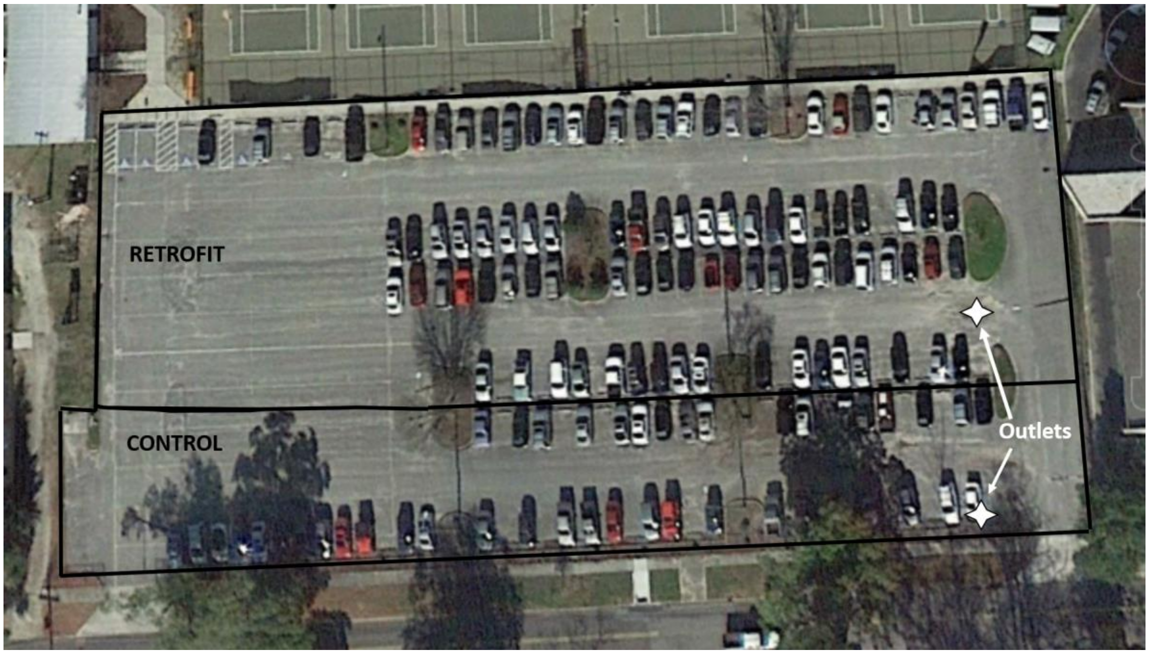


Figure 3-3: An aerial view of the parking lot at NHHS pre-retrofit. The black line delineates the two sub-watersheds within the lot.

Table 3-1: Description of the two sub-watersheds pre-retrofit.

Parameter	Watershed	
	Control	Retrofit
Drainage Area (m^2)	2015	4485
Length (m)	122	122
Width (m)	18	40
Impervious Fraction	0.97	0.95
Slope (%)	2	2
Soil Series	Leon Urban Land Complex	Leon Urban Land Complex
USDA Soil Class	Sand	Sand
Outlet Location	34.235754, -77.931037	34.235972, -77.931064
Receiving Water Body	Burnt Mill Creek	Burnt Mill Creek
River Basin	Cape Fear	Cape Fear

3.4 Materials and Methods

SCM Retrofit

The parking lot was retrofitted with SCMs in summer 2014 to treat runoff from the Retrofit watershed (Figure 3-4). The three parking lot islands that did not have large trees were converted to bioretention cells. The areas between parking stops were dug out to become bioswales. The end result is two linear systems of bioswales connecting the BRCs. The northern system will be referred to as “System 1” and the southern system will be referred to as “System 2”. Water flows west to east within the systems.

Figure 3-4: This aerial photograph shows the parking lot after SCM establishment with new watershed delineations. Note the linear systems between parking stops.

The bioretention cell surface areas range from 21.4 m^2 to 59.5 m^2 with a maximum ponding depth of 0.3 m. Due to sandiness of in-situ soils, the BRCs were not amended with engineered media and are not underdrained. Each BRC is sodded and has a River Birch

(*Betula nigra*) tree. The bioswales have a cement curb border structure with multiple inlets. Backfill was used as media in the bioswales based on quality upon inspection. Concrete check dams were installed to promote ponding as water moved along the system, creating an average ponding depth of 0.23 m. The overall surface area of the bioswales is 127.7 m^2 and they are mulched and planted with Muhly Grass (*Muhlenbergia capillaris*), a drought tolerant species. Figure 3-5 depicts several stages of SCM construction and one of the final systems.

Figure 3-5: Phases of construction of the SCMs. Clockwise from Top Left: curb installed and systems dug out; check dams installed in swales with mulch; Muhly Grass planted within swales; resulting system with swales and bioretention areas.

System 2 combines the bioswales and remaining tree islands, culminating in a small bioretention cell. Upon installation, System 2 was disconnected by a tree island with a double inlet directly before the tree island. After observing several rainfall events a pipe was installed through the tree island to promote connectivity of the system. In System 1, excess ponding was observed in the final bioretention cell. Clogging was suspected so holes were bored in the cell and refilled with sand to promote better infiltration (Figure 3-6).

Figure 3-6: Post-construction amendments made to the systems as issues arose. (Left) Pipe installed through tree island; (Right) Sand cores installed to promote infiltration in BRC.

The overall surface area of the systems is 250 m^2 treating a watershed with 4485 m^2 of impervious area. This is severely undersized according to NC standards laid out in the BMP Manual. If traditional design methods were followed for this watershed using a 38.1 mm design storm and a ponding depth of 0.23 m, then the required infiltrating surface area would be 678 m^2. As constructed, the SCM surface area is 37% of the regulation surface area. The loading ratio is a measure of treatment ability for infiltrating SCMs (Equation 3-1).

The loading ratio for this site is approximately 18:1. Designed loading ratios are normally between 10:1 and 5:1 (PA DEP, 2005).

Loading Ratio = Impervious Drainage Area : Infiltrating Area   Equation 3-1

Monitoring Scheme

The initial monitoring scheme for this project was a paired watershed design (Clausen & Spooner, 1993) to evaluate hydrology and water quality of the parking lot. This approach requires two watersheds (Control and Retrofit) in a close vicinity and two monitoring periods (Calibration and Treatment). During the Calibration period conditions within the watersheds remain unchanged. After the Calibration period, a treatment is applied to one of the watersheds. In this case the retrofit SCMs were installed in the Retrofit watershed. The Treatment period continues monitoring post-retrofit. The paired watershed method benefits from the removal of climatic variables affecting end results. Any change in the Retrofit watershed should be directly attributable to the retrofit treatment.

Monitoring equipment was installed in the Control and Retrofit watershed catch basins in February 2014 (Table 3-2). ISCO 6712™ portable automated samplers were installed near the catch basins. Ninety-degree V-notch weirs and weir boxes were mounted within the catch basins to accurately measure discharge and volume from the parking lot (Figure 3-7). ISCO 730™ bubbler flow modules were used in concert with the ISCO 6712™ to measure stage above the weirs at two minute intervals. Bubbler and sampler tubing were run under protective plastic speed bumps across the drive aisles into the catch basins. Samplers were powered by 12-volt batteries and an attached solar panel. Rainfall was monitored utilizing an automated gauge and manual gauge. A HOBO™ tipping bucket rain gauge was installed alongside a cylinder gauge on a wooden post in a clear area (Figure 3-7). The tipping bucket gauge was connected to the Retrofit ISCO 6712™ sampler and recorded rainfall in 0.25 mm increments on two-minute intervals.

Table 3-2: Summary of equipment installed for water quality and hydrology monitoring.

Equipment	Type	Interval
Weir	90° V-notch	N/A
Flow Monitoring Device	ISCO 730™ Bubbler Module	2-minute
Sampling Device	ISCO 6712™ Automated Sampler	Flow-paced
Power Source	12-volt Battery with 20-watt solar panel	N/A
Rainfall Monitoring Device	ISCO 674™ Tipping Bucket and Manual Rain Gauge	0.25 mm increments 2-minute

Figure 3-7: (Left) Tipping bucket and manual rain gauges; (Right) Weir box installed within catch basin.

The ISCO 6712™ samplers collected flow-weighted samples (200 mL) during storm events that were deposited in 1 of 24 1-L bottles. Flow weighting was adjusted based on expected rainfall amounts of incoming storms in order to capture at least 70% of the hydrograph. Samples were suctioned from the bottom of the weir box in an area of well-mixed flow.

Water quality samples were tested for Total suspend solids (TSS), total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrate-nitrite-nitrogen (NO_x-N), total phosphorous (TP), ortho-phosphate (O-PO_4^{3-}), copper (Cu), lead (Pb), zinc (Zn), and polycyclic aromatic hydrocarbons (PAHs). TSS and nutrient species were analyzed by the North Carolina Center for Applied Aquatic Ecology (CAAE) at NCSU in Raleigh, NC. PAHs and metals were analyzed by NCDEQ Environmental Chemistry Lab in Raleigh, NC. The labs are located 210 km from the study site. Laboratory methods and calculations are listed in Table 3-3.

Table 3-3: Laboratory methods and reporting limits for pollutants.

Pollutant	Name	Analytical Method	Reporting Limit (mg/L)
TKN[a]	Total Kjeldahl Nitrogen	EPA Method 351.2	0.28
NO_x-N[a]	Nitrate/Nitrite Nitrogen	SM 4500 NO3 F	0.0056
TAN[a]	Total Ammoniacal Nitrogen	SM 4500 NH3 G	0.007
TN	Total Nitrogen	=TKN + NO_x-N	NA
ON	Organic Nitrogen	=TKN – TAN	NA
TP[a]	Total Phosphorous	SM 4500 P F	0.01
O-PO_4^{3-}[a]	Ortho-Phosphate	SM 4500 P F	0.006
TSS[a]	Total Suspended Solids	SM 2540 D	2.5
Cu[b]	Copper	EPA 200.8	0.002
Pb[b]	Lead	EPA 200.8	0.002
Zn[b]	Zinc	EPA 200.7	0.010
PAH[b]	Polycyclic Aromatic Hydrocarbons	EPA 625/8270/3510	0.01-0.05

a: NC CAAE
b: NC DEQ

Water quality samples were collected within 24 hours of a rain event. Only storms producing 2.5 mm to 51 mm of rain were sampled as long as 70% of the hydrograph was accounted for. Additionally, both samplers were required to produce collectable samples in order to maintain the paired watershed design. Upon arrival, the flow-weighted samples were composited into one 24-L bottle and thoroughly mixed to re-suspend particles. At least 2 L was needed to fill all bottles for TSS, nutrient, and metal analyses. Five total liters were needed to add PAH analysis. A 1-L clear plastic bottle for TSS analysis was filled from the larger mixing bottle. From this smaller vessel a 30-mL sample was filtered through a 0.45-µm filter into a dark glass bottle for O-PO_4^{3-} testing. A 125-mL pre-acidified plastic bottle was filled for other nutrients. A 500-mL clear plastic bottle was filled and then preserved with nitric acid for metals analysis. On occasions when enough water was collected for PAH samples, a 3-L dark glass bottle was also filled. The large mixing bottle was agitated any time extra water was needed to fill the variety of bottles. Gloves were worn while sampling and the samples were immediately placed on ice.

Monitoring Challenges

The main challenge with this project was not discovered until the end of the monitoring period. As part of System 2, two curb cuts were placed in one location to allow runoff to enter from either side (Figure 3-8). This is the same location that required a pipe through the tree island. Storms of certain depth and intensity caused ponding within the cell to a height of the inlets. Any additional rain caused runoff to flow from the Retrofit watershed through the inlets and into the Control watershed and catch basin. After observing cross-over occur several times, it was determined that this was a very frequent occurrence. In effect, a new watershed was created during the Treatment period breaking the paired watershed assumptions (Table 3-4, Figure 3-4).

Table 3-4: Summary of watershed characteristics during the two monitoring periods.

Watershed	Dates	Drainage Area (m^2)	Impervious Fraction
CAL-Control	(February 2014-	2015	0.972
CAL-Retrofit	July 2014)	4485	0.950
TREAT-Control	(September 2014-	2507	0.966
TREAT-Retrofit	December 2015)	3996	0.916

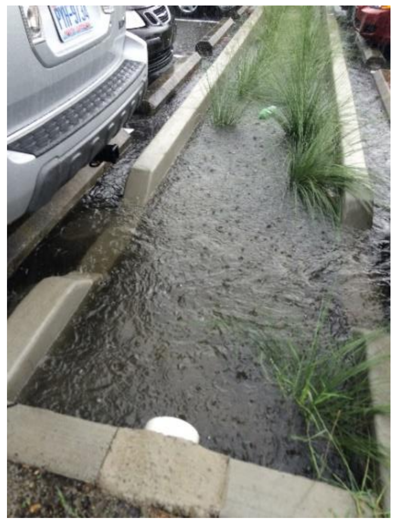


Figure 3-8: Stormwater flows from Retrofit watershed on right, across the swale, and exits to Control watershed on the left.

Other monitoring challenges were due to equipment malfunctions. Tubing had to be run across a drive aisle in the Retrofit watershed. Although it had a protective speed bump, continual wear and tear from speed bump movement caused tubing to break twice (Figure 3-9). The Control watershed tubing ran through a parking spot which led to an eventual break due to weight of vehicles. Loss of power due to battery outage was an issue during colder months. Equipment issues were often exaggerated due to distance from the project location. In several cases, storms were missed because the issue was discovered on a sampling trip.

Figure 3-9: (Left) Broken bubbler tubing due to friction from speed bump; (Right) Large amounts of organic litter clogging hidden catch basin.

The Control watershed contains two large deciduous trees and many flowering bushes, leading to large amounts of organic material clogging the catch basin during leaf fall and flowering seasons (Figure 3-9). In addition to removing this material from the catch basin grate, the weir box within also had to be continually cleaned out to keep flow unimpeded.

During installation of monitoring equipment for the Calibration period a mistake was made with the automated rain gauge. This resulted in missing rainfall data for nine storms. The project site is located 5.6 km from the Wilmington International Airport, site of a National Weather Service (NWS) weather station from which hourly rainfall data were acquired for missing storms.

Data Analysis

Hydrologic data were first reviewed within FLOWLINK Version 5.12 for any abnormalities (ISCO, 2005). Rainfall amounts were adjusted by a scaling factor calculated by comparing the tipping bucket totals to manual gauge totals. Rainfall events were separated for storms with at least 2.54 mm of rain and a six hour antecedent dry period. The data were then exported from FLOWLINK for further analysis and transformation. Five-minute and hourly intensities were calculated from transformed two-minute rainfall data. For the missing rainfall events in the Calibration period only hourly intensities could be computed. Flow was calculated from the recorded two-minute stage data using the stage-discharge weir equation from ISCO (Equation 3-2). Metric conversions were made after computation. From the two-minute flow data cumulative volume, runoff coefficient (ROC), and peak discharge could be calculated for each storm. The ROC represents the fraction of rainfall that becomes runoff.

$$Q = 2.5H^{2.5} \qquad \text{Equation 3-2}$$

Where,

Q = Discharge (cfs)

H = Head on Weir (ft)

Water quality data from the labs came in the form of event mean concentrations (EMCs). Sampling for PAHs was ended several months into the Treatment period because all concentrations were below detection limits. For other constituents, any concentrations less than the reporting limit were assigned a concentration one half the reporting limit. Concentrations were converted to pollutant loads for each storm using Equation 3-3.

$$L = \frac{V \times C}{A \times 1000} \quad \text{Equation 3-3}$$

Where,

L = Pollutant Load (g/ha)

V = Runoff Volume (L)

C = Event Mean Concentration (mg/L)

A = Area of Watershed (ha)

Statistical Analysis

SAS Version 9.3™ was used for all statistical analyses (SAS Institute, 2012). Hydrology and water quality datasets were first tested for normality both visually and diagnostically. Inspection of histograms and quintile-quintile plots in combination with three goodness of fit tests (Shapiro-Wilk, Anderson-Darling, and Lilliefors) was used to make the decision. Data that were not normal were log-transformed and retested for normality. Any data that remained not normal were tested with non-parametric methods.

Due to the failure of the paired watershed design, simple tests were used to evaluate the Retrofit watershed pre- and post-SCM. If data were normal, a two-sample t-test was performed. Otherwise, a Wilcoxon rank-sum test was done. Comparisons were made between runoff depth, runoff coefficient, peak discharge, and all water quality variables. Data were analyzed for significance with 95% confidence (α=0.05). An example of SAS code used for statistical analyses is provided in Appendix B. Additionally, runoff pollutant concentrations were compared to ambient water quality standards from various sources.

3.5 Results

Precipitation

Monitoring of the Calibration period occurred February 26, 2014 through July 3, 2014. In this time 16 hydrologic events were recorded, but three were eliminated due to technical difficulties. Rainfall for remaining storms to be analyzed ranged from 4.06 mm to 91.69 mm. The Treatment period lasted from September 6, 2014 to December 21, 2015. Seventy-seven events were recorded and 12 were removed due to equipment error. Rainfall for the events used in analyses for the Treatment period ranged from 2.54 mm to 64.01 mm. A "same season" comparison was made between Calibration events and Treatment events (March-June 2014-15). In the "Like-Season" Treatment period 17 events were recorded. During the Calibration period, 58% of rainfall was captured and used in analyses. In the Treatment period this number was 81% (Table 3-5). Table 3-6 describes the seasonal breakdown during the monitoring periods.

Table 3-5: Summary of rainfall during the monitoring periods.

Parameter	Calibration	Treatment	Like-Season[a]
Number of Hydrologic Events	13	65	17
Mean Rainfall Depth (mm)	18.9	19.5	16.7
Median Rainfall Depth (mm)	10.7	13.2	10.9
Minimum Rainfall Depth (mm)	4.1	2.5	4.6
Maximum Rainfall Depth (mm)	91.7	64.0	50.6
Mean 5-minute Peak Intensity	2.6	2.7	2.8
Median 5-minute Peak Intensity	2.7	2.0	1.5
Minimum 5-minute Peak Intensity	0.5	0.3	0.3
Maximum 5-minute Peak Intensity	4.6	10.2	9.7
Mean Hourly Peak Intensity (mm/hr)	7.7	8.2	7.3
Median Hourly Peak Intensity (mm/hr)	6.1	6.4	5.6
Minimum Hourly Peak Intensity (mm/hr)	1.5	0.8	0.8
Maximum Hourly Peak Intensity (mm/hr)	19.6	34.0	17.3

a: Refers to sub-dataset of Treatment data during same season as Calibration

Table 3-6: Number of rainfall events per season during monitoring periods.

Monitoring Period	Spring	Summer	Fall	Winter
Calibration	9	4	0	0
Treatment	13	18	21	13
Like-Season	13	1	0	3

The 30-year average rainfall for Wilmington is 1448 mm (Table 2-8). Overall, 2014 was an average year for rainfall (1518 mm). However, the end of the Calibration period was significantly drier than normal. The Treatment period had above average rainfall. In fact, rainfall in 2015 was 35% greater than the normal. Fall 2015 was one of the wettest on record, with rainfall in October and November being a cumulative 390 mm above normal (NWS, 2016).

Hydrology

Three hydrologic variables were used as a metric in retrofit analysis: runoff depth, ROC, and peak discharge. Due to watershed area changes, runoff volume was normalized by area to be tested as runoff depth and peak discharge was normalized by area as well (L/s·ha). The Treatment period was much longer than the Calibration period, so the metrics were compared for the Like-Season Treatment events as well.

Medians and means of the hydrologic variables during the Calibration and Treatment period are presented in Table 3-7. Differences in medians and means for runoff depth and peak discharge point to the need for transformation of the data. ROC data were normal for both periods. Statistical testing using two-sample t-tests shows that the reduction in ROC is significant (Table 3-8). The addition of the SCMs decreases the fraction of rainfall that becomes runoff.

Table 3-7: Summary of hydrologic variables and reductions between the Calibration and Treatment periods.

Variable	Median		Mean		Median Reduction (%)	Mean Reduction (%)
	CAL	TREAT	CAL	TREAT		
Runoff Depth (mm)	5.2	3.4	8.8	7.5	53	15
Runoff Coefficient	0.45	0.29	0.45	0.29	36	36
Peak Discharge (L/s/ha)	52.8	32.1	54.7	83.5	39	-53

Table 3-8: Summary of statistical analyses on reductions between the Calibration and Treatment periods.

Variable	n*	Distribution	Significance Test	p-value	Significant Difference
Runoff Depth	78	Log-Normal	Two-sample t-test	0.2528	no
Runoff Coefficient	78	Normal	Two-sample t-test	0.0011	**yes**
Peak Discharge	78	Log-Normal	Two-sample t-test	0.8325	no

*Combined, Calibration=13 Treatment=65

Summary statistics for the Calibration and Like-Season Treatment data resulted in similar distributions as for the full Treatment period (Table 3-9). Normality testing of the Like-Season Treatment data showed that ROC was normal while runoff depth and peak discharge were log-normal. Two sample t-tests proved that the differences in ROC pre- and post-retrofit are significant (Table 3-10). Scaling down to the smaller dataset did not improve results for hydrologic metrics. Boxplots comparing the distributions of the variables are shown in Figures 3-10 to 3-12.

Table 3-9: Summary of hydrologic variables and reductions between the Calibration and Like-Season Treatment data.

Variable	Median CAL	Median LIKE	Mean CAL	Mean LIKE	Median Reduction (%)	Mean Reduction (%)
Runoff Depth (mm)	5.2	5.1	8.8	3.4	2	61
Runoff Coefficient	0.45	0.26	0.45	0.28	42	38
Peak Discharge (L/s/ha)	52.8	39.4	54.7	76.4	25	-40

Table 3-10: Summary of statistical analyses on reductions between the Calibration and Like-Season periods.

Variable	n*	Distribution	Significance Test	p-value	Significant Difference
Runoff Depth	30	Log-Normal	Two-sample t-test	0.2300	no
Runoff Coefficient	30	Normal	Two-sample t-test	0.0060	**yes**
Peak Discharge	30	Log-Normal	Two-sample t-test	0.7695	no

*Combined, Calibration=13 Like-Season=17

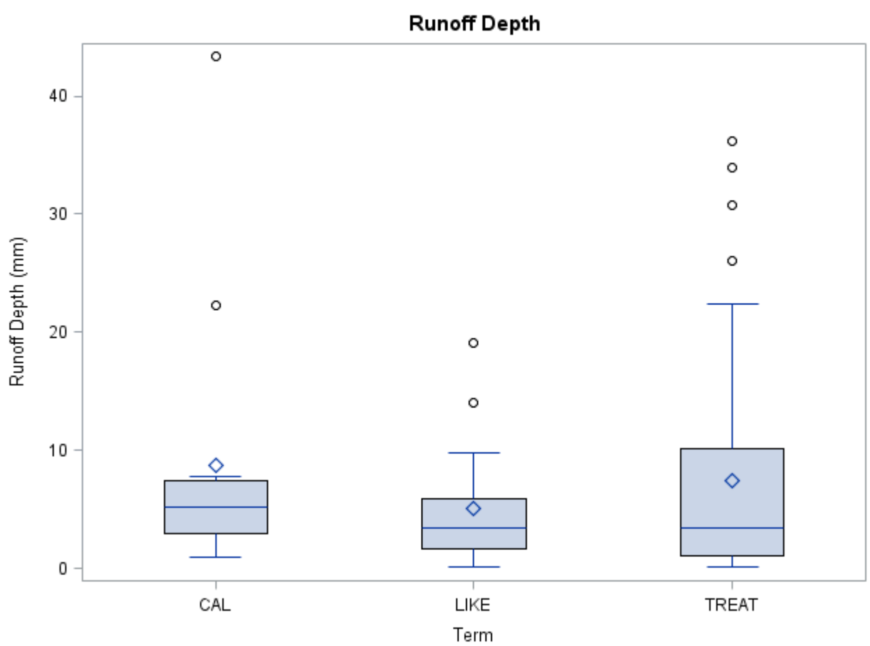


Figure 3-10: Boxplots of the runoff depth for the Calibration, Like-Season, and Treatment periods.

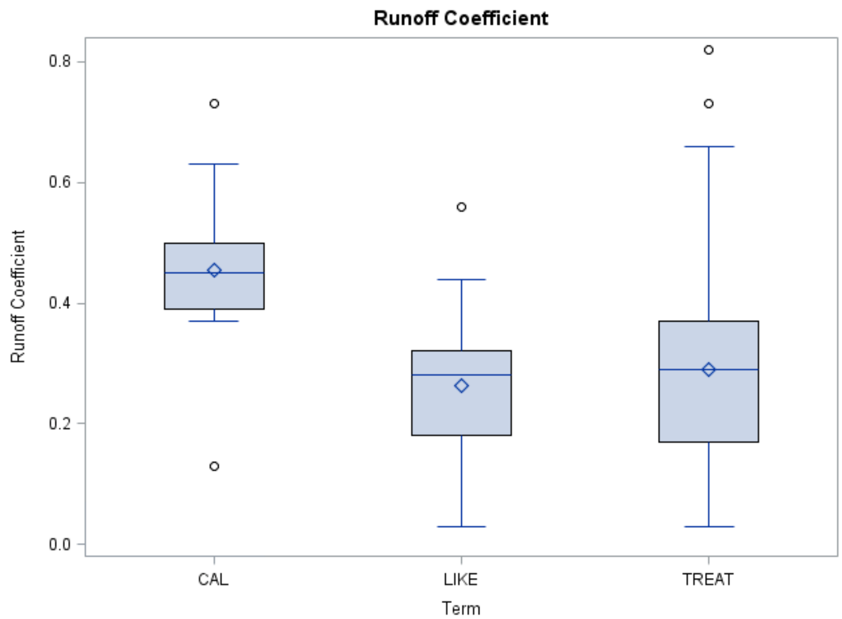


Figure 3-11: Boxplots of runoff coefficient for the Calibration, Like-Season, and Treatment periods.

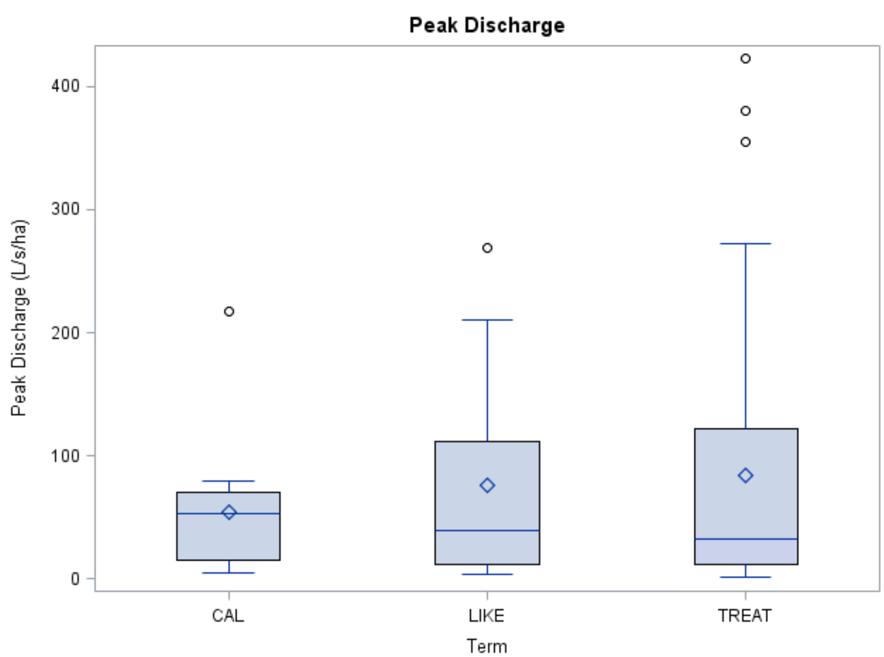


Figure 3-12: Boxplots of peak discharge for the Calibration, Like-Season, and Treatment periods.

Water Quality

During the Calibration period, six water quality samples were collected, however one was discarded due to equipment malfunction (Table 3-11). Rainfall for these events ranged from 9.40 mm to 91.69 mm with an average antecedent dry period of 90.9 hours. Seventeen water quality samples were collected during the Treatment period. Sampling events for this period ranged from 4.83 mm to 35.31 mm with an average antecedent dry period of 109.7 hours. The Like-Season rainfall ranged 4.8 to 31 mm and mean antecedent dry period of 99.67 hours. At least three storms per season were sampled for water quality (Table 3-12).

Table 3-11: Summary of rainfall events that were sampled for water quality analysis.

Parameter	Calibration	Treatment	Like-Season
Number of Water Quality Events	5	17	8
Mean Rainfall (mm)	27.9	18.3	14.2
Median Rainfall (mm)	12.5	17.8	10.9
Minimum Rainfall (mm)	9.4	4.8	4.8
Maximum Rainfall (mm)	91.7	35.3	31.0
Mean Peak Hourly Intensity (mm/hr)	9.7	8.6	4.7
Median Peak Hourly Intensity (mm/hr)	7.6	7.6	5.1
Minimum Peak Hourly Intensity (mm/hr)	6.1	0.8	0.8
Maximum Peak Hourly Intensity (mm/hr)	18.0	21.3	7.6
Mean Antecedent Dry Period (hr)	90.9	109.7	99.7
Median Antecedent Dry Period (hr)	67.0	62.6	59.6
Mean Event Duration (hr)	9.0	9.4	10.7
Median Event Duration (hr)	4.0	9.9	12.2

Table 3-12: Breakdown of water quality sampling events per season.

Monitoring Period	Spring	Summer	Fall	Winter
Calibration	5	0	0	0
Treatment	6	3	4	4
Like-Season	6	0	0	2

Table 3-13 presents means and medians with respective reductions for pollutant EMCs during the Calibration and Treatment periods. All pollutants had to be log-transformed except TAN, which was non-normal. Statistical analyses showed that none of the differences are significant (Table 3-14).

Table 3-13: Mean and median reductions of pollutants between the Calibration and Treatment periods.

Pollutant	Median (mg/L)		Mean (mg/L)		Median Reduction (%)	Mean Reduction (%)
	Calibration	Treatment	Calibration	Treatment		
TKN	1.11	0.58	0.94	0.67	48	28
NO_x-N	0.09	0.14	0.09	0.18	-54	-101
TAN	0.04	0.03	0.05	0.05	26	-17
TN	1.12	0.75	1.02	0.85	33	17
ON	1.08	0.52	0.89	0.62	52	30
TP	0.14	0.10	0.12	0.10	31	12
O-PO_4^{3-}	0.01	0.01	0.01	0.01	25	15
TSS	80.89	42.38	67.76	51.91	48	23
Cu	0.005	0.005	0.006	0.006	-10	1
Pb	0.003	0.004	0.004	0.004	-26	-11
Zn	0.031	0.037	0.036	0.038	-19	-5

Table 3-14: Summary of statistical analyses for the pollutant reductions between the Calibration and Treatment periods.

Variable	n*	Distribution	Significance Test	p-value	Significant Difference?
TKN	22	Log-normal	Two-sample t-test	0.2619	no
NO_x-N	22	Log-normal	Two-sample t-test	0.1486	no
TAN	22	Not Normal	Wilcoxon Rank Sum Test	0.2827	no
TN	22	Log-normal	Two-sample t-test	0.5317	no
ON	22	Log-normal	Two-sample t-test	0.2416	no
TP	22	Log-normal	Two-sample t-test	0.9549	no
O-PO_4^{3-}	22	Log-normal	Two-sample t-test	0.2733	no
TSS	22	Log-normal	Two-sample t-test	0.6527	no
Cu	22	Log-normal	Two-sample t-test	0.4646	no
Pb	22	Log-normal	Two-sample t-test	0.5533	no
Zn	22	Log-normal	Two-sample t-test	0.5369	no

*Combined, Calibration=5 Treatment=17

Calibration and Like-Season Treatment EMCs were also analyzed (Table 3-15). Similar to the Calibration-Treatment analysis, statistical analyses showed that the differences were not significant at the 95% confidence level (α=0.05) (Table 3-16). Figures 3-13 to 3-16 display boxplots of the pollutant concentrations during the monitoring periods.

Table 3-15: Mean and median reductions of pollutants between the Calibration and Like-Season periods.

Pollutant	Median (mg/L)		Mean (mg/L)		Median Reduction (%)	Mean Reduction (%)
	Calibration	Like-Season	Calibration	Like-Season		
TKN	1.11	0.70	0.94	0.79	37	16
NO_x-N	0.09	0.18	0.09	0.20	-94	-113
TAN	0.04	0.03	0.05	0.05	29	-7
TN	1.12	0.86	1.02	0.99	23	3
ON	1.08	0.67	0.89	0.74	37	17
TP	0.14	0.11	0.12	0.12	20	0
O-PO_4^{3-}	0.01	0.01	0.01	0.01	56	37
TSS	80.89	43.96	67.76	64.76	46	4
Cu	0.005	0.005	0.006	0.006	-6	-2
Pb	0.003	0.003	0.004	0.003	-5	17
Zn	0.031	0.037	0.036	0.037	-19	-3

Table 3-16: Summary of statistical analyses for the pollutant reductions between the Calibration and Like-Season periods.

Variable	n*	Distribution	Significance Test	p-value	Significant Difference?
TKN	13	Log-normal	Two-sample t-test	0.6753	no
NO_x-N	13	Log-normal	Two-sample t-test	0.0723	no
TAN	13	Not Normal	Wilcoxon Rank Sum Test	0.4118	no
TN	13	Log-normal	Two-sample t-test	0.9803	no
ON	13	Log-normal	Two-sample t-test	0.6696	no
TP	13	Log-normal	Two-sample t-test	0.7821	no
O-PO_4^{3-}	13	Log-normal	Two-sample t-test	0.0564	no
TSS	13	Log-normal	Two-sample t-test	0.9996	no
Cu	13	Log-normal	Two-sample t-test	0.5630	no
Pb	13	Log-normal	Two-sample t-test	0.9532	no
Zn	13	Log-normal	Two-sample t-test	0.5952	no

*Combined, Calibration=5 Like-Season=8

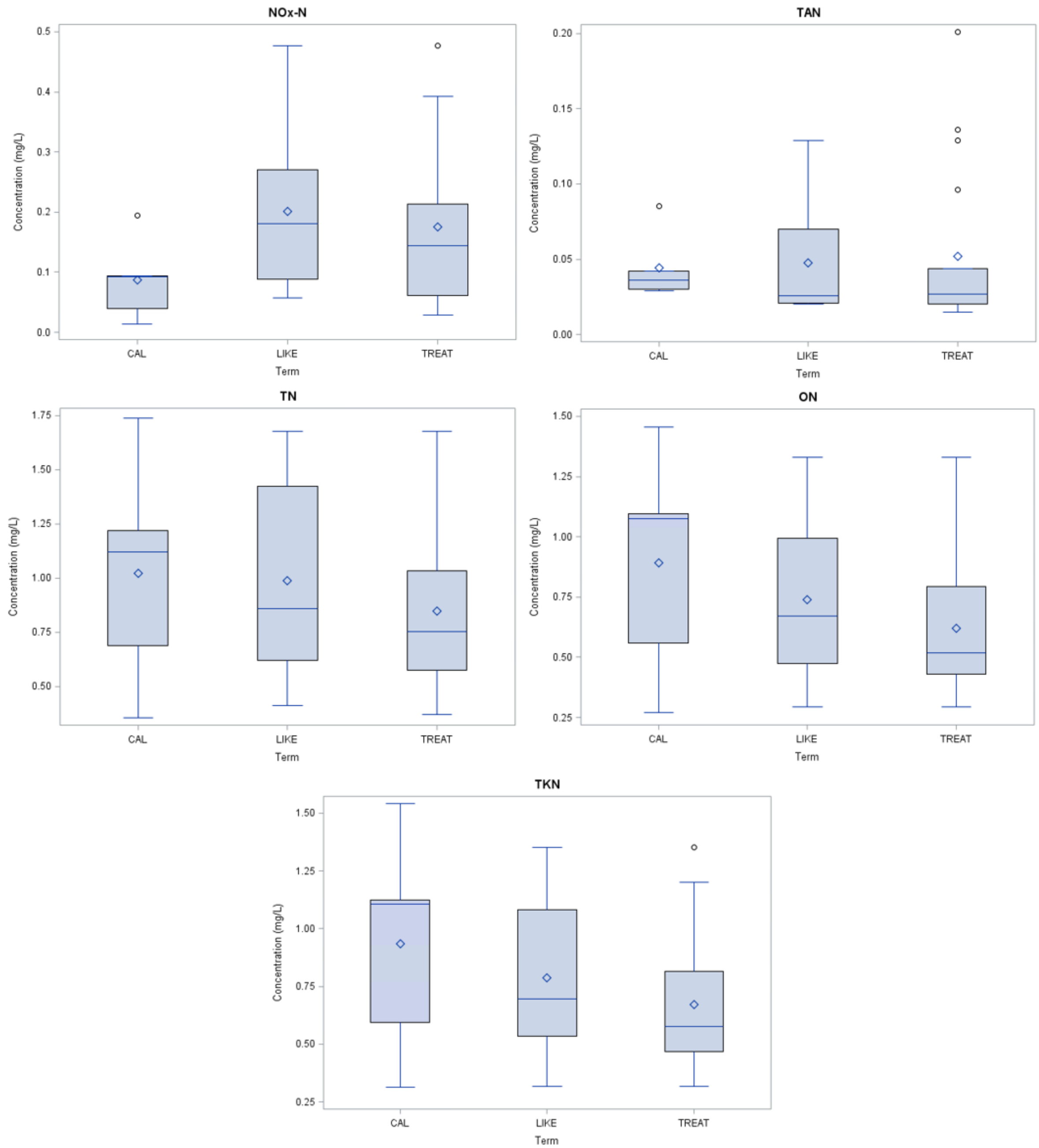


Figure 3-13: Boxplots comparing the distributions of nitrogen species concentrations for the Calibration, Like-Season, and Treatment data.

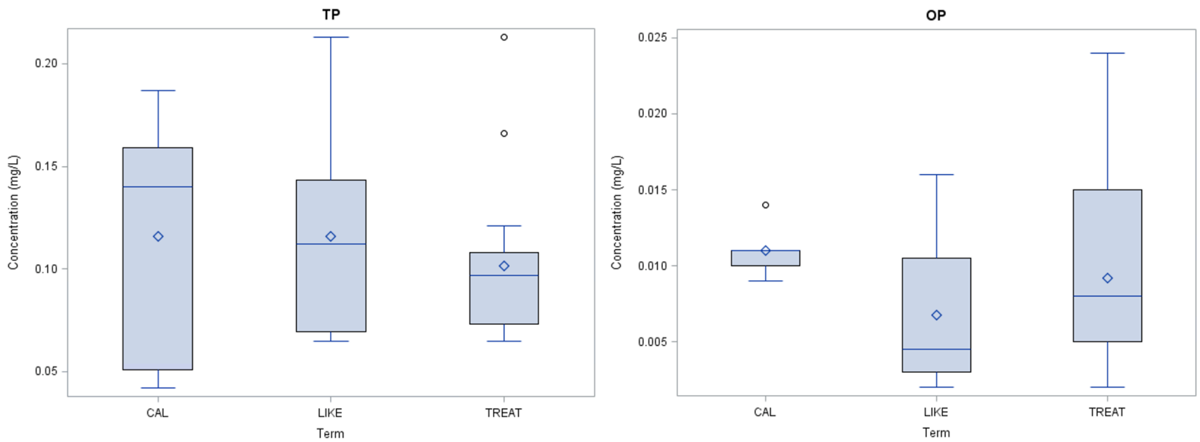


Figure 3-14: Boxplots comparing the distributions of phosphorous species concentrations for the Calibration, Like-Season, and Treatment data.

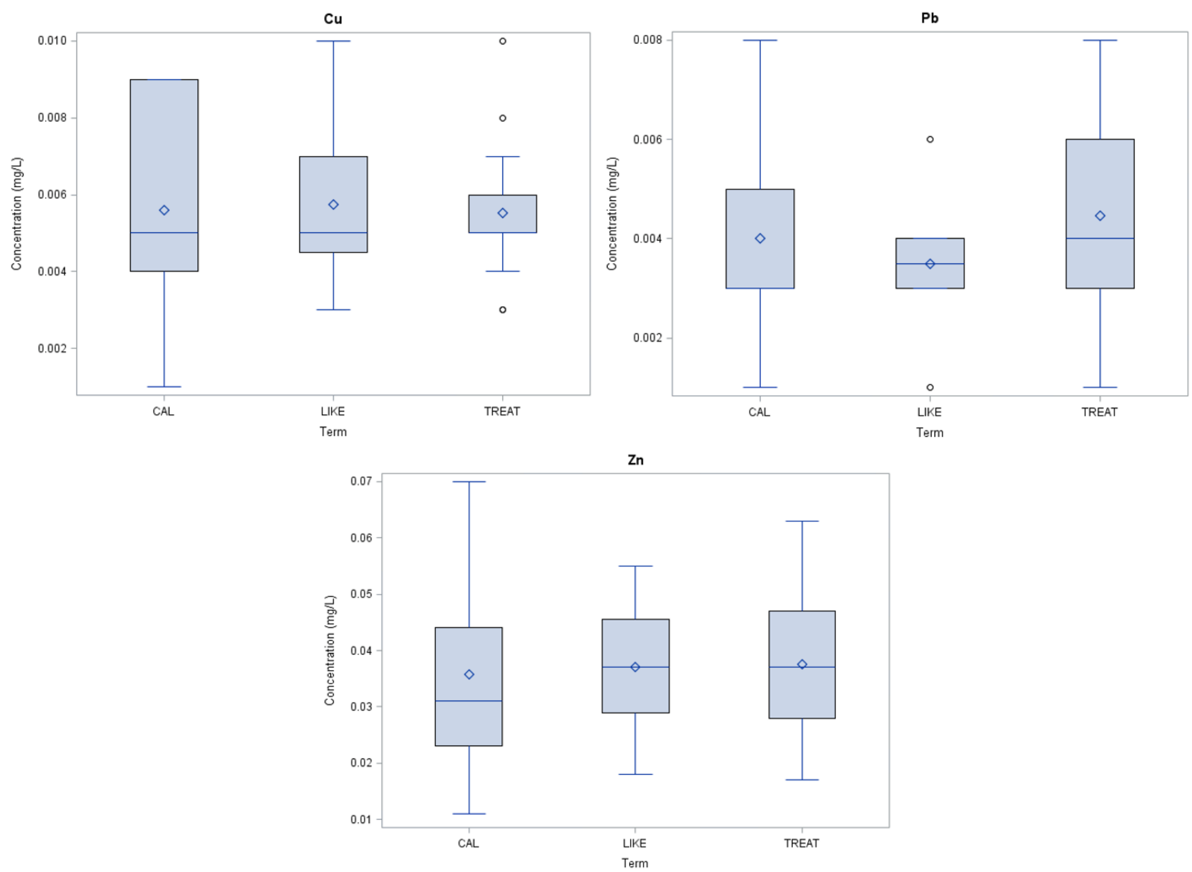


Figure 3-15: Boxplots comparing the distributions of heavy metal concentrations for the Calibration, Like-Season, and Treatment data.

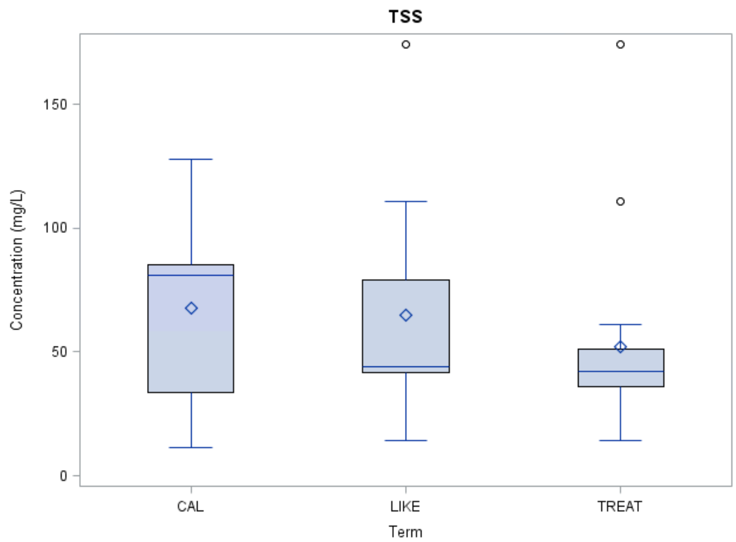


Figure 3-16: Boxplot comparing the distributions of TSS concentrations for the Calibration, Like-Season, and Treatment data.

Load Analysis

Loads were calculated for all water quality storms (Table 3-11) using Equation 3-2 and analyzed using methods described in section 3.3. Loads were normalized by watershed area, enabling them to be compared. Comparisons between the Calibration period with the Treatment period and Like-Season Period were made.

Disparities between the means and medians of pollutant loads point to the need for log transformation (Table 3-17). Only reductions of ON and TSS were significant at the 95% (α=0.05) confidence level (Table 3-18). Reductions in TKN, TN, TP, and Cu were significant at the 90% (α=0.10) confidence level.

Table 3-17: Mean and median reductions in pollutant loads between the Calibration and Treatment periods.

Pollutant	Median (g/ha)		Mean (g/ha)		Median Reduction (%)	Mean Reduction (%)
	Calibration	Treatment	Calibration	Treatment		
TKN	68.15	26.69	78.54	43.98	61	44
NO_x-N	7.13	4.41	8.20	11.63	38	-42
TAN	2.78	1.79	5.87	2.78	36	53
TN	69.03	32.50	86.74	55.62	53	36
ON	66.30	22.57	72.66	41.20	66	43
TP	8.62	4.66	9.86	5.76	46	42
O-PO_4^{3-}	0.60	0.30	1.50	0.75	49	50
TSS	4985	1774	4770	2351	64	51
Cu	0.44	0.23	0.41	0.36	47	12
Pb	0.28	0.14	0.31	0.26	51	16
Zn	2.38	1.77	2.90	1.99	26	31

Table 3-18: Summary of statistical analyses on pollutant reductions between the Calibration and Treatment periods.

Variable	n*	Distribution	Significance Test	p-value	Significant Difference?
TKN	22	Log-normal	Two-sample t-test	0.0516	no
NO_x-N	22	Log-normal	Two-sample t-test	0.9109	no
TAN	22	Log-normal	Two-sample t-test	0.1537	no
TN	22	Log-normal	Two-sample t-test	0.0841	no
ON	22	Log-normal	Two-sample t-test	0.0488	**yes**
TP	22	Log-normal	Two-sample t-test	0.0891	no
O-PO_4^{3-}	22	Log-normal	Two-sample t-test	0.1014	no
TSS	22	Log-normal	Two-sample t-test	0.0283	**yes**
Cu	22	Log-normal	Two-sample t-test	0.0502	no
Pb	22	Log-normal	Two-sample t-test	0.2316	no
Zn	22	Log-normal	Two-sample t-test	0.1581	no

*Combined, Calibration=5 Treatment=17

Comparisons between the Calibration and Like-Season datasets were more likely to be significant than those with the Treatment period (Table 3-19). All pollutants but NO_x-N and TAN were significantly reduced (Table 3-20). Figures 3-17 through 3-20 show boxplots of the pollutant loads during all three periods.

Table 3-19: Mean and median reductions of pollutants between the Calibration and Like-Season periods.

Pollutant	Median (g/ha)		Mean (g/ha)		Median Reduction (%)	Mean Reduction (%)
	Calibration	Like-Season	Calibration	Like-Season		
TKN	68.15	18.57	78.54	27.80	73	65
NO_x-N	7.13	3.76	8.20	7.55	47	8
TAN	2.78	0.82	5.87	2.44	70	58
TN	69.03	23.67	86.74	35.35	66	59
ON	66.30	17.25	72.66	25.35	74	65
TP	8.62	3.38	9.86	3.60	61	63
O-PO_4^{3-}	0.60	0.11	1.50	0.24	82	84
TSS	4985	1482	4770	1717	70	64
Cu	0.44	0.13	0.41	0.21	70	48
Pb	0.28	0.09	0.31	0.10	67	67
Zn	2.38	1.02	2.90	1.25	57	57

Table 3-20: Summary of statistical analyses on pollutant reductions between the Calibration and Like-Season periods.

Variable	n	Distribution	Significance Test	p-value	Significant Difference?
TKN	13	Log-normal	Two-sample t-test	0.0061	**yes**
NO_x-N	13	Log-normal	Two-sample t-test	0.7517	no
TAN	13	Log-normal	Two-sample t-test	0.0929	no
TN	13	Log-normal	Two-sample t-test	0.0119	**yes**
ON	13	Log-normal	Two-sample t-test	0.0049	**yes**
TP	13	Log-normal	Two-sample t-test	0.0116	**yes**
O-PO_4^{3-}	13	Log-normal	Two-sample t-test	0.0072	**yes**
TSS	13	Log-normal	Two-sample t-test	0.0047	**yes**
Cu	13	Log-normal	Two-sample t-test	0.0165	**yes**
Pb	13	Log-normal	Two-sample t-test	0.0042	**yes**
Zn	13	Log-normal	Two-sample t-test	0.0222	**yes**

*Combined, Calibration=5 Like-Season=8

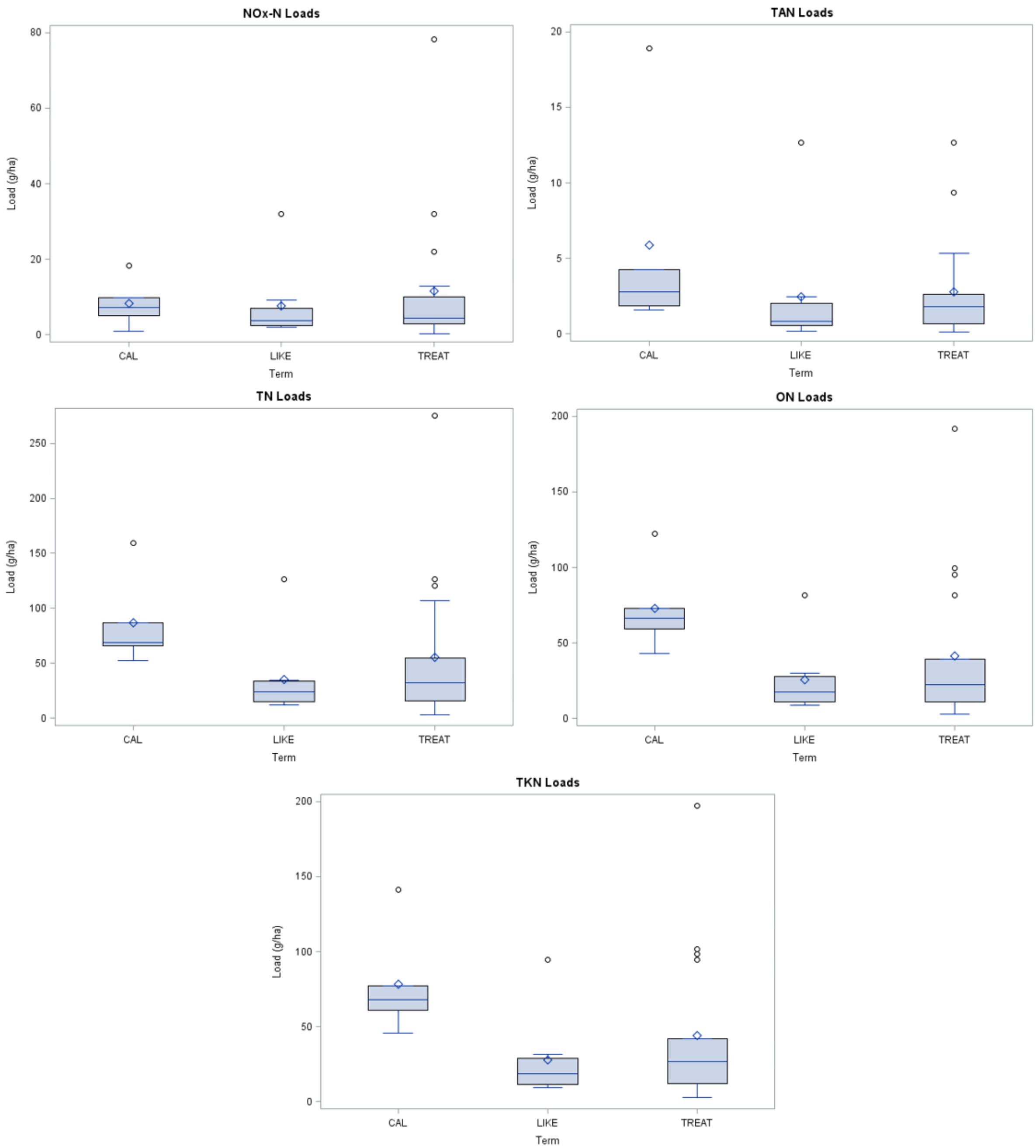


Figure 3-17: Boxplots comparing the distributions of nitrogen species loads for the Calibration, Like-Season, and Treatment data.

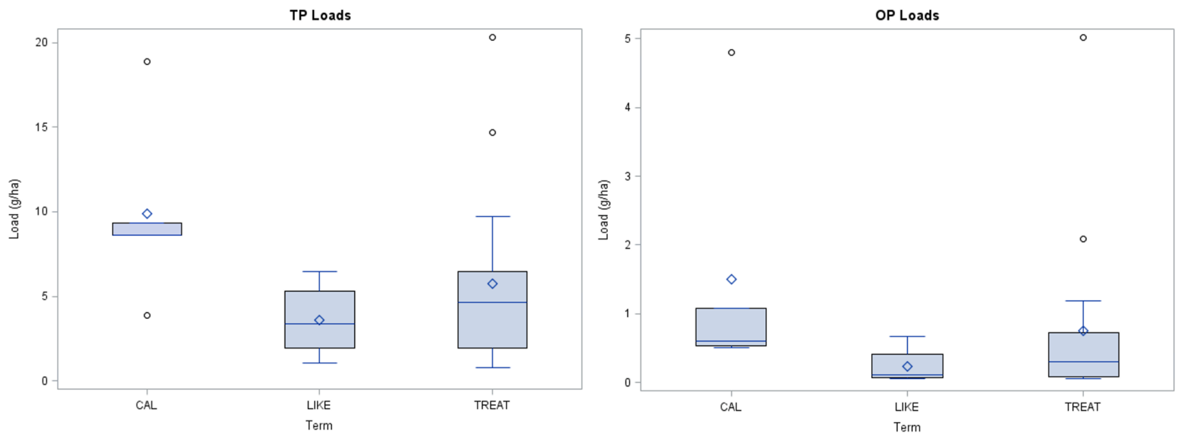


Figure 3-18: Boxplots comparing the distributions of phosphorous species loads for the Calibration, Like-Season, and Treatment data.

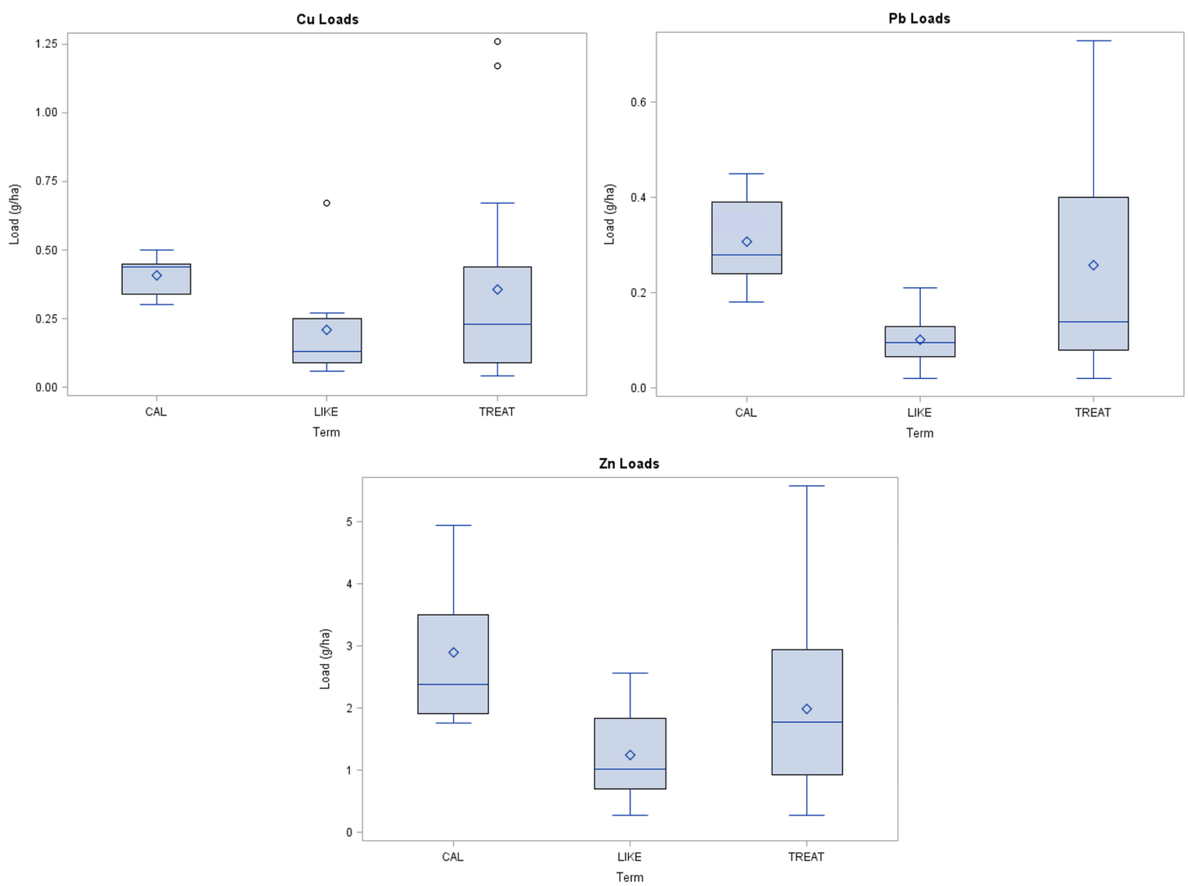


Figure 3-19: Boxplots comparing the distributions of heavy metal loads for the Calibration, Like-Season, and Treatment data.

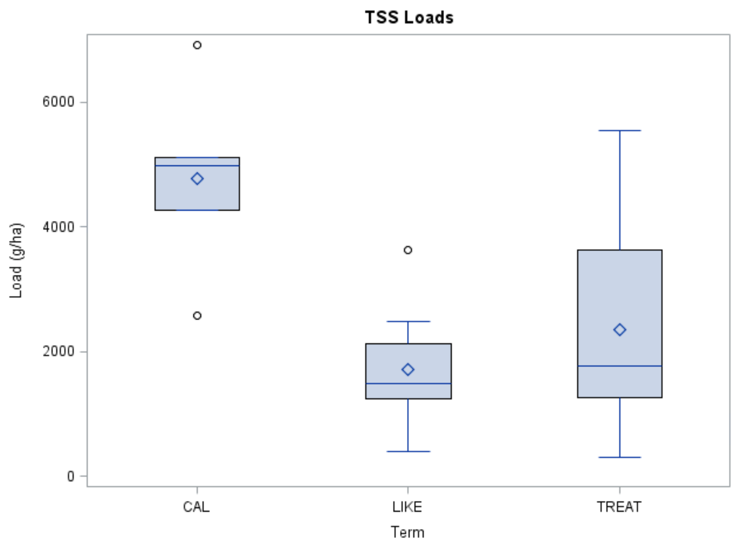


Figure 3-20: Boxplot comparing the distribution of TSS loads for the Calibration, Like-Season, and Treatment data.

Ambient Water Quality Comparison

Event mean concentration reduction is not the only way to evaluate a retrofit (Lenhart & Hunt, 2011; Strecker et al., 2001). McNett et al (2010) developed water quality thresholds for North Carolina streams based on benthic macroinvertebrate health. Waters were rated “Excellent” to “Poor” based on the presence of “Very Sensitive” to “Very Tolerant” benthic species. According to this study, for “Good” macroinvertebrate health in the Coastal Plain, TP should be limited to 0.09 mg/L respectively (Mcnett et al., 2010). NCDEQ places a limit of 20 mg/L of TSS on high quality waters (NCDEQ, 2016). Due to its designation as shellfishing waters, Burnt Mill Creek is a high quality water. Limits for metal concentrations are assigned based on acute toxicity to freshwater aquatic life by NCDEQ (2016). The limits for Cu, Pb, and Zn are 3.6, 14, and 36 µg/L respectively (NCDEQ, 2016).

Nutrient, TSS, and Cu concentrations tended to be greater than the thresholds set forth by McNett et al. (2010) and NCDEQ (2016, Table 3-21). Median and mean Pb concentrations remained below NCDEQ limits throughout monitoring. Zinc median and mean concentrations are similar to the NCDEQ threshold.

Table 3-21: Mean and median concentrations for selected pollutants for the three periods in comparison to water quality thresholds set by various sources.

Pollutant	Median Concentration			Mean Concentration			Threshold
	Calibration	Treatment	Like-Season	Calibration	Treatment	Like-Season	
TP[1]	0.14	0.10	0.11	0.12	0.10	0.12	0.09
TSS[1]	80.9	42.4	44.0	67.8	51.9	64.8	20.0
Cu[2]	5	5.4	5.3	5.6	5.6	5.7	3.6
Pb[2]	3	3.9	3.2	4	4.4	3.3	14
Zn[2]	31	37	37	36	38	37	36

1: (mg/L) 2: (μg/L)

Cumulative probability plots were created to compare pollutant data from all three monitoring periods to ambient water quality thresholds (Figures 3-21 to 3-26). The plots show the relative probability of EMCs crossing the thresholds. The similarity of the monitoring periods within the plots illustrates how retrofits had little water quality impact. TP concentrations exceeded the “Good” benthic health limit 60-65% of the time respectively. More than 80% of TSS EMCs exceeded the NCDEQ threshold. Eighty percent and 82% of Cu EMCs exceeded the aquatic health threshold during the Calibration and Treatment periods respectively. The Zn threshold was surpassed over 40% of the time for all monitoring periods. Runoff water quality did not surpass the Pb threshold.

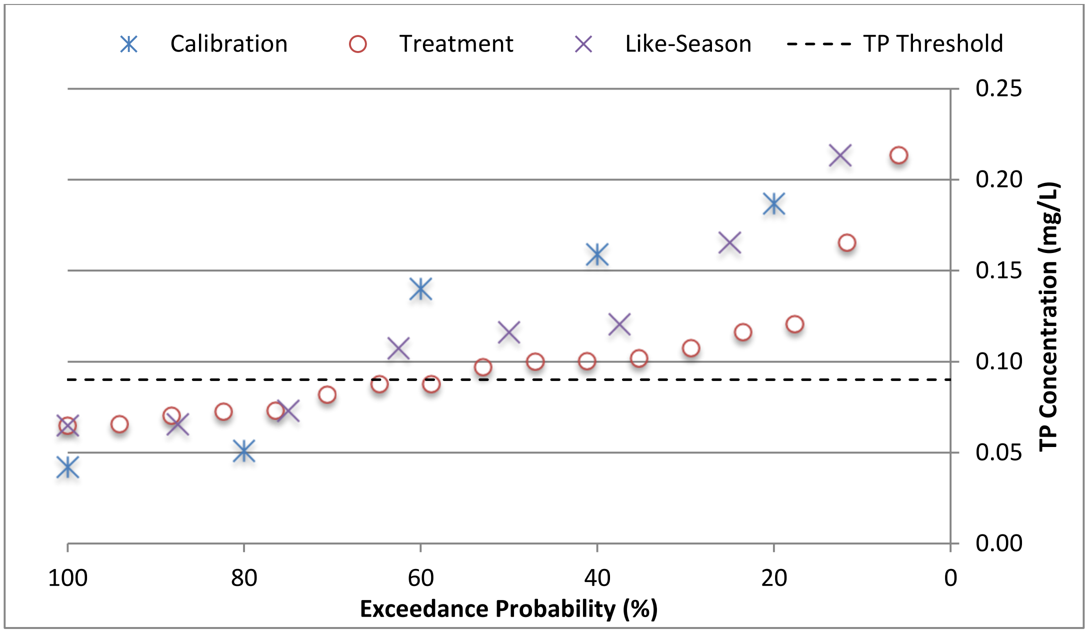


Figure 3-21: Exceedance probability plot of TP concentrations for the Calibration, Treatment, and Like-Season data in relation to the TP water quality threshold of 0.09 mg/L (McNett et al., 2010).

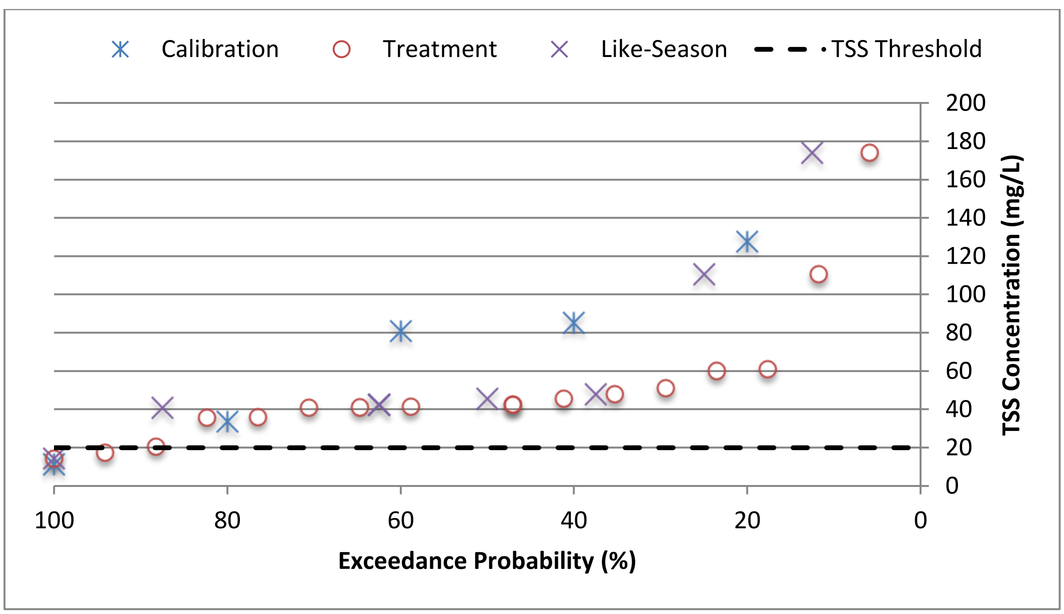


Figure 3-22: Exceedance probability plot of TSS concentrations for the Calibration, Treatment, and Like-Season data in relation to the TSS water quality threshold of 20 mg/L (NCDEQ, 2016).

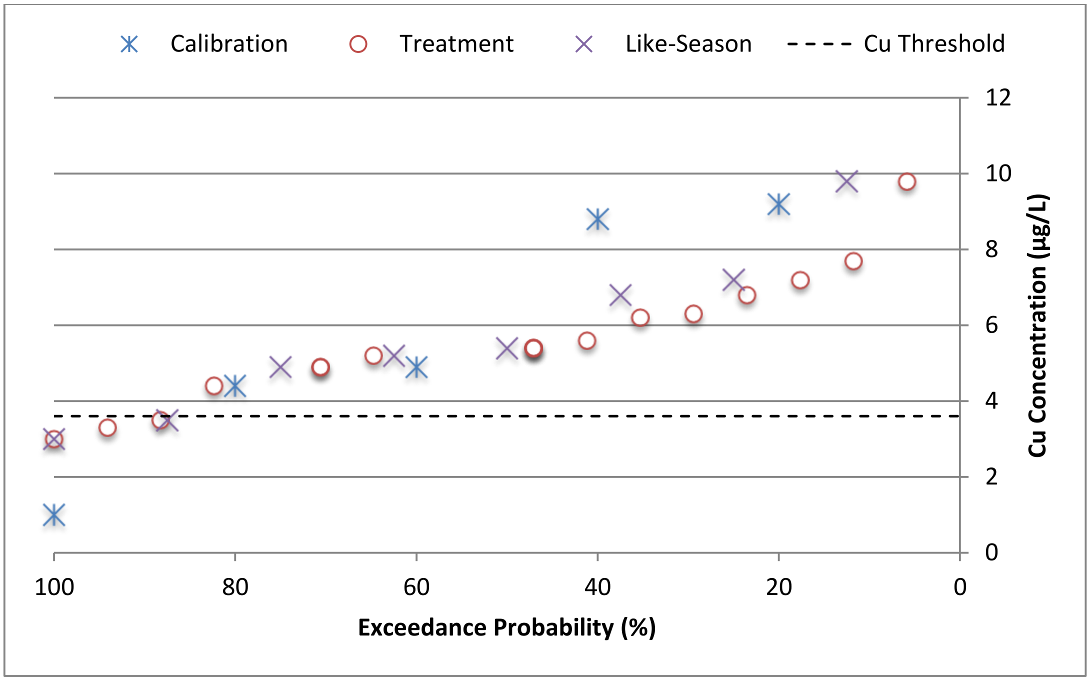


Figure 3-23: Exceedance probability plot of Cu concentrations for the Calibration, Treatment, and Like-Season data in relation to the Cu water quality threshold of 3.6 µg/L (NCDDEQ, 2016).

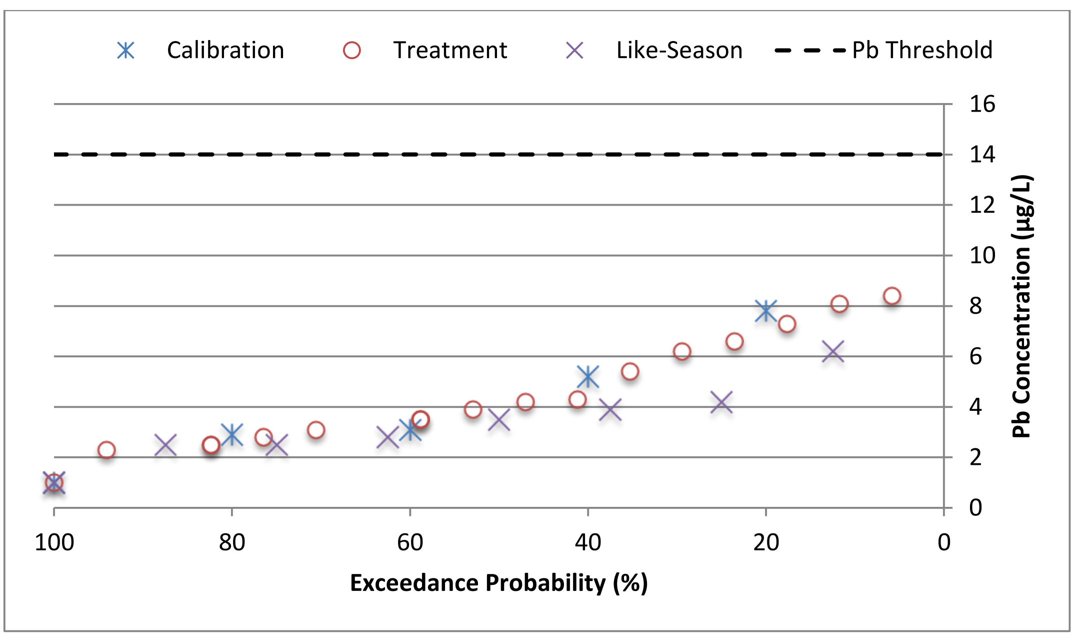


Figure 3-24: Exceedance probability plot of Pb concentrations for the Calibration, Treatment, and Like-Season data in relation to the Pb water quality threshold of 14 µg/L (NCDEQ, 2016).

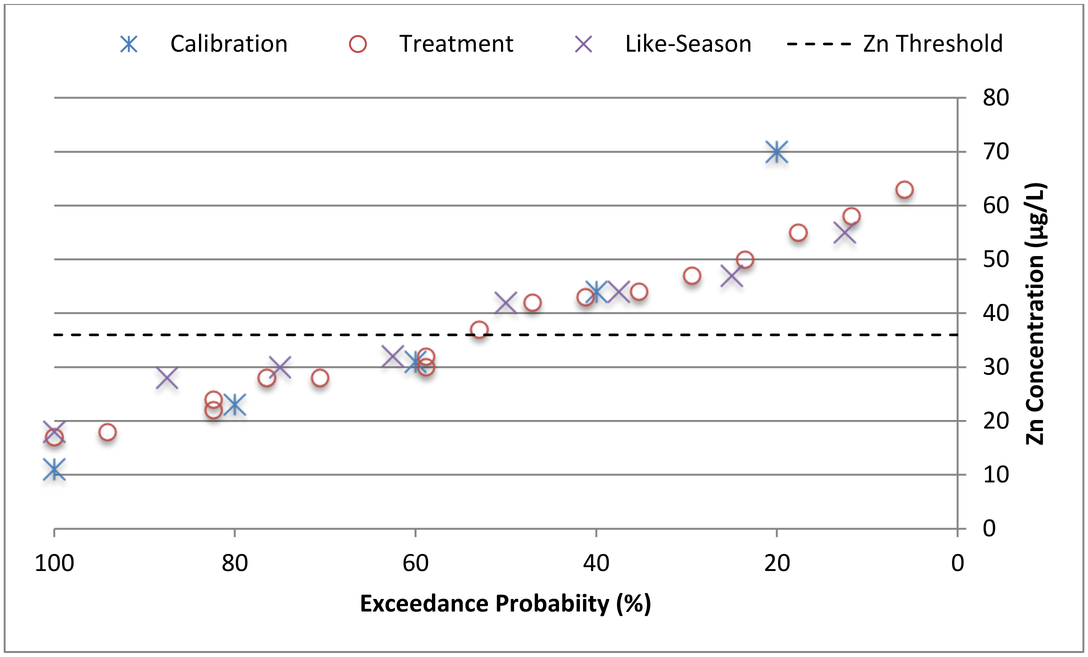


Figure 3-25: Exceedance probability plot of Zn concentrations for the Calibration, Treatment, and Like-Season data in relation to the Zn water quality threshold of 36 µg/L (NCDEQ, 2016).

Discussion

The difference in sample size between the Calibration and Treatment periods limited the ability to fully assess the SCM retrofit. Time constraints for SCM construction resulted in a very small dataset for the Calibration period. The violation of the paired watershed assumptions reduced the statistical power to rule out climatic variation and sample size inequality. Analyzing the Like-Season data showed how the retrofit could be beneficial. Future SCM analyses should ensure monitoring periods have similar duration to improve assessment.

Statistical analysis of normalized runoff volume and peak discharge showed that these two variables did not change between the monitoring periods. However, the ROC for the parking lot was reduced from 0.45 to 0.29. Rushton (2010) found similar ROCs (0.51-

0.58) for an asphalt parking lot in Florida, and found that ROCs were lower (0.16-0.35) when swales were installed. The ROC is the runoff depth normalized by rainfall depth, and therefore represents runoff depth regardless of climatic variation. Peak discharge was not altered because the main flow paths of the parking lot were not changed by the retrofit.

There were no differences in pollutant EMCs between the monitoring periods. Pollutant load reductions were significant for TSS and ON during the Treatment period, but almost all load reductions were significant for the Like-Season data. When climatic and sample size variability are decreased, the retrofit does show water quality benefits. The lack of change in EMCs paired with a significant change in loads demonstrates the ability of these SCMs to capture runoff. A statistical analysis of runoff depth for water quality storms showed that runoff depth was less during the Like-Season period ($p=0.04$), explaining load reductions. Other research has shown that percent reductions of concentrations or loads should not be the lone metric for SCM success (Lenhart & Hunt, 2011; McNett et al., 2010; Strecker et al., 2001). Therefore pollutant EMCs were compared to ambient water quality thresholds for freshwater aquatic toxicity in coastal NC. TP, TSS, Cu, and Zn EMCs exceeded ambient water quality thresholds for a majority of the monitoring periods.

The experimental design in this study has been successfully deployed multiple times in NC (Page et al., 2015). The failure of this study may be attributed to the limited period of observation and consequent lack of data for the parking lot. Additionally, prior to the design, the topographic survey was not sufficiently detailed (i.e. did not contain enough points) to predict preferential flow within micro-topography of the old lot. Future retrofit designers need to fully understand micro-topography so that flow conditions are known before completing designs. Additionally, the SCMs were installed parallel to the major flow paths within the lots, decreasing the amount of runoff intercepted by the retrofit. It may be beneficial to either resurface an old parking lot prior to installation or build retrofits that intersect flow paths to ensure runoff will be treated. Otherwise, speed bumps can be installed with the retrofit to redirect flow.

3.6 Summary and Conclusions

This study examined the effects of an undersized SCM retrofit of a parking lot in the Coastal Plain of North Carolina. Two linear infiltrating SCMs were installed at New Hanover High School in 2014. Hydrology and water quality monitoring occurred pre- and post-retrofit. The following conclusions were drawn:

1) Statistical analyses were limited by the disparities in sample size between the Calibration and Treatment periods. SCM construction time restraints resulted in a much lower number of observations for the Calibration period. Future studies should work to ensure the pre- and post-retrofit datasets are of similar duration.
2) Average runoff depth and peak discharge did not change after the retrofit. Parking lot design allowed runoff from large portions of the parking lot to flow directly to the catch basins without being intercepted by SCMs. Additionally statistical analyses could not discount the effect of climatic variation between monitoring periods for these variables.
3) The ROC of the watershed decreased from 0.45 to 0.29 after the retrofit. The fraction of rainfall becoming runoff decreases due to a decrease in impervious fraction for the watershed. The SCMs increase runoff volume storage.

4) There is no significant difference in pollutant EMCs after the retrofit. Sediment was observed to accumulate within the SCMs, but the aging parking lot surface adds sediment as it erodes. The lot has not been resurfaced in at least 10 years, beyond the recommended maintenance schedule.
5) TSS and ON loads were significantly reduced post-retrofit by 51% and 43% respectively. Although these EMCs were not reduced, the SCMs were observed to collect sediment during storms. ON may be primarily particulate bound in this parking lot.
6) All pollutant loads but NO_x-N and TAN were reduced between the Calibration and Like-Season datasets, ranging from 48% to 84%. Because EMCs did not change, any reduction is primarily due to the decrease in runoff depth that occurred as a result of the retrofits.
7) EMCs were also compared to various ambient water quality thresholds for freshwater aquatic life in coastal NC (McNett et al., 2010; NCDEQ, 2016). Greater than 50% of TP, Cu, and Zn EMCs exceeded thresholds for Calibration, Treatment, and Like-Season data. TSS EMCs exceeded the 20 mg/L threshold over 90% of the time. Pb EMCs were always less than water quality thresholds.
8) The age and condition of the lot affected the capacity of the SCMs to treat runoff. Retrofitting requires full knowledge of existing flow in order to optimize SCMs.

3.7 References

Bannerman, R., Owens, D., Dodds, R., & Homewer, N. (1993). Sources of Pollutants in Wisconsin Stormwater. *Water Science and Technology, 28*(3-5), 241–259.

Bledsoe, B. P. (2002). Stream Erosion Potential and Stormwater Management Strategies. *Journal of Water Resources Planning and Management, 128*(6), 451–455.

Brinkmann, W. (1985). Urban Stormwater Pollutants: Sources and Loadings. *GeoJournal, 11*(3), 277–283.

Brown, R., & Hunt, W. (2011). Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. *Journal of Irrigation and Drainage Engineering, 137*, 132–143.

Clausen, J. & Spooner, J. (1993). Paired Watershed Study Design. United States Environmental Protection Agency, Washington, DC.

Davis, A. (2005). Green Engineering Principles Promote Low-Impact Development. *Environmental Science & Technology, 6*(8), 338A–344A.

Davis, A. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering, 13*(2), 90–95.

Davis, A., Shokouhian, M., Ni, S. (2001). Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere, 44*, 997-1009.

Davis, A., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water Quality Improvement through Bioretention Media : Nitrogen and Phosphorus Removal. *Water Environment Research, 78*(3), 284–293.

DeBusk, K. M., Hunt, W. F., & Line, D. E. (2011). Bioretention Outflow : Does It Mimic Nonurban Watershed Shallow Interflow? *Journal of Hydrologic Engineering, 16*, 274–279.

DiBlasi, C., Li, H., Davis, A., & Ghosh, U. (2009). Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility. *Environmental Science & Technology, 43*(2), 494–502.

Dietz, M., & Clausen, J. (2005). A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air, and Soil Pollution, 167*(1-4), 123–138.

Drapper, D., Tomlinson, R., & Williams, P. (2000). Pollutant Concentrations in Road Runoff: Southeast Queensland Case Study. *Journal of Environmental Engineering, 126*(4), 313–320.

Grebel, J., Mohanty, S., Torkelson, A., Boehm, A., Higgins, C., Maxwell, R., Sedlak, D. (2013). Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environmental Engineering Science*, *30*(8), 437–454.

Hope, D., Naegeli, M. W., Chan, A. H., & Grimm, N. B. (2004). Nutrients on asphalt parking surfaces in an urban environment. *Water, Air, and Soil Pollution*, *4*(2-3), 371–390.

Hunt, W. F., Davis, A. P., & Traver, R. G. (2012). Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *Journal of Environmental Engineering, 138*(6), 698–707.

Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *Journal of Environmental Engineering, 134*(5), 403–408.

ISCO Flowlink Software V 5.11.206. (2005). Teledyne ISCO, Inc. Lincoln, Nebraska.

James, R. R., Wilbon, P., & Divincenzo, J. P. (2010). Pervious and impervious urban stormwater runoff in a rapidly urbanizing region: Occurrence of fluoranthene and pyrene. *Bulletin of Environmental Contamination and Toxicology, 85*(1), 32–36.

Jennings, D., & Jarnagin, S. (2002). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology, 17*, 471–489.

LeFevre, G. H., Paus, K. H., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering, 141*(1).

Lenhart, H. & Hunt, W. (2011). Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland. *Journal of Environmental Engineering, 137*(2), 155-162.

Leopold, L. (1968). Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. United States Department of the Interior, Washington, DC.

Li, H., & Davis, A. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *Journal of Environmental Engineering*, *135*, 567–576.

Li, J., & Davis, A. P. (2015). A unified look at phosphorus treatment using bioretention. *Water Research, 90*, 141–155.

Line, D., & White, N. (2007). Effects of Development on Runoff and Pollutant Export. *Water Environment Research, 79*(2), 185–190.

Mahler, B., Van Metre, P., Bashara, T., Wilson, J., & Johns, D. (2005). Parking Lot Sealcoat: An Unrecognized Source of Urban Polycyclic Aromatic Hydrocarbons. *Environmental Science & Technology, 39*(15), 5560–5566.

McIntyre, J. K., Edmunds, R. C., Anulacion, B. F., Davis, J. W., Incardona, J. P., Stark, J. D., & Scholz, N. L. (2016). Severe Coal Tar Sealcoat Runoff Toxicity to Fish Is Prevented by Bioretention Filtration. *Environmental Science & Technology, 50*(3), 1570–1578.

McNett, J. K., Hunt, W. F., & Osborne, J. A. (2010). Establishing Storm-Water BMP Evaluation Metrics Based upon Ambient Water Quality Associated with Benthic Macroinvertebrate Populations, *Journal of Environmental Engineering, 136*(5), 535–541.

NC DEQ. (2014). 303d List of Impaired Waters. North Carolina Department of Environmental Quality, Raleigh, North Carolina.

NC DEQ. (2016). North Carolina Surface Water Standards and Protective Values. North Carolina Department of Environmental Quality, Raleigh, North Carolina

Ngabe, B., Bidleman, T., & Scott, G. (2000). Polycyclic aromatic hydrocarbons in storm runoff from urban and coastal South Carolina. *The Science of the Total Environment, 255*, 1–9.

NWS. (2016). Regional Climate Report. National Weather Service Wilmington International Airport.

PA DEP. (2005). Pennsylvania Stormwater Best Management Practices Manual. North Carolina Department of Environmental Protection, Pittsburgh, Pennsylvania.

Passeport, E., & Hunt, W. (2009). Asphalt Parking Lot Runoff Nutrient Characterization for Eight Sites in North Carolina, USA. *Journal of Hydrologic Engineering, 14*(4), 352–361.

Paul, M., & Meyer, J. (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics*, *32*(1), 333–365.

Pitt, R., & Bannerman, R. (2005). Sources of pollutants in urban areas (Part 1)–Older monitoring projects. *Effective Modeling of Urban Water Systems*, 1–20.

Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability. *Water Environment Research, 67*(3), 260–275.

Rushton, B. (2001). Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management, 127*, 172–179.

SAS Institute Inc. (Version 9.2) [Software]. (2008). The SAS system for Windows.

State Climate Office of NC. (2016). 1971-2000 Climate Normals. Accessed March 1, 2016.

Strecker, E., Quigley, M., Urbonas, B., Jones, J., & Clary, J. (2001). *Journal of Water Resources Planning and Management, 127*(3), 144-149.

US Census Bureau. (2014). QuickFacts Wilmington, North Carolina. United States Department of Commerce, Washington, DC.

USDA. (1977). Soil Survey of New Hanover County, North Carolina. United States Department of Agriculture Soil Conservation Service.

CHAPTER 4: SUMMARY, RECOMMENDATIONS, AND FURTHER RESEARCH

4.1 Summary of Studies

A parking lot in Wilmington, NC was monitored for over a year for hydrology and water quality (Chapter 2). The ageing condition of the lot increases surface storage, thereby decreasing the volume of runoff leaving the lot. Runoff volume and peak discharge, normalized by watershed area, were lower than those found at other parking lot sites (Davis, 2008; Li et al., 2009). The runoff coefficient (ROC) (0.31) was similar to that of an asphalt parking lot in Florida (Rushton, 2001). Total suspended solids (TSS) event mean concentrations (EMCs) (53.8 mg/L) were greater than those found by other parking lot studies due to heavy particulate coverage from surface erosion (Hunt et al., 2008; Li & Davis, 2009; Passeport et al., 2009; Rushton, 2001). Copper (Cu) and Zinc (Zn) concentrations (5 µg/L and 36 µg/L, respectively) were lower than those found in other studies because this lot has a much lower average daily traffic than other sites (Hunt et al., 2008; Li & Davis, 2009; Rushton, 2001). Parking lot EMCs are generally lower than highway EMCs (Kayhanian et al., 2007; US EPA, 1983; Stagge et al., 2012).

MLR models were created to further explain variations in runoff quantity and quality for this parking lot. Hydrologic variables were best explained by rainfall depth, peak hourly rainfall intensity, and temperature. Pollutant EMCs were negatively correlated with duration, indicating a dilution effect that was further supported by a first flush analysis in which the first 13 mm of rainfall produced the greatest pollutant loads (as normalized by runoff depth). Pollutant loads are best explained by a combination of rainfall depth, peak hourly rainfall intensity, and temperature.

This parking lot was retrofitted with undersized infiltrating SCMs. Chapter 3 provides an analysis of the retrofit's effect on parking lot runoff hydrology and water quality. The ROC of the watershed was decreased from 0.45 to 0.29. Sample size inequality led to the testing of retrofit effects on a 'Like-Season' Treatment sub-dataset. Although pollutant EMCs did not change, all pollutant loads but NO_x-N and TAN were significantly reduced (48-84%) for the Like-Season after retrofit were installed. However TP, TSS, Cu, and Zn EMCs were consistently above ambient water quality criteria for freshwater aquatic life.

4.2 Recommendations for Design and Monitoring

The parking lot retrofit study suffered from an experimental design failure. The retrofit did not capture runoff from a portion of its intended watershed. The original survey of the parking lot (used for design of the retrofits) did not contain enough points to fully describe preferential flow patterns. Retrofit designers should observe runoff on an existing parking lot to analyze surface flow for targeted surveying, which in turn can lead to a functioning design.

Aging parking lots can have flow patterns contrary to expectations. It may be beneficial to resurface a lot in concurrence with a retrofit to ensure grading directs flow into the SCM. Additionally, retrofits should intersect the major flow paths within the lot (rather than be installed in parallel to preferential flow) for greatest effect when possible.

The monitoring flaw with this study (Chapter 3) was the low sample size during the Calibration period. While this was unavoidable due to limited construction scheduling flexibility, it impacted statistical analyses. Monitoring design should ensure that sample sizes pre- and post-retrofit are similar and sufficiently long, if possible.

This parking lot's runoff is affected by its age and usage. It will be important for any parking lot retrofit designer to fully evaluate the condition of the lot in order to optimize the SCM. Additionally, parking lot runoff is not similar to highway runoff, and should not be assigned comparable characteristics when designing stormwater management for large watersheds.

4.3 Future Research

MLR analysis did not produce models that fully explain variability in runoff variables. A study of multiple parking lots in the Coastal Plain may introduce more factors that could improve these models. It would also provide more data for comparisons of Coastal Plain parking lots to lots in other parts of North Carolina. Underlying soils and climate in the Coastal Plain are different from other ecoregions of North Carolina, suggesting that SCM design in this area should be different as well.

The apparent effect of age on this parking lot's runoff suggests the need for greater study on parking lot condition. While an older lot may store more runoff on its surface, it also produces particulates as asphalt wears. Perhaps a chronosequence of parking lots (since their last resurfacing) would allow a stronger comparison. This parking lot's daily usage was limited due to school hours. It was concluded that heavy metal concentrations in this lot were lower because of the light traffic. It would be interesting to know if parking lot traffic or vehicle type has an effect on pollutant concentrations as has been shown on roadways (Kayhanian et al., 2003).

The initial SCM retrofit experimental design was a paired watershed study. This statistical analysis removes climatic variation as a factor, attributing changes in runoff to the retrofit. However, this was not accomplished at this site due to unexpected conditions. Another retrofit study utilizing the paired watershed design with equal pre- and post-retrofit sample sizes will more fully explain the effect of a retrofit.

4.4 References

Davis, A. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering*, *13*(2), 90–95.

Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *Journal of Environmental Engineering, 134*(5), 403–408.

Kayhanian, M., Singh, A., Suverkropp, C., & Borroum, S. (2003). Impact of Annual Average Daily Traffic on Highway Runoff Pollutant Concentrations. *Journal of Environmental Engineering*, *129*(11), 975-990.

Kayhanian, M., Suverkropp, C., Ruby, A., & Tsay, K. (2007). Characterization and prediction of highway runoff constituent event mean concentration. *Journal of Environmental Management*, *85*, 279-295.

Li, H., & Davis, A. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *Journal of Environmental Engineering*, *135*, 567–576.

Li, H., Sharkey, L., Hunt, W., & Davis, A. (2009). Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. *Journal of Hydrologic Engineering*, *14*, 407–415.

Passeport, E., Hunt, W. F., Line, D. E., Smith, R.., & Brown, R. (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. *Journal of Irrigation and Drainage Engineering, 135*(4), 505–510.

Rushton, B. (2001). Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management, 127*, 172–179.

Stagge, J. H., Davis, A. P., Jamil, E., & Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research, 46*(20), 6731–6742.

US EPA. (1983). Results of the Nationwide Urban Runoff Program, Volume 1-Final Report. National Technical Information Service (NTIS), Washington, DC.

APPENDICES

Appendix A. Example MLR SAS Code

```
**CONCENTRATION MLRs**;
**TN MLR***;

*scatterplots of variables vs. TN;

proc sgplot data=wqmlr;
reg x=peakint y=logTN;
run;

proc sgplot data=wqmlr;
reg x=avgint y=logTN;
run;

proc sgplot data=wqmlr;
reg x=rain y=logTN;
run;

proc sgplot data=wqmlr;
reg x=duration y=logTN;
run;

proc sgplot data=wqmlr;
reg x=ADP y=logTN;
run;

proc sgplot data=wqmlr;
reg x=volume y=logTN;
run;

proc sgplot data=wqmlr;
reg x=season y=logTN;
run;

proc sgplot data=wqmlr;
reg x=vehicle y=logTN;
run;

proc sgplot data=wqmlr;
reg x=grow y=logTN;
run;

proc sgplot data=wqmlr;
```

```
reg x=temp y=logTN;
run;

proc sgplot data=wqmlr;
reg x=impfrac y=logTN;
run;

proc sgplot data=wqmlr;
reg x=area y=logTN;
run;



Data wqmlrreg;
SET wqmlr;
    If season= 'Fall' Then dummy1=1 ; Else dummy1=0;
    If season= 'Winter' Then dummy2=1 ; Else dummy2=0;
    If season= 'Spring' Then dummy3=1 ; Else dummy3=0;
    If vehicle= 'y' Then dummy5=1 ; Else dummy5=0;
    If grow= 'y' Then dummy6=1 ; Else dummy6=0;
Run;

proc glmselect data=wqmlr;
class season vehicle grow;
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=stepwise (select=sl slentry=.1 slstay=.1);
run;

proc glmselect data=wqmlr;
class season vehicle grow;
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=forward (select=sl slentry=.1);
run;

proc glmselect data=wqmlr;
class season vehicle grow;
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=backward(select=sl slstay=.1);
run;



proc glmselect data=wqmlr;
class season vehicle grow;
```

```
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=stepwise(choose=adjrsq);
run;

proc glmselect data=wqmlr;
class season vehicle grow;
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=forward(choose=adjrsq);
run;

proc glmselect data=wqmlr;
class season vehicle grow;
model logTN= rain peakint avgint duration ADP temp impfrac season vehicle grow /
Selection=backward(choose=adjrsq);
run;


**Model Adequacy**;
ods graphics on;
proc glm data=wqmlr plots=all;
model logTN= peakint duration temp impfrac / solution clparm p;
output out=stat p=pred r=residual rstudent=rstud dffits=df cookd=cookd h=hatvalue
press=res_del;
run;
quit;

proc glm data=wqmlr plots=all;
class grow;
model logTN= peakint duration temp impfrac grow/ solution clparm p;
output out=stat p=pred r=residual rstudent=rstud dffits=df cookd=cookd h=hatvalue
press=res_del;
run;
quit;
```

Appendix B. Example Retrofit SAS Code

```
*TTESTS;

ods graphics on;

proc ttest cochran ci=equal umpu;
class Term;
var logTKN;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logNOX;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logTN;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logON;
run;

proc ttest cochran ci=equal umpu;
class Term;
var lgTP;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logOP;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logCU;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logTSS;
```

```
run;

proc ttest cochran ci=equal umpu;
class Term;
var logPB;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logZN;
run;

proc ttest cochran ci=equal umpu;
class Term;
var logvol;
run;


*WILCOXON TEST;

proc npar1way data=wq wilcoxon;
class Term;
var TKN;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var NOX;
exact wilcoxon;
run;


proc npar1way data=wq wilcoxon;
class Term;
var NH3;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var TN;
exact wilcoxon;
run;
```

```
proc npar1way data=wq wilcoxon;
class Term;
var ON;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var TP;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var OP;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var CU;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var TSS;
exact wilcoxon;
run;


proc npar1way data=wq wilcoxon;
class Term;
var PB;
exact wilcoxon;
run;

proc npar1way data=wq wilcoxon;
class Term;
var ZN;
exact wilcoxon;
run;
```

Appendix C. Raw Pollutant Data

Table C-1: Raw nitrogen pollutant concentrations for both watersheds.

Period	Date	TKN (mg/L)		$NO_{2,3}$-N (mg/L)		NH_3-N (mg/L)	
		Control	Retrofit	Control	Retrofit	Control	Retrofit
CAL	4/15/14	1.24	1.11	0.01	0.01	0.02	0.03
CAL	4/18/14	0.51	0.31	0.04	0.04	0.06	0.04
CAL	4/30/14	1.54	1.12	0.08	0.09	0.05	0.03
CAL	6/9/14	2.36	1.54	0.09	0.19	0.09	0.09
CAL	6/12/14	0.57	0.60	0.07	0.09	0.03	0.04
TREAT	9/7/14	0.75	0.35	0.11	0.06	0.04	0.04
TREAT	9/12/14	0.49	0.76	0.03	0.04	0.01	0.02
TREAT	9/23/14	0.26	0.34	0.04	0.03	0.02	0.02
TREAT	11/1/14	1.32	0.69	0.29	0.35	0.10	0.14
TREAT	1/18/15	0.50	0.47	0.06	0.14	0.01	0.03
TREAT	2/16/15	0.82	0.63	0.16	0.21	0.11	0.20
TREAT	3/5/15	0.70	0.53	0.09	0.08	0.07	0.10
TREAT	3/14/15	0.64	0.58	0.03	0.06	0.02	0.03
TREAT	3/22/15	0.57	0.32	0.10	0.10	0.03	0.02
TREAT	4/15/15	0.99	1.20	0.31	0.48	0.06	0.04
TREAT	4/30/15	0.56	0.54	0.17	0.21	0.04	0.02
TREAT	5/20/15	1.67	1.35	0.18	0.21	0.02	0.02
TREAT	6/4/15	1.20	0.82	0.06	0.15	0.03	0.02
TREAT	6/18/15	1.10	0.96	0.32	0.33	0.14	0.13
TREAT	7/14/15	1.91	0.99	0.26	0.39	0.04	0.03
TREAT	10/1/15	0.46	0.47	0.06	0.10	0.15	0.02
TREAT	11/2/15	0.64	0.43	0.01	0.04	0.02	0.03

Table C-2: Raw phosphorous and total suspended sediment concentrations for both watersheds.

Period	Date	TP (mg/L)		OPO_4 (mg/L)		TSS (mg/L)	
		Control	Retrofit	Control	Retrofit	Control	Retrofit
CAL	4/15/14	0.16	0.14	0.015	0.009	24.52	80.89
CAL	4/18/14	0.08	0.04	0.011	0.011	21.23	11.39
CAL	4/30/14	0.26	0.16	0.013	0.011	44.70	127.70
CAL	6/9/14	0.31	0.19	0.026	0.010	120.28	85.26
CAL	6/12/14	0.09	0.05	0.020	0.014	44.92	33.58
TREAT	9/7/14	0.14	0.09	0.017	0.015	81.77	35.76
TREAT	9/12/14	0.08	0.07	0.014	0.016	41.58	41.41
TREAT	9/23/14	0.04	0.10	0.013	0.009	11.68	36.07
TREAT	11/1/14	0.32	0.10	0.149	0.009	88.46	60.14
TREAT	1/18/15	0.09	0.09	0.012	0.010	66.64	41.10
TREAT	2/16/15	0.13	0.10	0.008	0.005	74.52	51.08
TREAT	3/5/15	0.13	0.11	0.004	0.003	57.00	47.87
TREAT	3/14/15	0.10	0.07	0.001	0.002	48.65	45.53
TREAT	3/22/15	0.10	0.06	0.013	0.004	28.25	42.38
TREAT	4/15/15	0.09	0.12	0.015	0.006	14.20	42.38
TREAT	4/30/15	0.09	0.12	0.039	0.015	12.24	40.84
TREAT	5/20/15	0.26	0.21	0.009	0.005	156.29	174.17
TREAT	6/4/15	0.22	0.17	0.015	0.016	104.64	110.64
TREAT	6/18/15	0.15	0.07	0.031	0.003	30.46	14.27
TREAT	7/14/15	0.24	0.10	0.054	0.006	29.63	20.61
TREAT	10/1/15	4.01*	0.07	0.029	0.024	15.73	17.28
TREAT	11/2/15	0.19	0.08	0.111	0.008	28.70	60.98

*Removed from analyses

Table C-3: Raw metals concentrations for both watersheds.

Period	Date	Cu (µg/L)		Pb (µg/L)		Zn (µg/L)	
		Control	Retrofit	Control	Retrofit	Control	Retrofit
CAL	4/15/14	6.4	4.9	1*	2.9	23	31
CAL	4/18/14	1*	1*	1*	1*	12	11
CAL	4/30/14	10	9.2	5.5	5.2	57	44
CAL	6/9/14	8.9	8.8	10	7.8	86	70
CAL	6/12/14	3.4	4.4	2.3	3.1	19	23
TREAT	9/7/14	5.3	7.7	10	8.4	30	50
TREAT	9/12/14	2.7	3.3	3.6	5.4	27	22
TREAT	9/23/14	2.1	5.4	1*	6.6	11	37
TREAT	11/1/14	6.6	6.2	5.9	7.3	79	58
TREAT	1/18/15	5.0	4.9	7.6	8.1	50	43
TREAT	2/16/15	3.4	4.4	4.4	4.3	59	63
TREAT	3/5/15	4.0	3.5	3.4	3.5	43	42
TREAT	3/14/15	3.9	4.9	3.4	3.9	48	47
TREAT	3/22/15	3.1	3.0	1*	2.5	25	32
TREAT	4/15/15	6.7	9.8	1*	2.5	21	30
TREAT	4/30/15	4.6	5.4	1*	2.8	15	44
TREAT	5/20/15	6.6	7.2	3.6	6.2	53	55
TREAT	6/4/15	5.5	5.2	3.9	4.2	42	28
TREAT	6/18/15	2.3	6.8	1*	1*	21	18
TREAT	7/14/15	8.9	6.3	3.0	2.3	37	28
TREAT	10/1/15	2.7	5.6	2.3	3.5	5*	17
TREAT	11/2/15	4.8	5.4	3.0	3.1	20	24

*One-half practical reporting limit

Appendix D. Photos of Parking Lot

Figure D-1: Clockwise from Top Left 1) Erosional features near Retrofit watershed catch basin 2) Cracks and sediment accumulation in the Control watershed 3&4) Surface runoff storage in Control watershed.

Figure D-2: Left: Surface storage and channelization of flow in Retrofit watershed Right: Accumulation of sediment in bioswale.