ABSTRACT

PAGE, JONATHAN LEWIS. Catchment-scale Evaluation of the Hydrologic and Water Quality Impacts of Residential Stormwater Street Retrofits in Wilmington, North Carolina. (Under the direction of Dr. William F. Hunt, III).

Low Impact Development (LID) is a design approach that utilizes Stormwater Control Measures (SCMs) to maintain and restore the natural hydrologic regime of an urban watershed through infiltration, runoff treatment at the source, and minimization of impervious surfaces. This paired watershed study evaluated the impacts of LID SCMs on hydrology and water quality at a catchment-scale in a small urban drainage area (0.53 ha). In February 2012, a bioretention cell (BRC) bumpout, four permeable pavement parking stalls installed in two separate sections and a tree filter device were constructed to treat residential street runoff in Wilmington, North Carolina. In the SCM-Retrofit catchment, 52% of the directly connected impervious area (DCIA) and 69% of the total drainage area was treated for potential mitigation of peak discharge and runoff volume. For water quality improvement, 94% of the DCIA and 91% of the total drainage area was retrofitted. Underlying soils in the study area were Baymeade Urban and Leon Urban sands. Post-retrofit, peak discharge significantly decreased 28% and lag times in the catchment remained unchanged, while mean runoff depth significantly decreased 52%. When compared to the control catchment, runoff depths in the SCM-Retrofit catchment were significantly less for storms with low hourly storm intensities (<2.7 mm/hr), but significantly greater for storms with high intensities (>7.4 mm/hr). Runoff thresholds in the SCM-Retrofit and control catchments were 5.2 mm and 3.5 mm, respectively. The SCM-Retrofit runoff coefficient significantly decreased from 0.38 to 0.18, and is substantially less than other runoff coefficients reported for traditional residential development. SCM-Retrofit concentrations of TKN, TP, TSS, Cu, Pb and Zn significantly

decreased by 62%, 38%, 82%, 55%, 89% and 76%, respectively. Concentrations of $NO_{2,3}$-N and TAN did not change. Mass exports of TKN, TAN, O-PO_4^{-3}, TP, TSS, Cu, Pb and Zn significantly decreased by 78%, 61%, 55%, 73%, 91%, 53%, 88% and 77%, respectively. $NO_{2,3}$-N load decreased by 46%, although this was not significant. Most improvements in water quality were due to dramatic decreases of particulate and particulate-bound pollutant loads. This was attributed to first flush retention of runoff by the BRC and permeable pavement that treated 52% of the DCIA and treatment by the tree filter unit that serviced 42% of the DCIA. This study has shown that a limited number of LID SCMs installed within a medium-density residential street right-of-way over sandy soils can mitigate some hydrologic and water quality impacts of existing development.

Catchment-scale Evaluation of the Hydrologic and Water Quality Impacts of Residential Stormwater Street Retrofits in Wilmington, North Carolina

by
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DEDICATION

For the places and people I call home.

BIOGRAPHY

Born 4 April 1987 to Larry and Dawn Page, Jonathan Lewis Page was raised on Hilton Head Island, South Carolina. Growing up he spent most of his time in and around the saltwater marshes and sounds of Beaufort County. Post-high school, he attended North Carolina State University (NCSU) where he received a B.S. in Civil Engineering in 2009. On 28 June 2009 he married Sarah Margaret Craft and together worked in Addis Ababa, Ethiopia through 2010. In 2011, he resumed his academic career at NCSU in Biological and Agricultural Engineering under the direction of Dr. William F. Hunt, III. His M.S. work evaluated several innovative Stormwater Control Measures in Wilmington, North Carolina.

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First, I must thank Dr. Bill Hunt; it has been a pleasure to be a member of the NCSU Stormwater Research Group and an opportunity I greatly appreciate. Dr. Greg Jennings and Dr. Rich McLaughlin have graciously served on my committee. I did not complete this work alone; Mr. Ryan Winston and Mr. Shawn Kennedy were instrumental in the design, construction and monitoring of the SCMs in Wilmington. Jenny James and Linda McKenzie at the North Carolina Center for Applied Aquatic Ecology were extremely helpful and flexible with their time to accommodate all of my water quality analyses. Dr. Grabow provided excellent support and answers to my statistical questions. To the former and current graduate students of the NCSU Stormwater Group, I appreciate your support and time while learning with you.

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CHAPTER 1: REVIEW OF LITERATURE

1.1 Urban Stormwater Impacts

Impervious land cover associated with urbanization has led to increases in stormwater runoff volumes and pollutants entering surface waters (Jennings and Jarnagin, 2002). In forested watersheds of the Southeastern United States, 95% of rainfall evapotranspires or infiltrates the soil to become groundwater, with just 5% of rainfall being converted to surface runoff (Figure 1-1) (Swift et al., 1987). As a watershed is developed, soil compaction and impervious surfaces including rooftops, roadways and parking lots can cause 55% (or more) of annual precipitation to become surface runoff (Figure 1-2) (Tourbier and Westmacott, 1981). Increased runoff volumes and frequency of erosive peak discharges leads to stream bank instability, which is detrimental to macroinvertebrate communities and stream ecosystems (Pratt et al., 1981; Walsh et al., 2001).

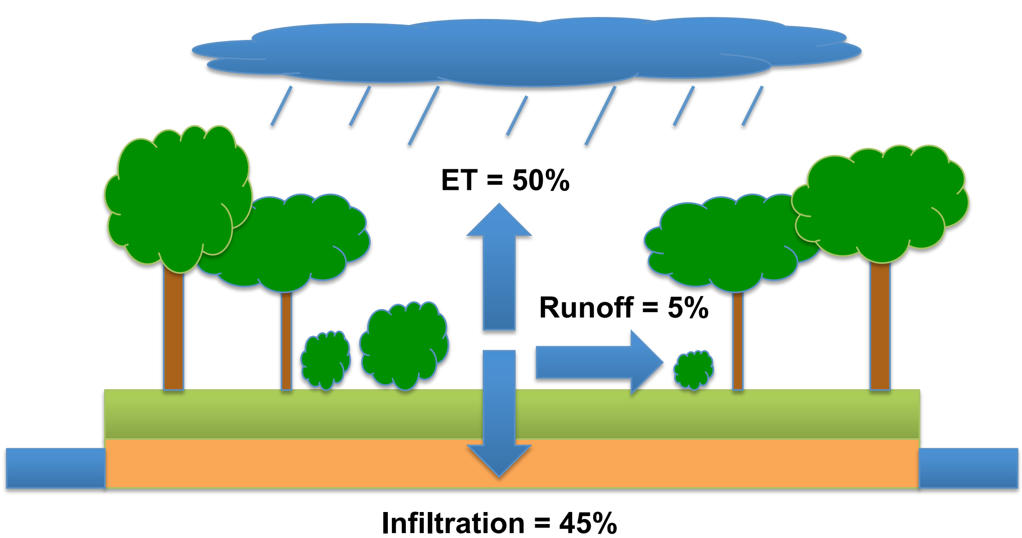

Figure 1-1: Annual rainfall allocation in forested watersheds (Swift et al., 1987)

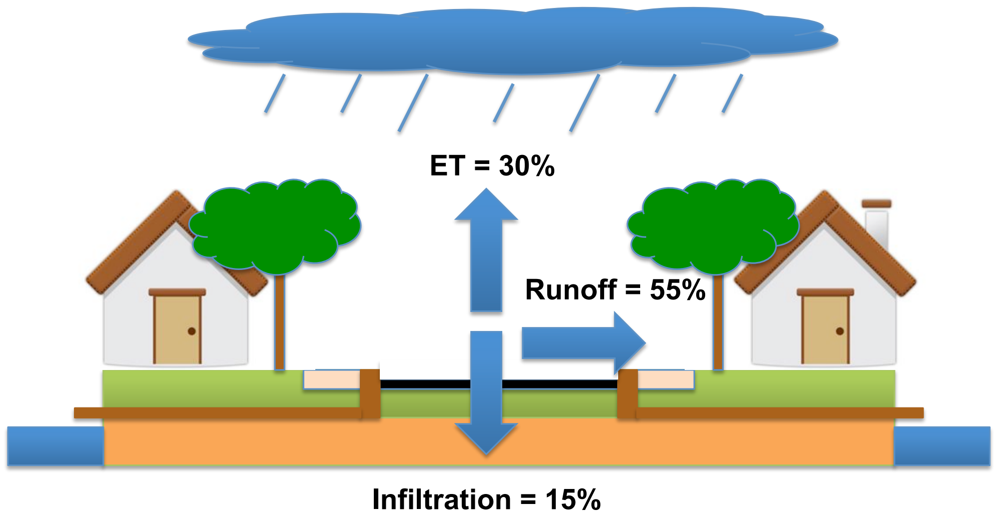

Figure 1-2: Annual rainfall allocation in developed watersheds (Tourbier and Westmacott, 1981)

Imperviousness is a critical indicator for evaluating the impacts of urbanization on water resources (Schueler, 1994; Arnold and Gibbons, 1996). Pollutants that accumulate on impervious surfaces are subsequently transported to surface waters through precipitation and runoff in a buildup – wash off cycle (Pitt et al., 1995; Wu et al., 1998; Bannerman et al., 1993). Ten percent impervious cover in a watershed can negatively impact nearby streams, rivers, lakes and estuaries, and a strong correlation has been shown between the fraction of impervious cover in a watershed and the degree to which the receiving water body is impaired (Schueler, 1992; Novotny, 2003). The National Water Quality Inventory estimates that 44% of stream km, 64% of lake ha and 30% of estuary km^2 are impaired, with urban runoff listed as a primary source of impairment (US EPA, 2009).

1.2 Stormwater Regulations

The Federal Water Pollution Control Act of 1948 was the first regulatory attempt to control surface water pollution in the United States. This legislation was amended in 1972 and again in 1977 when it became known as the Clean Water Act (CWA), which was established to "restore and maintain the chemical, physical and biological integrity of the Nation's waters" (US EPA, 2009). Amendments added in 1977 focused on regulating point source pollution to surfaces waters, but acknowledged the need for study and planning to address growing concerns over nonpoint source pollution (i.e., stormwater runoff). Nonpoint source pollution control is now recognized as a critical component in preserving and protecting the nation's waterways.

Phase I of the National Pollutant Discharge Elimination System (NPDES) was enacted in 1990 as part of the CWA. It included regulations for municipalities serving populations greater than 100,000 with municipal separate storm sewer systems (MS4s) to develop stormwater management plans for new and existing development within their jurisdiction. Phase II of NPDES extended the stormwater management requirements to communities with greater than 10,000 residents (US EPA, 2000b). Specifically in North Carolina, other stormwater regulations exist to protect certain water resources. Coastal communities, and those in the Jordan Lake Watershed, Neuse River Basin or Tar-Pam River Basin face more restrictive runoff volume and nutrient management requirements (NCDENR, 2009).

1.3 Streets and Roadways

Street surfaces are sources of stormwater runoff pollutants and pathways for the transport of pollutants from adjacent land areas. Streets have been identified as a primary pollutant source area for all urban land uses, and generate the majority of pollutant loads in residential areas (Bannerman et al., 1993). Most municipal streets and roadways are directly connected to conventional storm sewer networks with curb and gutter drainage systems. Directly connected impervious area (DCIA) is the main contributor of runoff volume and pollutant loads in small rainfall events (<25.4 mm) (Walsh, 2000; Walsh et al., 2004; Flint and Davis, 2007). Walsh et al. (2004) suggests DCIA is a more appropriate predictor of stormwater impacts to surface waters than total impervious area of a watershed. DCIA is particularly important in watersheds with sandy soils (Lee and Heaney, 2001).

Organic and inorganic particulate material including sediment, heavy metals nutrients, leaf litter, woody debris, polycyclic aromatic hydrocarbons (PAHs), gross solids and pathogens are pollutants that accumulate on streets and roadways (Bannerman et al., 1993; Barrett et al., 1998; Wu et al., 1998). The rate of contaminant export from the street surface is influenced by rainfall intensity, pavement type and particle size (Sartor et al., 1974; Barrett et al., 1993). Particulates range from 25 μm to 3000 μm in size, and up to 90% of the particulate load from streets may be found within 30 cm (12 in) of the curb (Sartor et al., 1974). Residential streets have been shown to have sediment and solids exports up to four times greater than commercial streets (Sartor and Gaboury, 1984).

Copper (Cu) and zinc (Zn) in urban runoff originates from vehicular brake usage, tire wear and atmospheric deposition (Barrett et al., 1998; Wu et al. 1998). In residential watersheds, lead (Pb) and Zn in runoff have been linked to aged exterior paint and building siding (Davis et al., 2001). Heavy metals do not degrade over time and become toxic to benthic aquatic life as they accumulate in sediments of streams, lakes and estuaries. Leaf litter and woody debris is a source of organic nitrogen (ON) on streets where trees and landscaping are present. Sources of PAHs on roadways include incomplete combustion of fossil fuels, vehicular fluids, and pavement sealants (Pitt et al., 1995; Ngabe et al., 2000; Van Metre et al., 2000, Mahler et al., 2005; Watts et al., 2010). A strong correlation has been found between increased population growth and traffic activity in a watershed with accumulation of PAHs in stream and reservoir bed sediments (Van Metre et al., 2000). Pathogens tend to be more prevalent in residential areas when compared to other urban land uses due to pet and wildlife wastes (Bannerman et al., 1993).

Street sweeping is utilized by many cities and towns to control debris on the roadway and to reduce pollutant loads. However, evaluations of street sweeping operations have shown this practice is largely for aesthetics rather than providing any noticeable water quality benefit (Bender and Terstriep, 1984). This is because the fine solids and sediment fraction on the street surface is less than 250 µm and contains nearly all of the pollutant load (Sartor and Gaboury, 1984). Conventional street sweeping operations readily remove leaf litter, debris and coarse sediment, but do not effectively remove fine particles; rather, the sweeper brush redistributes them over the whole roadway (Sartor et al., 1974; Sartor and Gaboury, 1984).

In residential areas, nutrients are transported by streets to the storm sewer network. Nutrients found in runoff include multiple forms of nitrogen (N) and phosphorus (P), which may originate from fertilizers, animal wastes and atmospheric deposition on rooftops, driveways and roads (Bannerman et al., 1993; Barrett et al., 1998; Wu et al., 1998). Excess N and P, particularly in dissolved forms of nitrate (NO_3^-) and orthophosphate ($O\text{-}PO_4^{-3}$) discharged to surface waters can stimulate the growth of algae, including toxic "phantom-like" *Pfiesteria* strains (Burkholder et al., 1992; van Dolah, 2000). Rapid algal growth and die off increases microbial activity and dissolved oxygen demand, which can lead to eutrophication and hypoxia (Paerl, 1993). Treatment of NO_3^- is difficult because runoff must be retained in an anoxic environment for NO_3^- to be converted to dinitrogen gas (N^2) through denitrification. Filters or fill media that have enhanced adsorption properties may remove $O\text{-}PO_4^{-3}$.

1.4 Low Impact Development

Low Impact Development (LID) is an integrated design approach intended to mimic pre-development hydrology and water quality (Prince George's County, 1999; Coffman, 2000; Dietz, 2007). LID is an alternative to conventional storm sewer networks that have been shown to decrease the lag time to peak discharge and increase the magnitude of peak discharge by efficiently conveying runoff away from structures (Leopold, 1968). LID intends to preserve the natural characteristics and ecological integrity of a watershed, and when this is not possible, to reduce impacts to vegetation, topography, soils and aquatic communities. This is achieved by discretely locating and minimizing impervious surfaces and utilizing stormwater control measures (SCMs) to capture and treat runoff at the source (Coffman, 2000; Davis et al., 2006).

SCMs that mitigate the impacts of urbanization by promoting the capture and treatment of runoff at its source were initially adopted in the early 1990's in Prince Georges

County, Maryland (1999). LID SCMs provide infiltration, filtration, adsorption, storage and/or groundwater recharge. Examples include: bioretention cells (BRCs), level spreaders, tree filter boxes, grassed bioswales, green roofs and permeable pavements. Peer-reviewed literature of LID practices has shown promise in preserving or restoring pre-development hydrology and water quality at new and existing urban development (US EPA, 2000a; Dietz, 2007). The hydrologic and water quality impacts of several individual LID SCMs will be discussed further.

1.5 Bioretention Cells

BRCs are shallow depressions filled with a soil media supporting vegetation for retention and treatment runoff from impervious areas (NCDENR, 2009). Applied surface runoff enters the bowl, ponds temporarily before infiltrating into the fill media and may exit the system through (1) exfiltration to in-situ soils, (2) evapotranspiration or (3) drainage (Figure 1-3). BRCs maintain or restore pre-development hydrology by providing depressional storage and infiltration throughout a watershed, which enhances ground water recharge and natural base flow to streams (Davis et al., 2009; DeBusk et al., 2011). Hydrologically, BRCs perform better under warm and dry conditions (i.e., low antecedent moisture conditions and high potential evapotranspiration) (Hunt et al., 2006; Davis, 2008; Li et al. 2009). The ability of a BRC to mitigate peak discharge is directly linked to the infiltration rate and water-free pore space of the fill media, and BRCs have been shown to reduce peak discharges by up to 96% for events that do not overtop the bowl (Dietz and Clausen, 2005; Davis, 2008; Hunt et al., 2008; Davis 2009). In many studies BRCs eliminated runoff from small storms entirely (Dietz and Clausen, 2005; Hunt et al, 2006;

Davis, 2008; Brown and Hunt, 2011). BRCs with greater volumes of fill media are better suited to capture runoff volumes from larger rainfall events (Li et al., 2009).

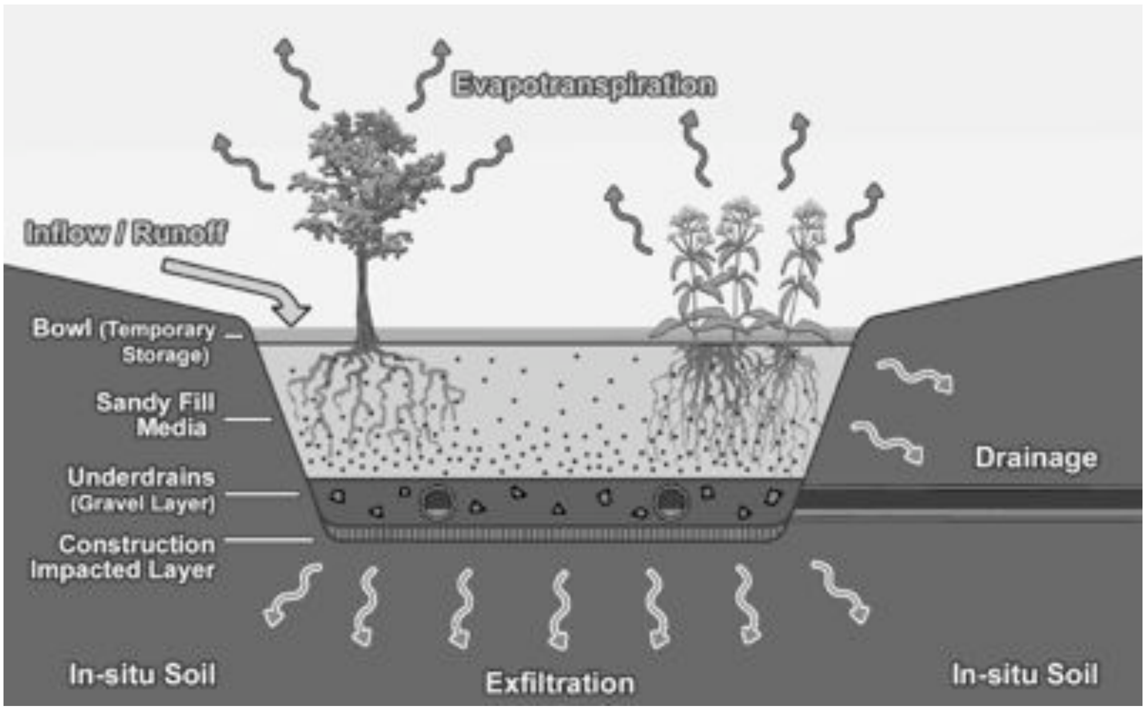

Figure 1-3. Bioretention cross-section (*Photo credit: Shawn Kennedy*)

Water quality evaluations have shown particulate pollutants are effectively removed by BRCs. The water quality benefits of BRCs are driven by hydrology as dramatic reductions in mass export are observed frequently with less substantial concentration reductions reported (Table 1-1) (Li and Davis, 2009; Brown and Hunt, 2011). Heavy metals and total suspended solids (TSS) have consistently been retained well by BRCs through filtration, sedimentation and adsorption; mass load reductions of TSS, Cu, Pb and Zn are usually greater than 85% (Hunt et al., 2008; Li and Davis, 2009; Brown and Hunt, 2011). Hunt et al.

(2006) found that P retention in BRCs is highly dependent upon the P-index of the fill media and TSS retention. Particle bound P is captured without difficulty at the fill media surface, but a low P-index in necessary to capture (dissolved) O-PO_4^{-3} (Hunt et al., 2006; Hatt et al., 2009). Retention of O-PO_4^{-3} is important in nutrient sensitive freshwater ecosystems because excess P can cause large algal blooms and lead to eutrophication in lakes (Schindler, 1975). In some instances, particle bound P separated from Fe or Al in BRC fill media under reduced redox potentials (Dietz and Clausen, 2006; Hunt et al., 2006).

Table 1-1: Summary of pollutant removal in BRCs

Study	**ID**	**Pollutant Removal (%)**								
		TSS	**$NO_{2,3}$-N**	**TAN**	**TKN**	**OP**	**TP**	**Cu**	**Pb**	**Zn**
Brown and Hunt, 2011(1)	0.6 m med	70	-86	77	36	-53	1			
	0.9 m med	84	-149	78	56	-18	41			
Davis et al., 2001(1)	Small Box				86		82			
	Large Box		97	79	97		99			
Dietz and Clausen, 2006(2)	RG 1,2		35	85	31		-110			
Hunt et al., 2006(1)	C1		13	86	45	69	65			
	G2	-170	75	-1	-5	-9	-240	99	81	98
Hunt et al., 2008(2)	HMBC	60	-5	72	44		31	54	31	77
Li and Davis, 2009	Cell CP(1)	96	-108		25		-36	65	83	92
	Cell CP(2)	88	-170		-11		-200	31	55	78
	Cell SS(1)	99	99		87		100	96	100	99
	Cell SS(2)	88	86		-30		0	0	0	80
Passeport et al., 2009(1)	North Cell		43	78	48	52	53			
	South Cell		1	88	68	77	68			
Mean(1)		**36**	**-2**	**69**	**60**	**20**	**23**	**87**	**88**	**96**
Mean(2)		**79**	**-14**	**79**	**9**	**NA**	**-70**	**28**	**29**	**78**

Negative sign "-" implies pollutant export
(1) Mass reduction
(2) Concentration reduction

N retention within BRCs is influenced by particulate capture, vegetation uptake and biological transformations (Table 1-1). ON and total ammoniacal nitrogen (TAN) (thus, TKN) are retained well by BRCs, but $NO_{2,3}$-N is retained poorly (Davis et al., 2003, Dietz and Clausen, 2005; Dietz, 2007; Hunt et al., 2008; Brown and Hunt, 2011). Unless specifically designed otherwise, BRCs are predominantly aerobic systems and transformations of ON and TAN to $NO_{2,3}$-N occurs readily through mineralization, ammonification and nitrification during inter-event dry periods (Kim et al., 2003; Lucas and Greenway, 2011; Hunt et al., 2012). $NO_{2,3}$-N in fill media is then flushed from the system during the next precipitation event, resulting in higher effluent concentrations of $NO_{2,3}$-N than were observed in untreated influent (Kim et al., 2003; Davis et al. 2001, 2006; Hsieh and Davis 2005; Roseen et al. 2006; Hunt et al. 2006, 2008; Hatt et al. 2009). Hunt (2003) and Kim et al. (2003) proposed the internal water storage zone (IWS) to increase NO_3^- retention by maintaining a saturated layer of soil within BRCs, and several studies have shown improved NO_3^- retention with the simple design modification (Passeport et al., 2009; Brown and Hunt, 2011; Lucas and Greenway, 2011). IWS also substantially improves runoff volume reduction with sandy underlying soils (Passeport et al., 2009; Brown and Hunt, 2011).

1.6 Tree Filter Boxes

Tree filter boxes are manufactured SCMs that use a high-flow engineered soil media with upland herbaceous or woody plants contained inside a concrete box. The devices function as rapid flow-through filters such that ponding at the surface does not occur. Lenth et al. (2010) measured infiltration rates of ten Filterra™ devices with varying maintenance periods (recent – 2 years) and found infiltration rates from 2200 mm/hr (86 in/hr) to 5200 mm/hr (205 in/hr) with up to 110 mm (4.5 in) of sediment accumulation at the surface. Volume reduction is negligible because the concrete lining does not allow exfiltration to occur, though some storage is available in the water free pore space of the media.

Field and laboratory studies have shown Filterra® devices provide treatment of total phosphorus (TP), TSS, Cu, and Zn (Table 1-2). TSS removal is consistently greater that 85% and mean Cu and Zn removal rates are 55% and 63%, respectively (Yu and Stafford, 2007; Lenth et al., 2010). TP removal is less consistent and may be a function of the dissolved vs. particle bound P in runoff. Limited data are available for TN and TKN removal. Particulate ON removal is expected to be good because the media filters and adsorbs particulates, as demonstrated by TSS, TP, Cu and Zn removal. NO_3^- removal is not likely to be appreciable with extremely low hydraulic residence times that are not conducive for denitrification to occur.

Table 1-2: Summary of pollutant removal in Tree Filter Systems

Study	Location	Removal Efficiency - Concentrations (%)					
		TKN	TN	TP	TSS	Cu	Zn
Lenth et al., 2010	Virginia			60	88	33	48
Lenth et al., 2010	Virginia			70	83		
Lenth et al., 2010	Maryland			45	88	77	79
Lenth et al., 2010	Washington			57	89		
Lenth et al., 2010	Washington			9	85	58	74
Yu and Stafford, 2007	Laboratory		76	82	95	91	
Yu and Stafford, 2007	Virginia	20		55	85	16	50
Number of Studies, n		1	1	7	7	5	4
Mean		**20**	**76**	**54**	**88**	**55**	**63**
Median		**20**	**76**	**57**	**88**	**58**	**62**

1.7 Permeable Pavement

Permeable pavement is an alternative to traditional impervious concrete and asphalt pavements. There are five main types of permeable pavements: permeable concrete (PC), pervious asphalt (PA), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP) and plastic grid pavers (PGP). Each type of permeable pavement has different structural properties and applications, but the general function of the pavements is the same. Surface runoff infiltrates through the pavement/paver for temporary storage in the aggregate sub-base and may exit the system via underdrains or exfiltration, which provides additional volume reduction (Figure 1-4) (Bean et al., 2007ab).

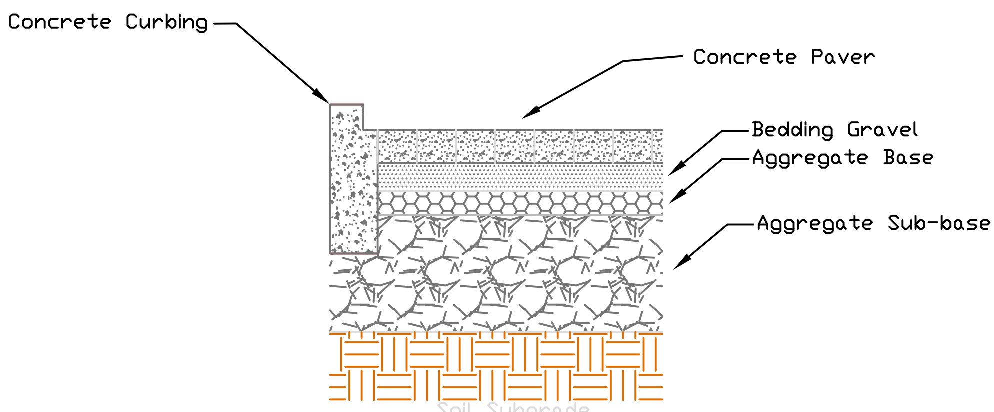

Figure 1-4: Typical permeable pavement cross-section (*Credit: NCSU Stormwater Group)*

Permeable pavement is well suited to mitigate the hydrologic impacts of urbanization through substantial reductions in peak discharge and runoff volume. (Bean et al., 2007b; Collins et al., 2008; Ball and Rankin, 2010). Bean et al. (2007b) reported a PICP installation in North Carolina eliminated all runoff when underdrains were removed from the system. In Connecticut, a 72% reduction in runoff volume from a PICP driveway was reported when compared to an adjacent asphalt driveway (Gilbert and Clausen, 2006). Permeable pavement was effective when installed over impermeable clay soils with high slopes (6.0 – 7.4%) in New Zealand. Runoff volume was reduced by 28% and peak discharge magnitude was the same or less than modeled pre-development conditions, in fact lag times and outflow durations were similar to a vegetated landscape (Fassman and Blackbourn, 2010).

Permeable pavements may improve street surface runoff quality, which tends to have higher concentrations of heavy metals and sediment (Bannerman et al., 1993; Steuer, 1997). Water quality evaluations of permeable pavements have shown TSS and heavy metals (Cu, Pb, Zn) are readily removed from influent runoff through filtration and sedimentation (Pratt et al., 1989; Pratt et al., 1995; Dierkes et al., 2002; Brattebo and Booth, 2003). Nutrient retention in permeable pavements varies by installation. At two field sites in North Carolina TP, TKN and TAN concentrations in outflow were significantly reduced (Bean et al., 2007b). In general, $NO_{2,3}$-N effluent concentrations are greater than influent, which is primarily caused by nitrification of NH_4^+ to NO_3^- in the aerobic aggregate sub-base (James and Shahin, 1998; Bean et al., 2007b; Collins et al., 2008). Laboratory analyses have suggested that up to 97% of applied motor oils and vehicular fluids may be removed from influent through biological activity in the aggregate sub-base (Pratt, 1999; Newman et al., 2004).

1.8 Street Trees

Street trees are a popular aesthetic component of LID street design, and some air quality benefits and mitigation of heat island effects have been reported. Urban trees may improve air quality through direct pollutant uptake and by cooling the air, thus slowing ozone producing photochemical reactions (Taha, 1996). Carbon dioxide, a primary component of climate change, is also readily sequestered by trees in urban centers (Rosenfeld et al., 1998; Nowak and Crane, 2002). Lawrence Berkley National Laboratory reported paved areas with mature tree canopies were 2.7° – 3° C cooler than paved areas with no trees (Akbari et al., 2001). In several urban centers, modeling efforts have shown that a larger urban forest will reduce electricity use and cooling costs (McPherson et al., 1994).

Urbanizing activities compact soils, which greatly reduces tree canopy height and width, root growth and life span (Yung, 1993). Structural soils were proposed to offset the effects of compacted urban soils by distributing the surface load over a coarse aggregate base with tree planting soil mixed into the aggregate void space (Smiley et al., 2006). However, evaluations of structural soils have shown that most street trees do not reach maturity when planted in structural soils because there is not enough soil available within the aggregate (Smiley et al., 2006). The Silva Cell™ suspended pavement system was developed to improve upon the principles of structural soil. Silva Cells are a plastic composite grid structure with 92% void space that support loads up to AASHTO H-20 standards. The static and active loads above the Silva Cells are transferred to the sub-grade by the composite columns and beams. The uncompacted soil volume contained in the Silva Cells is ideally suited for tree root growth, but also creates a potentially novel subsurface SCM.

The hydrologic and water quality impacts of a single street tree have not been documented, but city-scale modeling suggests a healthy urban forest can have a modest impact on runoff volume. In Tucson, Arizona, increasing urban canopy cover for two modeling scenarios from 21% to 35% and 50% provided 2% and 4% reductions in runoff volume, respectively (Lormand, 1988). The urban forest in Dayton, Ohio (22% of municipal land cover) was estimated to reduce runoff volume by 7% when compared to a modeled scenario without any urban trees (Sanders, 1986). Interception of rainfall is the primary mechanism by which street trees mitigate the impacts of urban runoff. Xiao et al. (1998) reported mean rainfall interception up to 36% during summer in California, and noted that interception fractions were greatest during the water quality event (<25.4 mm). No studies have evaluated the hydrologic and water quality impacts of urban trees receiving runoff from adjoining impervious areas. With careful design modifications, the Silva Cells' uncompacted soil volume could be used as a subsurface bioretention system to provide capture and treatment of street surface runoff.

1.9 Watershed-scale LID

Limited peer-reviewed literature is available on the hydrologic and water quality impacts of LID SCMs at a watershed or catchment-scale. Bedan and Clausen (2009) studied an LID residential neighborhood in Waterford, Conn., known as the Jordan Cove Project, where shared driveways, BRCs, grassed swales and permeable pavements were utilized. Impervious cover in the watershed increased from 0% to 21% after construction. However, no change in mean peak discharge was observed at the watershed outlet, and mean runoff depth was significantly reduced by 42%. The authors concluded this to be a direct result of distributing LID SCMs throughout the watershed designed to capture and treat runoff associated with the first 25.4 mm (1 in) of rainfall. When compared to an adjacent, traditional residential development, normalized mean lag times in the LID watershed were 1.4 times greater than those observed in the traditional development (Hood et al., 2007).

Bedan and Clausen (2009) reported pollutant mass exports of TKN, TAN, Pb, Zn and pathogens decreased post-construction although mass exports of TP and TSS increased. The increase in TP load was attributed to fertilizer application by homeowners, which is in common in residential watersheds (Gray and Becker, 2002; Dietz et al., 2004). Periodic erosion of the grassed swales was cited as the cause for increases in TSS exports. Mass loads and concentrations of Cu and biochemical oxygen demand (BOD) at the watershed outlet remained constant post-construction. Per US EPA (1983), medium and high-density watersheds have an average TN export of 9.6 kg/ha/yr and TP exports between 1.48 – 2.45 kg/ha/yr. Bedan and Clausen (2009) found TN and TP exports of 2 kg/ha/yr and 0.4 kg/ha/yr respectively, which is substantially less than the US EPA average and more similar to nutrient exports from forested watersheds (Frink, 1991).

Line et al. (2012) characterized runoff, nutrient and sediment exports from three commercial watersheds in North Carolina: (1) a site with no SCMs, (2) a site with a wet detention basin and (3) an LID site with undersized permeable pavement, BRC and stormwater wetland installations. The LID site provided a greater mass load reduction for TKN, TAN, TP, TSS and substantially greater runoff volume reduction (34%) than the wet detention site. Mass exports for three of the five pollutants (TKN, TAN, TSS) were significantly reduced at the LID site while the wet detention site only significantly reduced mass exports for one of the five pollutants (TAN). Line et al. (2012) noted the LID SCMs were not sized and constructed according to current regulatory standards in North Carolina, and suggested that the runoff and pollutant mass reductions may have been even greater with properly sized and constructed LID SCMs.

Applying LID SCMs to existing urban development as retrofits may require systems to be undersized. As discussed above, Line et al. (2012) showed that undersized SCMs effectively reduced runoff volumes and pollutant loads at a commercial watershed outlet when compared to a commercial site with no stormwater treatment in place. Brown and Hunt (2011) reported two undersized BRCs of different media depths (0.6 m and 0.9 m) substantially reduced TN, TP, and TSS pollutant loads and runoff volume, with the 0.9 m media-depth cell outperforming the 0.6 m cell. In another North Carolina study of an undersized BRC, TN and TSS loads were reduced by 27% and 49%, respectively (Luell et al., 2011).

1.10 SCMs within the Right-of-Way

Streets and roadways make up roughly 25% of the urban landscape and represent the majority of the impervious cover owned and maintained by municipalities (UACDC, 2010). Traditionally, roadways have been designed to provide maximum traffic flow and adequate drainage to prevent flooding in the driving lane with little regard for control and treatment of runoff. There is limited but usable space within the right-of-way, which includes the roadway, sidewalk and adjoining plaza area to install SCMs. It is becoming increasingly important to quantify the impacts of SCMs on street runoff quantity and quality as municipalities address goals for watershed management plans or comply with total maximum daily load (TMDL) requirements.

A myriad of pilot "green street" projects exist across the United States and internationally. However, nearly all of these projects involve the complete redevelopment of a residential street, and no peer-reviewed literature is available that quantifies their impacts on hydrology and water quality (Wise, 2008). The complete redevelopment of the residential streetscape is costly and may be unnecessary to achieve desired runoff quantity and quality goals; simple, well-placed SCMs may be successful at controlling and treating street runoff. Ideally from a stormwater management perspective, new municipal streets would be constructed similar to the interstate highway environment with filter strips, linear wetlands and swales to provide disconnection of the impervious area, conveyance and treatment (Winston et al., 2012). However, this is not easily incorporated into new roadway construction in urban centers due to numerous constraints on available corridor, lane width and pedestrian access. Existing streets with curb and gutter drainage present new challenges to providing stormwater capture and treatment. Sidewalks, significant trees, utilities, sight distance requirements, parking ordinances and adjacent landowners greatly impact the size and placement of SCMs within the right-of-way.

BRCs, permeable pavement and tree filters are well suited as retrofit applications to capture and treat street surface runoff. BRC bumpouts installed in the roadway provide treatment and storage of runoff while increasing pedestrian safety. Narrowing a residential roadway by 3.7 m (12 ft) reduced vehicle accident frequency by 73% (UACDC, 2010). Permeable pavements may be used to replace sections of existing asphalt and concrete pavement, or where speed and vehicular braking force is a concern, permeable pavements may be placed in parking lanes next to the driving lanes. Tree filters require minimal space for installation, but may provide effective particulate treatment for impervious areas with loading ratios up to 300:1. This study will evaluate the impacts of stormwater retrofits installed with the residential street right-of-way on hydrology and water quality at a catchment-scale.

1.11 References

Akbari, H., Pomerantz, M., and Taha, H. (2001). "Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas." *Solar Energy,* 70(3), 295-310.

Arnold Jr, C. L., and Gibbons, C. J. (1996). "Impervious surface coverage: the emergence of a key environmental indicator." *Journal of the American Planning Association,* 62(2), 243-258.

Bannerman, R. T., Owens, D. W., Dodds, R. B., and Hornewer, N. J. (1993). "Sources of Pollutants in Wisconsin Stormwater." *Water Science and Technology,* 28(3-5), 241-259.

Barrett, M. E., Irish, L. B., Malina, J. F., and Charbeneau, R. J. (1998). "Characterization of highway runoff in Austin, Texas, area." *Journal of Environmental Engineering-Asce,* 124(2).

Bean, E. Z., W. F. Hunt and D. A. Bidelspach. (2007a). "Field survey of permeable pavement surface infiltration rates. " *J.Irrig.Drainage Eng-ASCE*, 133(3): 249-255.

Bean, E. Z., Hunt, W. F., and Bidelspach, D. A. (2007b). "Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts." *J.Irrig.Drainage Eng-ASCE,* 133(6), 583-592.

Bedan, E. S., and Clausen, J. C. (2009). "Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds1." *Journal of the American Water Resources Association,* 45(4), 998-1008.

Bender, G., and Terstriep, M. (1984). "Effectiveness of street sweeping in urban runoff pollution control." *Sci.Total Environ.,* 33(1), 185-192.

Brattebo, B. O., and Booth, D. B. (2003). "Long-term stormwater quantity and quality performance of permeable pavement systems." *Water Res.,* 37(18), 4369-4376.

Brown, R. A., and Hunt, W. F.,III. (2011). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." *J.Irrig.Drainage Eng-ASCE,* 137(3), 132-143.

Burkholder, J. M., Noga, E. J., Hobbs, C. H., and Glasgow, H. B. (1992). "New Phantom Dinoflagellate is the Causative Agent of Major Estuarine Fish Kills." *Nature,* 358(6385).

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., and Smith, V. H. (1998). "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen." *Ecol.Appl.,* 8(3), 559-568.

Coffman, L.S. 2000. Low-Impact Developmeent Design: A New Paradigm for Stormwater Management Mimicking and Restoring the Natural Hydrologic Regime An Alternative Stormwater Management Technology. Department of Environmental Resources, Prince Georges County, Maryland.

Collins, K. A., Hunt, W. F., and Hathaway, J. M. (2008). "Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina." *J.Hydrol.Eng.,* 13(12), 1146-1157.

Davis, A. P. (2008). "Field performance of bioretention: Hydrology impacts." *J.Hydrol.Eng.,* 13(2).

Davis, A., Shokouhian, M., and Ni, S. (2001). "Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources." *Chemosphere,* 44(5), 997-1009.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C., and Winogradoff, D. (2003). "Water quality improvement through bioretention: Lead, copper, and zinc removal." *Water Environ.Res.,* 75(1).

Davis, A. P., Shokouhian, M., Sharma, H., and Minami, C. (2006). "Water quality improvement through bioretention media: Nitrogen and phosphorus removal." *Water Environ.Res.,* 78(3).

Davis, A. P., Hunt, W. F., Traver, R. G., and Clar, M. (2009). "Bioretention Technology: Overview of Current Practice and Future Needs." *Journal of Environmental Engineering-Asce,* 135(3), 109-117.

DeBusk, K. M., Hunt, W. F., and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" *J.Hydrol.Eng.,* 16(3), 274-279.

DiBlasi, C. J., Li, H., Davis, A. P., and Ghosh, U. (2009). "Removal and Fate of Polycyclic Aromatic Hydrocarbon Pollutants in an Urban Stormwater Bioretention Facility." *Environ.Sci.Technol.,* 43(2), 494-502.

Dierkes, C., Kuhlmann, L., Kandasamy, J., and Angelis, G. (2002). "Pollution retention capability and maintenance of permeable pavements." *Global Solutions for Urban Drainage, Proc. of the Ninth Int. Conf. on Urban Drainage, Sept 8-13 2002, Portland, OR.*

Dietz, M. (2007). "Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions." *Water, Air, & Soil Pollution,* 186(1), 351-363.

Dietz, M. E., and Clausen, J. C. (2005). "A field evaluation of rain garden flow and pollutant treatment." *Water Air and Soil Pollution,* 167(1-4).

Dietz, M. E., and Clausen, J. C. (2006). "Saturation to improve pollutant retention in a rain garden." *Environ.Sci.Technol.,* 40(4).

Dietz, M. E., and Clausen, J. C. (2008). "Stormwater runoff and export changes with development in a traditional and low impact subdivision." *J.Environ.Manage.,* 87(4), 560-566.

Dietz, M. E., Clausen, J. C., and Filchak, K. K. "Education and changes in residential nonpoint source pollution." *Environmental management* 34(5): 684-690.

Fach, S., and Geiger, W. F. (2005). "Effective pollutant retention capacity of permeable pavements for infiltrated road runoffs determined by laboratory tests." *Water Science and Technology,* 51(2), 37-45.

Fassman, E. A., and Blackbourn, S. (2010). "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." *J.Hydrol.Eng.,* 15(6), 475-485.

Flint, K. R., and Davis, A. P. (2007). "Pollutant mass flushing characterization of highway stormwater runoff from an ultra-urban area." *J.Environ.Eng.,* 133(6), 616-626.

Frink, C. R. (1991). "Estimating nutrient exports to estuaries." *J.Environ.Qual.,* 20(4), 717-724.

Gilbert, J. K., and Clausen, J. C. (2006). "Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut." *Water Res.,* 40(4), 826-832.

Gray, S. R., and Becker, N.S. (2002). "Contaminant flows in urban residential water systems." *Urban Water* 4(4): 331-346.

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

Hood, M. J., Clausen, J. C., and Warner, G. S. (2007). "Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development1." *JAWRA Journal of the American Water Resources Association,* 43(4), 1036-1046.

Hsieh, C., Davis, A. P., and Needelman, B. A. (2007). "Nitrogen removal from urban stormwater runoff through layered bioretention columns." *Water Environ.Res.,* 79(12).

Hunt III, W. F. (2003). *Pollutant removal evaluation and hydraulic characterization for bioretention stormwater treatment devices*. Diss. The Pennsylvania State University, University Park, PA.

Hunt, W. F., Jarrett, A. R., Smith, J. T., and Sharkey, L. J. (2006). "Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina." *Journal of Irrigation and Drainage Engineering-Asce,* 132(6), 600-608.

Hunt, W. F., Smith, J. T., Jadlocki, S. J., Hathaway, J. M., and Eubanks, P. R. (2008). "Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC." *Journal of Environmental Engineering-Asce,* 134(5).

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

James, W., and Shahin, R. (1998). "A laboratory examination of pollutants leached from four different pavements by acid rain." *Advances in Modeling the Management of Stormwater Impacts,* 6(17), 321.

Jennings, D. B., and Jarnagin, S. T. (2002). "Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed." *Landscape Ecol.,* 17(5), 471-489.

Kim, H. H., Seagren, E. A., and Davis, A. P. (2003). "Engineered bioretention for removal of nitrate from stormwater runoff." *Water Environ.Res.,* 75(4).

Lee, J. G., and Heaney, J. P. (2003). "Estimation of urban imperviousness and its impacts on storm water systems." *J.Water Resour.Plann.Manage.,* 129(5), 419-426.

Lenth, J., Dugopolski, R., Consultants, H. E., Quigley, M., Poresky, A., Leisenring, M., and Consultants, G. (2010). "Filterra® Bioretention Systems: Technical Basis for High Flow Rate Treatment and Evaluation of Stormwater Quality Performance." Richmond, VA.

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

Li, H., and Davis, A. P. (2009). "Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention." *Journal of Environmental Engineering-Asce,* 135(8).

Li, H., Sharkey, L. J., Hunt, W. F., and Davis, A. P. (2009). "Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland." *J.Hydrol.Eng.,* 14(4).

Line, D., White, N., Osmond, D., Jennings, G., and Mojonnier, C. (2002). "Pollutant export from various land uses in the upper Neuse River Basin." *Water Environ.Res.,* 74(1), 100-108.

Line, D. E., and White, N. M. (2007). "Effects of development on runoff and pollutant export." *Water Environ.Res.,* 79(2), 185-190.

Line, D.E., Brown, R. A., Hunt, W. F., and Lord, W. G. (2012). “Effectiveness of LID for Commercial Development in North Carolina” *J. Environ. Eng.* 138(6), 680-688.

Lormand, J. R. (1988). "The effects of urban vegetation on stormwater runoff in an arid environment."

Lucas, W. C., and Greenway, M. (2011). "Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part II-Nitrogen Retention." *Water Environ.Res.,* 83(8).

Luell, S. K., Hunt, W. F., and Winston, R. J. (2011). "Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff." *Water Science and Technology,* 64(4), 974-979.

Mahler, B. J., Van Metre, P. C., Bashara, T. J., Wilson, J. T., and Johns, D. A. (2005). "Parking Lot Sealcoat: An Unrecognized Source of Urban Polycyclic Aromatic Hydrocarbons." *Environ.Sci.Technol.,* 39(15), 5560-5566.

McPherson, E. G., Nowak, D. J., and Rowntree, R. A. (1994). *Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project*. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Radnor, PA.

NCDENR. (2009). Stormwater Best Management Practices Manual. North CarolinaDepartment of Environment and Natural Resources, Division of Water Quality. Raleigh, NC.

Newman, A. P., Puehmeier, T., Kwok, V., Lam, M., Coupe, S. J., Shuttleworth, A., and Pratt, C. J. (2004). "Protecting groundwater with oil-retaining pervious pavements: historical perspectives, limitations and recent developments." *Quarterly Journal of Engineering Geology and Hydrogeology,* 37 283-291.

Ngabe, B., Bidleman, T. F., and Scott, G. I. (2000). "Polycyclic aromatic hydrocarbons in storm runoff from urban and coastal South Carolina." *Sci.Total Environ.,* 255(1-3), 1-9.

Nowak, D. J., and Crane, D. E. (2002). "Carbon storage and sequestration by urban trees in the USA." *Environmental Pollution,* 116(3), 381-389.

Paerl, H. (1993). "Emerging Role of Atmospheric Nitrogen Deposition in Coastal Eutrophication - Biogeochemical and Trophic Perspectives." *Can.J.Fish.Aquat.Sci.,* 50(10), 2254-2269.

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

Pitt, R., Field, R., Lalor, M., and Brown, M. (1995). "Urban Stormwater Toxic Pollutants - Assessment, Sources, and Treatability." *Water Environ.Res.,* 67(3), 260-275.

Pratt, C., Mantle, J., and Schofield, P. (1989). "Urban stormwater reduction and quality improvement through the use of permeable pavements." *Water Science & Technology,* 21(8-9), 769-778.

Pratt, C., Mantle, J., and Schofield, P. (1995). "UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality." *Water Science and Technology,* 32(1), 63-70.

Pratt, C., Newman, A., and Bond, P. (1999). "Mineral oil bio-degradation within a permeable pavement: Long term observations." *Water Science & Technology,* 39(2), 103-109.

Pratt, J. M., Coler, R. A., and Godfrey, P. J. (1981). "Ecological effects of urban stormwater runoff on benthic macroinvertebrates inhabiting the Green River, Massachusetts." *Hydrobiologia,* 83(1), 29-42.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Avelleneda, P., Wildey, R., and Briggs, J. (2006). "Storm water low-impact development, conventional structural, and manufactured treatment strategies for parking lot runoff: Performance evaluations under varied mass loading conditions." *Transportation Research Record: Journal of the Transportation Research Board,* 1984(-1), 135-147.

Rosenfeld, A. H., Akbari, H., Romm, J. J., and Pomerantz, M. (1998). "Cool communities: strategies for heat island mitigation and smog reduction." *Energy Build.,* 28(1), 51-62.

Sanders, R. A. (1986). "Urban vegetation impacts on the hydrology of Dayton, Ohio." *Urban Ecology,* 9(3), 361-376.

Sartor, J. D., Boyd, G. B., and Agardy, F. J. (1974). "Water pollution aspects of street surface contaminants." *Journal (Water Pollution Control Federation),* 458-467.

Sartor, J., and Gaboury, D. (1984). "Street sweeping as a water pollution control measure: lessons learned over the past ten years." *Sci.Total Environ.,* 33(1), 171-183.

Schindler, D. W. (1975). *Whole Lake Eutrophication Experiments with Phosphorus Nitrogen and Carbon.*

Schueler, T. R. 1992. "Mitigating the Adverse Impacts of Urbanization on Streams: A Comprehensive Strategy for Local Government." *Watershed Restoration Sourcebook.* Publication #92701, Metropolitan Washington Council of Governments. Washington, D.C.

Schueler, T. R. 1994. "The Importance of Imperviousness." *Watershed Protection Techniques*, 1(3): 100–11.

Smiley, E. T., Calfee, L., Fraedrich, B. R., and Smiley, E. J. (2006). "Comparison of structural and noncompacted soils for trees surrounded by pavement." *Arboriculture and Urban Forestry,* 32(4), 164.

Steuer, J. (1997). *Sources of contamination in an urban basin in Marquette, Michigan and an analysis of concentrations, loads, and data quality*. US Dept. of the Interior, US Geological Survey. Washington, D.C.

Swift, L.W., G.B. Cunningham, J.E. Douglass. (1987). Climatology and Hydrology. Forest Hydrology and Ecology at Coweeta. Eds. W.T. Swank and D.A. Crossley. Springer New York, NY pp 35-57.

Taha, H. (1996). "Modeling impacts of increased urban vegetation on ozone air quality in the South Coast Air Basin." *Atmos.Environ.,* 30(20), 3423-3430.

Tourbier, J. T., and Westmacott, R. N. (1981). *Water resources protection technology: A handbook of measures to protect water resources in land development*. Urban Land Institute Washington, DC.

UACDC. 2010. *Low Impact Development: a design manual for urban areas*. University of Arkansas Press. University of Arkansas Community Design Center. Fayetteville, AR.

US EPA. (1983). Results of the Nationwide Urban Runoff Program. United States Environmental Protection Agency. National Technical Information Service, PB84-185545.

US EPA. (2000a). Low Impact Development (LID), a Literature Review. United States Environmental Protection Agency, EPA-841-B-00-005.

US EPA. (2000b). Stormwater Phase II Final Rule: An Overview. United States Environmental Protection Agency. EPA 833-F-00-001. Available at: http://www.epa.gov/npdes/pubs/fact1-0.pdf. Accessed 22 October 2011.

US EPA. (2009). History of the Clean Water Act. Laws, Regulations, Guidance, and Dockets. United States Environmental Protection Agency. Available at: http://www.epa/gov/lawsregs/laws.cwahistory/html. Accessed 22 October 2011.

Van Dolah, F. M. (2000). "Marine algal toxins: Origins, health effects, and their increased occurrence." *Environ.Health Perspect.,* 108.

Van Metre, P. C., Mahler, B. J., and Furlong, E. T. (2000). "Urban sprawl leaves its PAH signature." *Environ.Sci.Technol.,* 34(19), 4064-4070.

Walsh, C. J. (2000). "Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration." *Hydrobiologia,* 431(2), 107-114.

Walsh, C. J., Sharpe, A. K., Breen, P. F., and Sonneman, J. A. (2001). "Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities." *Freshwat.Biol.,* 46(4), 535-551.

Walsh, C. J. (2004). "Protection of in-stream biota from urban impacts: minimize catchment imperviousness or improve drainage design?" *Marine and Freshwater Research,* 55(3), 317-326.

Watts, A. W., Ballestero, T. P., Roseen, R. M., and Houle, J. P. (2010). "Polycyclic Aromatic Hydrocarbons in Stormwater Runoff from Sealcoated Pavements." *Environ.Sci.Technol.,* 44(23), 8849-8854.

Wise, S. (2008). "Green Infrastructure Rising." *Planning,* 74(8), 14-19.

Wu, J. S., Allan, C. J., Saunders, W. L., and Evett, J. B. (1998). "Characterization and pollutant loading estimation for highway runoff." *Journal of Environmental Engineering-Asce,* 124(7), 584-592.

Xiao, Q., McPherson, E. G., Simpson, J. R., and Ustin, S. L. (1998). "Rainfall interception by Sacramento's urban forest." *Journal of Arboriculture,* 24 235-244.

Yu, S.L. and Stanford, R.L. (2007). “Field Evaluation of a Stormwater Bioretention Filtration System.” *Journal of Environmental Engineering-Asce*. 17(1), 63-70.

Yung, C. (1993). "Soil compaction as a constraint to tree growth in tropical & subtropical urban habitats." *Environ.Conserv.,* 20(1).

CHAPTER 2: CATCHMENT-SCALE EVALUATION OF THE HYDROLOGIC IMPACTS OF RESIDENTIAL STORMWATER STREET RETROFITS IN WILMINGTON, NORTH CAROLINA

2.1 Abstract

Low Impact Development (LID) is a design approach that utilizes Stormwater Control Measures (SCMs) to maintain and restore the natural hydrologic regime of an urban watershed through infiltration, runoff treatment at the source, and minimization of impervious surfaces. This paired watershed study evaluated the impacts of LID SCMs on hydrology at a catchment-scale. In February 2012, a bioretention cell (BRC) bumpout, two permeable pavement parking stalls and a tree filter device were installed to treat residential street runoff in Wilmington, North Carolina. In the SCM-Retrofit catchment, 52% of the directly connected impervious area (DCIA) and 69% of the total drainage area was retrofitted for potential hydrologic mitigation. Underlying soils in the study area were Baymeade Urban and Leon Urban sands. Post-retrofit, peak discharge significantly decreased by 28% and lag times in the catchment remained unchanged, while runoff depth significantly decreased by 52%. When compared to the control catchment, runoff depths in the SCM-Retrofit catchment were significantly less for storms with low hourly storm intensities (<2.7 mm/hr), but significantly greater for storms with high intensities (>7.4 mm/hr). Runoff thresholds in the LID and control catchments were 5.2 mm and 3.5 mm, respectively. The LID runoff coefficient significantly decreased from 0.38 to 0.18, and is substantially less than other runoff coefficients reported for traditional residential development. This study has shown that a limited number of LID SCMs installed within a medium-density residential street right-of-way over sandy soils can mitigate some hydrologic impacts of existing development.

2.2 Introduction

Impervious land cover associated with urbanization has led to increases in stormwater runoff volumes and pollutant loads entering surface waters (Jennings and Jarnagin, 2002; Line and White, 2007). Ten percent impervious cover in a watershed can negatively impact nearby streams, rivers, lakes and estuaries, and a strong correlation has been shown between the fraction of impervious cover in a watershed and the degree to which the receiving water body is impaired (Schueler, 1992; Schueler, 1994; Novotny, 2003). The National Water Quality Inventory estimates 44% of stream km, 64% of lake ha and 30% of estuary km^2 are impaired, with urban runoff listed as a primary cause of impairment (US EPA, 2009).

Street surfaces are sources of stormwater runoff volume and pollutants as well as pathways for the transport of runoff from adjoining land areas (Bannerman et al., 1993). Most municipal streets and roadways are directly connected to conventional storm sewer networks with curb and gutter drainage systems. The subsurface channelization of runoff in urban watersheds has been shown to increase peak discharges and decrease lag times (Leopold, 1968; Booth et al., 2002). Directly connected impervious area (DCIA) rapidly conveys runoff to the watershed outlet and is the primary contributor of storm flow during small rainfall events (<25.4 mm) (Walsh, 2000; Walsh et al., 2004; Flint and Davis, 2007). Walsh et al. (2004) suggest DCIA is a more appropriate predictor of stormwater impacts to surface waters than total impervious area (TIA) of a watershed, and DCIA is particularly important in watersheds with sandy soils (Lee and Heaney, 2001).

Low Impact Development (LID) is an integrated design approach intended to mimic pre-development hydrology by discretely locating impervious surfaces and utilizing stormwater control measures (SCMs) to capture and treat runoff at the source (Prince Georges County, 1999; Coffman, 2000; Davis et al., 2006; Dietz, 2007). For the most part, studies of LID practices, such as bioretention cells (BRCs) and permeable pavements, have focused on individual systems or side-by-side comparisons to refine design and regulatory standards (Brattebo and Booth, 2003; Hunt et al., 2006; Brown and Hunt, 2011; Wardynski et al., 2013). BRCs have been shown to maintain or restore pre-development hydrology by providing depressional storage and infiltration, which enhances ground water recharge and natural base flow to streams (Davis et al., 2009; DeBusk et al., 2011). Permeable pavements are well suited to mitigate the hydrologic impacts of urbanization through substantial reductions in peak discharge and runoff volume. (Collins et al., 2008; Ball and Rankin, 2010; Fassman and Blackbourn, 2010). Compared to conventional asphalt pavements, permeable pavements have been shown to generate 72% less runoff when installed over sandy loam soils (Gilbert and Clausen, 2006). When constructed over sandy soils, BRCs and permeable pavements may eliminate nearly all runoff volume (Bean et al., 2007b; Brown and Hunt, 2011).

Limited peer-reviewed literature is available on the hydrologic impacts of LID SCMs at a watershed or catchment-scale (Hood et al., 2007; Bedan and Clausen, 2009; Line et al., 2012). At a residential LID site in Waterford, Conn., BRCs, grassed swales and permeable pavements effectively mitigated the hydrologic impacts of development (Hood et al., 2007; Bedan and Clausen, 2009). Runoff volumes and flowrates were 2.5 and 3 time less than an adjacent traditional residential development, respectively. The authors concluded this to be a direct result of distributing LID SCMs throughout the watershed designed to capture and treat runoff associated with the first 25.4 mm (1 in) of rainfall. In North Carolina, Line et al. (2012) reported a commercial LID watershed with undersized BRC, permeable pavement and stormwater wetland installations provided greater runoff volume reduction than a commercial watershed with a conventional wet detention pond. Line et al. (2012) noted the LID SCMs were not sized and constructed according to current regulatory standards in North Carolina, and suggested that the decrease in runoff volume may have been even greater with properly sized and constructed LID SCMs.

Streets and roadways make up approximately 25% of the urban landscape and represent the majority of the impervious cover owned and maintained by municipalities (UACDC, 2010). Traditionally, roadways have been designed to provide maximum traffic flow and adequate drainage to prevent flooding in the driving lane with little regard for control and treatment of runoff. Limited, but usable, space exists within the right-of-way to install SCMs, which includes the roadway, sidewalk and plaza area. It is becoming increasingly important to quantify the impacts of SCMs on existing residential development runoff quantity as municipalities comply with total maximum daily load (TMDL) requirements or address goals for other watershed management plans. This study examined the impacts of LID SCM retrofits installed within the medium-density residential street right-of-way on hydrology at a catchment-scale.

2.3 Materials and Methods

Site Description

The project site is located in Wilmington, North Carolina. Wilmington (population 110,000) is located in the southern coastal plain between the Cape Fear River and the

Atlantic Ocean. Normal mean temperatures in summer and winter range from 23.9° – 27.2° C and 7.7° – 12.7° C, respectively (NC State Climate Office, 2012). The study site is part of the Burnt Mill Creek watershed of the Cape Fear River Basin. The Burnt Mill Creek watershed is on North Carolina's 303(d) list, with toxicity and sedimentation cited as the primary causes of impairment (NCDENR, 2004). Two residential street catchments, a control and retrofit (SCM-Retrofit), were selected for use in this paired watershed study (Figure 2-1). The control and SCM-Retrofit drainage areas are 0.35 ha (0.86 ac) and 0.53 ha (1.31 ac), respectively. The straight-line distance between the catchments is 0.5 km (0.3 mi).

Both catchments are medium-density residential areas with street surfaces, sidewalks, driveways, rooftops and open space; they are serviced by conventional curb and gutter drainage systems. Control and SCM-Retrofit housing densities are 25.7 home/ha (10.5 homes/ac) and 28.3 homes/ha (11.5 homes/ac), respectively. Impervious cover is the same in each catchment at 60%. However, the directly connected impervious area (DCIA) (street surface) in the SCM-Retrofit catchment is 24%, which is substantially greater than 16% DCIA observed in the control catchment (Table 2-1). The catchment outlets are existing stormwater catch basins. The control outlet is located at the northwest corner of the intersection of 8^{th} Street and Orange Street, and the SCM-Retrofit outlet is located at the southwest corner of 12^{th} Street and Dock Street.

New Hanover County Orthophoto

Figure 2-1: Control and SCM-Retrofit drainage areas in Wilmington, NC

Table 2-1: Summary of catchment areas and imperviousness

Parameter	Catchment	
	SCM-Retrofit	Control
Drainage Area (m^2) (%)	5,300	3,480
Impervious Fraction	3,180 (60%)	2,088 (60%)
Street Surface (DCIA)	1,278 (24%)	557 (16%)
Rooftop	1,378 (26%)	1218 (35%)
Sidewalk	530 (10%)	313 (9%)
Open Space	2,120 (40%)	1,392 (40%)
Slope	0.5%	0.7%
Soil Series	Baymeade Urban	Leon Urban
USDA Soil Class	Sand	Sand
Outlet Location	N 34.235293 W 77.934061	N 34.233696 W 77.939200
Receiving Water Body	Burnt Mill Creek	
River Basin	Cape Fear	

The New Hanover County soil survey indicates underlying soils in the control and SCM-Retrofit catchments are Baymeade Urban and Leon Urban, respectively. Particle size analysis (PSA) using the hydrometer method (Gee and Bauder, 1986) showed the USDA texture classification for the underlying soils is sand (Gee and Or, 2002). Infiltration rates in sandy urban soils range from 50 mm/hr (2 in/hr) to 460 mm/hr (18 in/hr) and are greatly impacted by compaction (Pitt et al., 2008). Maximum longitudinal slopes in the control and SCM-Retrofit catchments are similar at 0.7% and 0.5%, respectively.

LID SCM Retrofits

LID SCMs constructed in February 2012 included a BRC bumpout, four permeable pavement parking spaces installed in two separate sections and one tree filter box installed along Dock Street and 12th Street (Figure 2-2, 2-4, 2-5). Post-retrofit, TIA decreased from 60% to 58% and DCIA decreased from 24% to 12%. The BRC bumpout was constructed just west of the intersection of Jasmine Street and Dock Street to treat runoff from Dock Street. The BRCs extend 1.8 m (6 ft) into the existing roadway to create 3.5 m (11.5 ft) driving lanes (east and west bound) for the added benefit of traffic calming and pedestrian safety. Four permeable pavement parking stalls 7 m x 2.4 m (23 ft x 8 ft) each were installed in two separate sections on 12th Street between Dock Street and Orange Street to treat runoff from 12th Street. Permeable pavement loading ratios (DCIA/SCM surface area) of 7.8 and 6.6 are atypical, and the impacts of loading ratios this large have not been reported in the literature. Flow diverters (16 mm tall) were installed along the curb and gutter at 3.6 m intervals to force runoff into the parking areas (Figure 2-3). The BRC and permeable pavement combined to treat 52% of the street surface and 69% of the total drainage area for potential hydrologic mitigation (Table 2-2). Detailed design summaries of the SCMs are included in Appendix B.

Figure 2-2: Clockwise from top: BRC bumpouts along Dock Street, tree filter device at intersection of 12th Street and Dock Street, and permeable pavement parking stalls on 12th Street

A Filterra® tree filter device was installed on Dock Street at the southwest corner of the intersection with 12th Street to treat runoff from Jasmine Street and Dock Street that is down-slope of the bioretention bumpouts. The tree filter treats any overflow from the BRC.

The devices function as high flow filters such that ponding at the surface does not occur. Lenth et al. (2010) measured infiltration rates of ten Filterra® devices with varying maintenance periods (recent – 2 years) and found infiltration rates from 2200 mm/hr (86 in/hr) to 5200 mm/hr (205 in/hr) with up to 110 mm (4.5 in) of sediment accumulation at the surface. Volume reduction is negligible because the concrete lining does not allow exfiltration to occur.

Table 2-2: Summary of LID SCM design parameters

Parameter	BRC[a]	Filterra®	PP I[b]	PP II[c]
Surface Area	19 m^2	3 m^2	34 m^2	34 m^2
Street Surface Area	160 m^2	539 m^2	265 m^2	226 m^2
Loading Ratio[d]	8.4:1	180:1	7.8:1	6.6:1
Street Surface Area Treated	13%	42%	21%	18%
Total Catchment Area Treated	12%	22%	30%	27%
As Built Design Rainfall Event[e]	33 mm	N/A	24 mm	27 mm
Underdrain	No	Yes	No	No

[a]Bioretention Cell on Dock Street
[b]North permeable pavement parking area on 12th Street
[c]South permeable pavement parking area on 12th Street
[d]Calculated as drainage area/SCM surface area
[e]Runoff from given rainfall depth that is stored in SCM before overflow occurs, assuming no infiltration to underlying soils

Figure 2-3: Flow diverters installed on permeable pavement parking stalls along curb and gutter of 12th Street

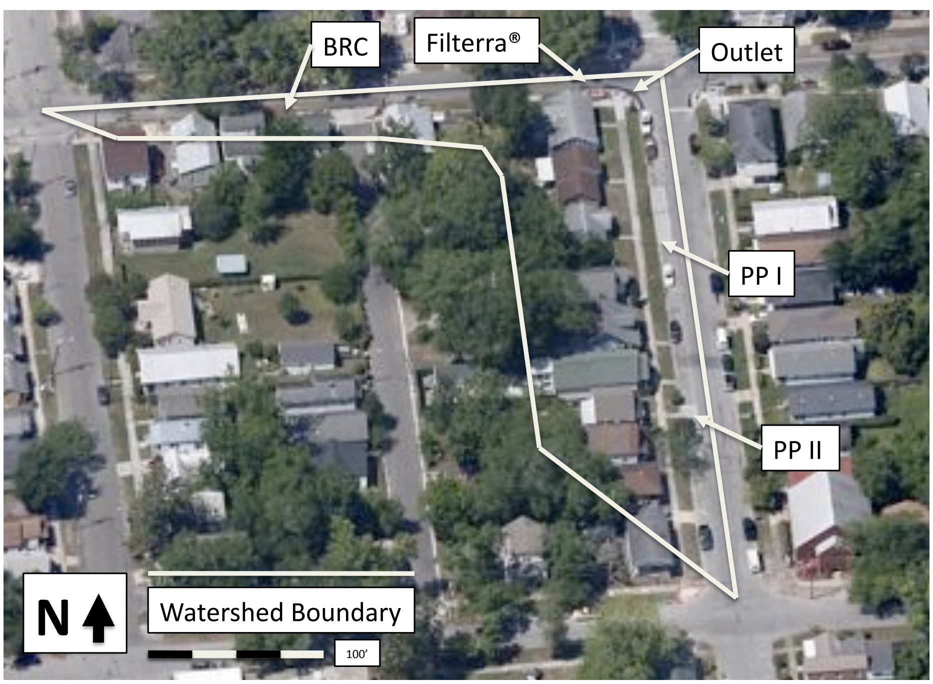

Figure 2-4: Aerial photo post-retrofit with approximate watershed boundary

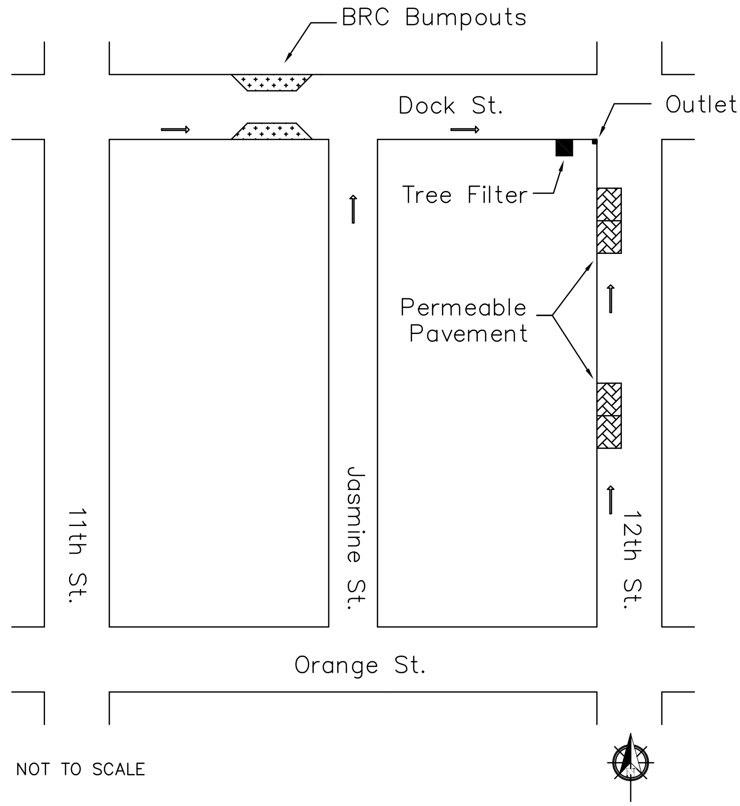

Figure 2-5: Layout of LID SCMs with arrows indicating direction of flow (not to scale)

Monitoring Design

The paired watershed study design was used to evaluate the hydrologic impacts of the LID SCM retrofits (Clausen and Spooner, 1993; Grabow et al., 1999). This approach requires two watersheds: control and treatment (SCM-Retrofit) and two monitoring periods: calibration and treatment. During the calibration period, management practices in the catchments remained the same (no SCMs), the SCMs were installed in the SCM-Retrofit catchment and treatment monitoring began post-construction (Table 2-3). The paired watershed approach is underpinned by a quantifiable and predictable (linear) relationship between the catchments. A relationship is developed during the calibration period, and is considered valid until the SCM treatment is applied, at which time a new relationship between the catchments is developed during the second period of monitoring (Clausen and Spooner, 1993).

Table 2-3: Paired watershed study design

Period	Catchment	
	SCM-Retrofit	**Control**
Calibration	No SCMs	No SCMs
Treatment	SCMs	No SCMs

Monitoring equipment was installed at the catchment outlets in May 2011. Manual and HOBO™ Tipping Bucket rain gauges were installed on a wooden post free of trees and overhead obstructions at the LID station (Table 2-4). An ISCO 6712™ portable sampler logged rainfall data from the tipping bucket. Hydrologic data were recorded by installing V-notch weirs and weir boxes inside the existing catch basins (Figure 2-6). Forty-five degree and 60° V-notch weirs were installed at the control and SCM-Retrofit stations, respectively. The V-notch weirs and weir boxes were fitted with a 1 m (3.3 ft) long contracted rectangular weir to pass discharges from large storms. ISCO 730™ bubbler flow modules were used to monitor discharge and total runoff volume by measuring stage above the weir at two minute intervals.

Table 2-4: Summary of monitoring equipment

Equipment	SCM-Retrofit	Control
Location	Southwest corner of intersection of 12th and Dock St	Northwest corner of intersection of 8th and Orange St.
Structure	60° V-notch weir	45° V-notch weir
Flow Monitoring Device	ISCO 730™ Bubbler Module	ISCO 730™ Bubbler Module
Rain Gauges	Manual and HOBO™ Tipping Bucket	NA[a]

[a]Control station located 0.5 km from LID station

Figure 2-6: V-notch weir and weir box being installed inside existing catch basins

During each site visit hydrologic and rainfall data were downloaded with an ISCO Rapid Transfer Device™ (RTD) at both stations. The ISCO 730™ bubbler flow modules were calibrated by bringing the water level in the weir box up to the weir invert, and the bubbler tubing was purged with an air compressor to combat moisture intrusion. Bubbler module desiccant was replaced when it became saturated approximately every two weeks during summer and fall and every four weeks during winter and spring.

Monitoring Challenges

The primary monitoring challenge was keeping the weirs and weir boxes clear of debris. Leaf litter, woody material, trash and coarse sediment that accumulated on the street surface (Figure 2-3) were frequently deposited in the base of the weir box during a storm (Figure 2-7). This was more common at the control station during fall and winter sampling seasons. Debris was removed from the weirs and weir boxes, during each site visit. In October 2011 the City of Wilmington was required to make existing crosswalks ADA compliant, including the western crosswalk at the intersection of 8th Street and Orange Street, which was 1 m (3 ft) upslope of the control station. This required the control station to be removed in November 2011, ending calibration monitoring. The ADA crosswalk was installed incorrectly in December 2011 allowing runoff to bypass the catch basin where the control station had been installed. In May 2012 the ADA crosswalk was corrected and runoff from the control catchment was directed into the original catch basin enabling treatment monitoring to begin.

Figure 2-7: Debris clogging weir (left) and removing organic material from weir box (right)

Data Processing

Hydrologic data were reviewed using FLOWLINK Version 5.0 software (ISCO, 2005) and compared to field notes. Rainfall intensities and total depths were adjusted by a scaling factor developed from the discrepancy (deficit) recorded by the tipping bucket vis-à-vis manual rain gauges. Four and five storms were removed from the calibration and treatment data sets, respectively, when paired data points were not collected due to power failure, equipment malfunction or weir obstructions.

Statistical Analysis

SAS Version 9.3™ was used for all statistical analyses (SAS Institute, 2010). Data sets from the calibration and treatment periods were log transformed and tested separately using analysis of variance (ANOVA) for a significant linear relationship with metrics from the SCM-Retrofit and control catchments as covariates (control = x, SCM-Retrofit = y). The residuals of regression were inspected graphically for normality and constant variance. Skew coefficients and the Shapiro-Wilk goodness-of-fit test were also used to assess normality of the residuals. Analysis of covariance (ANCOVA) was utilized to detect significant impacts on the slopes and intercepts of peak discharge, lag time, runoff depth and runoff coefficient regressions. All statistical tests were conducted using α=0.05 unless otherwise noted. Significant differences in slopes or intercepts of the calibration and treatment regressions lines indicated the hydrologic impact of the LID SCM treatment was significant. If a significant difference in slopes was not detected, the slope term was removed from the full ANCOVA model and the reduced ANCOVA model was used for analysis. Least squared means (LSM) analysis was used to quantify significant changes in the hydrologic parameters from calibration to treatment monitoring. Percent reductions were calculated using Equation 3-1.

$$Change(\%) = [\frac{10^{\bar{Y}_T}}{10^{\bar{Y}_C}} - 1] \times 100 \qquad \text{Equation 2-1}$$

Where,

$\bar{Y}_T$ = SCM-Retrofit LSMean during treatment monitoring

$\bar{Y}_C$ = SCM-Retrofit LSMean during calibration monitoring

To compare means from the second monitoring period by storm size and intensity, differences in paired data points from the SCM-Retrofit and control catchments were checked for normality using the Shapiro-Wilk goodness-of-fit test. If the differences were not normally distributed, the raw data sets were log transformed and tested again. Differences that were approximately normal were tested for a significant difference with a Student's t-test. In instances where the paired differences remained non-normally distributed, the non-parametric sign test was used.

2.4 Results and Discussion

Precipitation

Normal annual rainfall at Wilmington International Airport is 1,448 mm (57 in) (NC State Climate Office, 2012). The calibration and treatment monitoring periods occurred from 10 May 2011 to 31 October 2011 and 8 June 2012 to 13 February 2013, respectively. Total rainfall recorded during the calibration and treatment periods was 514 mm (20.2 in) and 957 mm (37.7 in), respectively. Rainfall recorded over the cumulative 1.14 year study period was 11% below normal. Storms less than 2.5 mm (0.1 in) were not included in the data set. A six-hour antecedent dry period was used to separate discrete rainfall events.

Similar rainfall characteristics were observed in both monitoring periods. Median storm depth during the calibration period was 10.7 mm (0.42 in) compared to 9.9 mm (0.39 in) recorded during treatment monitoring. Rainfall depth and hourly intensity from the 50th and 75th percentile storms were used to partition rainfall data and make comparisons between means of the hydrologic metrics (Tables 2-5 and 2-6). Bean (2005) reported rainfall depth percentiles for Wilmington, NC, and peak hourly storm intensities were determined by cumulative probability analysis from 10-year weather records (1999 – 2008) at Wilmington International Airport (ILM).

Table 2-5: Precipitation summary for calibration and treatment periods (all units in mm)

Period	n[a]	Range	50th Percentile		75th Percentile		Mean	Median	Total
			<12.7	>12.7	<30	>30			
Calibration	17	3.3 - 143	10 (59%)	7 (41%)	14 (82%)	3 (18%)	21.3	10.7	436
Treatment	34	3.3 - 72	19 (56%)	15 (44%)	28 (82%)	7 (18%)	19.3	9.9	811

[a]Number of events >2.5 mm

Table 2-6: Peak hourly intensity summary for calibration and treatment periods (all units in mm/hr)

Period	n[a]	Range	50th Percentile		75th Percentile		Mean	Median
			<2.7	>2.7	<7.4	>7.4		
Calibration	17	0.8 - 13.7	8 (47%)	9 (53%)	15 (88%)	2 (12%)	3.3	3.3
Treatment	34	1.0 - 15.7	17 (50%)	17 (50%)	30 (88%)	4 (12%)	3.3	2.7

[a]Number of events >2.5 mm

Pre-retrofit, data collection was limited due to crosswalk construction in the control catchment (see *Monitoring Challenges)*. Ideally, the calibration and treatment monitoring periods would have lasted for one year or more each, as outlined by Clausen and Spooner (1993). The watersheds in this study were small urban drainage areas located 0.5 km apart with similar land use, imperviousness, topography, soil and nearly identical climate and weather patterns. The only difference between the catchments during this study was the SCM treatment. During the shortened calibration monitoring period the linear relationships established between the catchments were sufficient to make valid statistical comparisons using ANCOVA and LSM.

Peak Discharge

Median peak discharge in the SCM-Retrofit catchment decreased from 8.8 L/s to 5.5 L/s post-retrofit. The LID SCMs had a significant impact on flowrates evidenced by the difference in intercepts of the calibration and treatment regression lines in the reduced ANCOVA model (Table 2-7) (Figure 2-8). Peak discharge in the LID catchment significantly decreased 28% during post-retrofit monitoring by LSM comparison (α=0.10).

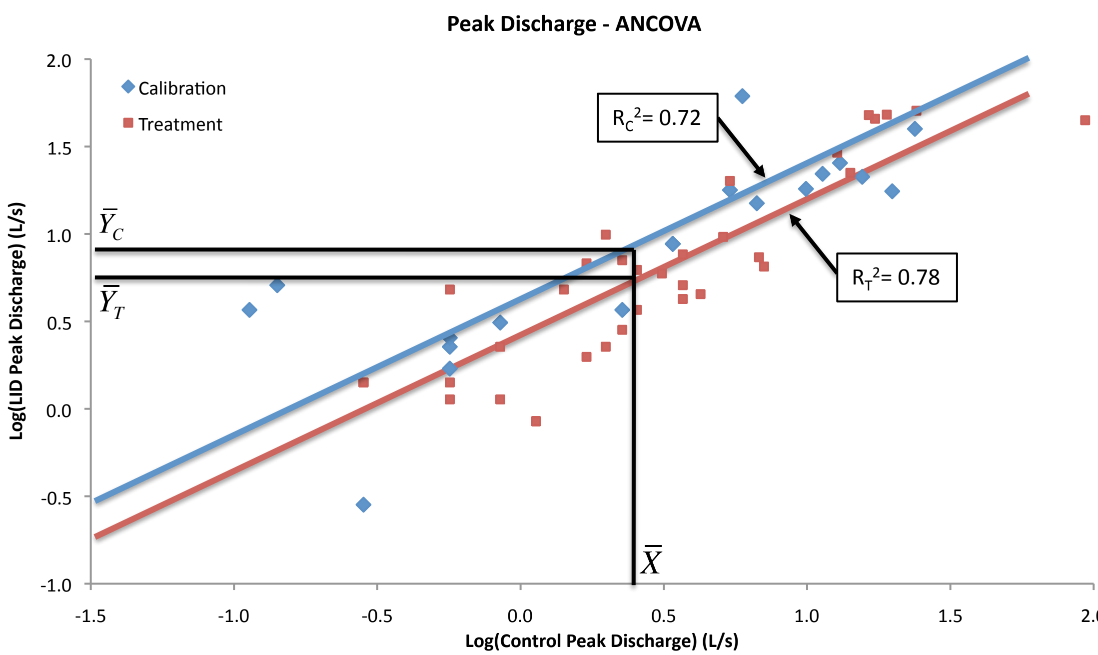

Figure 2-8: Reduced ANCOVA model for peak discharge

Bedan and Clausen (2009) reported that peak discharge did not significantly change post-development at a residential LID watershed in Connecticut. BRCs and permeable pavements have frequently been shown to the capture runoff from small storms entirely, thus eliminating peak discharge (Brattebo and Booth, 2003; Bean et al., 2007a; Davis, 2008; Hunt et al., 2008; Li et al., 2009; Jones and Hunt, 2009; Wardynski et al., 2012). Li et al. (2009) found that the hydrologic benefits of BRCs are substantial for smaller storms, but deteriorate rapidly for storms with greater rainfall depths and intensities. In a statistical comparison of treatment monitoring flowrates, there were no significant differences between the SCM-Retrofit and control drainage areas using hourly rainfall intensities as a basis. The decrease in peak discharge may have been greater if more than 52% of the DCIA had been retrofitted for potential hydrologic mitigation.

Table 2-7: Means and ANCOVA summary for hydrologic metrics

Period	Mean	Median	LSM	ANCOVA		
				LSM	Slope	Intercept
Peak Discharge (L/s)						
Calibration	15.0	8.8	7.8			
Treatment	12.4	5.5	5.7	0.1000*	-	<0.0001*
Change[a]	-17%	-38%	-28%			
Lag Time (hrs)						
Calibration	1.94	0.43	0.86			
Treatment	2.40	0.73	0.73	0.1802[NS]	0.0367*	0.3848[NS]
Change[a]	78%	70%	-15%			
Runoff Depth (mm)						
Calibration	8.1	2.2	2.5			
Treatment	3.6	1.1	1.2	0.0002*	0.0001*	0.0259*
Change[a]	-55%	-50%	-52%			
Runoff Coefficient						
Calibration	0.22	0.14	0.18			
Treatment	0.13	0.10	0.10	0.0002*	-	0.0002*
Change[a]	-41%	-29%	-47%			

*Significant
[NS]Not Significant
[a]Negative sign "-" implies reduction

Lag Time

Lag is defined as the time rainfall begins to the time peak discharge occurs. The full ANCOVA model does indicate a significant difference in slopes of the regression lines, however this did not translate to a significant change in lag times in the SCM-Retrofit catchment (Table 2-7) (Figure 2-9). Leopold (1991) suggests lag time is a useful theoretical variable to consider in watershed hydrology because it assimilates multiple components of runoff generation. Lag times are influenced by several watershed and climatic factors including soil type, topography, land use, rainfall, intensity and time of peak intensity. Mean and median lag times in the SCM-Retrofit catchment increased during treatment monitoring, however both metrics increased similarly in the control catchment.

The greater slope of the treatment regression line in the full ANCOVA model shows that lag times decreased at lower values of lag time. The decrease in lag time at lower values was due to the disconnection of the upper reaches of the street surface (points most distant from the outlet) by the SCMs. Lower values of lag time are usually associated with small storms and short durations. Underdrains were not installed with the BRC and permeable pavement because underlying soils were sandy, meaning all runoff that entered the systems was retained rather than being released at a later time. The SCMs likely captured most of the runoff generated by smaller events, thus decreasing the magnitude of peak discharge but caused it to occur sooner at the catchment outlet because the street surface nearest the outlet had no SCM treatment. Hood et al. (2007) found that LID SCMs incorporated into the original site design with designated open space and a cluster housing arrangement significantly increased lag times at the watershed outlet.

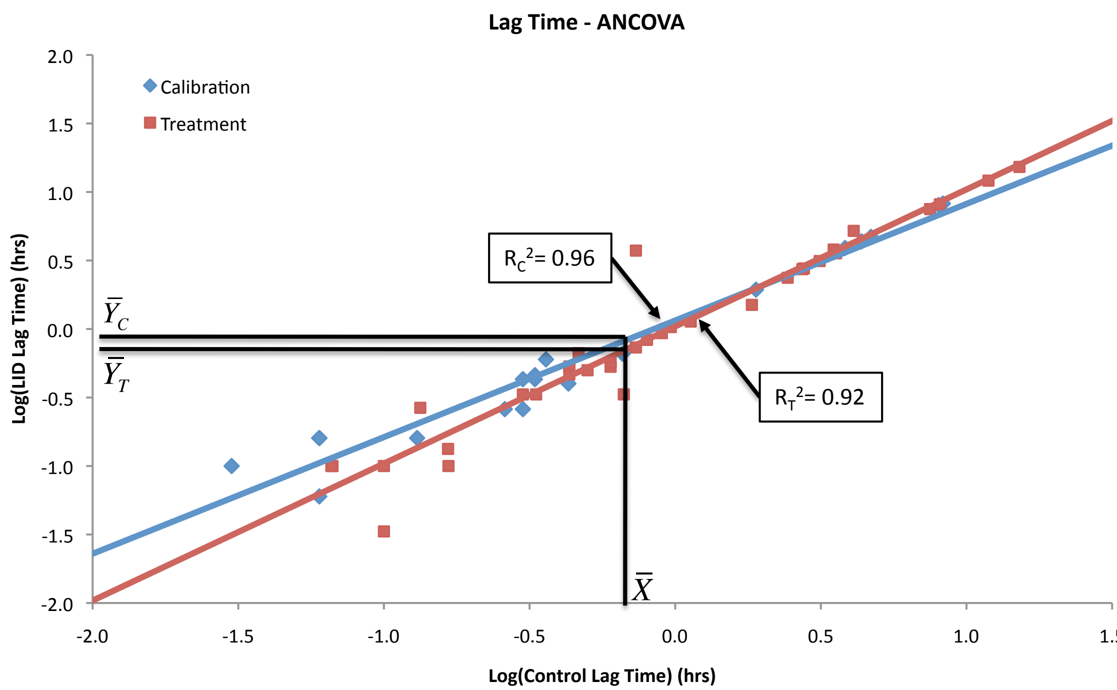

Figure 2-9: Full ANCOVA model for lag time

Runoff Depth

Mean runoff depth in the SCM-Retrofit catchment significantly decreased by 52% during the post-retrofit period (Table 2-7) (Figure 2-10). The slopes and intercepts of the calibration and treatment regression lines are significantly different. Decreases in runoff depth were not consistent across all values, unlike observations reported by Bedan and Clausen (2009). In the full ANCOVA model for runoff depth, the greater slope of the treatment regression line and magnitude of the difference at lower values of runoff depth indicates greater decreases at smaller runoff depths and little to no change at greater runoff depths.

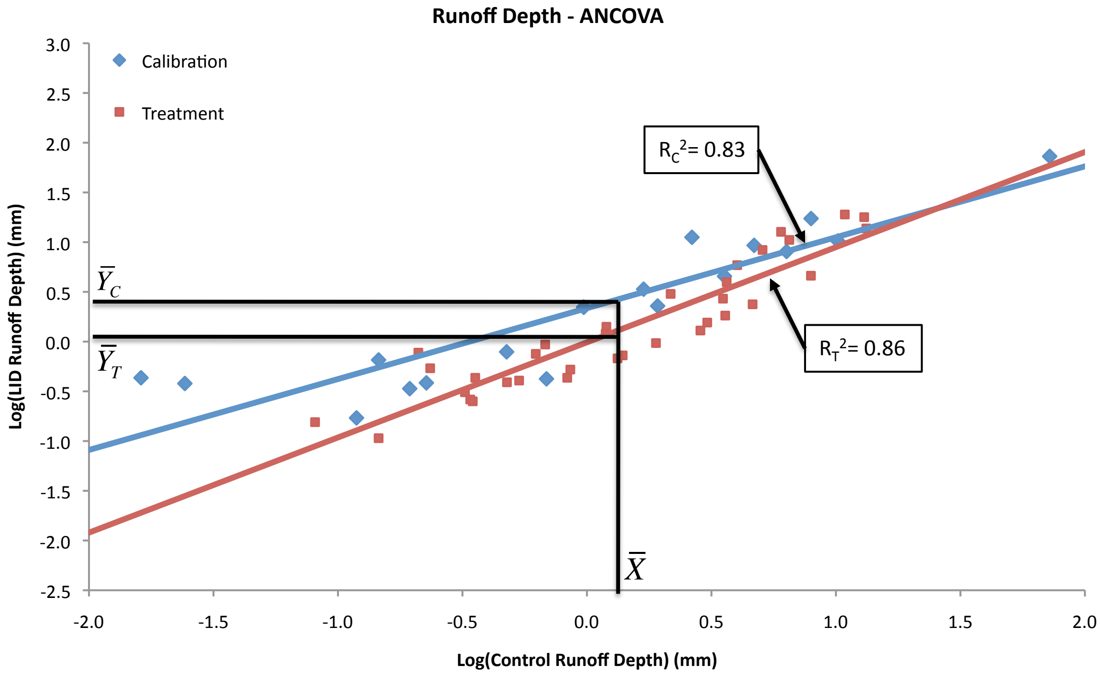

Figure 2-10: Full ANCOVA model for runoff depth

This relationship was investigated further by comparing runoff depth means with respect to storm size and intensity in the SCM-Retrofit and control catchments. SCM-Retrofit mean runoff depth was not significantly different from control mean runoff depth for rainfall amounts greater or less than the 50th and 75th percentile storms (Table 2-8). However, mean runoff depths in the SCM-Retrofit catchment were significantly less than the control catchment for storms with hourly *intensities* less than the 50th percentile storm (Table 2-9). For storms with intensities above the 75th percentile, mean runoff depth in the SCM-Retrofit catchment was significantly greater than mean runoff depth in the control drainage area. This suggests the capacity of the LID SCMs to mitigate runoff depth is driven by storm intensity rather than storm depth in this study.

Table 2-8: Runoff depth means by rainfall depth during treatment monitoring

Rainfall Depth (P)	n[a]	Mean Runoff Depths (mm)		p-value
		SCM-Retrofit	Control	
P < 50th	19	0.6	0.7	0.6720[NS]
P > 50th	15	7.3	5.9	0.1534 [NS]
P < 75th	27	1.8	1.6	0.7544 [NS]
P > 75th	7	10.3	8.5	0.3394 [NS]

[a]Number of storms in category
[NS]Not Significant

Table 2-9: Runoff depth means by storm intensity treatment monitoring

Storm Intensity (I)	n[a]	Mean Runoff Depths (mm)		p-value
		SCM-Retrofit	Control	
I < 50th	17	1.9	2.5	0.0569*
I > 50th	17	5.2	3.5	0.2381 [NS]
I < 75th	30	2.6	2.5	0.2518 [NS]
I > 75th	4	10.7	7.1	0.0118*

[a]Number of storms in category
*Significant
[NS]Not Significant

Although the permeable pavement loading ratios were higher than other loading ratios evaluated in the peer-reviewed literature, it is unlikely that insufficient storage within the SCMs caused the systems to have a minimal impact on runoff depth for storms with hourly intensities greater than 7.4 mm/hr. Assuming exfiltration to the underlying soil does not occur during a storm, as-built design rainfall events for the BRC, PP I and PP II were 33 mm (1.3 in), 24 mm (0.95 in) and 27 mm (1.05 in), respectively (Table 2-2). Underlying soils beneath the SCMs were 95% - 98% sand (Table B-4), indicating exfiltration potential from the BRC and permeable pavement was high and likely occurred. During larger and more intense storms, resulting runoff moved swiftly along the existing curb and gutter at a greater depth, which may have overwhelmed the flow diverters, thus providing no opportunity for infiltration for 39% of the DCIA. The Rational equation was used to estimate peak discharge from the DCIA for both permeable pavement installations, and Manning's equation was used to determine the depth of flow of runoff in the gutter. All storms during treatment monitoring had five-minute peak intensities (>2.3 mm/hr) that generated discharges and subsequent gutter flow depths large enough to overtop the flow diverters.

Clogging of the permeable pavement was also a primary cause for the SCMs limited effectiveness on peak hourly storm intensities greater than 7.4 mm/hr. Streets are documented sources of woody debris, leaf litter, fine solids and sediment, particularly in residential areas (Sartor et al., 1974; Sartor and Gaboury, 1984; Bannerman et al., 1993). Bean et al. (2007a) found that fine particles clogging the void space of the permeable pavement surface reduced median infiltration rates by three orders of magnitude, from 20,000 mm/hr to 80 mm/hr. The parking stalls were maintained with a high suction vacuum truck approximately every four months, however leaf litter from adjacent deciduous trees and fine sediment accumulation at the surface of the permeable pavers was observed throughout treatment monitoring and likely reduced the infiltration rate.

The decrease in mean runoff depth observed in this study was similar to other findings reported in the literature for BRCs and permeable pavement. Fassman and Blackbourn (2010) found a permeable pavement installation over tight clay soils reduced runoff volume by 28% with a 4.3:1 loading ratio. In North Carolina, all runoff was eliminated from a permeable pavement parking lot constructed over sandy soils when underdrains were removed from the system (Bean et al., 2007b). At the watershed outlet of an LID residential neighborhood with permeable pavement and BRCs, Bedan and Clausen (2009) reported a 42% reduction in runoff depth despite impervious cover increasing from 0% to 21%. Line et al. (2012) reported a 34% reduction in runoff volume from a commercial SCM-Retrofit watershed (76% imperviousness) with just one-third of the site draining to properly functioning SCMs.

In North Carolina, SCMs are typically required to capture and detain runoff associated with 25 mm (1 in) or 38 mm (1.5 in) of rainfall (NCDENR, 2009). Based on the cumulative 1.14 years of monitoring data from the control catchment, 25 mm of rainfall generated 4.3 mm of runoff and 38 mm of rainfall generated 6.7 mm of runoff. These runoff depths are shown in Figures 2-11 and 2-12 with the corresponding runoff depths in the SCM-Retrofit catchment. For 25 mm and 38 mm rainfall depths, the decreases in runoff depths from calibration to treatment monitoring were 35% and 28%, respectively.

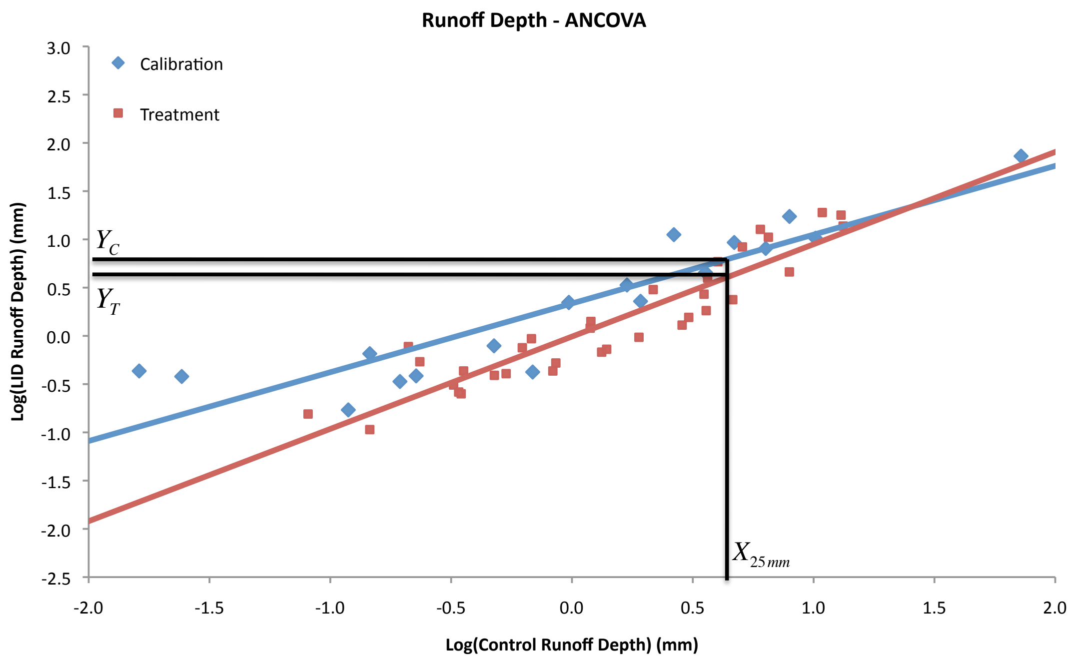

Figure 2-11: Runoff depths associated with 25 mm (1 in) of rainfall

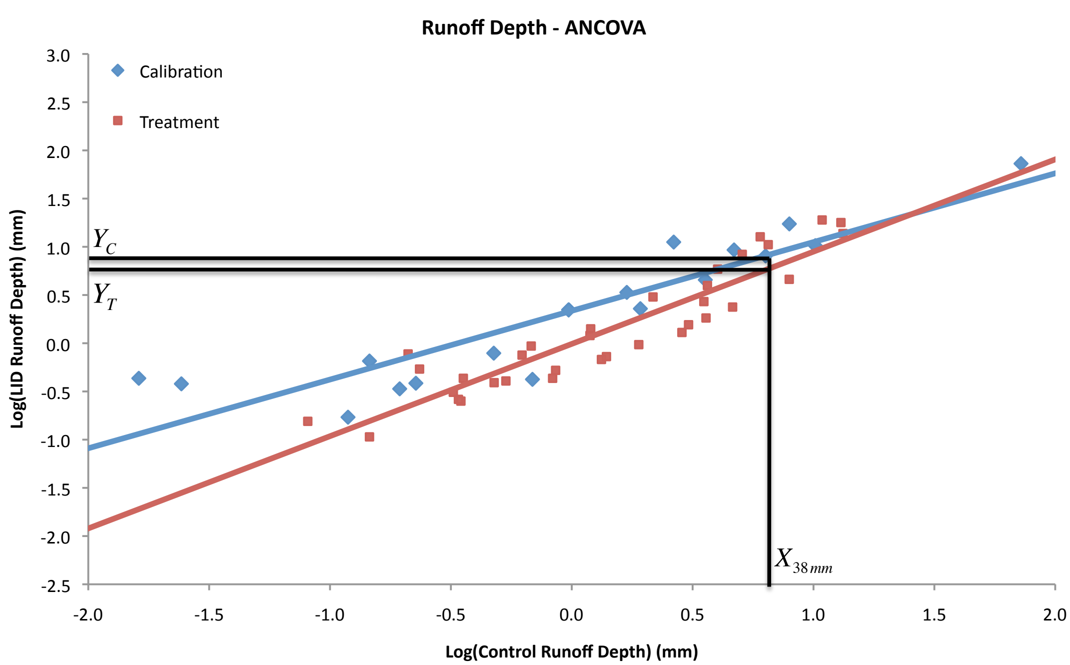

Figure 2-12: Runoff depths associated with 38 mm (1.5 in) of rainfall

Runoff threshold is the rainfall depth at which runoff is generated and was determined by the x-intercept of the regression line from a rainfall depth vs. runoff depth plot. All paired data points from post-construction monitoring were used in the analysis. SCM-Retrofit and control runoff thresholds were 5.2 mm and 3.5 mm, respectively (Figures 2-13 and 2-14). The greater runoff threshold in the SCM-Retrofit catchment is due to the BRC and permeable pavement installations that provided infiltration and depressional storage. These thresholds are very similar to those observed by Hood et al. (2007) in Connecticut, where runoff thresholds from residential LID and traditional watersheds were 6.0 mm and 3.0 mm, respectively.

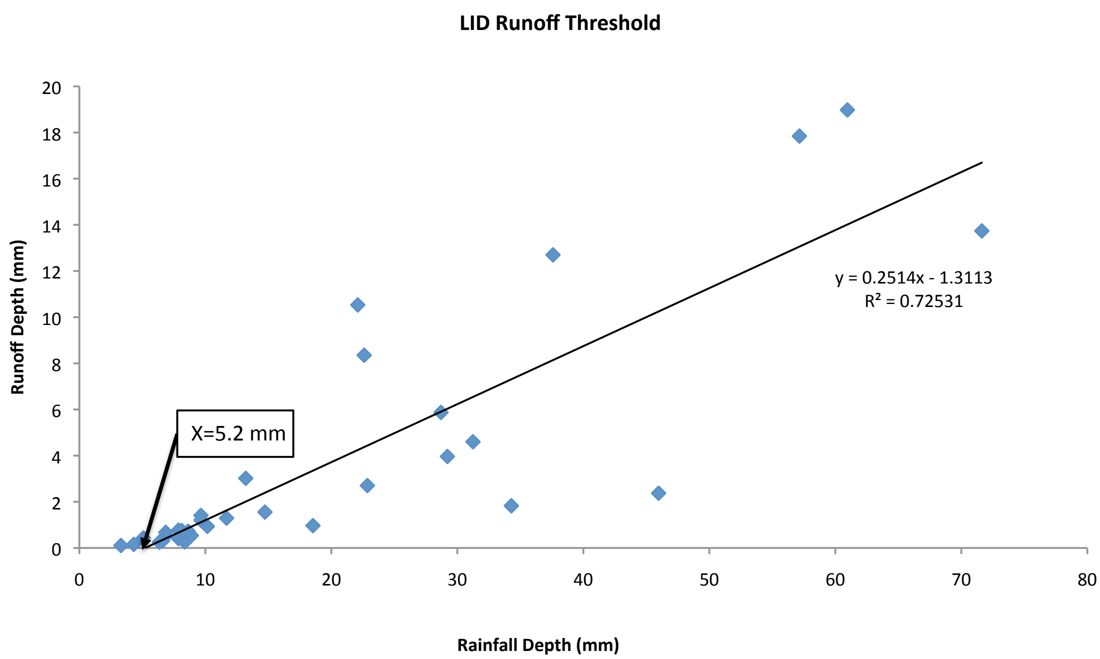

Figure 2-13: Runoff threshold in the SCM-Retrofit catchment

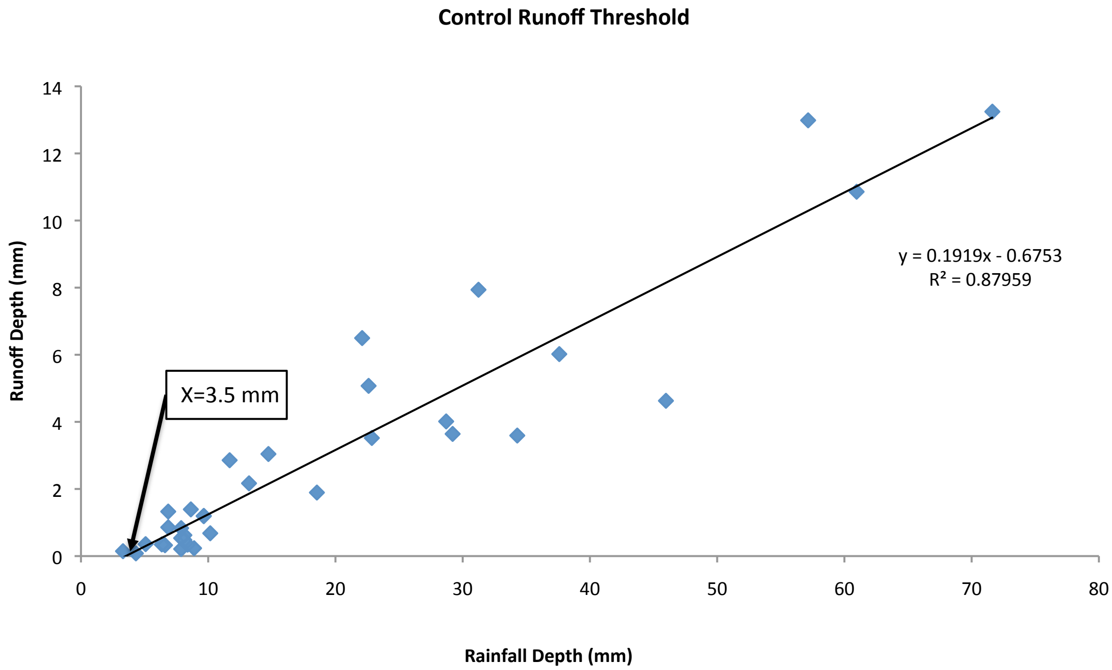

Figure 2-14: Runoff threshold in the Control catchment

Runoff Coefficients

Runoff coefficient is a metric that shows the fraction of rainfall that is converted to runoff and is determined by dividing total runoff depth by total rainfall recorded. Line and White (2007) and Leopold (1991) have shown that runoff coefficients increase with impervious cover and urbanization in a watershed. Runoff coefficients before construction in the SCM-Retrofit and control catchments were 0.38 and 0.21, respectively (Table 2-7). The greater runoff coefficient observed pre-retrofit in the SCM-Retrofit catchment is due to the greater DCIA fraction. Line et al. (2002) reported a runoff coefficient of 0.57 for a residential drainage area with 25% DCIA in the Piedmont region of North Carolina, which is substantially greater than runoff coefficients reported in this study. The difference is caused by higher slopes (2%-10%) and sandy loam soils in the watershed monitored by Line et al. (2002). As noted previously, soils in the study area were very sandy, and the topography was flat (0.5% - 0.7% slopes).

In the reduced ANCOVA model for single storm runoff coefficients, the intercepts of the calibration and treatment regression lines are significantly different (Figure 2-15). SCM-Retrofit runoff coefficient significantly decreased by 47% (Table 2-7). During treatment monitoring, the runoff coefficient was 0.18 in the SCM-Retrofit catchment. Hood et al. (2007) reported a mean runoff coefficient of 0.07 from a residential LID watershed with no DCIA and a TIA of 21%. During larger, more intense storms LID SCMs have been shown to be less effective at mitigating the hydrologic impacts of urbanization when compared to smaller storms (Hood et al., 2007; Li et al., 2009).

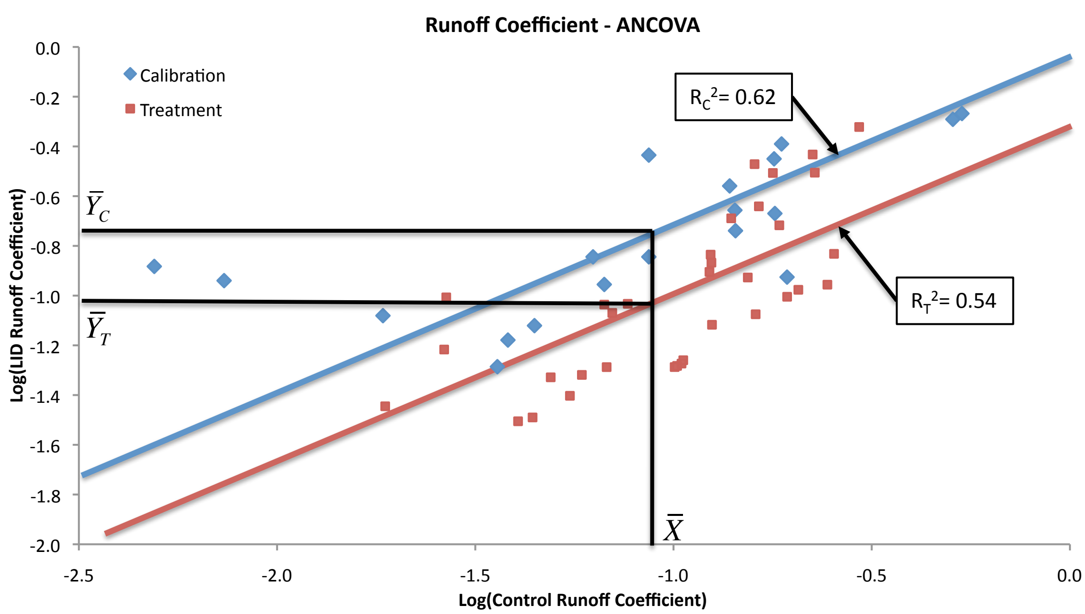

Figure 2-15: Reduced ANCOVA model for single storm runoff coefficients

Runoff coefficients from treatment monitoring were sorted by 50^{th} percentile rainfall depth (</>12.7 mm) and hourly intensity (</>2.7 mm/hr) (Table 2-10). Runoff coefficients were lowest in both catchments for smaller storms (<12.7 mm), and differences between the control and SCM-Retrofit coefficients did not vary by storm intensity. The SCMs provided the greatest decrease of rainfall converted to runoff when compared to the control catchment for larger storms (>12.7 mm) with low rainfall intensities (<2.7 mm/hr).

Table 2-10: Runoff coefficients partitioned by 50^{th} percentile rainfall depth (</> 12.7 mm) and 50^{th} percentile hourly rainfall intensity (</> 2.7 mm/hr) during treatment monitoring

	Hourly Intensity < 2.7 mm/hr			**Hourly Intensity > 2.7 mm/hr**		
		Runoff Coefficient			**Runoff Coefficient**	
	n[a]	**SCM-Retrofit**	**Control**	**n[a]**	**SCM-Retrofit**	**Control**
Storms < 12.7 mm	11	0.08	0.10	8	0.08	0.09
Storms > 12.7 mm	6	0.12	0.16	9	0.29	0.19

[a]Number of storms in category

Conversely, the SCMs did not have a noticeable impact on runoff coefficients for larger storms (>12.7 mm) with high intensities (>2.7 mm/hr). Here, SCM-Retrofit and control runoff coefficients in were 0.29 and 0.19, respectively. This difference is also reflected in the ANCOVA plot where there is substantial scatter of post-retrofit data above the treatment regression line for x-values greater than 0.15 (log[0.15]=-0.82) (Figure 2-13). Similar to observations of runoff depth, runoff coefficients varied by storm intensity, which is likely due to runoff overwhelming the flow diverters and clogging at the surface of the permeable pavement. Also, rainfall depths greater than 12.7 mm with high hourly intensities

(>2.7 mm/hr) may have generated runoff from the entire SCM-Retrofit drainage area, rather than just the DCIA, thereby increasing the runoff volume observed at the SCM-Retrofit outlet.

2.5 Summary and Conclusions

In this study, 52% of the DCIA and 69% of the total drainage area was retrofitted with a BRC and permeable pavement. The SCMs were sized based on the contributing DCIA because soils in the study area were very sandy. Results have shown that LID SCMs installed as retrofits within the residential street right-of-way can mitigate some of the hydrologic impacts of existing residential development at a catchment-scale. The following conclusions were drawn from this study:

- Post-retrofit, peak discharge at the SCM-Retrofit outlet significantly decreased by 28%. Lag times decreased for small storms, which likely occurred because the street surface nearest the outlet was not retrofitted for potential hydrologic mitigation. The impacts on flowrates and lag times may have been more substantial if more than 52% of the DCIA had been retrofitted for potential hydrologic improvement.
- Runoff depth in the SCM-Retrofit catchment decreased significantly by 52%, which is comparable to other studies of individual BRC and permeable pavement systems and watershed-scale studies of LID SCMs (Bedan and Clausen, 2009; Line et al., 2012). The SCM-Retrofit runoff threshold was 49% greater than the threshold observed in the control catchment, and both were similar to runoff thresholds reported by Hood et al. (2007) for traditional residential and SCM-Retrofit watersheds in Connecticut.

- Runoff coefficient in the SCM-Retrofit catchment significantly decreased by 47%. During treatment monitoring, the SCM-Retrofit runoff coefficient was 0.18, which is substantially less than other values reported for traditional residential developments and is approaching the runoff coefficient (0.07) reported for a larger residential LID watershed (Line et al., 2002; Hood et al., 2007).
- Permeable pavement maintenance is imperative for systems installed along residential streets where leaf litter and loose sediment are present. Maintenance more frequent than every four months may be necessary. Adequately sized flow diverters should be used to ensure runoff has an opportunity to infiltrate the surface of the permeable pavers for all storm sizes, particularly when greater loading ratios are used. Alternative curb and gutter configurations and pavement grading that shed water in the direction of the permeable pavement may also be considered.
- In this study, the SCMs were installed over very sandy soils and seemed to be adequately sized to capture and retain runoff for most of the storms observed. Future residential street retrofit projects in watersheds with less permeable soils should consider sizing the SCMs for the entire contributing drainage area in lieu of just the DCIA.

2.6 References

Bannerman, R. T., Owens, D. W., Dodds, R. B., and Hornewer, N. J. (1993). "Sources of Pollutants in Wisconsin Stormwater." *Water Science and Technology,* 28(3-5), 241-259.

Bean, E. Z. (2005). "A field study to evaluate permeable pavement surface infiltration rates, runoff quantity, runoff quality, and exfiltrate quality." Thesis. North Carolina State University, Raleigh, NC.

Bean, E. Z., W. F. Hunt and D. A. Bidelspach. (2007a). "Field survey of permeable pavement surface infiltration rates. " *J.Irrig.Drainage Eng-ASCE*, 133(3): 249-255.

Bean, E. Z., Hunt, W. F., and Bidelspach, D. A. (2007b). "Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts." *J.Irrig.Drainage Eng-ASCE,* 133(6), 583-592.

Bedan, E. S., and Clausen, J. C. (2009). "Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds." *Journal of the American Water Resources Association,* 45(4), 998-1008.

Bender, G., and Terstriep, M. (1984). "Effectiveness of street sweeping in urban runoff pollution control." *Sci.Total Environ.,* 33(1), 185-192.

Brattebo, B. O., and Booth, D. B. (2003). "Long-term stormwater quantity and quality performance of permeable pavement systems." *Water Res.,* 37(18), 4369-4376.

Brown, R. A., and Hunt, W. F.,III. (2011). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." *J.Irrig.Drainage Eng-ASCE,* 137(3), 132-143.

Clausen, J.C. and J. Spooner, 1993. *Paired Watershed Study Design*. U.S. Environmental Protection Agency, USEPA 841-F-93-009.

Coffman, L.S. 2000. Low-Impact Developmeent Design: A New Paradigm for Stormwater Management Mimicking and Restoring the Natural Hydrologic Regime An Alternative Stormwater Management Technology. Department of Environmental Resources, Prince Georges County, Maryland.

Collins, K. A., Hunt, W. F., and Hathaway, J. M. (2008). "Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina." *J.Hydrol.Eng.,* 13(12), 1146-1157.

DeBusk, K. M., Hunt, W. F., and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" *J.Hydrol.Eng.,* 16(3), 274-279.

Dietz, M. (2007). "Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions." *Water, Air, & Soil Pollution,* 186(1), 351-363.

Fassman, E. A., and Blackbourn, S. (2010). "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." *J.Hydrol.Eng.,* 15(6), 475-485.

Flint, K. R., and Davis, A. P. (2007). "Pollutant mass flushing characterization of highway stormwater runoff from an ultra-urban area." *J.Environ.Eng.,* 133(6), 616-626.

Gee, G.W. and Bauder, J. W. (1986). “Particle-size analysis.” In Methods of Soil Analysis, Part 1. Agron. Monogr. 9. Klute, A, ed. Soil Science Society of America, Madison, WI. 383-411.

Gee, G. W., and Or, D. (2002). "2.4 Particle-size analysis." *Methods of Soil Analysis: Physical Methods,* 5:255.

Gilbert, J. K., and Clausen, J. C. (2006). "Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut." *Water Res.,* 40(4), 826-832.

Grabow, G., Spooner, J., Lombardo, L., Line, D., and Tweedy, K. (1998). *Has Water Quality Improved?: Use of SAS for Statistical Analysis of Paired Watershed, upstream/downstream and before/after Monitoring Designs*. No. X825012. US EPA-NCSU-CES Grant, Raleigh, NC.

Hood, M. J., Clausen, J. C., and Warner, G. S. (2007). "Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development1." *JAWRA Journal of the American Water Resources Association,* 43(4), 1036-1046.

Hunt, W. F., Jarrett, A. R., Smith, J. T., and Sharkey, L. J. (2006). "Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina." *Journal of Irrigation and Drainage Engineering-Asce,* 132(6), 600-608.

ISCO Flowlink Software V 5.10.206. (2005). Teledyne ISCO, Inc. Lincoln, NE.

ISCO Open Channel Flow Measurement Handbook: Sixth Edition. (1978). Teledyne ISCO, Inc. Lincoln, NE.

Jennings, D. B., and Jarnagin, S. T. (2002). "Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed." *Landscape Ecol.,* 17(5), 471-489.

Lee, J. G., and Heaney, J. P. (2003). "Estimation of urban imperviousness and its impacts on storm water systems." *J.Water Resour.Plann.Manage.,* 129(5), 419-426.

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

Leopold, L. B. (1991). "Lag times for small drainage basins." *Catena,* 18(2): 157-171.

Line, D., White, N., Osmond, D., Jennings, G., and Mojonnier, C. (2002). "Pollutant export from various land uses in the upper Neuse River Basin." *Water Environ.Res.,* 74(1), 100-108.

Line, D. E., and White, N. M. (2007). "Effects of development on runoff and pollutant export." *Water Environ.Res.,* 79(2), 185-190.

Line, D.E., Brown, R. A., Hunt, W. F., and Lord, W. G. (2012). "Effectiveness of LID for Commercial Development in North Carolina" *J. Environ. Eng*. 138(6), 680-688.

Luell, S. K., Hunt, W. F., and Winston, R. J. (2011). "Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff." *Water Science and Technology,* 64(4), 974-979.

NCDENR. (2004). "Assessment Report: Biological Impairment in the Burnt Mill Creek Watershed." North Carolina Department of Environment and Natural Resources, Division of Water Quality-Planning Branch. Raleigh, NC.

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

Pitt, R., Field, R., Lalor, M., and Brown, M. (1995). "Urban Stormwater Toxic Pollutants - Assessment, Sources, and Treatability." *Water Environ.Res.,* 67(3), 260-275.

Pitt, R., Chen, S. E., Clark, S. E., Swenson, J., and Ong, C. K. (2008). "Compaction's impacts on urban storm-water infiltration." *J.Irrig.Drain.Eng.,* 134(5), 652-658.

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

Sartor, J. D., Boyd, G. B., and Agardy, F. J. (1974). "Water pollution aspects of street surface contaminants." *Journal (Water Pollution Control Federation),* 458-467.

Sartor, J., and Gaboury, D. (1984). "Street sweeping as a water pollution control measure: lessons learned over the past ten years." *Sci.Total Environ.,* 33(1), 171-183.

Schueler, T. R. 1992. "Mitigating the Adverse Impacts of Urbanization on Streams: A Comprehensive Strategy for Local Government." *Watershed Restoration Sourcebook*. Publication #92701, Metropolitan Washington Council of Governments. Washington, D.C.

Schueler, T. R. 1994. "The Importance of Imperviousness." *Watershed Protection Techniques*, 1(3): 100–11.

State Climate Office of North Carolina. (2012). 1971-2000 Climate Normals. Available: < http://www.nc-climate.ncsu.edu/cronos/normals.php>. Accessed 15 November 2012.

UACDC. 2010. *Low Impact Development: a design manual for urban areas*. University of Arkansas Press. University of Arkansas Community Design Center. Fayetteville, AR.

US EPA. (2009). History of the Clean Water Act. Laws, Regulations, Guidance, and Dockets. United States Environmental Protection Agency. Available at: http://www.epa/gov/lawsregs/laws.cwahistory/html. Accessed 22 October 2011.

Walsh, C. J. (2000). "Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration." *Hydrobiologia,* 431(2), 107-114.

Walsh, C. J., Sharpe, A. K., Breen, P. F., and Sonneman, J. A. (2001). "Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities." *Freshwat.Biol.,* 46(4), 535-551.

Walsh, C. J. (2004). "Protection of in-stream biota from urban impacts: minimize catchment imperviousness or improve drainage design?" *Marine and Freshwater Research,* 55(3), 317-326.

Wardynski, B. J., Winston, R. J., and Hunt, W. F. (2012). "Internal water storage enhances exfiltration and thermal load reduction from permeable pavement in the North Carolina mountains." *J.Environ.Eng., 139(2), 187-195*.

CHAPTER 3: CATCHMENT-SCALE EVALUATION OF THE WATER QUALITY IMPACTS OF RESIDENTIAL STORMWATER STREET RETROFITS IN WILMINGTON, NORTH CAROLINA

3.1 Abstract

Low Impact Development (LID) is a design approach that utilizes Stormwater Control Measures (SCMs) to maintain or restore the natural hydrologic regime of an urban watershed through infiltration, runoff treatment at the source, and minimization of impervious surfaces. This paired watershed study evaluated the impacts of LID SCMs on water quality at a catchment-scale in a small urban drainage area (0.53 ha). In February 2012, bioretention cell (BRC) bumpout, four permeable pavement parking stalls (installed in two separate sections) and a tree filter device were installed to treat residential street runoff in Wilmington, North Carolina. In the SCM-Retrofit catchment, 94% of the directly connected impervious area (DCIA) and 91% of the total drainage area was treated for potential water quality improvement. Underlying soils in the study area were Baymeade Urban and Leon Urban sands. Post-retrofit, concentrations of TKN, TP, TSS, Cu, Pb and Zn significantly decreased by 62%, 38%, 82%, 55%, 89% and 76%, respectively. Dissolved pollutant concentrations of $NO_{2,3}$-N, TAN and O-PO_4^{-3} did not change. Mass exports of TKN, TAN, O-PO_4^{-3}, TP, TSS, Cu, Pb and Zn significantly decreased by 78%, 61%, 55%, 73%, 91%, 53%, 88% and 77%, respectively. $NO_{2,3}$-N load decreased 46%, though this was not significant. Improvements in water quality were due to decreases in particulate and particulate-bound pollutant concentrations and loads. This was attributed to first flush retention of runoff by the BRC and permeable pavement that treated 52% of the DCIA and treatment by the tree filter unit that serviced another 42% of the DCIA. This study has shown that a limited number of LID

SCMs installed within a medium-density residential street right-of-way over sandy soils can mitigate some water quality impacts of existing development.

3.2 Introduction

Impervious land cover associated with urbanization has led to increases in stormwater runoff volumes and pollutant loads entering surface waters (Jennings and Jarnagin, 2002; Line and White, 2007). Ten percent imperviousness in a watershed can negatively impact nearby streams, rivers, lakes and estuaries, and a strong correlation has been shown between the fraction of impervious cover in a watershed and the degree to which the receiving water body is impaired (Schueler, 1992; Schueler, 1994; Novotny, 2003). The National Water Quality Inventory estimates 44% of stream km, 64% of lake ha and 30% of estuary km^2 are impaired, with urban runoff listed as a primary source of impairment (US EPA, 2009).

Most municipal streets and roadways are directly connected to conventional storm sewer networks with curb and gutter drainage systems. Street surfaces are sources of stormwater runoff volume and pollutants as well as pathways for the transport of pollutants from adjoining land areas (Bannerman et al., 1993). Directly connected impervious area (DCIA) is the primary contributor of runoff volume and pollutant loads in small rainfall events (<25.4 mm) (Walsh, 2000; Walsh et al., 2004; Flint and Davis, 2007). Organic and inorganic particulate material including sediment, heavy metals, nutrients, leaf litter, woody debris, polycyclic aromatic hydrocarbons (PAHs), gross solids and pathogens are pollutants that accumulate on streets and roadways (Bannerman et al., 1993; Barrett et al., 1998; Wu et al., 1998).

Street sweeping is utilized by many municipalities to control debris on the roadway and to reduce pollutant loads. However, evaluations of street sweeping operations have shown this practice is largely for aesthetics rather than providing a noticeable water quality benefit (Bender and Terstriep, 1984). This is because the fine solids and sediment fraction on the street surface is less than 250 μm and contains nearly all of the pollutant load (Sartor and Gaboury, 1984). Conventional street sweeping operations readily remove leaf litter, debris and coarse sediment, but do not effectively remove fine particles; rather, the sweeper brush redistributes them over the whole roadway (Sartor et al., 1974; Sartor and Gaboury, 1984).

Low Impact Development (LID) is an integrated design approach intended to mimic pre-development hydrology and water quality by discretely locating impervious surfaces and utilizing Stormwater Control Measures (SCMs) to capture and treat runoff at the source (Prince Georges County, 1999; Coffman, 2000; Davis et al., 2006; Dietz, 2007). For the most part, studies of LID practices, such as bioretention cells (BRCs), permeable pavements and tree filter units, have focused on individual systems or side-by-side comparisons to refine design and regulatory standards (Brattebo and Booth, 2003; Hunt et al., 2006; Brown and Hunt, 2011; Wardynski et al., 2013). Water quality evaluations have shown particulate pollutants are effectively removed by BRCs, and pollutant retention is driven by hydrology as dramatic reductions in mass export are observed frequently with less substantial concentration reductions reported (Li and Davis, 2009; Brown and Hunt, 2011). Permeable pavements have been shown to readily removed TSS and heavy metals (Cu, Pb, Zn) from influent runoff through filtration and sedimentation (Pratt et al., 1989; Pratt et al., 1995; Dierkes et al., 2002; Brattebo and Booth, 2003).

Limited peer-reviewed literature is available on the water quality impacts of LID SCMs at a watershed or catchment-scale. From a residential LID watershed, Bedan and Clausen (2009) reported pollutant mass exports of TKN, TAN, Pb, Zn and pathogens decreased post-construction although mass exports of TP and TSS increased. Line et al. (2012) characterized nutrient and sediment exports from three commercial watersheds in North Carolina: (1) a site with no SCMs, (2) a site with a wet detention basin and (3) an LID site with undersized permeable pavement, BRC and stormwater wetland installations. The LID site provided a greater mass load reduction for TKN, TAN, TP and TSS than the site with a conventional wet detention basin.

Streets and roadways make up approximately 25% of the urban landscape and represent the majority of the impervious cover owned and maintained by municipalities (UACDC, 2010). Traditionally, roadways have been designed to provide maximum traffic flow and adequate drainage to prevent flooding in the driving lane with little regard for control and treatment of runoff. Limited, but usable, space exists within the right-of-way to install SCMs, which includes the roadway, sidewalk and adjoining plaza area. It is becoming increasingly important to quantify the impacts of SCMs on existing residential development runoff quality as municipalities comply with total maximum daily load (TMDL) requirements or address goals for other watershed management plans. This study examined the impacts of LID SCM retrofits installed within the medium-density residential street right-of-way on water quality at a catchment-scale.

3.3 Materials and Methods

Site Description

The project site is located in Wilmington, North Carolina. Wilmington (population 110,000) is located in the southern coastal plain between the Cape Fear River and the Atlantic. Normal mean temperatures in summer and winter range from 23.9° – 27.2° C and 7.7° – 12.7° C, respectively (NC Climate Office, 2012). The study site is part of the Burnt Mill Creek watershed of the Cape Fear River Basin. The Burnt Mill Creek watershed is on North Carolina's 303(d) list, with toxicity and sedimentation cited as the primary causes of impairment (NCDENR, 2004). Two residential street catchments, a control and retrofit (SCM-Retrofit) were selected in for use in a paired watershed study (Figure 3-1). The control and SCM-Retrofit drainage areas are 0.35 ha (0.86 ac) and 0.53 ha (1.31 ac), respectively. The straight-line distance between the catchments is 0.5 km (0.3 mi).

Both catchments are medium-density residential areas with street surfaces, sidewalks, driveways, rooftops and open space; they are serviced by conventional curb and gutter drainage systems. Control and SCM-Retrofit housing densities are 25.7 home/ha (10.5 homes/ac) and 28.3 homes/ha (11.5 homes/ac), respectively. Impervious cover is the same in each catchment at 60%. However, the directly connected impervious area (DCIA) (street surface) in the SCM-Retrofit catchment is 24%, which is substantially greater than 16% DCIA observed in the control catchment (Table 3-1). The catchment outlets are existing stormwater catch basins. The control outlet is located at the northwest corner of the intersection of 8th Street and Orange Street, and the SCM-Retrofit outlet is located at the southwest corner of 12th Street and Dock Street.

Figure 3-1: Control and SCM-Retrofit drainage areas in Wilmington, NC

Table 3-1: Summary of catchment areas and imperviousness

Parameter	**Catchment**	
	SCM-Retrofit	**Control**
Drainage Area (m^2) (%)	5,300	3,480
Impervious Fraction	3,180 (60%)	2,088 (60%)
Street Surface (DCIA)	1,278 (24%)	557 (16%)
Rooftop	1,378 (26%)	1218 (35%)
Sidewalk	530 (10%)	313 (9%)
Open Space	2,120 (40%)	1,392 (40%)
Slope	0.5%	0.7%
Soil Series	Baymeade Urban	Leon Urban
USDA Soil Class	Sand	Sand
Outlet Location	N 34.235293 W 77.934061	N 34.233696 W 77.939200
Receiving Water Body	Burnt Mill Creek	
River Basin	Cape Fear	

The New Hanover County soil survey indicates underlying soils in the control and SCM-Retrofit catchments are Baymeade Urban and Leon Urban, respectively (Figure 3-1). Particle size analysis (PSA) using the hydrometer method (Gee and Bauder, 1986) showed the USDA texture classification for the underlying soils is sand (Gee and Or, 2002). Infiltration rates in sandy urban soils range from 50 mm/hr (2 in/hr) to 460 mm/hr (18 in/hr), and are greatly impacted by compaction (Pitt et al., 2008). Maximum longitudinal slopes in the control and SCM-Retrofit drainage areas are similar at 0.7% and 0.5%, respectively.

LID SCM Retrofits

LID SCMs constructed in February 2012 included a BRC bumpout, four permeable pavement parking spaces installed in two separate sections and one tree filter box installed along Dock Street and 12th Street (Figure 3-2, 3-4, 3-5). Post-retrofit TIA decreased from 60% to 58% and DCIA decreased from 24% to 12%. The BRC bumpout was constructed just west of the intersection of Jasmine Street and Dock Street to treat runoff from Dock Street. The BRCs extend 1.8 m (6 ft) into the existing roadway to create 3.5 m (11.5 ft) driving lanes (east and west bound) for the added benefit of traffic calming and pedestrian safety. Four permeable pavement parking stalls 7 m x 2.4 m (23 ft x 8 ft) each were installed in two separate sections on 12th Street between Dock Street and Orange Street to treat runoff from 12th Street. Permeable pavement loading ratios (DCIA/SCM surface area) of 7.8 and 6.6 are atypical, and the impacts of loading ratios this large have not been reported in the literature. Flow diverters were installed along the curb and gutter at 3.6 m intervals to force runoff into the parking areas (Figure 3-3). A detailed design summary of SCMs is included in Appendix B.

Figure 3-2: Clockwise from top: BRC bumpouts along Dock Street, tree filter device at intersection of 12th Street and Dock Street, and permeable pavement parking stalls on 12th Street

A Filterra® tree filter device was installed on Dock Street at the southwest corner of the intersection with 12th Street to treat runoff from Jasmine Street and Dock Street that is down-slope of the BRC bumpout. The tree filter treats any overflow from the BRC. The devices function as high flow filters such that ponding at the surface does not occur. Lenth et al. (2010) measured infiltration rates of ten Filterra™ devices with varying maintenance periods (recent – 2 years) and found infiltration rates from 2200 mm/hr (86 in/hr) to 5200 mm/hr (205 in/hr) with up to 110 mm (4.5 in) of sediment accumulation at the surface. Volume reduction is negligible because the concrete lining does not allow exfiltration to occur. The BRC, permeable pavement and Filterra® unit combined to treat 94% of the street surface and 91% of the total drainage area for potential water quality improvement (Table 3-2).

Table 3-2: Summary of LID SCM design parameters

Parameter	BRC[a]	Filterra®	PP I[b]	PP II[c]
Surface Area	19 m^2	3 m^2	34 m^2	34 m^2
Street Surface Area	160 m^2	539 m^2	265 m^2	226 m^2
Loading Ratio[d]	8.4:1	180:1	7.8:1	6.6:1
Street Surface Area Treated	13%	42%	21%	18%
Total Catchment Area Treated	12%	22%	30%	27%
As Built Design Rainfall Event[e]	33 mm	N/A	24 mm	27 mm
Underdrain	No	Yes	No	No

[a]Bioretention Cell on Dock Street
[b]North permeable pavement parking area on 12th Street
[c]South permeable pavement parking area on 12th Street
[d]Calculated as drainage area/SCM surface area
[e]Runoff from given rainfall depth that is stored in SCM before overflow occurs, assuming no infiltration to underlying soils

Figure 3-3: Flow diverters installed on permeable pavement parking stalls along curb and gutter of 12th Street

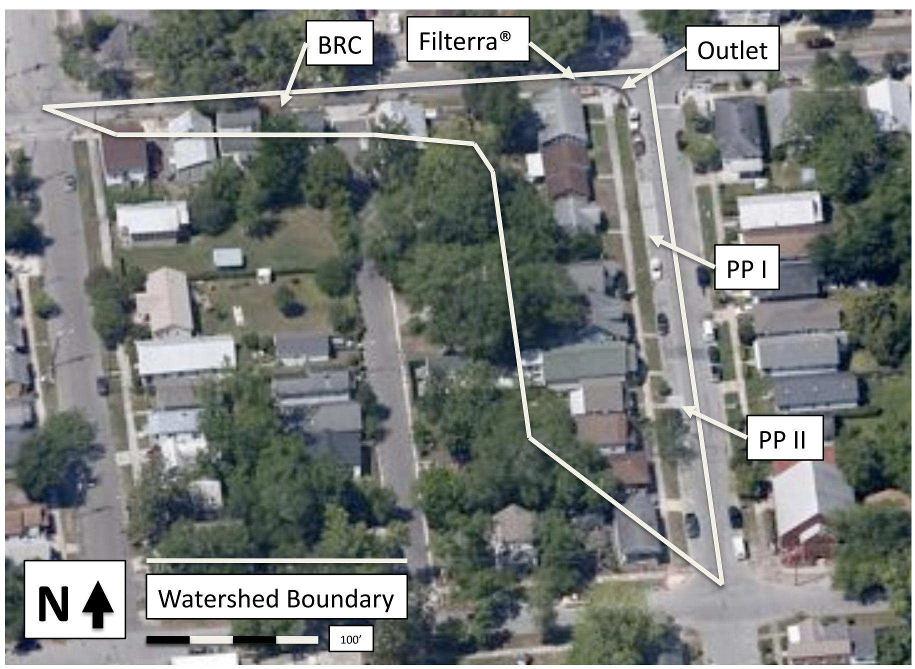

Figure 3-4: Post-retrofit aerial photo with approximate watershed boundary *(Google Maps)*

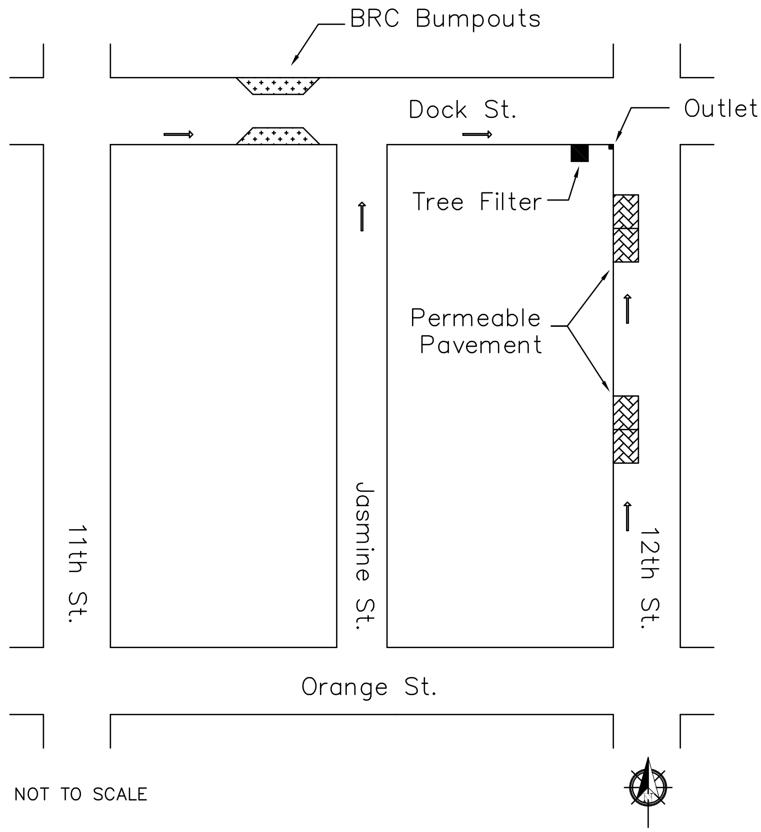

Figure 3-5: Layout of LID SCMs with arrows indicating direction of flow (not to scale)

Monitoring Design

The paired watershed study design was used to evaluate the water quality impacts of the LID SCM retrofits (Clausen and Spooner, 1993; Grabow et al., 1999). This approach requires two watersheds: control and treatment (SCM-Retrofit) and two monitoring periods: calibration and treatment. During the calibration period, management practices in the catchments remained the same (no SCMs), the SCMs were installed in the SCM-Retrofit catchment and treatment monitoring began post-construction (Table 3-3). The paired watershed approach is underpinned by a quantifiable and predictable (linear) relationship between the catchments. A relationship is developed during the calibration period, and is considered valid until the SCM treatment is applied, at which time a new relationship between the catchments is developed during the second period of monitoring (Clausen and Spooner, 1993).

Table 3-3: Paired watershed study design

Period	Catchment	
	SCM-Retrofit	**Control**
Calibration	No SCMs	No SCMs
Treatment	SCMs	No SCMs

Monitoring equipment was installed at the catchment outlets in May 2011. Manual and HOBO™ Tipping Bucket rain gauges were installed on a wooden post free of trees and overhead obstructions at the SCM-Retrofit station (Table 3-4). An ISCO 6712™ portable sampler logged rainfall data from the tipping bucket. Hydrologic data were recorded by installing V-notch weirs and weir boxes inside the existing catch basins (Figure 3-6). Forty-five degree and 60° V-notch weirs were installed at the control and SCM-Retrofit stations, respectively. The weir boxes were fitted with a 1 m (3.3 ft) long contracted rectangular weir to pass discharges from large storms. ISCO 730™ bubbler flow modules connected to ISCO 6712™ portable samplers were used to monitor discharge and total runoff volume by measuring stage above the weir at two minute intervals.

Table 3-4: Summary of monitoring equipment

Equipment	SCM-Retrofit	Control
Location	Southwest corner of intersection of 12th and Dock St	Northwest corner of intersection of 8th and Orange St.
Structure	60° V-notch weir	45° V-notch weir
Flow Monitoring Device	ISCO 730™ Bubbler Module	ISCO 730™ Bubbler Module
Sampling Device	ISCO 6712™ Portable Sampler	ISCO 6712™ Portable Sampler
Rain Gauges	Manual and HOBO™ Tipping Bucket	NA[a]

[a]Control station located 0.5 km from LID station

Figure 3-6: V-notch weir and weir box installed inside existing catch basin

Sampling Protocol

The ISCO 6712™ portable samplers were programmed to suction 200 mL aliquots per specified runoff volume that was deposited into a 1 L bottle (Figure 3-7). Each sampler contained 24 1 L bottles. A minimum of 10 aliquots (2 L) was needed for a full set of water quality analyses to be conducted. The samplers were programmed to collect samples from rainfall events ranging from 6 mm to 380 mm (0.25 in to 1.5 in). Runoff samples were suctioned from the base of the weir box, 10 cm (4 in) behind the weir in an area of well-mixed flow.

Figure 3-7: Retrofit station with JoBox ™ , rain gauges, and weir box inside existing catch basin (left), two ISCO 6712™ portable samplers with ISCO CDMA Cellular Phone Modem™ installed inside retrofit JoBox™ (right)

Water quality samples were collected within 24 hours of a rainfall event. Total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrate-nitrite-nitrogen ($NO_{2,3}$-N), total phosphorous (TP), and ortho-phosphate ($O\text{-}PO_4^{-3}$) samples were analyzed by the North Carolina Center for Applied Aquatic Ecology at NCSU in Raleigh, NC. Total nitrogen (TN) concentrations were calculated by summing TKN and $NO_{2,3}$-N; organic nitrogen (ON) concentrations were determined by subtracting TAN from TKN for each sampled storm event. Total polycyclic aromatic hydrocarbons (∑PAHs), copper (Cu), lead (Pb) and zinc (Zn) samples were analyzed by the NCDENR Environmental Chemistry Lab in Raleigh, NC. Both labs were located approximately 210 km (130 mi) from the study site. Laboratory analytical methods are listed in Table 3-5.

Table 3-5: Laboratory analytical methods and reporting limits

Pollutant	Pollutant Name	Analytical Method	RL[a]	Unit
$NO_{2,3}$-N	Nitrate + Nitrite Nitrogen	SM 4500-NO3-F[b]	0.0056	mg/L
TKN	Total Kjeldahl Nitrogen	EPA 351.1[c]	0.14	mg/L
TAN	Total Ammoniacal Nitrogen	SM 4500-NH3-H[b]	0.007	mg/L
ON	Organic Nitrogen	= TKN - TAN	NA	mg/L
TN	Total Nitrogen	= TKN + $NO_{2,3}$-N	NA	mg/L
O-PO_4^{-3}	Orthophosphate	SM 4500-P-F[b]	0.006	mg/L
TP	Total Phosphorus	SM 4500-P-F[b]	0.01	mg/L
TSS	Total Suspended Solids	SM 2540 D[b]	1	mg/L
Cu	Copper	EPA 200.8[c]	2	µg/L
Pb	Lead	EPA 200.8[c]	10	µg/L
Zn	Zinc	EPA 200.7[c]	10	µg/L
∑PAH	Polycyclic Aromatic Hydrocarbons	EPA 625/8270/3510[c]	10-50	µg/L

[a]Reporting Limit
[b]Eaton et al., 1995
[c]US EPA, 1993

Upon arrival in Wilmington, both stations were checked to ensure the weirs were clear of debris and the samplers had collected adequate paired samples. Individual 1-liter bottles with aliquots were poured into a 24 L mixing vessel. The mixing vessel was agitated to re-suspend particulates and pollutants. From the mixing vessel, a plastic TSS bottle (1000 mL) and total metals bottle (500 mL) was filled. Nitric acid ampoules were added to each metals sample bottle. A pre-acidified plastic nutrients bottle (125 mL) was filled, and approximately 30 mL of water was filtered through a 0.45 µm filter into a glass bottle for O-PO_4^{-3} analysis. Latex gloves were used while sampling, and samples were placed on ice immediately for transportation to the laboratories (Figure 3-8).

Figure 3-8: Sample bottles placed on ice for transport (left) and research vehicle with sampling equipment (right)

Monitoring Challenges

The primary monitoring challenge was keeping the weirs and weir boxes clear of debris. Leaf litter, woody material, trash and coarse sediment that accumulated on the street surface (Figure 3-3) were frequently deposited in the base of the weir box during a storm (Figure 3-9). This was more common at the control station during fall and winter sampling seasons. Debris was removed from the weirs and weir boxes during each site visit. In October 2011 the City of Wilmington was required to make existing crosswalks ADA compliant, including the western crosswalk at the intersection of 8th Street and Orange Street, which was 1 m (3 ft) upslope of the control station. This required the control station to be removed in November 2011, ending calibration monitoring. The ADA crosswalk was installed incorrectly in December 2011 allowing runoff to bypass the catch basin where the control station had been installed. In May 2012 the ADA crosswalk was corrected and runoff from the control catchment was directed into the original catch basin enabling treatment monitoring to begin.

Figure 3-9: Debris clogging control weir (left) and removing organic material from control weir box (right)

Data Processing

Hydrologic data were reviewed using FLOWLINK Version 5.0 software (ISCO, 2005) and compared to field notes. Rainfall intensities and total depths were adjusted by a scaling factor developed from the discrepancy (deficit) recorded by the tipping bucket and manual rain gauges. During pre-retrofit monitoring, all laboratory analysis of storms sampled for ∑PAH indicated concentrations were below the practical reporting limits (PQL); therefore ∑PAH sampling was suspended for the second period of monitoring. For other pollutant concentrations that were less than the PQL, one-half the value of the PQL was used for calculations and statistical analysis. Pollutant loads for each storm were calculated in units of grams/hectare (g/ha) using Equation 3-1 for statistical analysis. Annual mass export rates were calculated in units of kilograms/hectare/year (kg/ha/yr) using the ratio method shown in Equation 3-2.

$$L = \frac{Q \times C_P}{A_{WS} \times 1000} \qquad \text{Equation 3-1}$$

Where,

L = Pollutant load (g/ha)

Q = Storm runoff volume (L)

C_p = Pollutant concentration (mg/L)

A_{WS} = Watershed area (ha)

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

Where,

L_{annual} = estimated annual load (kg/ha/yr)

$L_{measured}$ = pollutant load measured (kg/ha)

P_{annual} = long term average annual rainfall (mm)

$P_{measured}$ = rainfall measured during monitoring (mm)

Statistical Analysis

SAS Version 9.3™ was used for all statistical analyses (SAS Institute, 2012). Data sets from the calibration and treatment periods were log transformed and tested separately using analysis of variance (ANOVA) for a significant linear relationship with metrics from the SCM-Retrofit and control catchments as covariates (control = x, SCM-Retrofit = y). The residuals of regression were inspected graphically for normality and constant variance. Skew coefficients and the Shapiro-Wilk goodness-of-fit test were also used to assess residual normality. Analysis of covariance (ANCOVA) was used to detect significant impacts on the slopes and intercepts of concentration and mass load regressions for each water quality constituent. All statistical tests were conducted using α=0.05 unless otherwise noted. No significant differences in slopes were observed, thus the reduced ANCOVA model with constant slopes was used for all water quality analyses. A significant difference in intercepts of calibration and treatment regression lines implied the LID SCM treatment had a significant impact on that water quality parameter. Least squared means (LSM) analysis was used to statistically quantify changes in pollutant concentrations and loads from calibration to treatment monitoring. Percent reductions were calculated using Equation 3-3.

$$Change(\%) = [\frac{10^{\bar{Y}_T}}{10^{\bar{Y}_C}} - 1] \times 100 \qquad \text{Equation 3-3}$$

Where,

$\bar{Y}_T$ = SCM-Retrofit LSM during treatment monitoring

$\bar{Y}_C$ = SCM-Retrofit LSM during calibration monitoring

Significant linear relationships did not exist for O-PO_4^{-3}, Pb, Zn and TSS concentrations during the calibration period, thus statistical comparisons were made between the control and SCM-Retrofit drainage areas using paired post-retrofit water quality data. Differences in paired data points from the SCM-Retrofit and control catchments were checked for normality using the Shapiro-Wilk goodness-of-fit test. If the differences were not normally distributed, the raw data sets were log transformed and tested again. Differences that were determined to be approximately normal were tested for a significant difference with a Student's t-test. In instances where the paired differences remained non-normally distributed, the non-parametric sign test was used.

3.4 Results and Discussion

Precipitation

Average annual rainfall at Wilmington International Airport (ILM) is 1,448 mm (57 in) distributed relatively uniformly throughout the year (NC State Climate Office, 2012). The calibration and treatment monitoring periods occurred from 10 May 2011 to 31 October 2011 and 8 June 2012 to 13 February 2013, respectively. Rainfall recorded during the calibration and treatment periods was 514 mm and 957 mm, respectively. Over the cumulative 1.14 year study period recorded rainfall was 11% below normal. Storms less than 6 mm (0.25 in) were not sampled for water quality analysis. A six-hour antecedent dry period was used to separate discrete rainfall events. During calibration monitoring, six events were sampled in summer and three in fall (Table 3-6). Post-retrofit, water quality samples were collected for all four seasons.

Table 3-6: Seasonal distribution of sampling events

Period	Spring	Summer	Fall	Winter
Calibration	-	6	3	-
Treatment	2	5	5	4

Similar rainfall characteristics were observed in both monitoring periods. Median storm depth during the calibration period was 19.1 mm (0.75 in) compared to 16.9 mm (0.67) in) recorded during treatment monitoring. Rainfall depth from the 50th percentile storm (12.7 mm) (0.5 in) was used to partition rainfall data (Tables 3-7). Bean (2005) reported rainfall depth percentiles for Wilmington, NC.

Table 3-7: Precipitation summary for calibration and treatment periods (all units in mm)

Period	n[a]	Range	50th Percentile		Mean	Median	Total
			<12.7	>12.7			
Calibration	9	7.1 - 143	3 (33%)	6 (67%)	33.5	19.1	514
Treatment	16	7.9 - 72	6 (38%)	10 (62%)	24.1	16.8	957

[a]Number of storms sampled for water quality during monitoring period

Pre-retrofit, data collection was limited due to crosswalk construction in the control catchment (see *Monitoring Challenges)*. Ideally, the calibration and treatment monitoring periods would have lasted for one year or more each, as outlined by Clausen and Spooner (1993). The watersheds in this study were small urban drainage areas located 0.5 km apart with similar land use, imperviousness, topography, soil and nearly identical climate and weather patterns. The only difference between the catchments during this study was the SCM treatment. Although calibration monitoring was shortened, linear relationships established between the catchments were sufficient to make valid statistical comparisons using ANCOVA and LSM.

Nutrients – Nitrogen

For the most part, median pollutant concentrations were less than the computed means due several events with spikes in concentrations in runoff at both monitoring stations. During treatment monitoring, TKN concentrations from the SCM-Retrofit catchment significantly decreased by 62% (Table 3-8) (Figure 3-10). The median SCM-Retrofit TKN concentration was 0.45 mg/L, which is more than three times less than median TKN concentration of 1.48 mg/L reported by Line et al. (2002) for traditional residential development in North Carolina. The median control TKN concentration was 1.14 mg/L. Dissolved nitrogen concentrations of TAN and $NO_{2,3}$-N remained unchanged after the SCMs were installed (Figure 3-11).

Sources of TKN and TAN in residential watersheds include organic material, animal wastes and atmospheric deposition on rooftops, driveways and roads (Bannerman et al., 1993). LID TAN concentrations were similar to those reported for LID commercial and residential sites (Table 3-8). The decrease in SCM-Retrofit TKN concentration was likely due to particulate ON retention (leaf litter and woody debris). Median $NO_{2,3}$-N concentrations at the control and SCM-Retrofit outlets were 0.14 mg/L and 0.07 mg/L, respectively, which are less than $NO_{2,3}$-N concentrations observed at other residential sites and well below a previously suggested irreducible concentration (0.7 mg/L) by Schueler and Holland (2000) (Table 3-8). $NO_{2,3}$-N in runoff tends to originate from commercial fertilizer use (Bannerman et al., 1993). In both drainage areas monitored, there was minimal ornamental landscaping and lawn area, and fertilizer use was not documented.

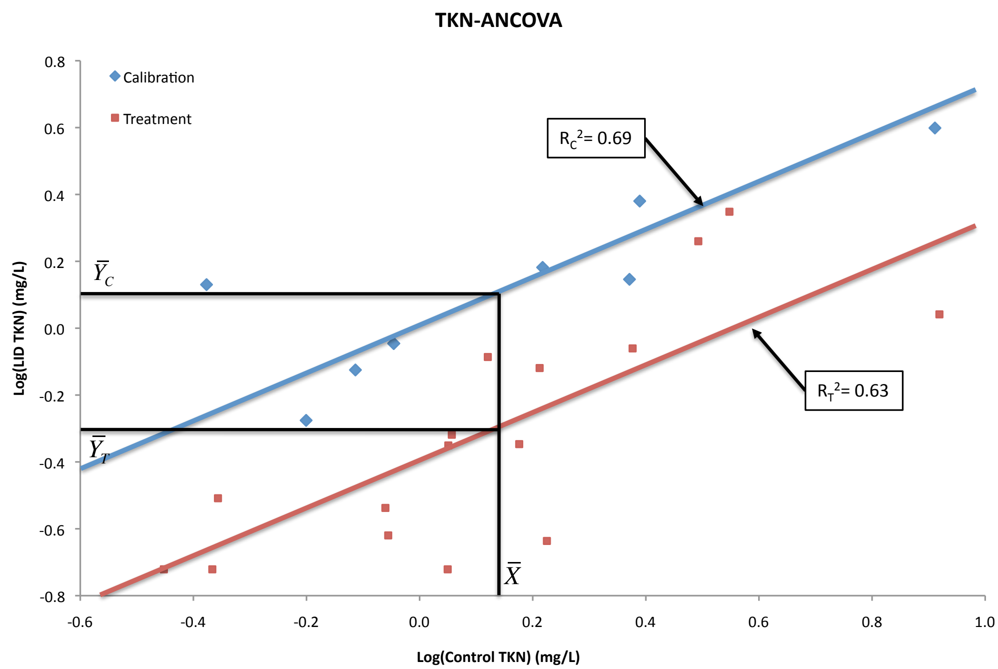

Figure 3-10: Reduced ANCOVA model for TKN concentration (mg/L)

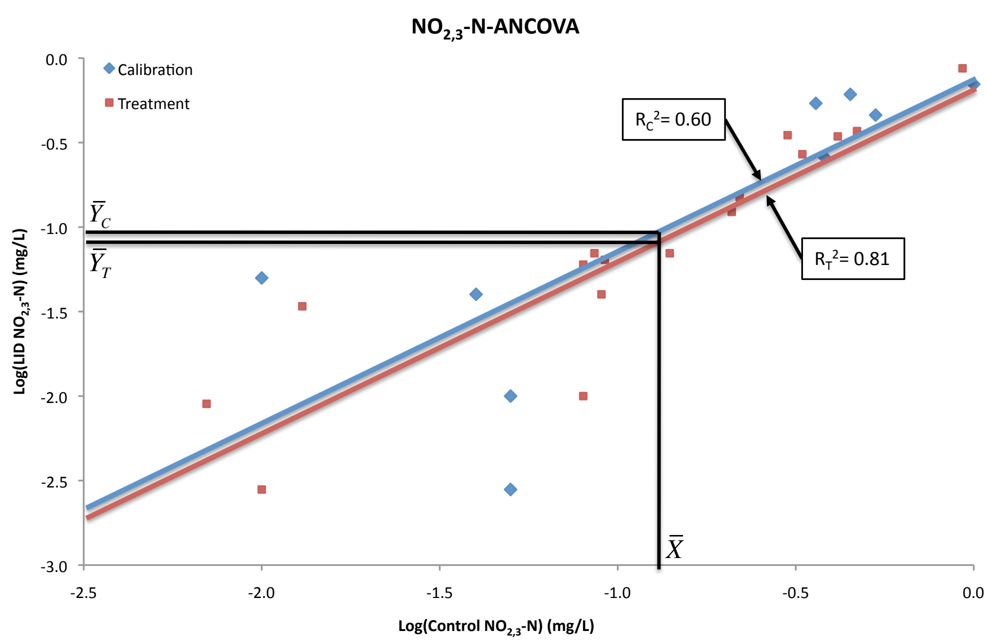

Figure 3-11: Reduced ANCOVA model for $NO_{2,3}$-N concentration (mg/L)

Table 3-8: Summary of nutrient and sediment concentrations at the catchment outlets (mg/L)

Station	Duration (yr)	n[a]	TKN	TAN	$NO_{2,3}$-N	TSS	O-PO_4^{-3}	TP
Control	1.14	25						
Mean			1.92	0.20	0.25	53	0.23	0.44
Median			1.14	0.06	0.14	42	0.10	0.22
SCM-Calibration	0.47	9						
Mean			1.52	0.07	0.30	50	0.21	0.29
Median			1.35	0.04	0.26	54	0.11	0.21
SCM-Treatment	0.67	16						
Mean			0.66	0.04	0.18	11	0.12	0.21
Median			0.45	0.03	0.07	7	0.10	0.17
LSM Difference[b]			-62%*	0%[NS]	0%[NS]	-82%[T]*	-54%[S]*	-38%*
US Residential[1]			1.51	-	0.48	172	0.12	0.26
NC Residential[2]			1.48	0.34	0.49	42	-	0.40
LID Residential[3]			1.30	0.04	0.40	11	-	0.29
LID Commercial[4]			0.69	0.06	0.56	18	0.01	0.06

*Significant
[NS]Not Significant
[T]Paired t-test used for statistical comparison between control and SCM-Retrofit catchments with treatment data set
[S]Sign test used for statistical comparison between control and SCM-Retrofit catchments with treatment data set
[a]Number of events sampled
[b]Negative sign "-" implies reduction
[1]Claytor and Schueler, 1996
[2]Line et al., 2002
[3]Bedan and Clausen, 2009
[4]Line et al., 2012

Overall, annual nitrogen mass export rates from the catchments in this study were less than those reported for residential development in North Carolina and the U.S. (Table 3-9). This is primarily due to the sandy soils in the study area, which is reflected by the low runoff coefficients (runoff/rainfall) of the control and SCM-Retrofit drainage areas. At the SCM-Retrofit outlet, mass exports of TKN and TAN significantly decreased by 78% and 61%, respectively. $NO_{2,3}$-N mass export rate decreased by 47%; although this was not significant.

Post-retrofit, annual SCM-Retrofit TKN load was five times less than the untreated control drainage area (0.5 kg/ha/yr compared to 2.6 kg/ha/yr). TKN and $NO_{2,3}$-N loads at the SCM-Retrofit station were similar to those reported by Bedan and Clausen (2009) for a residential LID watershed in Connecticut. TAN mass export from the SCM-Retrofit catchment was 0.1 kg/ha/yr, which is nearly the same as TAN load for an undeveloped watershed in North Carolina (Table 3-9). Decreases in TAN and $NO_{2,3}$-N loads were due to decreases in runoff volume after construction of the LID SCMs, as evidenced by the decrease in SCM-Retrofit runoff coefficient from 0.38 to 0.18.

Table 3-9: Summary of nutrient and sediment export rates (kg/ha/yr)

Station	Runoff Coefficient	n[a]	TKN	TAN	$NO_{2,3}$-N	TSS	O-PO_4^{-3}	TP
Control	0.21	24	2.6	0.3	0.4	113	0.2	0.6
SCM-Calibration	0.38	8	2.8	0.2	0.3	157	0.3	0.7
SCM-Treatment	0.18	16	0.5	0.1	0.1	12	0.1	0.2
LSM Difference[b]			-78%*	-61%*	-46%[NS]	-91%*	-55%*	-73%*
LID Residential[1]	0.07		0.9	0.0	0.3	8	-	0.2
NC Residential[2]	0.57		20.7	2.4	3.2	387	-	2.3
NC Undeveloped[3]	0.21		5.3	0.2	1.0	349	-	0.5

*Significant
[NS]Not Significant
[a]Number of events used to evaluate pollutant loads
[b]Negative sign "-" implies reduction
[1]Bedan and Clausen, 2009; Hood et al., 2007
[2]Line et al., 2002
[3]Line and White, 2007

Nutrients – Phosphorus

Post-retrofit, $O\text{-}PO_4^{-3}$ concentrations in the SCM-Retrofit catchment were 54% less than those observed in the control catchment (Table 3-8). However, mean $O\text{-}PO_4^{-3}$ concentrations in both drainage areas were skewed by several events with spikes in $O\text{-}PO_4^{-3}$ concentrations. Median $O\text{-}PO_4^{-3}$ concentrations (0.10 mg/L) in SCM-Retrofit catchment remained unchanged compared to those observed at the control station (0.11 mg/L) and pre-retrofit conditions (0.10 mg/L) (Table 3-8). Dissolved $O\text{-}PO_4^{-3}$ originates from fertilizers and lawns in residential watersheds, and can also be leached from soils that have reached their phosphorus sorption capacity (Waschbusch et al., 1999). Median $O\text{-}PO_4^{-3}$ concentrations observed in this study were nearly the same as those reported by Claytor and Schueler (1996) for residential sites in the U.S. SCM-Retrofit TP concentration significantly decreased by 38% (α=0.10). The modest decrease in TP concentration was mainly due to sediment retention by the SCMs.

Mass export of $O\text{-}PO_4^{-3}$ and TP at the SCM-Retrofit outlet significantly decreased by 55% and 73%, respectively (Table 3-9). Annual SCM-Retrofit TP load was three times less than TP load from the control catchment (0.2 kg/ha/yr compared to 0.6 kg/ha/yr). SCM-Retrofit TP mass export was the same as the TP load reported by Bedan and Clausen (2009) for a residential LID watershed and 11.5 times less than a residential watershed with no SCMs studied by Line et al. (2002). The primary reason for the decreases in $O\text{-}PO_4^{-3}$ and TP loads from the SCM-Retrofit catchment was a decease in runoff volume.

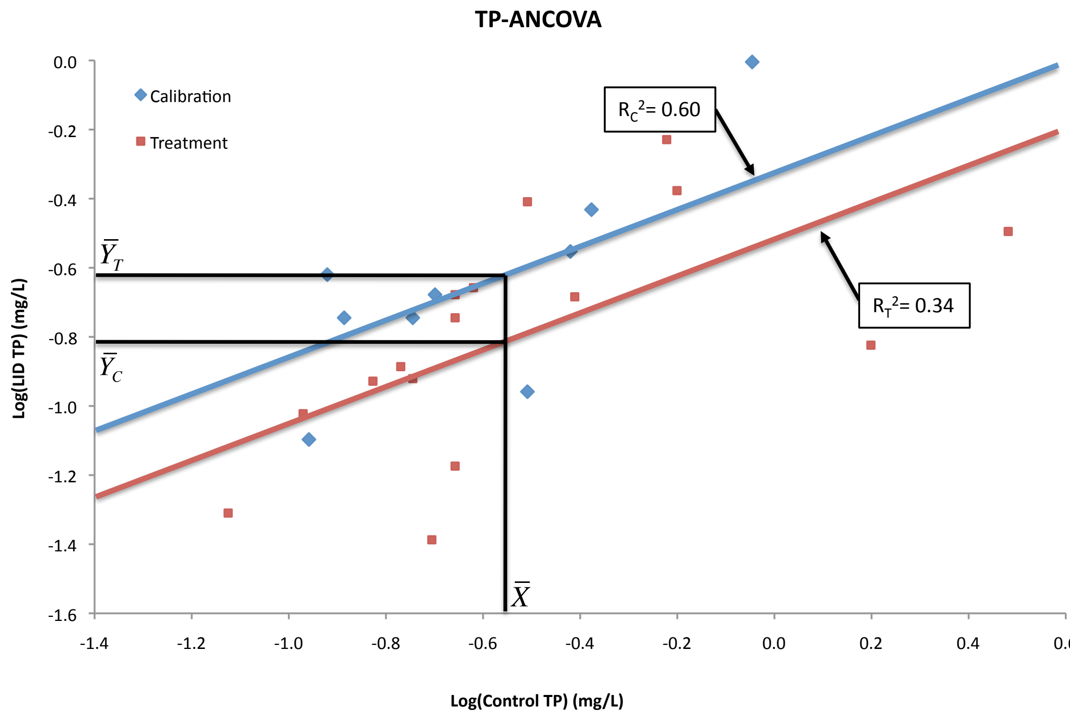

Figure 3-12: Reduced ANCOVA model for TP load (g/ha)

Total Suspended Solids

Mean SCM-Retrofit TSS concentration decreased from 50 mg/L to 11 mg/L, post-retrofit and was significantly less than TSS concentration (53 mg/L) observed at the control station (Table 3-8). LID TSS concentration was nearly the same as those observed by Line et al. (2012) and Bedan and Clausen (2009) from commercial and residential LID sites, respectively. TSS concentrations during the calibration period were similar to those reported by Line et al. (2002) at a residential watershed in North Carolina. However, mass export rates of TSS from both catchments in this study were less than half of TSS loads observed by Line et al. (2002), suspectedly due to the flat topography and sandy soils of drainage areas in this study that generated low runoff coefficients (Table 3-9). Post-retrofit, TSS load at the SCM-Retrofit outlet significantly decreased by 91% (Figure 3-13) (Table 3-9). The dramatic decrease in TSS load is due to runoff treatment and a decrease in runoff volume. At the SCM-Retrofit outlet, annual TSS load was 12 kg/ha/yr, which was similar to TSS loads observed by Bedan and Clausen (2009) where a low runoff coefficient of 0.07 was also reported.

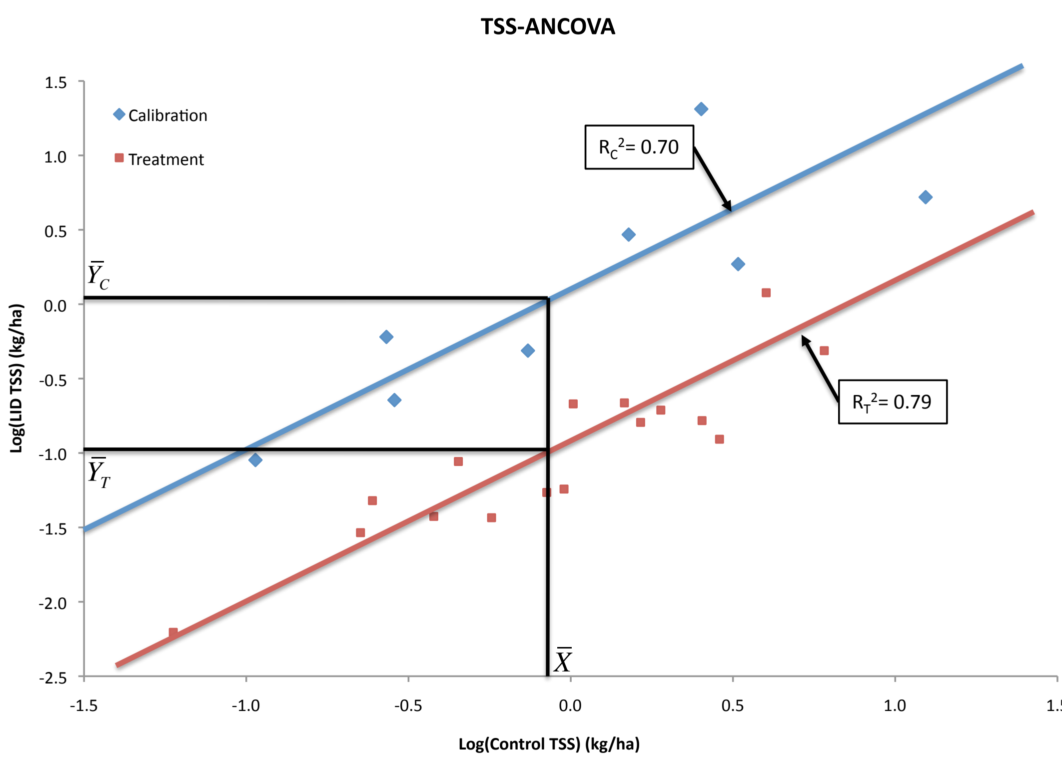

Figure 3-13: Reduced ANCOVA model for TSS load (kg/ha)

Metals – Cu, Pb and Zn

In residential watersheds, Cu, Pb and Zn in runoff have been linked to vehicular brake wear, aged exterior paint and tire wear, respectively (Bannerman et al., 1993; Davis et al., 2001). Cu concentrations in the SCM-Retrofit catchment significantly decreased by 55% (Table 3-10) (Figure 3-14). SCM-Retrofit concentrations of Pb and Zn were significantly less than those observed in the control catchment by 89% and 76%, respectively. In general, metals concentrations observed in this study were less than the average concentrations reported by Claytor and Schueler (1996) for residential streets across the U.S. Post-retrofit, Cu, Pb and Zn concentrations in the SCM-Retrofit catchment were similar to those reported by Bedan and Clausen (2009) from a residential LID watershed. Mass exports of Cu, Pb and Zn at the SCM-Retrofit outlet significantly decreased by 53%, 88%, and 77%, respectively. Dramatic decreases of heavy metals loads were due to treatment of runoff and a decrease in runoff volume leaving the SCM-Retrofit catchment.

Table 3-10: Summary of metals concentrations at the catchment outlets (µg/L)

Station	Duration (yr)	n[a]	Cu	Pb	Zn
Control	1.14	25			
Mean			16	37	84
Median			13	35	70
SCM-Calibration	0.47	9			
Mean			14	22	85
Median			14	14	65
SCM-Treatment	0.67	16			
Mean			6	4	21
Median			5	2	18
LSM Difference[b]			-62%*	-89%[T]*	-76%[T]*
NURP Residential[1]			25	51	173
LID Residential[2]			6	1	17
NC Parking Lots[3]			13	5	72

*Significant
[T]Paired t-test used for statistical comparison between catchments with treatment data set
[a]Number of events sampled
[b]Negative sign "-" implies reduction
[1]Claytor and Schueler, 1996
[2]Bedan and Clausen, 2009
[3]Hunt et al., 2008

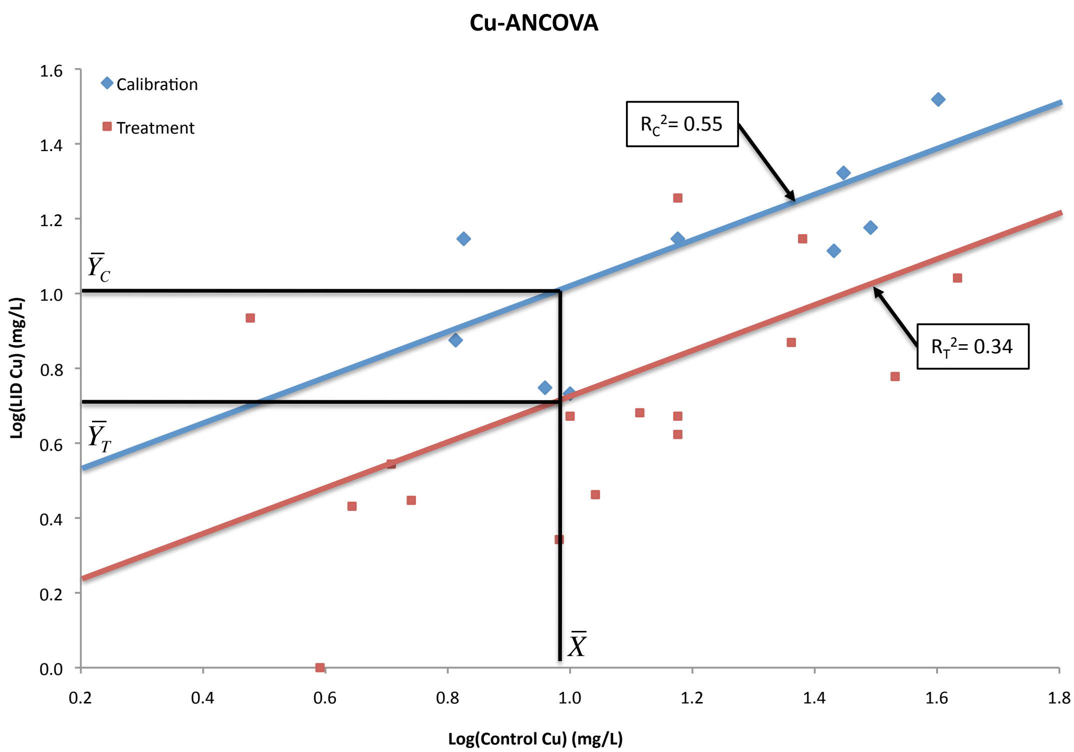

Figure 3-14: Reduced ANCOVA model for Cu concentrations (mg/L)

First Flush Phenomenon

During treatment monitoring, concentrations for all particulate or particulate-bound pollutants (TKN, TP, TSS, Cu, Pb, Zn) significantly decreased at the SCM-Retrofit outlet. This was partly due to the first flush nature of pollutant loading which suggests most of the particulate pollutant load is contained in the beginning stages of a storm (Bertrand-Krajewski et al., 1999; Sansalone et al., 2005), which the BRC and permeable pavement in this study were designed to capture and retain. Evaluations of highway runoff have shown that TSS and heavy metals produce a substantial first flush of pollutant load (Sansalone and Buchberger, 1997). In Maryland, Flint and Davis (2007) found that 81%-86% of TKN, $NO_{2,3}$-N, TP, TSS, Cu, Pb and Zn mass loads were contained in the first 13 mm (0.5 in) of roadway runoff. Assuming exfiltration to the underlying soil does not occur during a storm, as-built design rainfall events for the BRC, PP I and PP II were 33 mm (1.3 in), 24 mm (0.95 in) and 27 mm (1.05 in), respectively (Table 3-2). Prior to construction of the LID SCMs, 13 mm (0.5 in) of runoff at the LID watershed outlet corresponded to 30 mm (1.2 in) of rainfall based on regression analysis of a rainfall vs. runoff plot. Of the 16 events sampled for water quality post-retrofit, 12 were less than 30 mm and 11 were less than the minimum design rainfall event (24 mm) of the BRC and permeable pavement. This means that for 69% of for the storms monitored, the SCMs could have captured all influent runoff. For storms greater than the design events, the SCMs likely retained a large fraction of the first flush of pollutants from the first part of the storm. Underdrains were not installed in the BRC or permeable pavement, therefore all influent runoff exfiltrated to the underlying soil.

The BRC and permeable pavement parking areas combined to treat 52% of the DCIA and 69% of the total catchment. The decreases in pollutant loads observed in this study were similar to other studies of LID SCMs. Bean et al. (2007b) found that permeable pavement installed over sandy soil eliminated all runoff and subsequent pollutant loads when the underdrains were removed. Field studies have shown BRCs can capture runoff volume and pollutant loads from small storms entirely (Li and Davis, 2009; Li et al., 2009; Brown and Hunt, 2011). The tree filter device, which treated 42% of the DCIA and 22% of the total drainage area, also contributed to decreases in particulate pollutant concentrations and loads. The primary treatment processes within the Filterra® unit are filtration and sedimentation. Yu and Stafford (2007) found that Filterra® units removed 85% of influent TSS, 16% of Cu and 50% of Zn. Some nutrient retention was also reported for TKN (20%) and TP (55%), which was mainly attributed to particulate ON and TSS capture. The combined impacts of first flush volume and pollutant retention in the BRC and permeable pavement and high level of particulate retention in the tree filter unit resulted in significant decreases of all pollutant loads, except $NO_{2,3}$-N.

Impacts to In-stream Biota

Benthic macroinvertebrates are frequently used to assess water quality impairment in streams and have been used to evaluate the performance of SCMs (Barbour et al., 1999). McNett et al. (2010) used qualitative benthic macroinvertebrate health and corresponding in-stream nutrient and sediment concentrations in North Carolina to establish water quality thresholds and evaluate SCM effectiveness. "Good" water quality thresholds in coastal North Carolina for TN and TP are 0.73 mg/L and 0.09 mg/L, respectively. TN concentrations from the untreated control catchment exceeded 0.73 mg/L for 80% (13 of 16) of the events sampled (Figure 3-15). At the SCM-Retrofit outlet, TN concentrations were less than the 0.73 mg/L threshold for 70% (10 of 16) of the events sampled after the SCMs were installed. For TP, just one of the events sampled at the control site had concentrations less than 0.09 mg/L; SCM-Retrofit TP concentrations were less than 0.09 mg/L for 3 of 16 (19%) events sampled (Figure 3-16). Bannerman et al. (2004) suggested the target effluent TSS concentration from SCMs to be 25 mg/L. TSS concentrations at the control outlet exceeded 25 mg/L in 75% (13 of 16) of the storms sampled (Figure 3-17). At the SCM-Retrofit outlet, TSS concentrations for 90% (14 of 16) of the storms sampled were less than the 25 mg/L threshold.

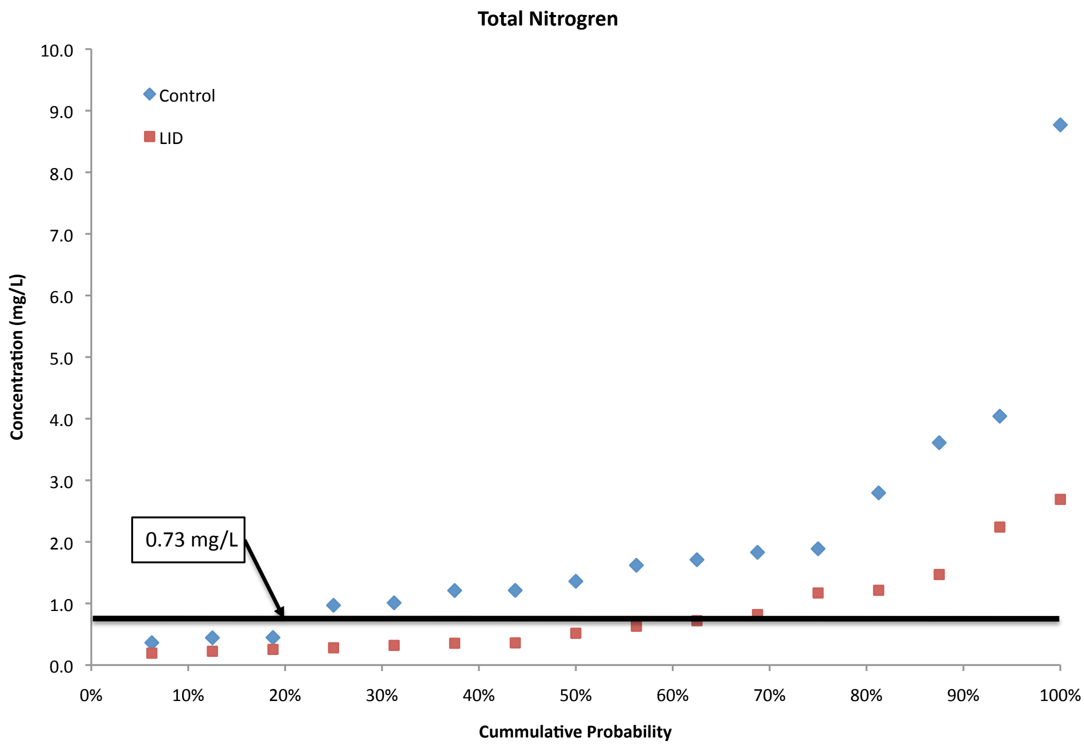

Figure 3-15: TN concentration cumulative probability with 0.73 mg/L water quality threshold

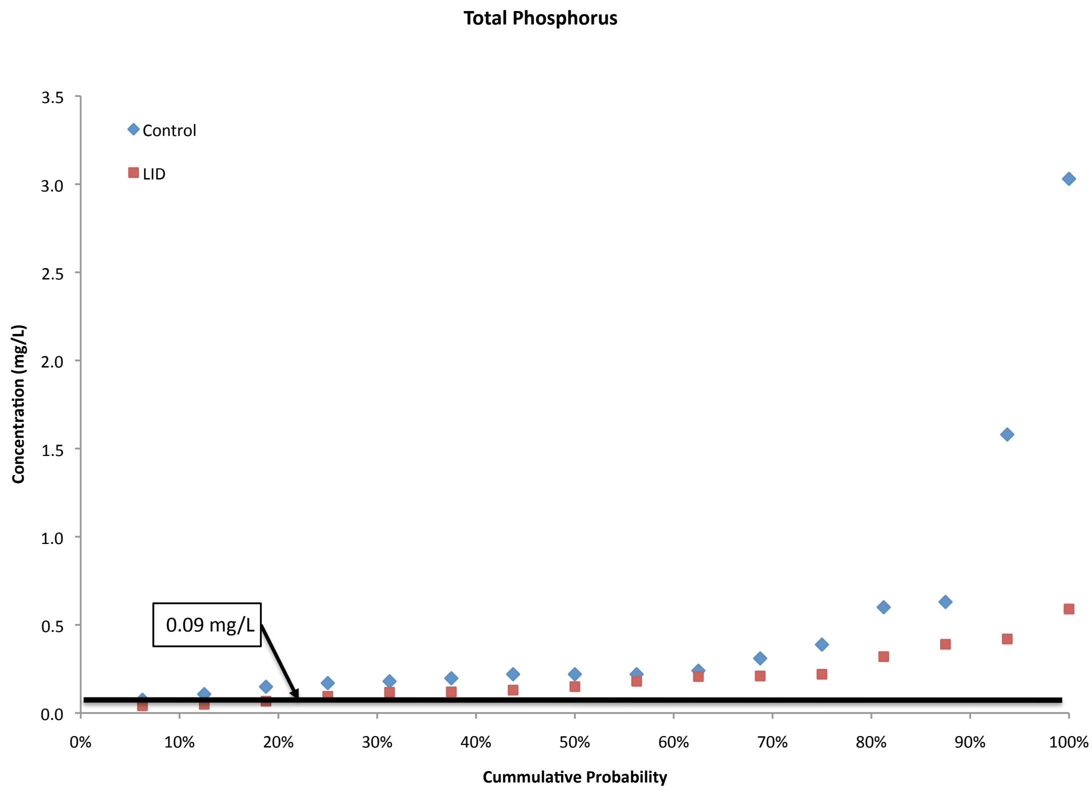

Figure 3-16: TP cumulative probability with 0.09 mg/L water quality threshold

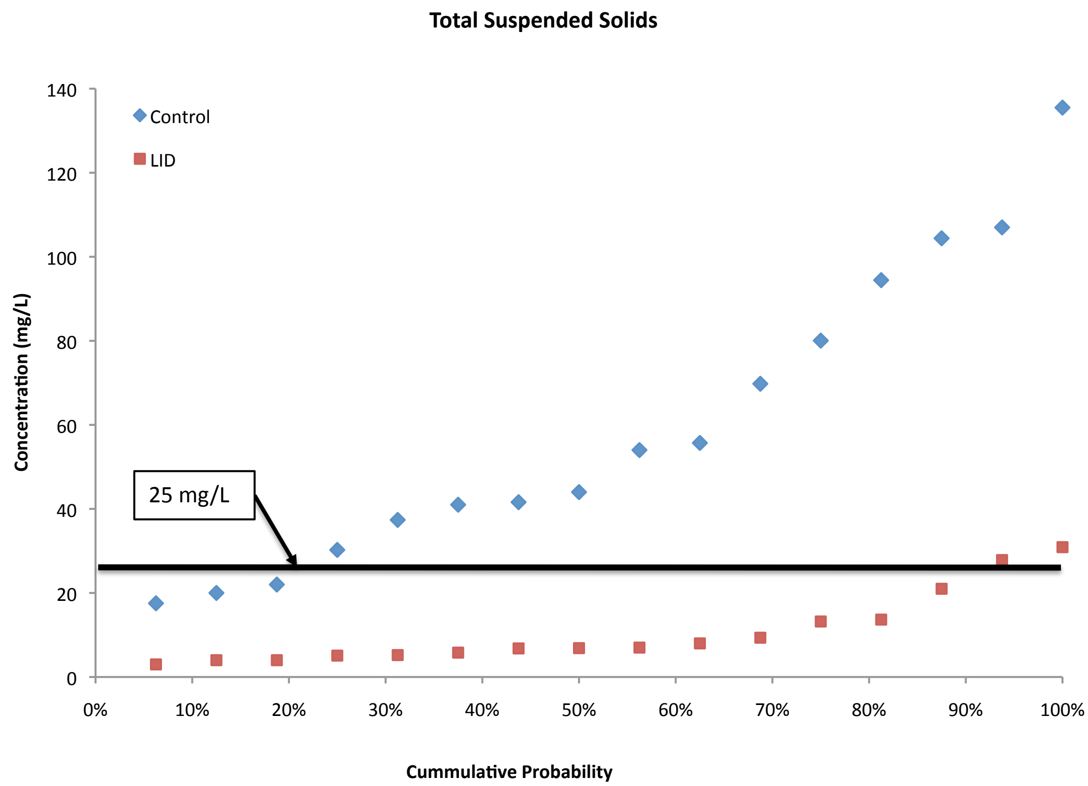

Figure 3-17: TSS concentration cumulative probability with 25 mg/L water quality threshold

3.5 Summary and Conclusions

This study has shown that strategically placed LID SCMs installed within the street right-of-way can mitigate some the water quality impacts of existing residential development in drainage areas with sandy soils. The following conclusions were drawn from this study:

- At the LID site post-retrofit, concentrations of TKN, TSS, Cu, Pb and Zn significantly decreased by 62%, 82%, 55%, 89% and 76%, respectively. TP concentration significantly decreased by 38% at α=0.10. Concentrations of $NO_{2,3}$-N and TAN did not change. TKN concentration reductions were due to particulate ON capture. Mean LID outlet concentrations of O-PO_4^{-3} were 55% less than those observed in the control drainage area, but median O-PO_4^{-3} concentrations not were different between the drainage areas or pre-retrofit conditions. Decreases in TP concentration were likely due to TSS retention by the SCMs.

- Mass exports of TKN, TAN, O-PO_4^{-3}, TP, TSS, Cu, Pb and Zn were significantly decreased by 78%, 61%, 55%, 73%, 91%, 53%, 88% and 77%, respectively. $NO_{2,3}$-N load decreased by 46% (although not significantly). Dramatic reductions of particulate and particulate-bound pollutant loads implied water quality treatment and runoff volume reduction. This was attributed to first flush retention of runoff by the BRC and permeable pavement that treated 52% of the DCIA and treatment by the tree filter unit serviced 42% of the DCIA.
- TN concentrations at the LID outlet were less than the "good" water quality threshold established by McNett et al. (2010) for 10 of 16 (70%) events sampled, compared to just 3 of 16 events (20%) at the control outlet. TP concentrations were below 0.09 mg/L for 1 of 16 (6%) and 3 of 16 (19%) sampling events at the control and LID sites, respectively. LID TSS concentrations were below the 25 mg/L target threshold for 90% of sampling events, while control TSS concentrations exceeded 25 mg/L in 75% of the events sampled.
- In this study the LID SCMs were installed over very sandy soils and seemed to be adequately sized to retain and treat the majority of pollutants in runoff for most of the storms observed. Future residential street retrofit projects in watersheds with less

permeable soils should consider sizing the SCMs for the entire contributing drainage area in lieu of just the DCIA.

- Dissolved nutrient concentrations and loads, namely $NO_{2,3}$-N, were not greatly impacted by the SCMs. This is not uncommon in studies of SCMs; $NO_{2,3}$-N retention in BRCs and permeable pavement systems has been problematic, frequently effluent concentrations are greater than those observed at the inlet. In areas where $NO_{2,3}$-N is the primary pollutant of concern or where fertilizers are used regularly, other SCMs specifically modified to create denitrifying conditions should be considered.

3.6 References

Bannerman, R. T., Owens, D. W., Dodds, R. B., and Hornewer, N. J. (1993). "Sources of Pollutants in Wisconsin Stormwater." *Water Science and Technology,* 28(3-5), 241-259.

Barrett, M. E., Irish, L. B., Malina, J. F., and Charbeneau, R. J. (1998). "Characterization of highway runoff in Austin, Texas, area." *Journal of Environmental Engineering-Asce,* 124(2).

Bean, E. Z. (2005). "A field study to evaluate permeable pavement surface infiltration rates, runoff quantity, runoff quality, and exfiltrate quality." Thesis. North Carolina State University, Raleigh, NC.

Bean, E. Z., W. F. Hunt and D. A. Bidelspach. (2007a). "Field survey of permeable pavement surface infiltration rates. " *J.Irrig.Drainage Eng-ASCE*, 133(3): 249-255.

Bean, E. Z., Hunt, W. F., and Bidelspach, D. A. (2007b). "Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts." *J.Irrig.Drainage Eng-ASCE,* 133(6), 583-592.

Bedan, E. S., and Clausen, J. C. (2009). "Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds." *Journal of the American Water Resources Association,* 45(4), 998-1008.

Bender, G., and Terstriep, M. (1984). "Effectiveness of street sweeping in urban runoff pollution control." *Sci.Total Environ.,* 33(1), 185-192.

Brattebo, B. O., and Booth, D. B. (2003). "Long-term stormwater quantity and quality performance of permeable pavement systems." *Water Res.,* 37(18), 4369-4376.

Brown, R. A., and Hunt, W. F.,III. (2011). "Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." *J.Irrig.Drainage Eng-ASCE,* 137(3), 132-143.

Clausen, J.C. and J. Spooner, 1993. *Paired Watershed Study Design*. U.S. Environmental Protection Agency, USEPA 841-F-93-009.

Coffman, L.S. 2000. Low-Impact Developmeent Design: A New Paradigm for Stormwater Management Mimicking and Restoring the Natural Hydrologic Regime An Alternative Stormwater Management Technology. Department of Environmental Resources, Prince Georges County, Maryland.

Collins, K. A., Hunt, W. F., and Hathaway, J. M. (2008). "Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina." *J.Hydrol.Eng.,* 13(12), 1146-1157.

DeBusk, K. M., Hunt, W. F., and Line, D. E. (2011). "Bioretention Outflow: Does It Mimic Nonurban Watershed Shallow Interflow?" *J.Hydrol.Eng.,* 16(3), 274-279.

Dietz, M. (2007). "Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions." *Water, Air, & Soil Pollution,* 186(1), 351-363.

Fassman, E. A., and Blackbourn, S. (2010). "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." *J.Hydrol.Eng.,* 15(6), 475-485.

Flint, K. R., and Davis, A. P. (2007). "Pollutant mass flushing characterization of highway stormwater runoff from an ultra-urban area." *J.Environ.Eng.,* 133(6), 616-626.

Gee, G.W. and Bauder, J. W. (1986). “Particle-size analysis.” In Methods of Soil Analysis, Part 1. Agron. Monogr. 9. Klute, A, ed. Soil Science Society of America, Madison, WI. 383-411.

Gee, G. W., and Or, D. (2002). "2.4 Particle-size analysis." *Methods of Soil Analysis: Physical Methods,* 5 255.

Gilbert, J. K., and Clausen, J. C. (2006). "Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut." *Water Res.,* 40(4), 826-832.

Grabow, G., Spooner, J., Lombardo, L., Line, D., and Tweedy, K. (1998). *Has Water Quality Improved?: Use of SAS for Statistical Analysis of Paired Watershed, upstream/downstream and before/after Monitoring Designs.*

Gregory, J., Dukes, M., Jones, P., and Miller, G. (2006). "Effect of urban soil compaction on infiltration rate." *J.Soil Water Conserv.,* 61(3), 117-124.

Hood, M. J., Clausen, J. C., and Warner, G. S. (2007). "Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development1." *JAWRA Journal of the American Water Resources Association,* 43(4), 1036-1046.

Hunt, W. F., Jarrett, A. R., Smith, J. T., and Sharkey, L. J. (2006). "Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina." *Journal of Irrigation and Drainage Engineering-Asce,* 132(6), 600-608.

ISCO Flowlink Software V 5.10.206. (2005). Teledyne ISCO, Inc. Lincoln, NE.

ISCO Open Channel Flow Measurement Handbook: Sixth Edition. (1978). Teledyne ISCO, Inc. Lincoln, NE.

Jennings, D. B., and Jarnagin, S. T. (2002). "Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed." *Landscape Ecol.,* 17(5), 471-489.

Lee, J. G., and Heaney, J. P. (2003). "Estimation of urban imperviousness and its impacts on storm water systems." *J.Water Resour.Plann.Manage.,* 129(5), 419-426.

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

Leopold, L. B. (1991). "Lag times for small drainage basins." *Catena,* 18(2): 157-171.

Line, D., White, N., Osmond, D., Jennings, G., and Mojonnier, C. (2002). "Pollutant export from various land uses in the upper Neuse River Basin." *Water Environ.Res.,* 74(1), 100-108.

Line, D. E., and White, N. M. (2007). "Effects of development on runoff and pollutant export." *Water Environ.Res.,* 79(2), 185-190.

Line, D.E., Brown, R. A., Hunt, W. F., and Lord, W. G. (2012). "Effectiveness of LID for Commercial Development in North Carolina*" J. Environ. Eng*. 138(6), 680-688.

Luell, S. K., Hunt, W. F., and Winston, R. J. (2011). "Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff." *Water Science and Technology,* 64(4), 974-979.

NCDENR. (2004). "Assessment Report: Biological Impairment in the Burnt Mill Creek Watershed." North Carolina Department of Environment and Natural Resources, Division of Water Quality-Planning Branch. Raleigh, NC.

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

Pitt, R., Field, R., Lalor, M., and Brown, M. (1995). "Urban Stormwater Toxic Pollutants - Assessment, Sources, and Treatability." *Water Environ.Res.,* 67(3), 260-275.

Pitt, R., Chen, S. E., Clark, S. E., Swenson, J., and Ong, C. K. (2008). "Compaction's impacts on urban storm-water infiltration." *J.Irrig.Drain.Eng.,* 134(5), 652-658.

Sansalone, J. J., Hird, J. P., Cartledge, F. K., and Tittlebaum, M. E. (2005). Event-based stormwater quality and quantity loadings from elevated urban infrastructure affected by transportation. Water Environment Research, 77(4), 348-365.

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

Sartor, J. D., Boyd, G. B., and Agardy, F. J. (1974). "Water pollution aspects of street surface contaminants." *Journal (Water Pollution Control Federation),* 458-467.

Sartor, J. D., and Gaboury, D. (1984). "Street sweeping as a water pollution control measure: lessons learned over the past ten years." *Sci.Total Environ.,* 33(1), 171-183.

Schueler, T. R. 1992. "Mitigating the Adverse Impacts of Urbanization on Streams: A Comprehensive Strategy for Local Government." *Watershed Restoration Sourcebook*. Publication #92701, Metropolitan Washington Council of Governments. Washington, D.C.

Schueler, T. R. 1994. "The Importance of Imperviousness." *Watershed Protection Techniques*, 1(3): 100–11.

Sparks, D.L. (2003). Environmental Soil Chemistry. 2nd Ed. San Diego, California: Elsevier.

State Climate Office of North Carolina. (2012). 1971-2000 Climate Normals. Available: < http://www.nc-climate.ncsu.edu/cronos/normals.php>. Accessed 15 November 2012.

UACDC. 2010. *Low Impact Development: a design manual for urban areas*. University of Arkansas Press. University of Arkansas Community Design Center. Fayetteville, AR.

US EPA. (2009). History of the Clean Water Act. Laws, Regulations, Guidance, and Dockets. United States Environmental Protection Agency. Available at: http://www.epa/gov/lawsregs/laws.cwahistory/html. Accessed 22 October 2011.

Walsh, C. J. (2000). "Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration." *Hydrobiologia,* 431(2), 107-114.

Walsh, C. J., Sharpe, A. K., Breen, P. F., and Sonneman, J. A. (2001). "Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities." *Freshwat.Biol.,* 46(4), 535-551.

Walsh, C. J. (2004). "Protection of in-stream biota from urban impacts: minimize catchment imperviousness or improve drainage design?" *Marine and Freshwater Research,* 55(3), 317-326.

Wardynski, B. J., Winston, R. J., and Hunt, W. F. (2013). "Internal water storage enhances exfiltration and thermal load reduction from permeable pavement in the North Carolina mountains." *J.Environ.Eng., 139(2), 187-195.*

Waschbusch RJ, Selbig WR, Bannerman RT. (1999). Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin. *USGS Water Resour. Invest.* Rep. 99–4021.

CHAPTER 4: FURTHER CONSIDERATIONS AND RESEARCH

SCMs are necessary to mitigate the impacts of impervious surfaces and urban development to maintain the quality of water resources. There will be many opportunities to retrofit existing development with SCMs as federal, state and municipal entities comply with regulatory standards for runoff quantity and quality. The following chapter identifies ways to improve retrofitting of future residential street projects based on "lessons learned" from this study in Wilmington, NC and outlines areas for future research.

4.1 Design Considerations

Residential Street SCM Sizing

This study has shown that LID SCMs installed over sandy urban soils can mitigate some of the hydrologic and water quality impacts of existing residential development. The BRC bumpout and permeable pavements were designed to capture a water quality volume based on the DCIA. Focusing on DCIA was a valid design approach over sandy soil because most runoff from impervious areas like rooftops and sidewalks that are not directly connected to the outlet likely infiltrated the sandy soil prior to entering the street. Designs of residential street retrofits for projects over less permeable soils should consider sizing the SCMs for the entire contributing drainage area in lieu of only the DCIA to ensure the actual water quality volume is captured. Underdrains may also be necessary in systems over impermeable soils to dewater the SCMs.

SCM Placement within the Watershed

Placement of SCMs in medium and high-density residential areas largely depends on available space, existing utility location and target hydrologic or water quality needs. When peak discharge mitigation or runoff volume reduction is the objective, SCMs that provide depressional storage throughout the drainage area should be used. Increased depressional storage has been shown to maintain or restore pre-development hydrology by providing detention and infiltration throughout a watershed, which enhances ground water recharge and natural base flow to streams (Davis et al., 2009; DeBusk et al., 2011). This includes BRCs, grassed swales and infiltration trenches. This study has shown that it is necessary to apply hydrologic treatment to a greater fraction of the DCIA to have a substantial impact on peak discharge. Placement of SCMs near the watershed outlet is important and may also result in more pronounced hydrologic benefits; however, an even distribution of SCMs throughout the watershed is ideal because it more closely replicates what may be observed in an undeveloped watershed. For water quality, a tree filter unit appeared to be sufficient for particulate pollutant retention. However, tree filter units do not seem to provide noticeable reductions in dissolved pollutant concentrations of $NO_{2,3}$-N, TAN or O-PO_4^{-3}. Dissolved pollutant retention is poor because contact time between the tree filter media and influent runoff are extremely low.

Curb and Gutter Configuration at Permeable Pavement Installations

In this study, flow diverters (16 mm tall) were installed at 3.6 m intervals along the permeable pavement parking areas. Results indicate runoff moving along the existing curb and gutter overwhelmed the flow diverters during storms with greater rainfall depths and intensities. For future permeable pavement projects on residential streets, alternative curb and gutter configurations should be considered. Increasing the elevation of the concrete gutter may be a viable option. Perhaps more ideal would be to install the gutter and permeable pavement on a slope away from the curb (Figure 4-1).

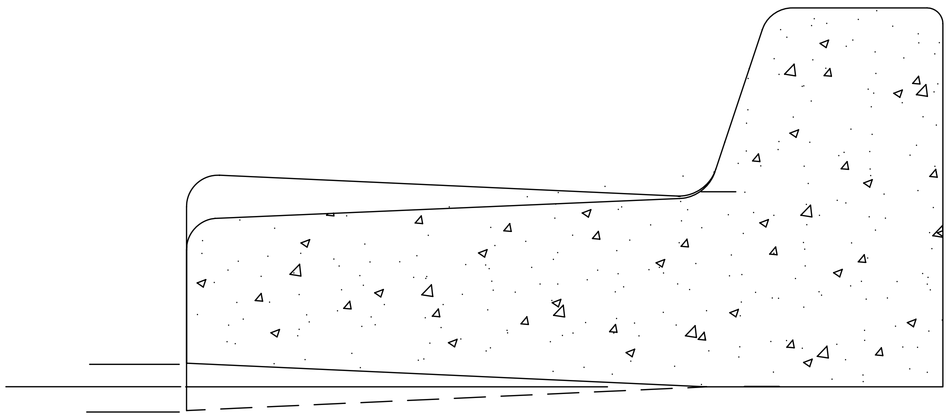

Figure 4-1: Proposed curb and gutter configuration with gutter sloping away from curb

Of course, there would be other pavement grading implications associated with this design, but they may be worthwhile given the likely increase in runoff volume retention of the permeable pavement if more runoff is allowed to infiltrate.

4.2 Further Research

Retrofitting with other SCMs and New Residential Development

Other SCMs that have shown promise in mitigating the impacts of urban development include grassed swales and filter strips. In areas with adequate space and slope, filter strips and grassed swales constructed similarly to those along interstate highways, could be a feasible low-cost SCM for residential street runoff providing conveyance and treatment. Although there are ample SCM retrofit opportunities, a watershed or catchment-scale analysis of SCMs incorporated into the street right-of-way of *new* high density residential development should be considered. During new construction, additional grading and curb and gutter configurations that are designed to efficiently direct runoff into SCMs may lead to more runoff being treated. For highly impervious (>50%) residential and commercial sites, multiple infiltrating SCMs may not provide enough detention to decrease post-development peak discharges and runoff volume or increase lag times. Therefore, a hybrid system of LID SCMs and detention facilities may lead to effective pollutant treatment and a hydrologic response that closely mimics undeveloped conditions.

Cost Analysis

Project cost is an important practical consideration municipalities face when retrofitting existing development for stormwater treatment within their jurisdiction. A benefit of this project was the limited number of SCMs used to reach a high level of pollutant removal and subsequently lower cost. A detailed cost analysis of this project in comparison with other types of stormwater treatment such as wet detention ponds, catch basin filter inserts or large-scale combined sewer treatment facilities would be a valuable asset to municipalities. Using actual data collected from each treatment type and project cost, stormwater treatment could be analyzed in metrics of kilogram TN removed per hectare per dollar ($) spent or runoff volume (m^3) retained per hectare per dollar ($) spent. This would allow municipalities to better allocate resources to optimize pollutant removal and cost.

APPENDICES

Appendix A: Additional Construction Photos

Figure A-1: BRC excavation on Dock Street and existing utilities

Figure A-2: BRC media and mulch installation on Dock Street

Figure A-3: Proof of Filterra® unit installation for University Accounting Office

Figure A-4: Filterra® unit installation at the intersection of 12th Street and Dock Street

Figure A-5: Filterra® unit underdrain installation

Figure A-6: Recently completed crosswalk at the intersection of 12th Street and Dock Street

Figure A-7: Permeable pavement excavation and ASTM #57 stone placement

Figure A-8: ASTM #78 stone placement and recently installed PICP pavers

Figure A-9: Completed permeable pavement parking stalls with flow diverters along existing curb and gutter

Figure A-10: Coastal North Carolina green roof

Appendix B: LID SCM Design Summary Tables

Table B-1: BRC Design Summary

BRC Characteristics	
Vegetative Cover	Shrubs/Perennials
BRC Area	19 m^2 (205 ft^2)
Watershed Area	160 m^2 (1722 ft^2)
Street Surface Area Treated	13%
Surface Storage	4 m^3 (138 ft^3)
Watershed % Impervious	100%
Loading Ratio	8.4:1
Surface Storage Design Event	3.8 cm (1.5 in)
Surface Layer Depth	Mulch: 5 cm (2 in)
Fill Media Depth	0.6 m (2 ft)
Fill Media Characteristics	4.5% Gravel, 87.4% Sand, 7% Silt, 1.1% Clay
Fill Media K_{sat}	7 cm/hr (2.75 in/hr) @ 85% compaction
Underdrain to Outlet	No

Table B-2: Tree Filter Design Summary

Tree Filter Characteristics	
Vegetation	Crepe Myrtle
Surface Area	3 m^2 (32 ft^2)
Watershed Area	539 m^2 (5,800 ft^2)
Street Surface Area Treated	42%
Watershed % Impervious	100%
Loading Ratio	180:1
Surface Layer Depth	Mulch: 7.6 cm (3 in)
Fill Media Depth	0.75 m (2.5 ft)
Fill Media Characteristics	Filterra® Mix
Underdrain to Outlet	Yes

Table B-3: Permeable Pavement Design Summary

Permeable Pavement (I and II) Design Characteristics	
Surface Area	PP I: 34 m^2 (366 ft^2) PP II: 34 m^2 (366 ft^2)
Watershed Area	PP I: 265 m^2 (2,852 ft^2) PP II: 226 m^2 (2,433 ft^2)
Street Surface Area Treated	PP I: 21% PP II: 18%
Watershed % Impervious	100%
Loading Ratio	PP I: 7.8:1 PP II: 6.6:1
Subsurface Storage Design Event	38 mm (1.5 in)
PICP Thickness	76 mm (3 in)
ASTM #78 Stone Thickness	76 mm (3 in)
ASTM #57 Stone Thickness	0.3 m (12 in)
Underdrain to Outlet	No

Table B-4: Underlying soil characteristics

Parameter	Catchment		
	CONTROL	**SCM-Retrofit**	**SCM-Retrofit**
Sample ID	CRTL	PP	BRC
Silt	1.8%	3.7%	0.0%
Clay	2.6%	1.6%	2.0%
Sand	95.6%	94.7%	98.0%
USDA Texture	**Sand**	**Sand**	**Sand**

Appendix C: Water Quality ANCOVA Plots

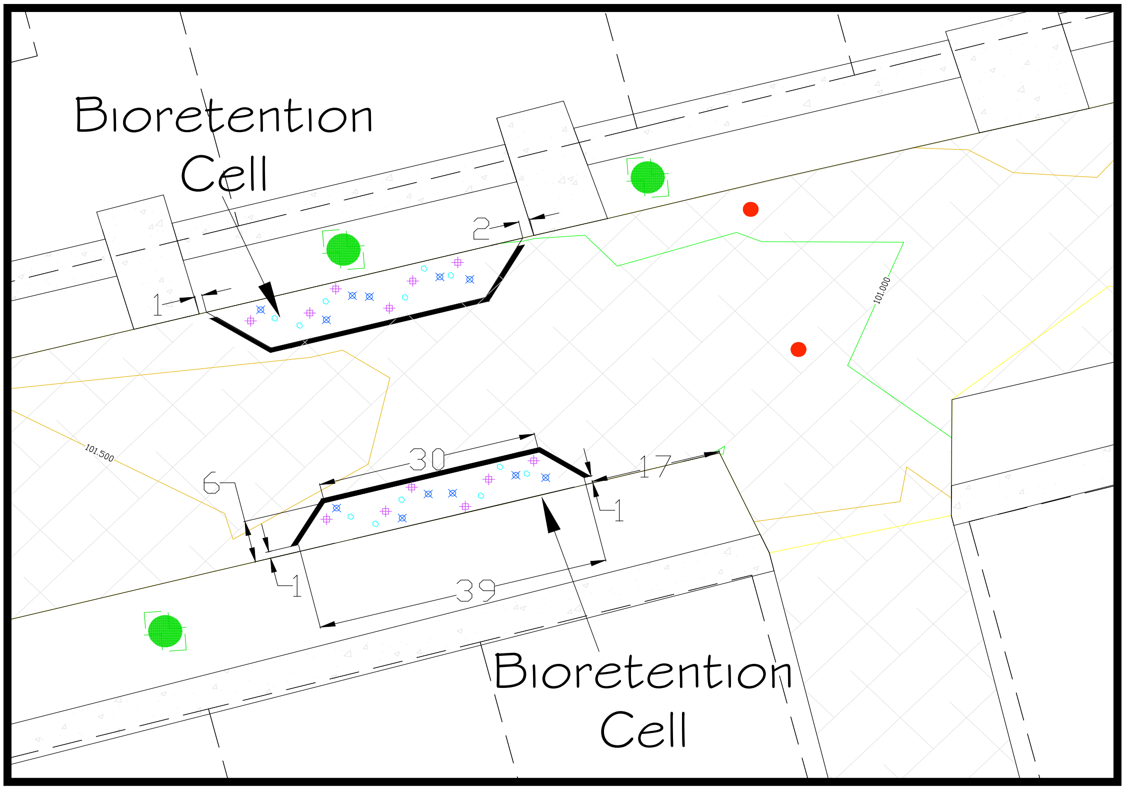

Figure C-1: BRC plan view

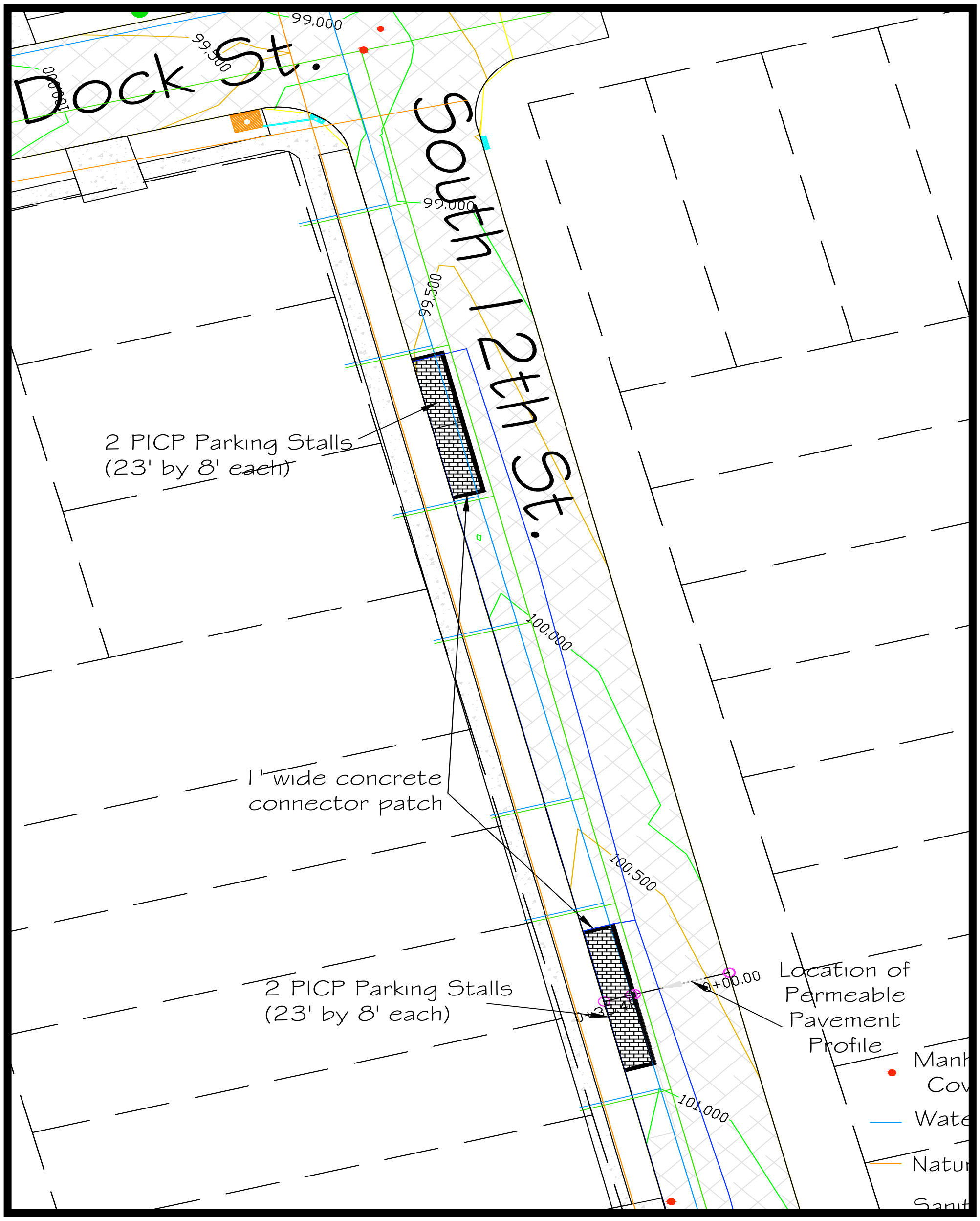

Figure C-2: Permeable pavement plan view

Appendix D: Water Quality ANCOVA Plots

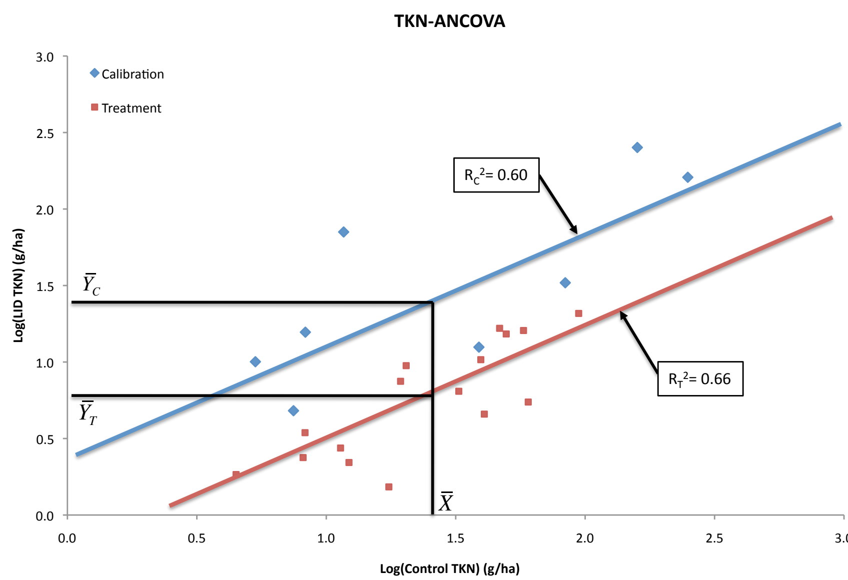

Figure D-1: Reduced ANCOVA model for TKN load (g/ha)

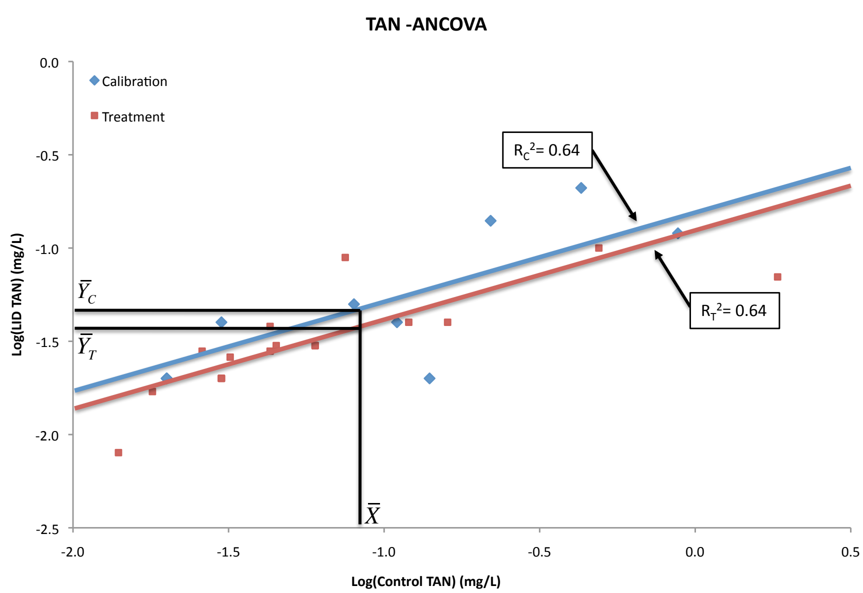

Figure D-2: Reduced ANCOVA model for TAN concentration (mg/L)

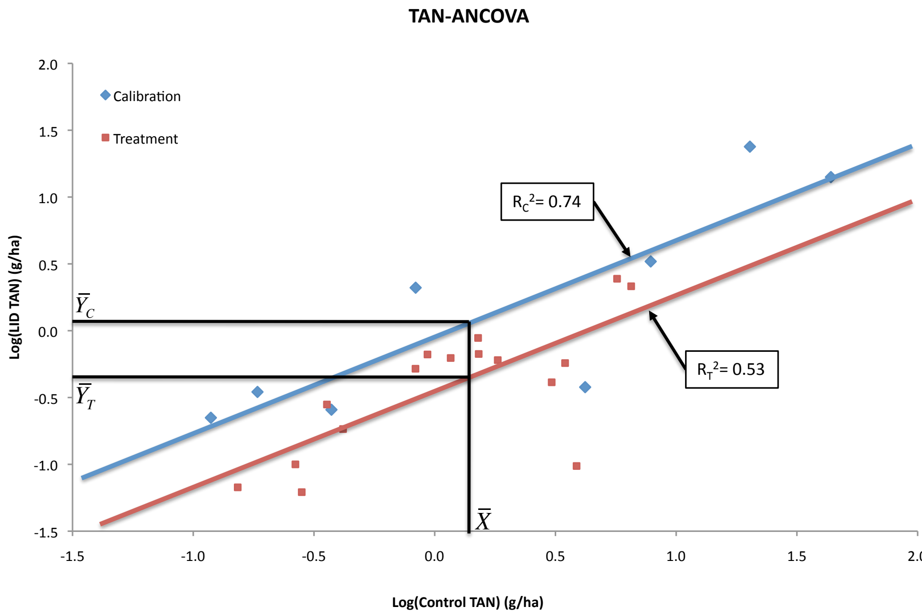

Figure D-3: Reduced ANCOVA model for TAN load (g/ha)

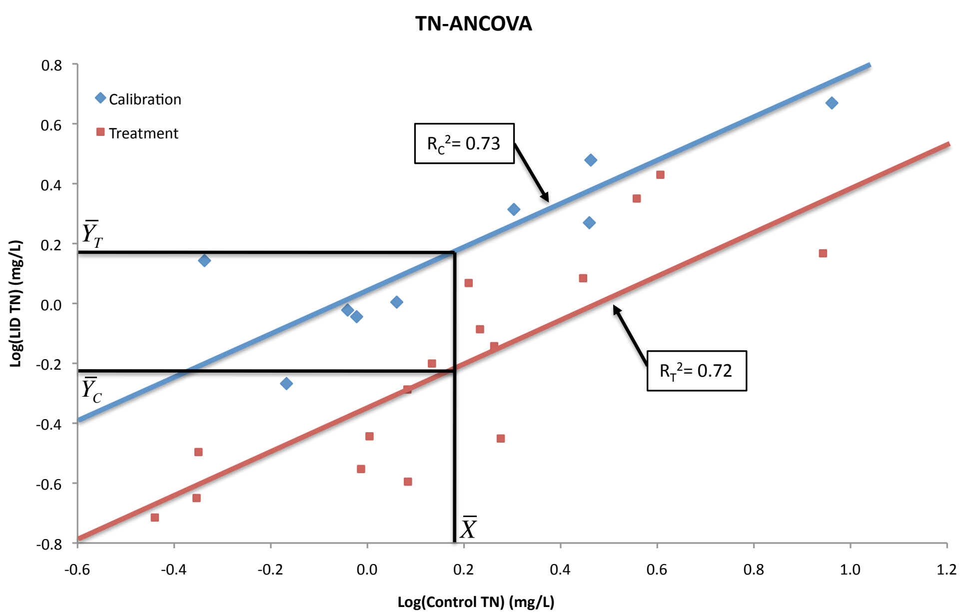

Figure D-4: Reduced ANCOVA model for TN concentration (mg/L)

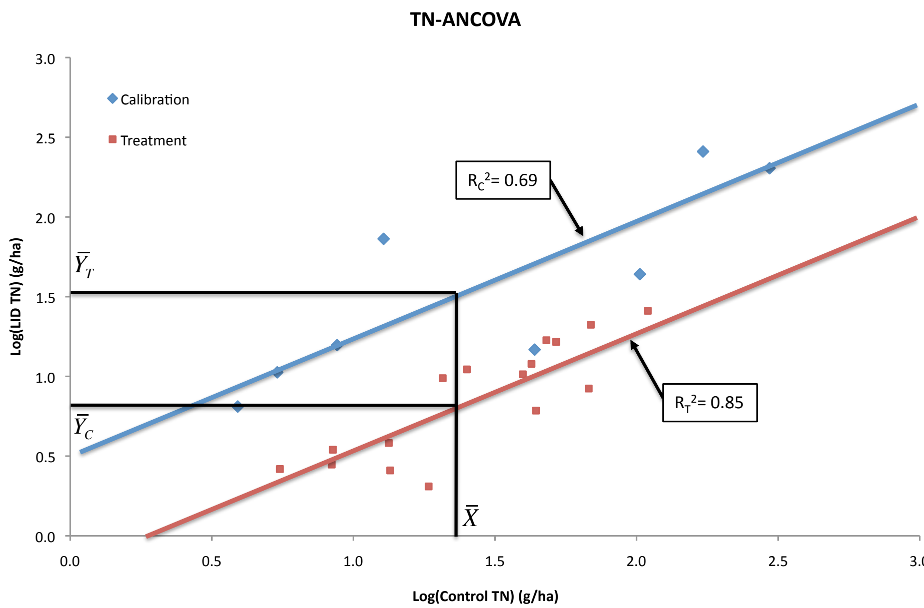

Figure D-5: Reduced ANCOVA model for TN load (g/ha)

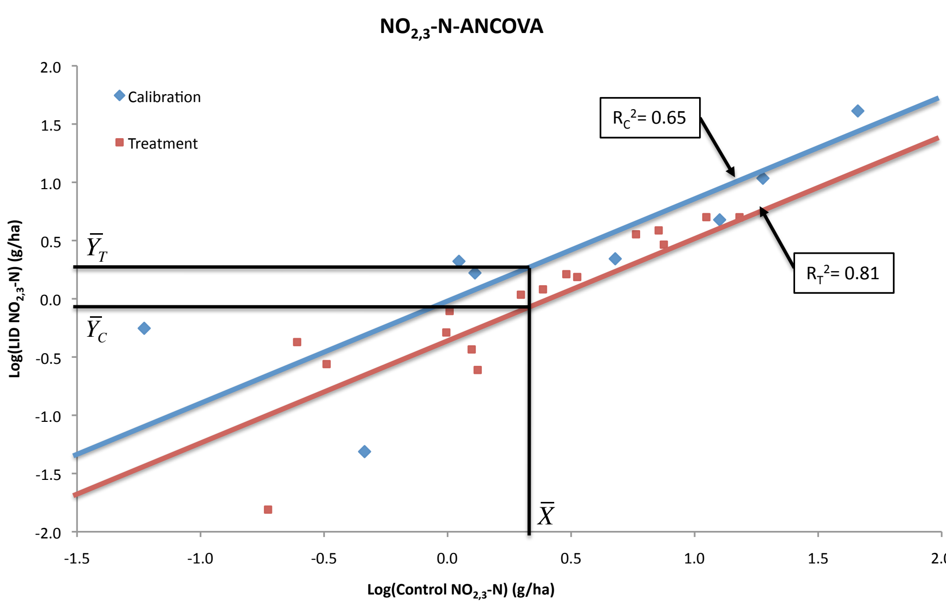

Figure D-6: Reduced ANCOVA model for $NO_{2,3}$-N load (g/ha)

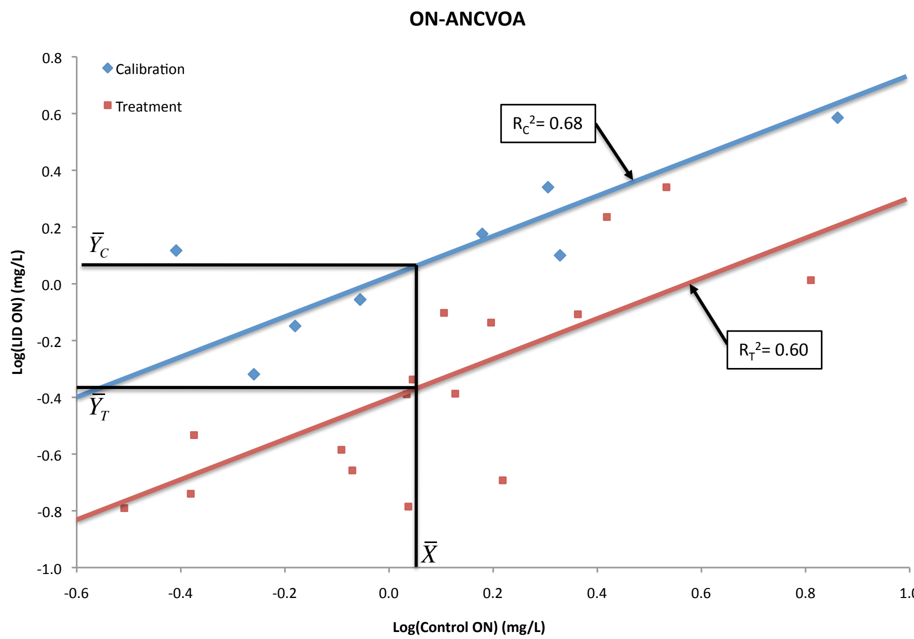

Figure D-7: Reduced ANCOVA model for ON concentration (mg/L)

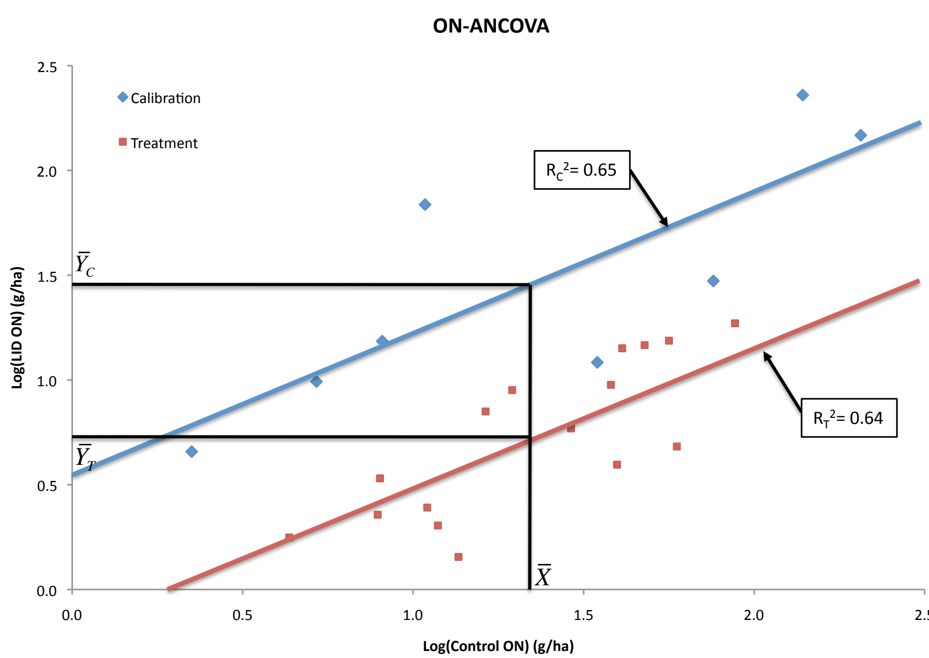

Figure D-8: Reduced ANCOVA model for ON load (g/ha)

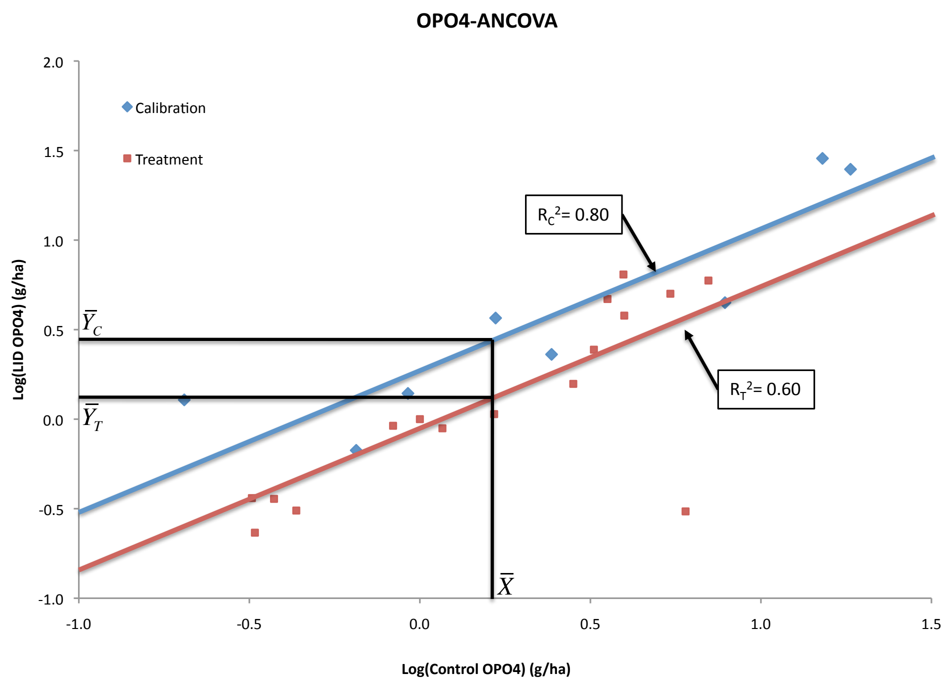

Figure D-9: Reduced ANCOVA model for O-PO_4^{-3} load (g/ha)

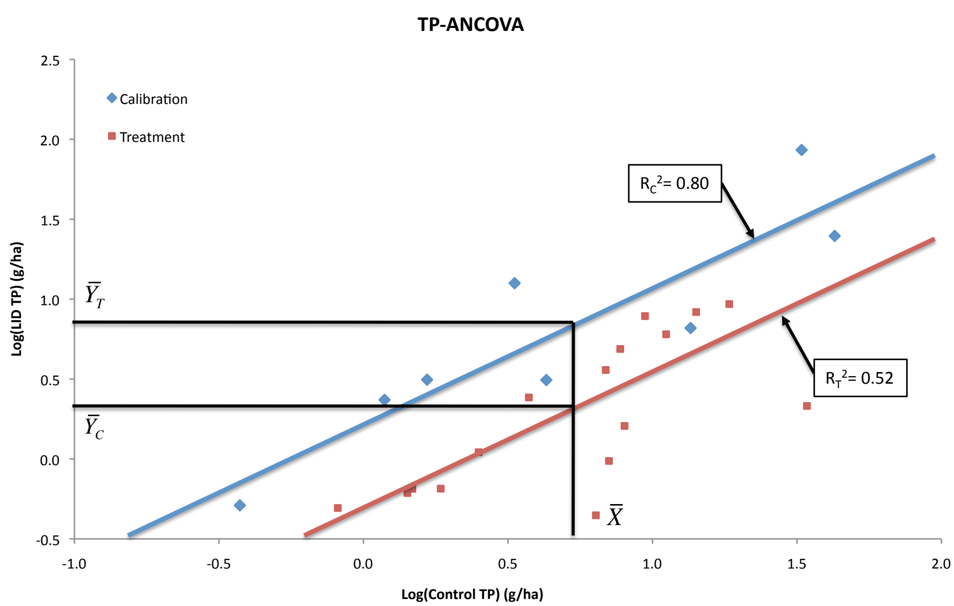

Figure D-10: Reduced ANCOVA model for TP load (g/ha)

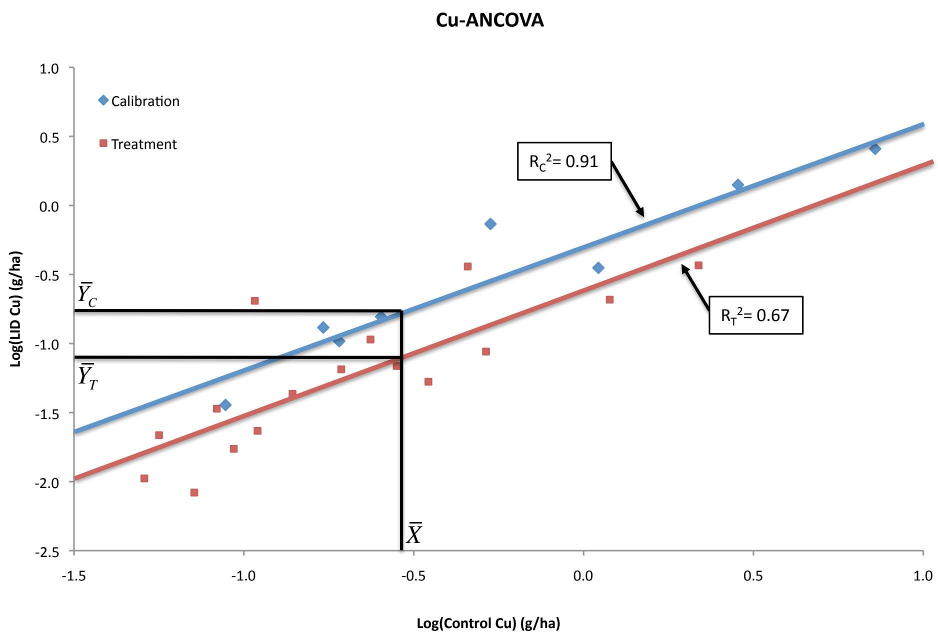

Figure D-11: Reduced ANCOVA model for Cu load (g/ha)

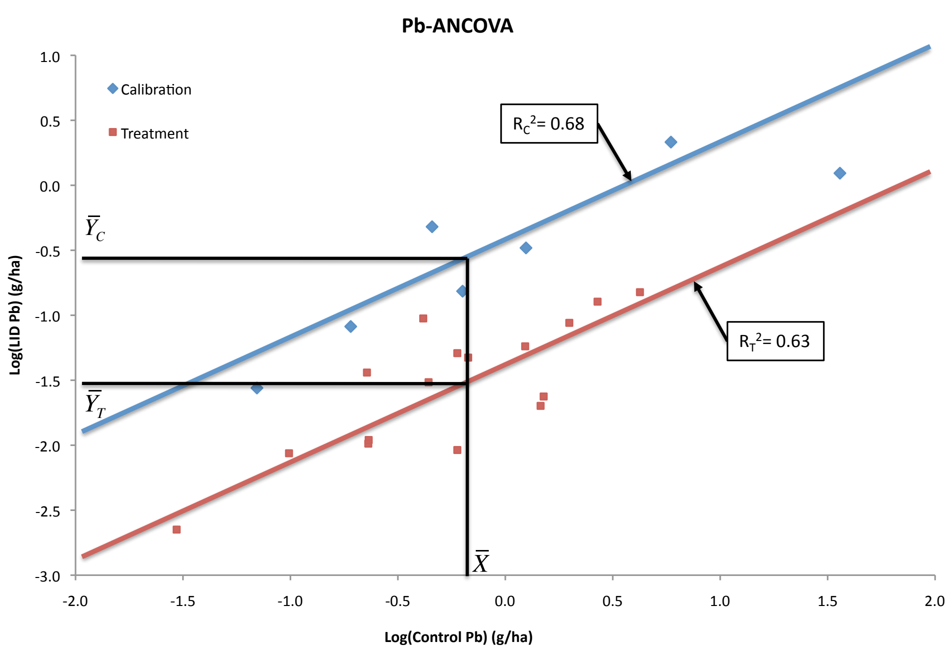

Figure D-12: Reduced ANCOVA model for Pb load (g/ha)

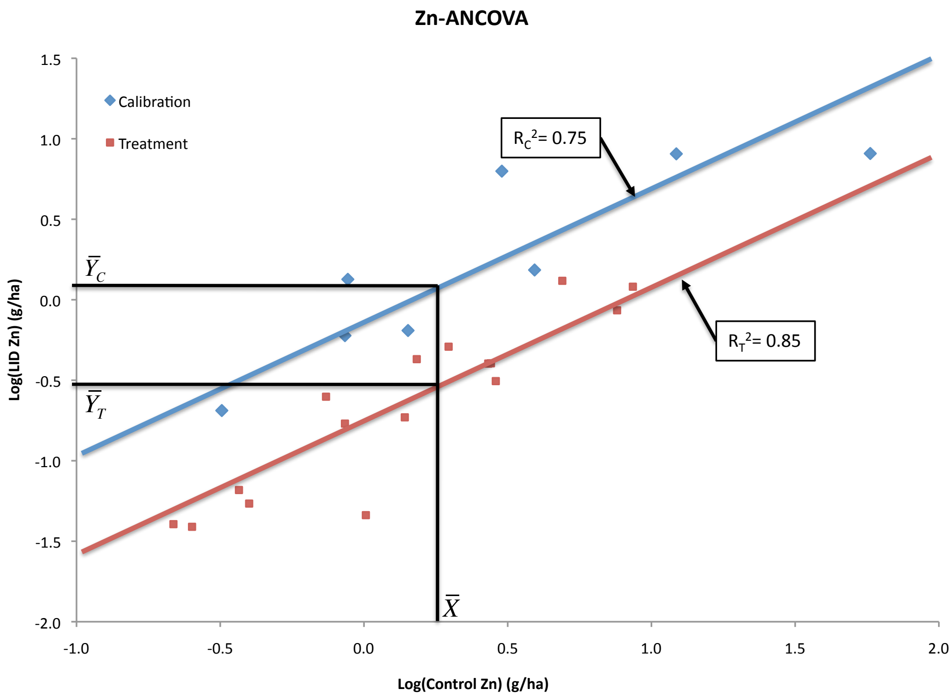

Figure D-13: Reduced ANCOVA model for Zn load (g/ha)

Appendix E: Raw Data Summary

Table E-1: Calibration nitrogen summary

Date	TKN (mg/L)		NO_3+NO_2 (mg/L)		NH_3N (mg/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/23/11	8.15	3.97	1.00	0.70	0.88	0.12
6/29/11	2.35	1.40	0.53	0.46	0.22	0.14
7/21/11	2.45	2.40	0.45	0.61	0.43	0.21
7/24/11	1.65	1.52	0.36	0.54	0.14	0.02
8/21/11	0.77	0.75	0.38	0.26	0.11	0.04
8/26/11	0.63	0.53	0.05	0.01	0.08	0.05
9/22/11	0.42	1.35	0.04	0.04	0.03	0.04
10/12/11	0.90	0.90	0.01	0.05	0.02	0.02
10/18/11	0.90	0.90	0.05	0.00	0.02	0.02
Mean	**2.02**	**1.52**	**0.32**	**0.30**	**0.21**	**0.07**
Median	**0.90**	**1.35**	**0.36**	**0.26**	**0.11**	**0.04**

Table E-2: Treatment nitrogen summary

Date	TKN (mg/L)		NO_3+NO_2 (mg/L)		NH_3N (mg/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/11/12	3.53	2.23	0.08	0.01	0.12	0.04
6/13/12	0.87	0.29	0.14	0.07	0.06	0.03
7/9/12	3.11	1.82	0.93	0.87	0.49	0.10
7/10/12	1.32	0.82	0.30	0.35	0.05	0.03
7/11/12	1.14	0.48	0.22	0.15	0.03	0.02
8/20/12	8.30	1.10	0.47	0.37	1.84	0.07
9/8/12	1.50	0.45	0.33	0.27	0.16	0.04
9/30/12	1.63	0.76	0.08	0.06	0.06	0.03
10/1/12	0.88	0.24	0.09	0.04	0.03	0.02
10/27/12	0.44	0.31	0.01	0.01	0.02	0.02
11/19/12	0.35	0.19	0.01	0.00	0.04	0.03
12/13/12	1.12	0.45	0.09	0.07	0.04	0.04
1/17/13	1.12	0.19	0.09	0.06	0.03	0.03
1/31/13	2.38	0.87	0.42	0.34	0.08	0.09
2/8/13	1.68	0.23	0.21	0.12	0.03	0.03
2/13/13	0.43	0.19	0.01	0.03	0.01	0.01
Mean	**1.86**	**0.66**	**0.22**	**0.18**	**0.19**	**0.04**
Median	**1.23**	**0.45**	**0.12**	**0.07**	**0.04**	**0.03**

Table E-3: Calibration sediment and phosphorus summary

Date	Ortho-P (mg/L)		Total-P (mg/L)		TSS (mg/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/23/11	0.51	0.73	0.90	0.99	60	72
6/29/11	0.22	0.19	0.38	0.28	92	79
7/21/11	0.18	0.37	0.42	0.37	122	78
7/24/11	0.14	0.11	0.31	0.11	30	24
8/21/11	0.06	0.20	0.11	0.08	11	14
8/26/11	0.06	0.06	0.13	0.18	4	43
9/22/11	0.06	0.07	0.12	0.24	19	56
10/12/11	0.11	0.06	0.20	0.21	16	54
10/18/11	0.10	0.08	0.18	0.18	28	28
Mean	**0.16**	**0.21**	**0.31**	**0.29**	**42**	**50**
Median	**0.11**	**0.11**	**0.20**	**0.21**	**28**	**54**

Table E-4: Treatment sediment and phosphorus summary

Date	Ortho-P (mg/L)		Total-P (mg/L)		TSS (mg/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/11/12	0.14	0.15	0.63	0.42	104	31
6/13/12	0.05	0.07	0.17	0.13	56	7
7/9/12	NS	NS	0.60	0.59	136	13
7/10/12	0.11	0.16	0.24	0.22	18	3
7/11/12	0.07	0.14	0.22	0.18	37	6
8/20/12	2.86	0.22	3.03	0.32	107	21
9/8/12	0.13	0.11	1.58	0.15	44	4
9/30/12	0.13	0.32	0.31	0.39	54	8
10/1/12	0.06	0.10	0.18	0.12	41	4
10/27/12	0.07	0.08	0.15	0.12	22	7
11/19/12	0.05	0.07	0.11	0.10	30	14
12/13/12	0.11	0.16	0.22	0.21	42	9
1/17/13	0.03	0.04	0.22	0.07	70	7
1/31/13	0.09	0.10	0.39	0.21	94	28
2/8/13	0.05	0.05	0.20	0.04	80	5
2/13/13	0.02	0.03	0.08	0.05	20	3
Mean	**0.26**	**0.12**	**0.58**	**0.22**	**60**	**11**
Median	**0.07**	**0.10**	**0.23**	**0.18**	**49**	**7**

Table E-5: Calibration metals summary

Date	Copper (Cu) (ug/L)		Lead (Pb) (ug/L)		Zinc (Zn) (ug/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/23/11	40	33	40	26	180	190
6/29/11	31	15	35	14	110	65
7/21/11	28	21	58	32	120	120
7/24/11	27	13	18	11	55	62
8/21/11	9.1	5.6	7.2	4.3	33	32
8/26/11	10	5.4	50	2.6	80	17
9/22/11	6.7	14	25	52	38	120
10/12/11	15	14	27	43	52	120
10/18/11	6.5	7.5	24	8.8	54	37
Mean	**19**	**14**	**32**	**22**	**80**	**85**
Median	**15**	**14**	**27**	**14**	**55**	**65**

Table E-6: Treatment metals summary

Date	Copper (Cu) (ug/L)		Lead (Pb) (ug/L)		Zinc (Zn) (ug/L)	
	CONTROL	LID	CONTROL	LID	CONTROL	LID
6/11/12	24	14	42	5.6	170	35
6/13/12	11	2.9	39	2.1	70	12
7/9/12	15	4.2	37	2.5	59	16
7/10/12	15	4.7	8.7	1	64	18
7/11/12	43	11	53	3.8	170	36
8/20/12	34	6	110	7.9	120	28
9/8/12	13	4.8	31	3.3	64	13
9/30/12	15	18	48	1	89	20
10/1/12	10	4.7	43	1	73	5
10/27/12	5.1	3.5	9.5	1	33	14
11/19/12	3.9	1	15	1	37	15
12/13/12	5.5	2.8	17	2.2	56	22
1/17/13	9.6	2.2	34	2.4	79	13
1/31/13	23	7.4	87	30	180	54
2/8/13	3	8.6	42	1	77	17
2/13/13	4.4	2.7	12	2.9	39	20
Mean	**15**	**6**	**39**	**4**	**86**	**21**
Median	**12**	**5**	**38**	**2**	**72**	**18**

Appendix F: Example SAS Code

```
*ANCOVA;

data concentration;
input period $ TKNCRTL TKNLID NO3CRTL NO3LID NH3CRTL NH3LID TNCRTL TNLID
ONCRTL      ONLID OPCRTL OPLID TPCRTL TPLID     TSSCRTL     TSSLID CuCRTL
CuLID PbCRTL PbLID ZnCRTL ZnLID;
logTKNCRTL=log10(TKNCRTL);
logTKNLID=log10(TKNLID);
logNO3CRTL=log10(NO3CRTL);
logNO3LID=log10(NO3LID);
logNH3CRTL=log10(NH3CRTL);
logNH3LID=log10(NH3LID);
logTNCRTL=log10(TNCRTL);
logTNLID=log10(TNLID);
logONCRTL=log10(ONCRTL);
logONLID=log10(ONLID);
logOPCRTL=log10(OPCRTL);
logOPLID=log10(OPLID);
logTPCRTL=log10(TPCRTL);
logTPLID=log10(TPLID);
logTSSCRTL=log10(TSSCRTL);
logTSSLID=log10(TSSLID);
logCuCRTL=log10(CuCRTL);
logCuLID=log10(CuLID);
logPbCRTL=log10(PbCRTL);
logPbLID=log10(PbLID);
logZnCRTL=log10(ZnCRTL);
logZnLID=log10(ZnLID);
cards;

*TKN;
proc glm data=concentration;
title 'TKN - ANCOVA';
class period;
model logTKNLID=logTKNCRTL period period*logTKNCRTL/solution;
lsmeans period/pdiff;
run;

proc glm data=concentration;
class period;
model logTKNLID=logTKNCRTL period/solution;
lsmeans period/pdiff;
run;


*NO3;
proc glm data=concentration;
title 'NO3 - ANCOVA';
class period;
```

```
model logNO3LID=logNO3CRTL period period*logNO3CRTL/solution;
lsmeans period/pdiff;
run;
proc glm data=concentration;
class period;
model logNO3LID=logNO3CRTL period/solution;
lsmeans period/pdiff;
run;

*LID and Control Pairwise comparisons;

data pairedconcentration;
input period $ TKNCRTL TKNLID NO3CRTL NO3LID NH3CRTL NH3LID TNCRTL TNLID
ONCRTL      ONLID OPCRTL OPLID TPCRTL TPLID     TSSCRTL     TSSLID CuCRTL
CuLID PbCRTL PbLID ZnCRTL ZnLID;
logTKNCRTL=log10(TKNCRTL);
logTKNLID=log10(TKNLID);
logNO3CRTL=log10(NO3CRTL);
logNO3LID=log10(NO3LID);
logNH3CRTL=log10(NH3CRTL);
logNH3LID=log10(NH3LID);
logTNCRTL=log10(TNCRTL);
logTNLID=log10(TNLID);
logONCRTL=log10(ONCRTL);
logONLID=log10(ONLID);
logOPCRTL=log10(OPCRTL);
logOPLID=log10(OPLID);
logTPCRTL=log10(TPCRTL);
logTPLID=log10(TPLID);
logTSSCRTL=log10(TSSCRTL);
logTSSLID=log10(TSSLID);
logCuCRTL=log10(CuCRTL);
logCuLID=log10(CuLID);
logPbCRTL=log10(PbCRTL);
logPbLID=log10(PbLID);
logZnCRTL=log10(ZnCRTL);
logZnLID=log10(ZnLID);
TKNdiff=TKNCRTL-TKNLID;
NO3diff=NO3CRTL-NO3LID;
NH3diff=NH3CRTL-NH3LID;
TNdiff=TNCRTL-TNLID;
ONdiff=ONCRTL-ONLID;
OPdiff=OPCRTL-OPLID;
TPdiff=TPCRTL-TPLID;
TSSdiff=TSSCRTL-TSSLID;
Cudiff=CuCRTL-CuLID;
Pbdiff=PbCRTL-PbLID;
Zndiff=ZnCRTL-ZnLID;
logTKNdiff=logTKNCRTL-logTKNLID;
logNO3diff=logNO3CRTL-logNO3LID;
logNH3diff=logNH3CRTL-logNH3LID;
logTNdiff=logTNCRTL-logTNLID;
logONdiff=logONCRTL-logONLID;
```

```
logOPdiff=logOPCRTL-logOPLID;
logTPdiff=logTPCRTL-logTPLID;
logTSSdiff=logTSSCRTL-logTSSLID;
logCudiff=logCuCRTL-logCuLID;
logPbdiff=logPbCRTL-logPbLID;
logZndiff=logZnCRTL-logZnLID;
cards;

proc univariate data=pairedconcentration plot normal;
title 'Post-retrofit comparison';
var OPdiff logOPKdiff;
histogram/normal;
run;
quit;
```