Water Resources Research Institute of The University of North Carolina

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WATERSHED RETROFIT AND MANAGEMENT EVALUATION FOR URBAN STORMWATER MANAGEMENT SYSTEMS IN NORTH CAROLINA, INCLUDING PROJECTED COSTS AND BENEFITS

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ABSTRACT

New regulations in the state of North Carolina, USA, require all communities within the Jordan Lake watershed – a water supply watershed – to reduce their nitrogen and phosphorus loadings to the lake by establishing stromwater control measures (SCMs) for new and existing development (NCDENR 2009). It is anticipated that these new regulations will be emulated in many urban areas across the state of North Carolina and the United States. As such, it is important to understand the feasibility, both physically and economically, of implementing such practices. The goal of this project was to evaluate the feasibility and cost-effectiveness of treating stormwater in urban areas that have already been developed. Furthermore, it was necessary to determine if the state-mandated nitrogen and phosphorus reduction goals of 8% and 5%, respectively, for existing development within the watershed were attainable via retrofit stormwater management practices. Seven North Carolina cities, that are members of the Urban Water Consortium Stormwater Group, served as the study locations: Raleigh, Durham, Greensboro, Wilmington, High Point, Winston-Salem and Charlotte. One watershed, between 260 and 520 ha, was selected from each of these cities for analysis. An eighth watershed was chosen from Greensboro as well. A ninth larger watershed was analyzed as well, though emphasis was placed on identifying large, regional SCMs as opposed to smaller, site-specific practices.

Annual total phosphorus and total nitrogen load reductions, as well as design, construction, land and maintenance costs were estimated. Results indicated that the quantity and type of retrofit opportunities were dictated primarily by land use, with commercial and industrial providing the most opportunities and rural and ultra-urban areas providing the least. Watersheds with greater numbers of retrofit practices produced higher potential load reduction estimates, indicating that focusing retrofit efforts on land uses that traditionally offer the most retrofit opportunities will most likely result in the highest pollutant load reductions. It was determined that certain site-specific stormwater control measures, namely level spreader-filter strips, constructed wetlands and bioretention often provide the most pollutant removal for the least amount of cost. Finally, the use of larger, regional SCMs provide a discernable benefit (for water quality improvement or economically) over smaller, site-specific practices.

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1.0 INTRODUCTION/BACKGROUND

In 1983, a reservoir was constructed in the state of North Carolina and has been classified as eutrophic or hypereutrophic since its formation. This reservoir, named B. Everett Jordan Lake, serves as the primary drinking water source for the towns of Apex and Cary, NC. Continuously declining water quality within the lake has recently prompted action by federal and state governments to prevent the necessity of building a new water treatment plant for citizens of Raleigh. These regulations require all communities within the Jordan Lake watershed to reduce their nitrogen and phosphorus loadings to the lake by establishing stormwater control measures (SCMs) - also referred to as best management practices (BMPs) - for new and existing development (NCDENR, 2009). These are the first regulations in the USA to require stormwater nutrient loading reductions from existing developments and it is anticipated that these new regulations will be emulated in many urban areas across the state of North Carolina and the United States. As such, it is important to understand the feasibility, both physically and economically, of implementing such practices.

2.0 PROJECT PURPOSE AND GOALS

The goal of this project was to evaluate the feasibility and cost-effectiveness of treating stormwater in urban areas that have already been developed. Furthermore, it was necessary to determine if the state-mandated nitrogen and phosphorus reduction goals for existing development within selected watersheds were attainable via retrofit SCMs.

3.0 METHODOLOGY AND EXECUTION

3.1 Watershed Selection

Seven North Carolina cities were the focus of this study: Raleigh, Durham, Greensboro, Wilmington, High Point, Charlotte and Winston-Salem. Each city was asked to select three potential urban watersheds, each approximately 500-1000 ac in size, for consideration and one of these watersheds would be selected from each city. Eight watersheds were selected from among the 7 participating municipalities. The land use compositions for the 21 watersheds received were delineated and calculated using GIS software and aerial photography. Categories of land use considered included rural, open space/park, roads (category includes sidewalks and railroad), commercial, residential, industrial, institutional and ultra-urban/downtown (Figure 1). Eight watersheds were chosen for analyses in accordance with three goals: 1) at least one watershed was selected from each municipality; 2) watersheds were selected to provide the broadest possible range of types and relative distributions of land uses among the eight selected; and 3) the watershed drained to an impaired stream listed on the 303-d list (preferred but not required). Table 1 provides basic information for the watersheds selected for analysis. Figure 1 depicts the land use compositions for the eight watersheds selected.

3.2 Identifying Potential SCM Retrofits

Geographic Information Systems (GIS) software was used to conduct preliminary analyses of each selected watershed. Surface water hydrology, topography, tax parcel boundaries, stormwater infrastructure and aerial photography data were obtained for each watershed. Most data were obtained through public resources, such as the NCSU library or NC OneMap; however, when data were not publicly available, municipalities were asked to provide the necessary data. Using the acquired GIS data, watersheds were scoured for potential BMP retrofit opportunities. Examples of areas flagged as potential retrofit sites included relatively flat parking lots or paved surfaces (potential permeable pavement retrofit), low-lying, undeveloped areas (potential wetland retrofit), flat roofs (potential green or blue roof retrofit) and parking lot median strips (potential bioretention retrofit). Stormwater control measures (SCMs) considered in these analyses were: bioretention, wet ponds, stormwater wetlands, vegetated swales, sand filters, green roofs, blue roofs, cisterns, level spreader/filter strip combinations, proprietary devices, downspout daylighting, streetsweeping, underground detention and permeable pavement. Watershed-scale SCMs such as streetsweeping and converting sidewalks to permeable pavement were also considered. Retrofitting existing wet retention ponds was not considered as a retrofit option. Figure 2 shows examples of identified potential retrofit sites in one of the watersheds studied.

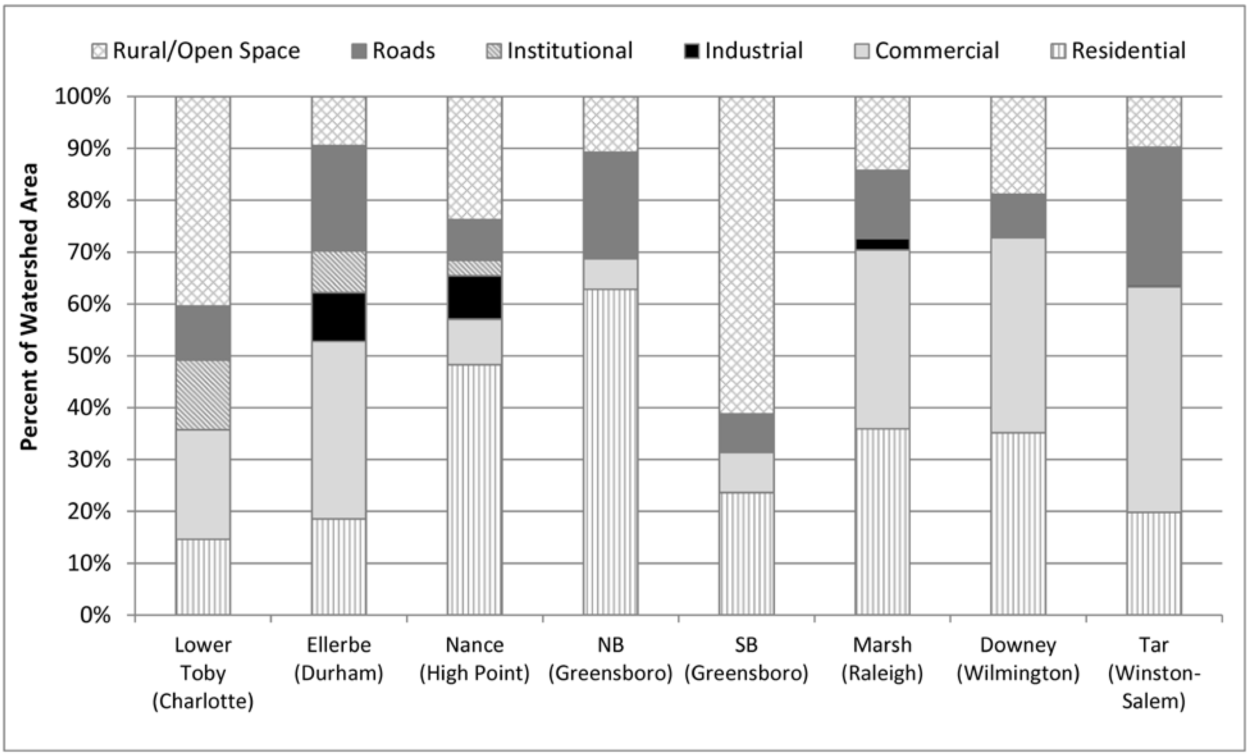

Figure 1. Types and relative distributions of land uses among the eight watersheds included in analyses.

Table 1. Watersheds selected for analyses and their characteristics, including area, associated municipality, and listed impairment(s) of receiving stream.

Watershed Name	Municipality Represented	Area (ac)	Receiving Stream	Receiving Stream Impairment(s)
Downey Branch	City of Wilmington	334.84	Burnt Mill Creek	Biological Integrity
Lower Toby Creek	City of Charlotte	1199.42	Mallard Creek	N/A
Marsh Creek	City of Raleigh	976.38	Marsh Creek	Biological Integrity Urban Runoff & Storm Sewers
Nance Avenue	City of High Point	477.35	Richland Creek	Biological Integrity – Fecal Coliform
NB	City of Greensboro	715.10	North Buffalo Creek	Biological Integrity – Fecal Coliform
Ellerbe Creek	City of Durham	464.84	Ellerbe Creek	Fecal coliform, Turbidity, Low DO, Biological Integrity
SB	City of Greensboro	747.87	South Buffalo Creek	Biological Integrity – Turbidity
Tar Branch	City of Winston-Salem	412.67	Tar Branch	N/A

After compiling a comprehensive list of potential retrofit practices for each of the eight watersheds, each potential site was visited. The purpose of these site visits was to ground-truth the GIS data and ensure the anticipated retrofit was feasible, or that another type of retrofit wasn't more appropriate. These site visits were also used to characterize the watersheds and identify potential retrofit locations that were not identified via GIS analyses. Figure 3 shows photographs taken during these site visits. The contributing watershed for each retrofit was determined and notes were made regarding issues that would impact sizing, location or implementation.

It is important to note that there were no minimum or maximum size requirements enforced when identifying retrofit opportunities. If multiple SCMs were feasible at one site, the SCM that provided the most pollutant reduction was chosen as the preferred practice. Furthermore, only SCMs that did not alter the current land use of a site were considered as retrofit options. For example, the removal of pavement or parking spaces was not considered a feasible retrofit option for parking lots (unless replaced by permeable pavement). Had land use alterations been allowed (i.e. impervious surface conversion/removal), it is expected that more potential SCMs would have been identified and higher pollutant load reductions would have been achievable.

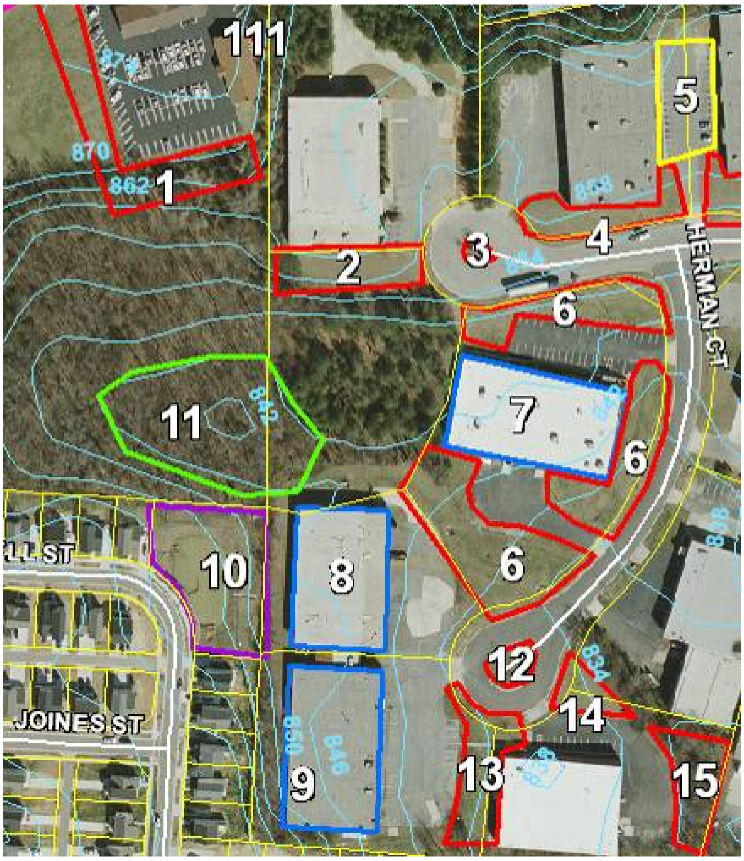

Figure 2. Potential stormwater control measure (SCM) retrofit sites identified via GIS analyses (red shapes indicate a potential bioretention SCM, yellow indicates permeable pavement, green indicates a wetland, purple indicates an existing wet pond, and blue indicates a potential water harvesting opportunity).

Figure 3. Photographs taken during site visits to confirm the feasibility of identified retrofit opportunities and/or identify additional sites not included in the original GIS analyses.

3.3 Calculating Runoff Volumes and Pollutant Loads

Runoff volumes and annual loadings of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) were calculated for the existing conditions of each watershed. Using aerial photography and GIS software, detailed land use data were delineated for each watershed to facilitate these calculations. Land uses were classified as one of the following categories: residential (broken into subcategories of driveway, roof and lawn), commercial/ultra-urban (broken into subcategories of parking lot, roof, open/landscaped), industrial (broken into subcategories of parking lot, roof, open/landscaped), institutional (broken into subcategories of parking lot, roof, open/landscaped), transportation (subcategories of high density- more than 20,000 cars per day, medium density – 5,000 to 20,000 cars per day, low density – less than 5,000 cars per day, sidewalks, and railroad), pervious aras (subcategories of woods, maintained grass, and pasture) and open water. The NRCS Curve Number (CN) Method (NRCS, 1986) was used to determine runoff volumes and each land use category was assigned a curve number based upon the land cover conditions. Table 2 displays the corresponding CN description and values for each land use category for hydrologic soil groups (HSGs) B (representative of Downey Branch, Lower Toby Creek, Marsh Creek, NB, and Tar Branch watersheds),C (representative of Nance Avenue and SB watersheds) and D (representative of Ellerbe Creek watershed.

Ten years of observed hourly precipitation data were acquired from the North Carolina State Climate Office for each watershed. These data were seperated into individual storm events, which were defined by the following criteria: (1) a minimum of 0.2 in of total rainfall; and (2) at least 6 hours since the previous recorded rainfall. The NRCS CN method was then applied to all individual storm events within the 10 year period for each CN represented by a land use category in the watershed. The individual storm runoff depths were then summed on an annual basis, and a median annual runoff depth was calculated for each land use category, as these data were not normally distributed. Total runoff volumes for the watershed were calculated by multiplying the median annual runoff depth for each land use by the corresponding area within the watershed and summing these volumes for all represented land use categories.

The Simple Method (Schueler, 1987) was the method by which annual pollutant loadings were estimated. This method required that a representative pollutant loading concentration be assigned to each land use type; therefore, a literature review was conducted to determine the most appropriate concentrations of TN and TP for each type of land use. Peer-reviewed literature in areas with similar climate and precipitation patterns as North Carolina was preferably considered. The representative pollutant concentration values for each land use category are reported in Table 3. Annual pollutant loads were calculated using these representative concentrations, the corresponding median annual runoff depth and the land use area. The annual loads for individual land uses were summed to produce an annual pollutant load for the watershed.

Table 2. NRCS CN assignments and corresponding land use descriptions for hydrologic soil groups (HSGs) B and C for each land use category.

Land Use Type	Corresponding NRCS Land Use	Curve Number (HSG B)	Curve Number (HSG C)	Curve Number (HSG D)
Residential				
Driveway	Impervious Area	98	98	98
Roof	Impervious Area	98	98	98
Lawn	Open Space - Good Condition	61	74	80
Commercial				
Parking lot	Impervious Area	98	98	98
Roof	Impervious Area	98	98	98
Open/Landscaped	Open Space - Good Condition	61	74	80
Industrial				
Parking lot	Impervious Area	98	98	98
Roof	Impervious Area	98	98	98
Open/Landscaped	Open Space - Fair Condition	69	79	84
Institutional				
Parking lot	Impervious Area	98	98	98
Roof	Impervious Area	98	98	98
Open/Landscaped	Open Space - Fair Condition	69	79	84
Transportation				
High density	Impervious Area	98	98	98
Med density	Impervious Area	98	98	98
Low density	Impervious Area	98	98	98
Sidewalks	Impervious Area	98	98	98
Railroad	Gravel Street and Road	85	89	91
Pervious Areas				
Woods	Woods - Fair Condition	60	73	79
Maintained grass	Meadow - Good Condition	58	71	78
Pasture	Pasture - Fair Condition	69	79	84
Open Water	Impervious Area	98	98	98

The drainage area for each potential retrofit SCM was delineated using topographic contours and stormwater infrastructure maps. The SCMs were then sized in accordance with state regulations to capture and treat the water quality event (2.5 cm in 7 of the 8 watersheds, 3.75 cm in the Wilmington watershed) (NCDENR, 2008). The annual runoff volumes and pollutant loads entering each SCM were calculated in the same manner as the volumes and loads for the entire watershed (NRCS CN method and the Simple Method).

Table 3. Representative pollutant loadings rates for individual land use types (Bannerman et al., 1993; Line et al., 2002; Moran, 2004; NCDENR, 2008; Passeport et al., 2009; Pitt et al., 2005; Skipper, 2008; Wu et al., 1998).

Land Use Type	TSS (mg/L)	TP (mg/L)	TN (mg/L)	Land Use Type	TSS (mg/L)	TP (mg/L)	TN (mg/L)
Residential				Institutional			
Driveway	173	0.39	1.44	Parking lot	173	0.39	1.44
Roof	27	0.15	1.08	Roof	27	0.15	1.08
Lawn	26.5	0.44	2.24	Open/Landscaped	26.5	0.44	2.24
Commercial/Ultra-Urban				Transportation			
Parking lot	58	0.16	1.44	High density	283	0.43	3.67
Roof	27	0.15	1.08	Medium density	93	0.52	1.4
Open/Landscaped	26.5	0.44	2.24	Low density	30	0.47	1.14
Industrial				Sidewalks	30	0.47	1.14
Parking lot	312	0.39	1.44	Railroad	93	0.52	1.4
Roof	27	0.15	1.08	Other			
Open/Landscaped	26.5	0.44	2.24	Woods	113	0.25	1.47
				Maintained grass	20	0.59	3.06
				Pasture	84	1.56	3.61
				Open Water	27	0.15	1.08

3.4 Estimating SCM Pollutant Load Reductions

Currently, there are three primary metrics used to evaluate SCM performance: mass reduction, concentration reduction and median effluent concentration. The percent annual pollutant load reductions provided by a SCM using the mass reduction metric is simply equal to the percent mass reduction assigned to the SCM. Using the percent concentration reduction, the method is defined by Equation 1. The mean effluent concentration metric establishes a representative effluent concentration for each type of BMP without accounting for influent concentration. The percent annual pollutant load reduction provided by a SCM is calculated using Equation 2 for this metric. Each metric is discussed in more detail below.

$$ALR_{conc} = \frac{(Conc_{in} \cdot Vol_{in}) - \left(\%Red_{conc} \cdot Conc_{in} \cdot Vol_{out}\right)}{(Conc_{in} \cdot Vol_{in})} \cdot 100 \qquad (1)$$

where ALR_{conc} = percent annual load reduction provided by the SCM using the concentration reduction metric (%),
$\%Red_{conc}$ = percent concentration reduction assigned to the SCM (dec),
Vol_{in} = volume entering the SCM (L),
Vol_{out} = volume exiting the SCM (L), and
$Conc_{in}$ = mean concentration of pollutant entering the BMP (mg/L).

$$ALR_{MEC} = \frac{(Conc_{in} \cdot Vol_{in}) - \left(MEC \cdot Vol_{out}\right)}{(Conc_{in} \cdot Vol_{in})} \cdot 100 \qquad (2)$$

where ALR_{MEC} = percent annual load reduction provided by the SCM using the median effluent concentration metric (%),
MEC = median effluent concentration assigned to the SCM (mg/L),
Vol_{in} = volume entering the SCM (L),
Vol_{out} = volume exiting the SCM (L), and
$Conc_{in}$ = mean concentration of pollutant entering the BMP (mg/L).

The state of North Carolina uses a percent mass reduction metric to characterize SCM performance. Percent mass reduction refers to the percent difference in the total annual load of pollutant entering a SCM versus the total annual load leaving. Each type of SCM was assigned a reduction credit for TSS, TN and TP based on peer-reviewed North Carolina-centric literature and these reduction credits were used to estimate the reduction in nutrients provided by each retrofit. These reductions are presented in Table 4.

The second metric used to evaluate SCM performance is concentration reduction, which applies a percent reduction to the incoming concentration of a given pollutant. The inflow and outflow concentrations, in conjunction with the estimated annual inflow and outflow runoff volumes, can be used to calculate the mass of pollutant entering and leaving the SCM annually and consequently the reduction in annual pollutant load. Representative concentration reductions were determined for each SCM considered in this study via a North Carolina-centric peer-reviewed literature review. These values are displayed in Table 5.

Table 4. Total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) mass reductions assigned to stormwater control measures (SCMs). (Irish et al., 1995; NCDENR, 2008; Hunt et al., 2008; Moran, 2004; Al-Hamdan et al., 2007; Passeport et al., 2009; Line and Hunt, 2009; Li et al., 2009; Sharkey, 2006; Hunt and Lord, 2006; Bass, 2000; Hathaway et al., 2007; Lenhart, 2008; Winston et. al, 2011; Hathaway and Hunt, 2008)

SCM Type	Mass Reduction (%)			SCM Type	Mass Reduction (%)		
	TSS	TN	TP		TSS	TN	TP
Bioretention	85	55	60	Rainwater Harvesting	75	75	75
Blue Roof	65	30	50	Sand Filter	85	40	45
Daylight Downspouts	85	60	45	Street Sweeping	50	0	40
Dry Detention Pond	65	15	10	Underground Detention	65	30	45
Green Roof	0	20	20	Vegetated Swale	75	0	50
Level Spreader	85	60	45	Wet Pond	70	30	45
Permeable Pavement	70	40	70	Wetland	65	50	65
Proprietary BMP	30	10	5				

Table 5. Total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) concentration and runoff volume reductions assigned to stormwater control measures (SCMs). (Irish et al., 1995; NCDENR, 2008; Hunt et al., 2008; Moran, 2004; Al-Hamdan et al., 2007; Passeport et al., 2009; Li et al., 2009; Sharkey, 2006; Lenhart, 2008; Winston et. al, 2011; Hathaway and Hunt, 2008)

SCM Type	Runoff Volume Reduction (%)	Concentration Reduction (%)		
		TSS	TN	TP
Bioretention	40	65	45	30
Blue Roof	0	65	45	50
Daylight Downspouts	45	35	25	25
Dry Detention Pond	0	65	15	15
Green Roof	50	0	0	0
Level Spreader	45	35	25	25
Permeable Pavement	5	35	5	35
Proprietary BMP	0	30	10	5
Rainwater Harvesting	75	0	0	0
Sand Filter	0	85	40	45
Street Sweeping	0	50	0	40
Underground Detention	0	65	45	50
Vegetated Swale	5	35	0	0
Wet Pond	10	65	25	40
Wetland	20	55	40	55

The third and final method of evaluation employs a median effluent concentration for each type of SCM. Regardless of influent concentration, a SCM is assumed to produce a median effluent concentration. As with the concentration reductions, the inflow and effluent concentrations can be multiplied by the inflow and outflow volumes to produce the mass of pollutant entering and exiting the SCM annually and consequently the reduction in annual pollutant mass. As with the previous metrics, representative effluent concentrations were determined by a review of peer-reviewed literature only for areas with climate and precipitation patterns similar to North Carolina. The resulting concentrations are displayed in Table 6.

Table 6. Total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) median effluent concentrations assigned to stormwater control measures (SCMs). (Irish et al., 1995; NCDENR, 2008; Hunt et al., 2008; Moran, 2004; Al-Hamdan et al., 2007; Passeport et al., 2009; Li et al., 2009; Sharkey, 2006; Lenhart, 2008; Winston et. al, 2011; Hathaway and Hunt, 2008)

SCM Type	Median Effluent Concentration (mg/L)			SCM Type	Median Effluent Concentration (mg/L)		
	TSS	TN	TP		TSS	TN	TP
Bioretention	10	0.92	0.14	Rainwater Harvesting	25	1.63	0.15
Blue Roof	10	1.08	0.12	Sand Filter	10	0.92	0.14
Daylight Downspouts	17	1.20	0.15	Street Sweeping	n/a	n/a	n/a
Dry Detention Pond	10	1.20	0.20	Underground Detention	10	1.08	0.12
Green Roof	25	1.01	1.03	Vegetated Swale	14	1.21	0.26
Level Spreader	17	1.20	0.15	Wet Pond	9	1.01	0.11
Permeable Pavement	7	0.95	0.05	Wetland	20	1.08	0.12
Proprietary BMP	40	1.30	0.10				

Assigning reductions/concentrations to SCMs required several underlying assumptions. All SCMs were assumed to be designed and constructed properly to capture and treat the designated water quality event. Bioretention cells were assumed to be constructed with a minimum media depth of 0.9m and an internal water storage zone, as recommended by Hunt and Lord (2006) and Brown and Hunt (2009). Rainwater harvesting systems were assumed to be designed with a designated water usage, thus providing a consistent volume (and consequently mass) reduction of 75%. Due to a lack of published data, underground detention practices were assigned the same reduction percentages and concentrations as wet ponds, as they employ the same basic pollutant removal principles. Similarly, downspout daylighting was assigned the same reductions/concentrations as level spreader/filter strip SCMs and blue roofs were assigned similar reductions/concentrations as rooftop runoff. The reductions assigned to streetsweeping assumed a sweeping frequency of once every two weeks. Median effluent concentrations were not assigned to streetsweeping due to lack of data; therefore, the concentration reduction metric was applied to streetsweeping practices when performing median effluent concentration reduction analyses. When determining applicable area for converting sidewalks to permeable pavement, it was realized that the areas calculated in GIS were substantially higher than what was reasonable (most likely due to the size of sidewalks and the relatively low resolution of aerial photography at such close ranges). Therefore, the linear footage of sidewalks was determined via GIS and a width of 5 feet was assumed to calculate applicable area for permeable sidewalks.

Potential pollutant removal provided by implementing the identified retrofits was estimated using each of the three metrics for comparison. These metrics were applied to the proposed retrofit practices as well as SCMs previously implemented within the watershed. These existing practices were used to adjust the pre-retrofit TN and TP loading totals, thus providing ‘baseline’ loading values for the watershed.

As with the existing SCMs, the annual load entering each proposed retrofit was estimated and each of the 3 evaluation metrics applied to calculate a percent annual reduction provided by each practice. The sum of TN and TP removed by all potential SCMs within a watershed produced the estimated annual reduction possible by implementing all identified retrofit opportunities. Values reported throughout this report that do not specify a particular metric refer to the percent mass reduction metric, as values produced using this method generally fell in the middle of those produced with the other two metrics.

3.5 Neighborhood SCMs

In addition to specific, individual SCMs discussed previously, more general SCMs were considered for residential communities. Neighborhoods were analyzed to determine the probability of implementing small stormwater practices such as rain gardens, rain barrels and permeable pavement driveways. Parcels of like size, age and appearance were grouped together as one neighborhood. Each neighborhood was characterized based upon appearance (upkeep of yard, presence of conservation-oriented practices such as recycling bins, rain barrels, etc., presence of well-kept shrubbery or flowers, etc.) and assigned a probability of successful SCM implementation. For example, a neighborhood where the majority of houses had well-kept lawns and elaborate flower gardens could may be assigned a probability of 1 in 4 houses that, with an active citizen participation or incentive program, would successfully implement a rain garden, rain barrel or permeable driveway.

To determine the applicable size and pollutant removal for these ‘neighborhood practices’, the following steps were taken. The appropriate number of parcels were randomly selected from a given neighborhood based upon the assigned probability. The total area of land within those selected parcels that was classified as either rooftop (for rain gardens and rain barrels) or driveway (for permeable pavement) was determined. Only rooftop area was deemed applicable for rain gardens and rain barrels for simplicity and due to the popular practice of diverting gutter downspouts to rain gardens and/or rain barrels. For rain gardens and rain barrels, 25% of the total rooftop area in the selected parcels was assumed to be treated and the practices were sized accordingly. One hundred percent of driveway area was considered treated, thus the size of the practice was the same as the area of driveway area. Runoff volume reduction and pollutant removal were calculated in the same manner as with the individual SCMs, as were the associated costs.

3.6 Estimating Costs of Implementing Retrofits

Costs regarding the design and implementation of all potential SCMs were estimated. Construction costs for most retrofit SCMs were acquired from the Urban Subwatershed Restoration Manual Series, published by the Center for Watershed Protection in Maryland, USA (CWP, 2007). Costs of proprietary devices were based on several estimates acquired from industry representatives. The costs used to estimate implementation costs for the identified retrofits are given in Table 7. Design and permitting costs were assumed to be 35% of the total construction cost for a given SCM (CWP, 2007).

Table 7. Construction costs used to estimate total implementation costs for identified retrofit stormwater control measures (SCMs) (CWP, 2007; Hunt and Lord, 2003; Erickson et al., 2009).

SCM Type	Estimated Construction Cost	SCM Type	Estimated Construction Cost
Bioretention (less than 2,500 ft^2)	\$30 per 1 ft^3 of volume treated	Proprietary BMP	\$17,000 per acre of impervious surface treated
Bioretention (greater than 2500 ft^2)	\$10.50 per 1 ft^3 of volume treated	Rainwater Harvesting	\$15 per 1 ft^3 of volume treated
Blue Roof	\$15 per 1 ft^2 of surface area	Sand Filter	\$65 per 1 ft^3 of volume treated
Daylight Downspouts	\$50 per downspout	Street Sweeping	\$375,000 per streetsweeper
Green Roof	\$225 per 1 ft^3 of volume treated	Underground Detention	\$65 per 1 ft^3 of volume treated
Level Spreader	\$1500 each	Vegetated Swale	\$12.50 per 1 ft^3 of volume treated
Permeable Pavement	\$120 per 1 ft^3 of volume treated	Wetland	\$19,440 per acre of impervious surface treated

Land acquisition costs were also considered in the cost analyses. The most recent tax data were acquired for the land parcels and/or buildings where the SCM would be placed. The land or building value was normalized by area, and the total land acquisition value was the resulting cost per ha multiplied by the required size of the SCM. Parcels or buildings owned by government entities were considered to have a land acquisition cost of zero. Buildings that allowed existing land uses to continue undisturbed, such as green roofs, permeable pavement and rainwater harvesting, were also assigned land acquisition values of zero, as were neighborhood practices.

Operation and maintenance costs were estimated as well based on recommendations and values produced by Hunt and Lord (2003) and Erickson et al. (2009). Data were not available on green roof operation and maintenance costs; therefore, a cost was not associated with green roofs for operation and maintenance.

3.7 Feasibility Analyses of Large, Regional SCMs

In addition to looking at site-specific retrofit practices in small urban watersheds, this study also analyzed the feasibility and effectiveness of implementing larger, more regional retrofit practices in a larger watershed. The watershed chosen for this part of the study was a larger portion of the Marsh Creek watershed in Raleigh, which encompasses the smaller watershed analyzed previously in this study. The total watershed area is approximately 6,082 ac and is comprised primarily of residential and commercial land uses.

Preliminary GIS analyses were used to identify potential retrofit locations. As the objective was to analyze the feasibility of implementing large, regional practices, the ideal locations chosen for potential retrofits included undeveloped, low-lying tracts of land with large contributing drainage areas. Site visits were performed to confirm feasibility of installing retrofits at the selected sites and to identify any other suitable locations not detected via GIS analyses. The methods described previously (except the concentration reduction metric) were then used to estimate baseline loadings for the watershed, potential annual pollutant load reductions provided by the identified retrofit practices and the estimated costs associated with implementing those practices.

4.0 OUTPUTS AND RESULTS

4.1 Individual Watershed Analyses – Charlotte (Lower Toby Creek)

The Lower Toby Creek watershed encompassed 1,200 ac and was centered around the intersection of East W.T. Harris Boulevard and University City Boulevard. The watershed was located within the City of Charlotte limits and included parts of the University of North Carolina-Charlotte campus. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. The most prominent land use within the watershed was undeveloped pervious areas (40%), followed by commercial (21%), residential (15%), institutional (13%), transportation (10%) and open water (1%). Figure 4 shows the land uses located within the Lower Toby Creek watershed.

There were several existing SCMs within the watershed, including 10 dry detention ponds and 5 retention ponds (“wet ponds”). Combined, these existing SCMs treated approximately 108 ac. Once the treatment provided by these SCMs was calculated, the baseline annual runoff volume and pollutant loads could be established. Table 8 displays this information for each of the 3 evaluation metrics considered in these analyses. The reasons the pollutant load values differ slightly is that the pollutant load of the 108 ac already treated by SCMs was valued differently by each of the metrics. Had no SCMs been present in the watershed, the existing pollutant loads would have been the same. When normalized by the watershed size and calculated using the mass reduction metric, Lower Toby Creek produces approximately 258 lbs/ac/yr TSS, 0.93 lbs/ac/yr TP and 5.10 lbs/ac/yr TN.

A total of 135 potential retrofit SCMs were identified during the preliminary GIS analyses. After conducting site visits, this number dropped to 98. The reasons for eliminating SCMs as possibilities were related to site constraints and/or the feasibility of implementing a practice at a given site, examples of which include utility conflicts, lack of space, slope, etc. The majority of the finalized SCMs were bioretention (32) or permeable pavement (32); however, there were numerous water harvesting (16) and wetland (11) opportunities as well. Other SCMs identified within this watershed include green roofs (2), sand filters (2), permeable sidewalks and streetsweeping. The identified SCMs were generally concentrated in the commercial and institutional land uses, with only a few identified in residential areas. Additionally, a total of 6 neighborhoods were identified and analyzed for the probability of implementing small SCMs, the details of which are located in the accompanying excel file.

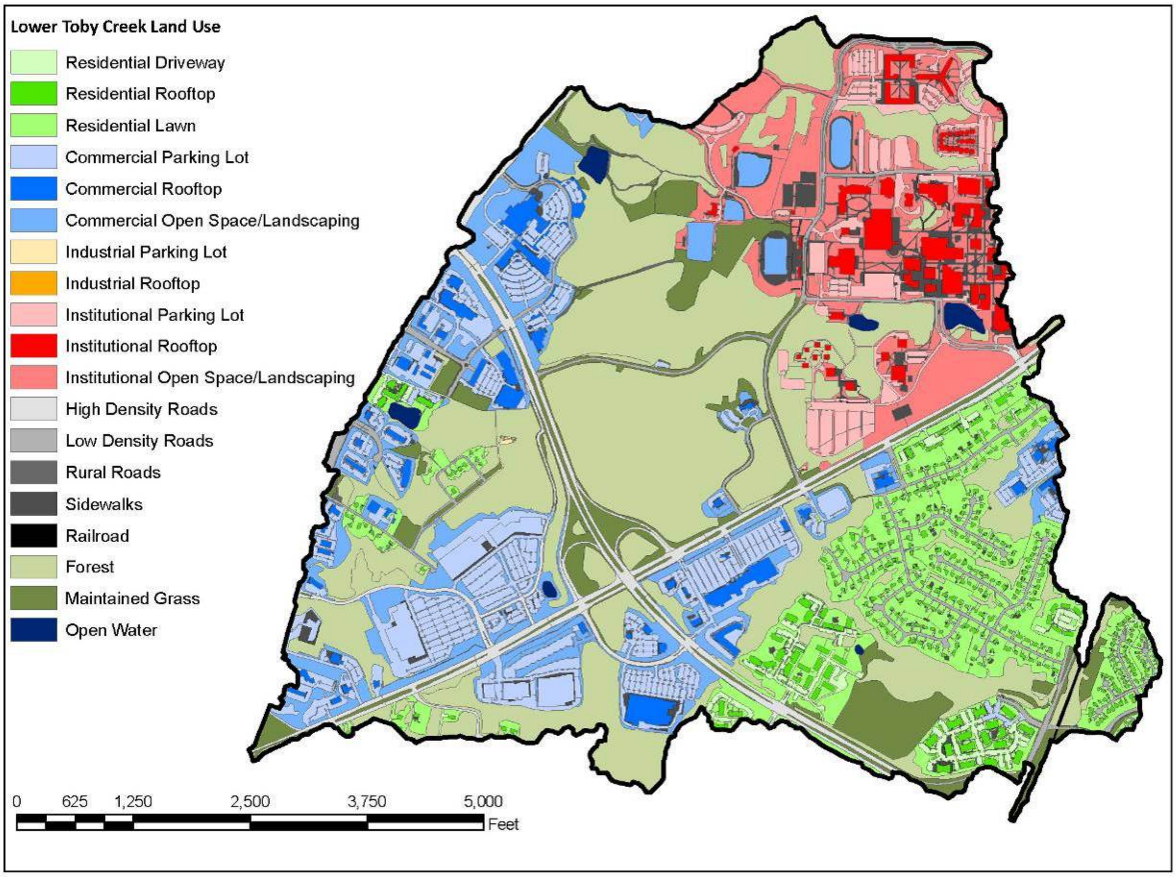

Figure 4. Lower Toby Creek watershed land uses, as classified based on 2009 aerial photography.

Table 8. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving Lower Toby Creek watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	59,794,872	302,651	1,102	6,106
Percent Mass Reduction Metric	59,794,872	310,047	1,121	6,124
Percent Concentration Reduction Metric	59,794,872	310,350	1,117	6,104

The cost for individual SCMs ranged from $530 to $5,676,470. If all identified retrofits were implemented within the watershed, the total implementation cost would be approximately $28,985,067 and the total annual maintenance cost would be approximately $421,611 (30-year maintenance cost would be approximately $12,648,330). However, not all SCMs provided a substantial amount of water quality treatment given the cost of the practice. As it would be difficult for any municipality to spend $29 million on a 1200 ac watershed, it was imperative to determine which identified SCMs provided the most benefit for the least amount of cost. To do this, the cost per kg of pollutant removed was determined for each SCM. The SCMs were then sorted in order from the least costly per kg of pollutant removed to the most costly. The cumulative amount of pollutant removed (either TP or TN, this was not applied to TSS) as well as the cumulative cost was calculated for each SCM. Only implementation costs were included in these analyses – operation and maintenance costs were not considered. These values were then plotted against each other. Figures 5 and 6 show the results of these analyses for TP and TN removal in the Lower Toby Creek watershed for all 3 evaluation metrics. As shown in the figures, a total of 206 kg (453 lbs) TN and 107 kg (235 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/2 of the practices are implemented.

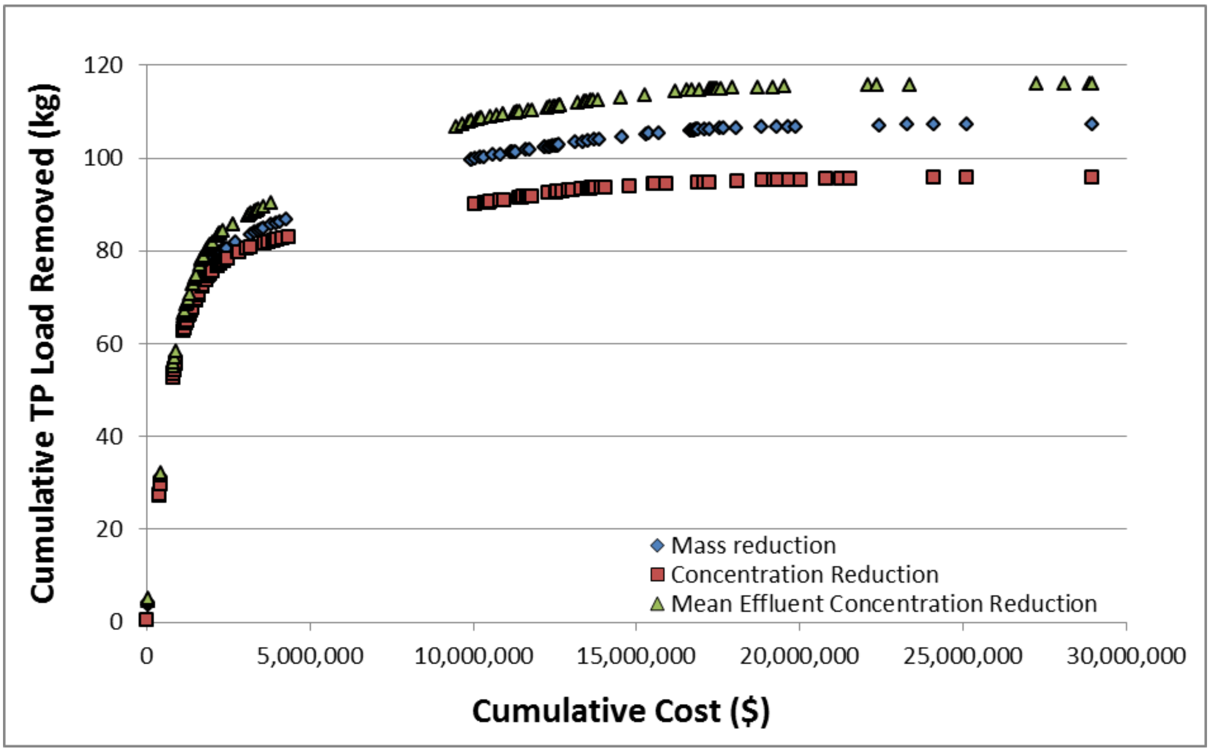

Figure 5. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Lower Toby Creek watershed, as sorted by the cost per kg of TP removed.

Figures 5 and 6 provide a wealth of information regarding the cost effectiveness of implementing the proposed retrofit SCMs. Firstly, the graph shows the maximum amount of pollutant that can be removed annually by implementing all identified retrofit practices and what the associated cost of that implementation would be. Secondly, the data are inherently grouped together to form priority groups, or groups of SCMs that are more cost-effective to implement than others. A greater slope along the lines indicate more cost effective SCMs (i.e. paying less money for more water quality benefit, while a flatter line indicates less cost effective SCMs (i.e. paying more money for less water quality benefit). While these graphs are helpful, they do not indicate which SCMs are represented in these groups, as does Figure 7.

Figure 7 shows information similar to that in Figure 6; however, the TN removal is displayed in terms of percent of annual baseline loading for the Lower Toby Creek watershed. Additionally, the type of SCM is indicated by different point values. As shown in the figure, certain types of SCMs tend to lie along the steepest parts of the line, indicating they are more cost effective than SCM types that tend to lie along less steep sections of the line. Examples of those SCMs in the Lower Toby Creek watershed include bioretention and wetlands. Sand filters fall in the middle, with one practice lying along the steep part of the line and the other along the flatter part of the line. SCM types that primarily lie along the flatter portion of the lines include water harvesting, permeable pavement, green roofs and streetsweeping. This indicates that on average the SCMs most likely to provide the most TN removal for the least amount of cost in this watershed include bioretention and wetlands. The vertical line displayed in Figure 7 indicates the ‘break point’ between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs.

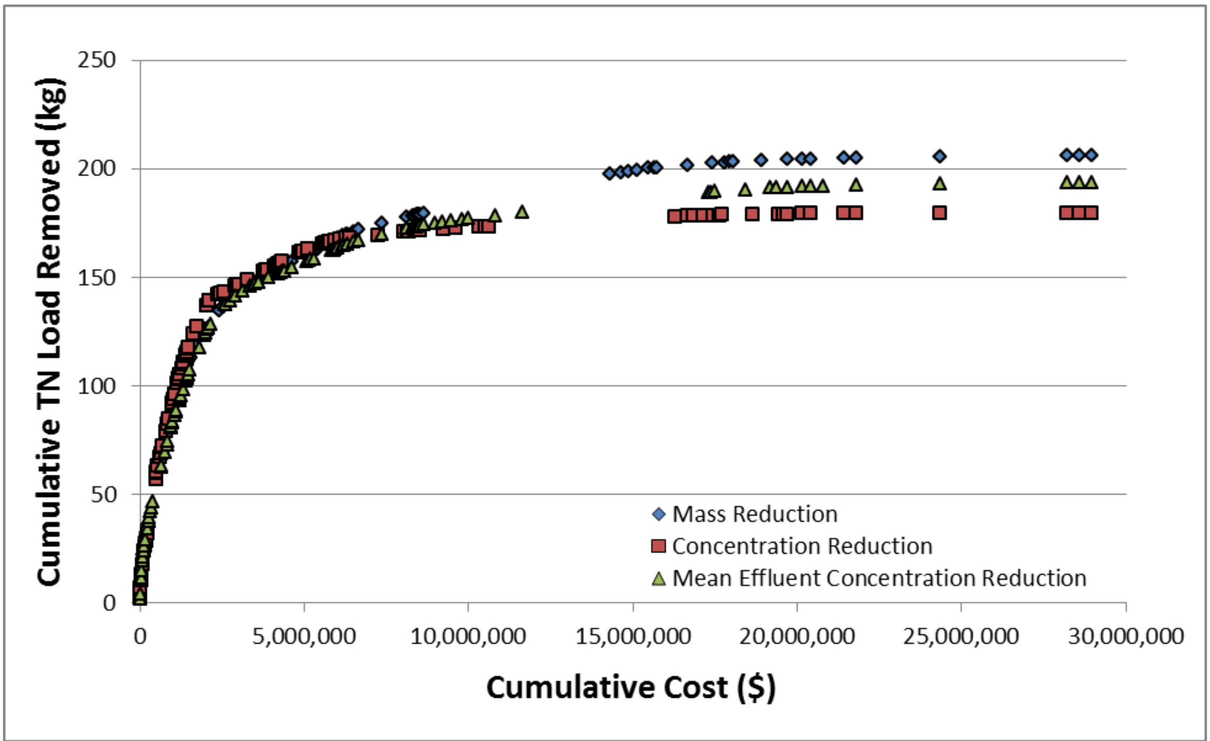

Figure 6. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Lower Toby Creek watershed, as sorted by the cost per kg of TN removed.

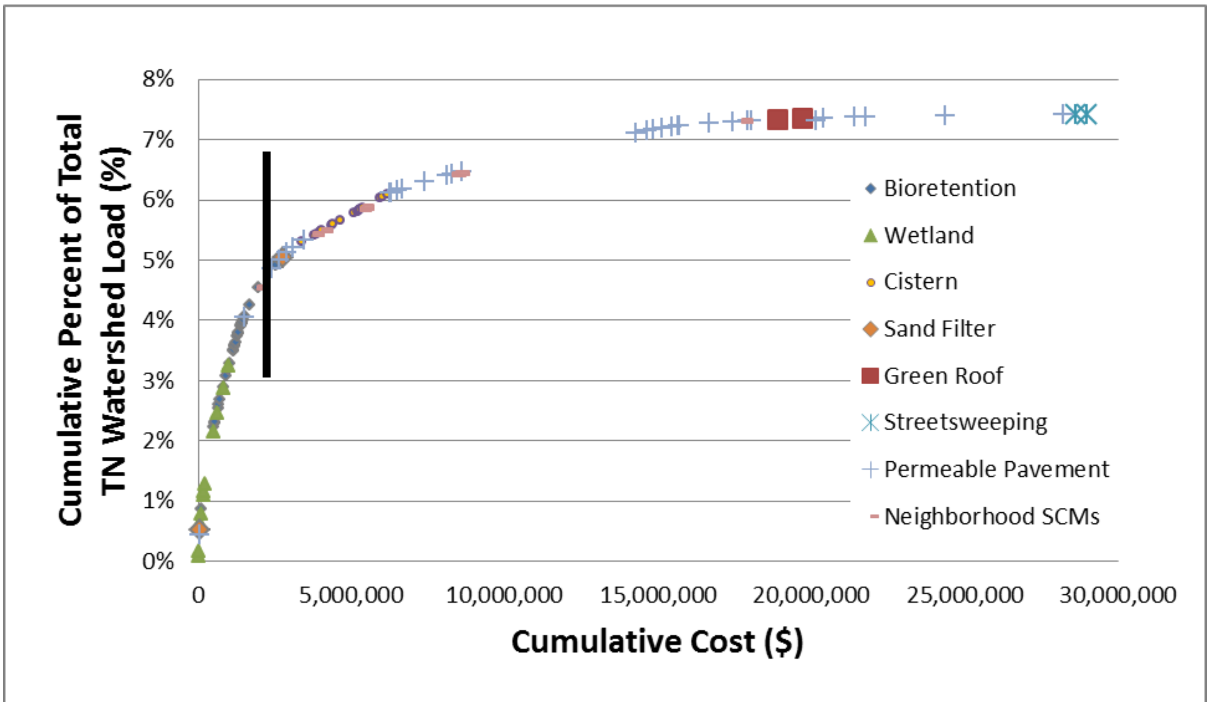

Figure 7. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric) for the Lower Toby Creek watershed. Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

As the processes by which nitrogen and phosphorus are removed from stormwater differ, it would be expected that the most cost effective SCMs would differ by pollutant as well. When a graph like Figure 7 is produced for TP (Figure 8), the following SCM types tend to provide the most TP removal for the least amount of cost: streetsweeping, wetlands and bioretention. SCM types that tend to be less cost effective include water harvesting, permeable pavement and green roofs. Sand filters fall in the middle, with one practice lying along the steep part of the line and the other along the flatter part of the line. As with Figure 7, the vertical line displayed in Figure 8 indicates the 'break point' between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. First- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the Lower Toby Creek watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

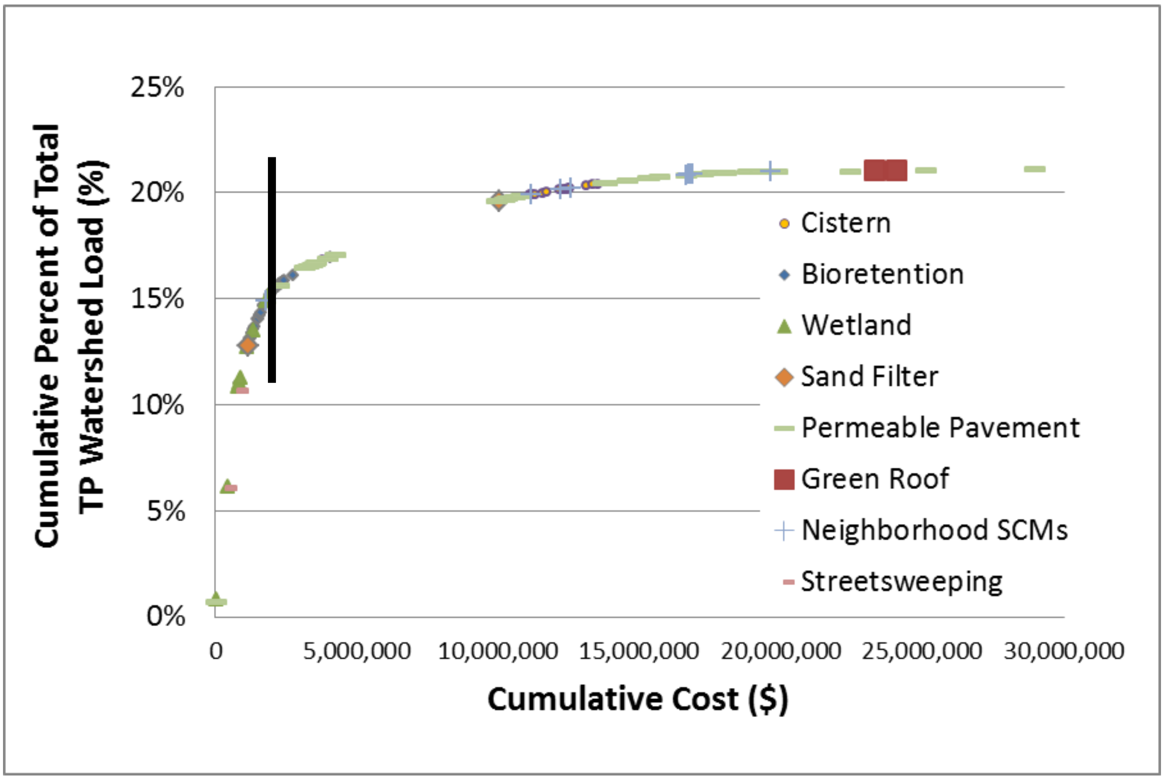

Figure 8. Cumulative percent of the baseline total phosphorus loading removed versus cumulative cost, as sorted by the cost per kg of TP removed (TP reduction calculated using the percent mass reduction metric) for the Lower Toby Creek watershed. Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.2 Individual Watershed Analyses – Durham (Ellerbe Creek)

The watershed chosen from the City of Durham was the Ellerbe Creek watershed, which is located where N. Duke Street and W. Main Street intersect. The watershed is approximately 470 ac and encompasses a portion of downtown Durham and Duke University's campus. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. Commercial and transportation land uses comprise the majority of the watershed (34% and 21%, respectively), followed by residential (19%), industrial (9%), institutional (8%), forest (5%) and maintained grass (4%). Figure 9 further displays the land use characteristics of the watershed.

Four existing SCMs were located within the watershed and all four were sand filters. Together, these four practices treated a total of 1.4 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the Ellerbe watershed, thus producing baseline values. These values are displayed in Table 9, as calculated via each of the 3 evaluation metrics. When normalized by the watershed size and calculated using the mass reduction metric, the Ellerbe Creek watershed produces approximately 305 lbs/ac/yr TSS, 1.54 lbs/ac/yr TP and 6.93 lbs/ac/yr TN.

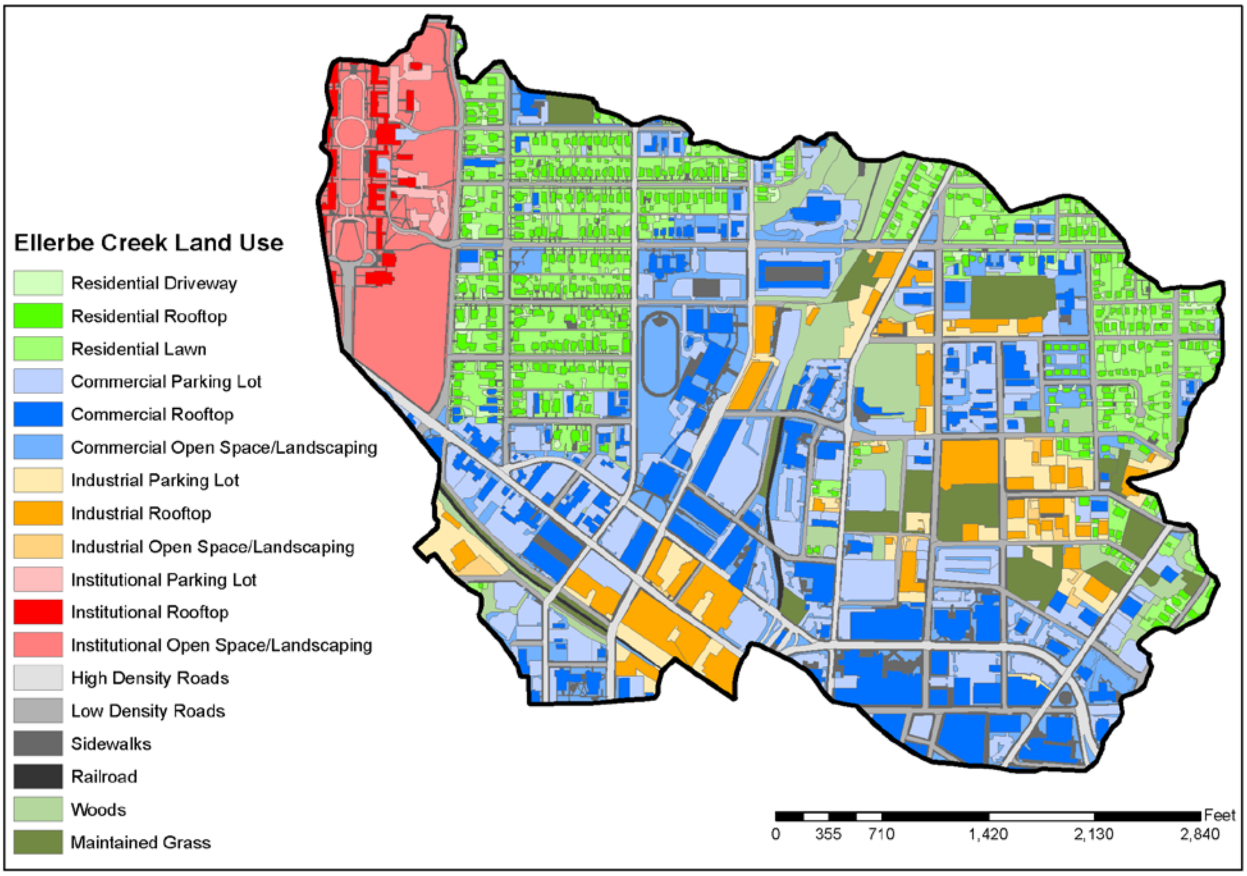

Figure 9. Ellerbe Creek watershed land uses, as classified based on 2005 aerial photography.

Table 9. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving Ellerbe Creek watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	38,712,589	141,526	718	3,222
Percent Mass Reduction Metric	38,712,589	141,600	718	3,221
Percent Concentration Reduction Metric	38,712,589	141,600	718	3,221

A total of 49 potential retrofit SCMs were identified via GIS analyses. After site visits were conducted, this number almost doubled to 92. As with Lower Toby Creek, the majority of these SCMs were located within commercial or institutional land uses; very few were located within residential or industrial areas. Additionally, permeable pavement and bioretention were the most numerous types of SCMs identified within the watershed (36 and 23, respectively), followed by green roofs (13), water harvesting (9), proprietary systems (4), vegetated swales and wetlands (2 each), and sand filters and underground detention (1 each). Additionally, one neighborhood was identified as a possible area for implementing permeable driveways, the details of which are located in the accompanying excel file.

The individual implementation costs of the identified SCMs ranged from $204 to $1,135,230. If all 92 SCMs were implemented, the total cost would be approximately $16,103,226, with an annual maintenance cost of $258,250 (30-year projected maintenance of $7,747,500); however, some of the identified SCMs are not cost effective with regard to the amount of water quality treatment they provided. Therefore, a similar analysis as the one completed for Lower Toby Creek was performed for this watershed. Figures 10 and 11 display cumulative cost versus the cumulative pollutant load removed for TP and TN, respectively. As shown in the figures, a total of 147 kg (324 lbs) TN and 84 kg (185 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/3 -1/2 of the practices are implemented.

These graphs can be used to determine the maximum amount of TN and TP that could be removed if all of the identified retrofit SCMs were implemented within the watershed and what the associated cost would be. As discussed previously, the slope of the lines can also indicate the general cost effectiveness of implementing a given practice.

Figure 12 provides more detail as to the types of practices that are generally relatively more cost effective. As shown in the figure, bioretention, water harvesting, underground detention and wetland practices tend to fall along the steep part of the line with respect to TN removal, thus indicating they provide the most water quality improvement for the least amount of cost. Vegetated swales, green roofs, streetsweeping, proprietary devices, sand filters and the majority of permeable pavement applications tend to be less cost effective for TN removal. For TP removal, this changes slighty; bioretention, wetlands, vegetated swales and streetsweeping are the most cost effectives practices, while permeable pavement, underground detention, sand filters, proprietary systems, and green roofs are least cost effective. Water harvesting falls in the middle, as half of the water harvesting practices lie along the flatter part of the line while the other half falls along the steeper part of the line. The vertical line displayed in Figure 12 indicates the ‘break point’ between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for Ellerbe Creek watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

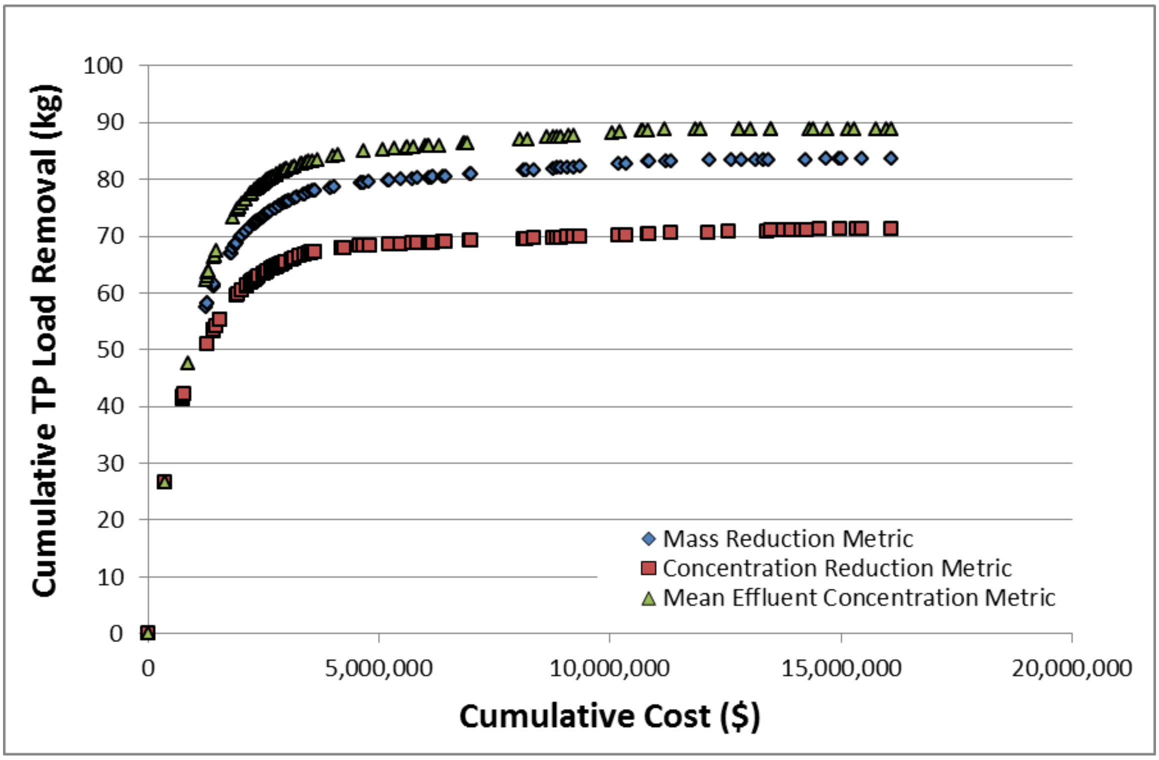

Figure 10. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Ellerbe Creek watershed, as sorted by the cost per kg of TP removed.

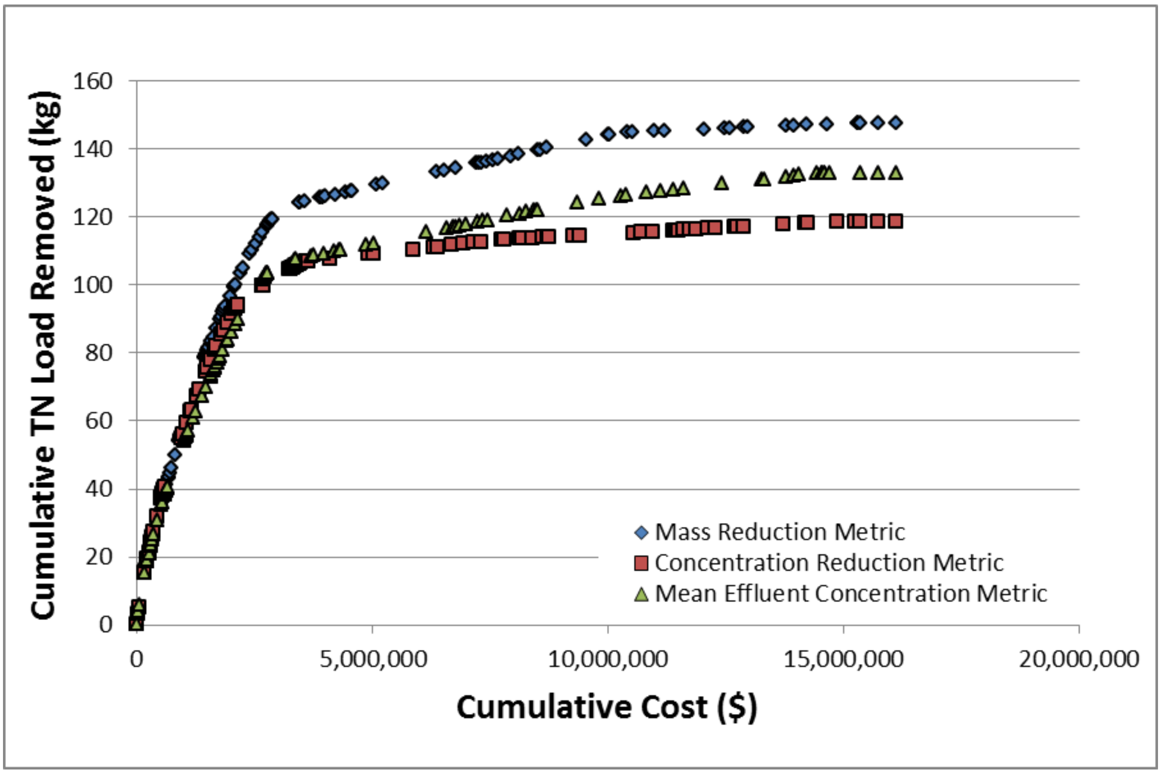

Figure 11. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Ellerbe Creek watershed, as sorted by the cost per kg of TN removed.

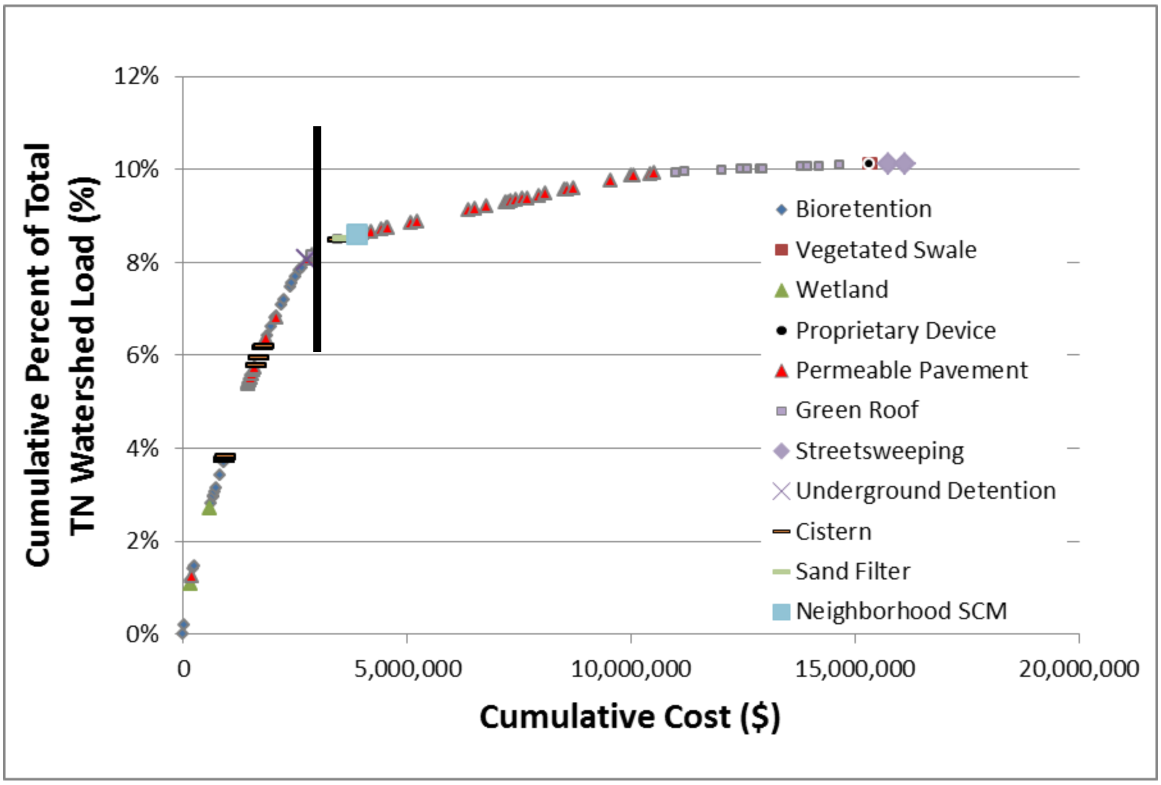

Figure 12. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the ‘break point’ between tier 1 and tier 2 SCMs.

4.3 Individual Watershed Analyses – High Point (Nance Avenue)

The Nance Avenue watershed totals approximately 477 ac and is located adjacent to the Baker Road and Fairfield Road intersection. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. As shown in Figure 13, the majority of the watershed is residential (48%) or wooded (22%), with some industrial (8%) and commercial (9%) areas scattered throughout. Several other land uses are also present, including transportation (8%), unmaintained grass (3%) pasture (1%) and open water (1%).

There were four existing SCMs located within the watershed, and all four were wet retention ponds. Total treatment area for these practices was 21.2 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the Nance Avenue watershed, thus producing baseline values. These values are displayed in Table 10, as calculated via each of the 3 evaluation metrics.

Preliminary GIS analyses identified 110 potential retrofit locations; however, watershed reconnaissance reduced this number to 63. This is substantially less than the Lower Toby Creek and Ellerbe Creek watersheds, which is most likely due to the large amount of residential and wooded land. These land use types tend to offer fewer opportunities for retrofit SCMs than do commercial and industrial land uses. Consequently, the majority of the SCMs identified were concentrated in the commercial and industrial areas of the watershed, with only a few located within residential or undeveloped areas. Bioretention was the primary retrofit identified, with 36 of the 63 practices. Other types included wetlands (9), permeable pavement (7), water harvesting (4), vegetated swale (3), underground detention (1) and sand filter (1). Streetsweeping was also an identified practice, and 7 neighborhoods were identified as potential retrofit locations, the details of which are located in the accompanying excel file.. When normalized by the watershed size and calculated using the mass reduction metric, the Nance Avenue watershed produces approximately 139 lbs/ac/yr TSS, 0.61 lbs/ac/yr TP and 2.68 lbs/ac/yr.

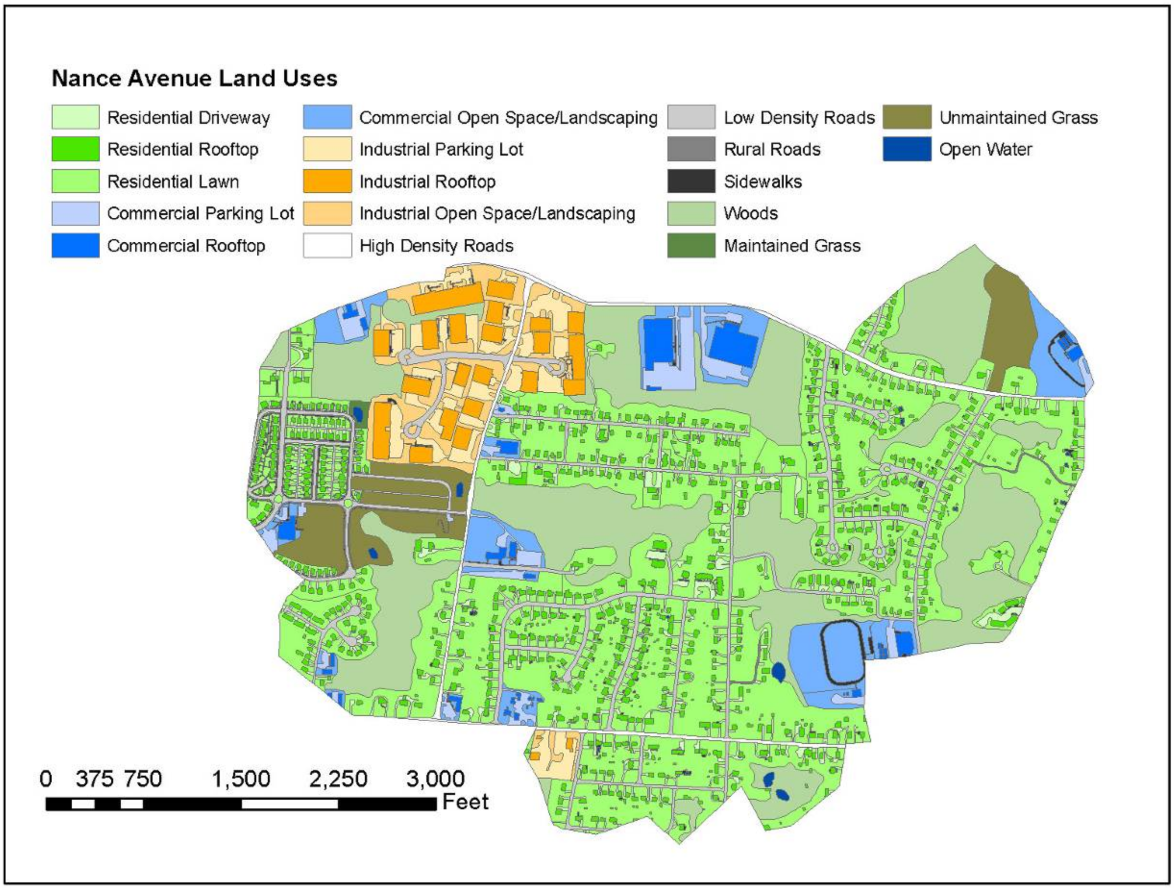

Figure 13. Nance Avenue watershed land uses, as classified based on 2008 aerial photography.

Table 10. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the Nance Avenue watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	14,632,778	65,860	288	1,277
Percent Mass Reduction Metric	14,632,778	66,139	293	1,278
Percent Concentration Reduction Metric	14,632,778	66,176	293	1,275

The individual implementation costs of the identified SCMs ranged from $2,122 to $464,071. If all identified SCMs were implemented, the total cost would be approximately $5,436,825. Annual operation and maintenance costs were estimated to be approximately $332,932 (with a 30-year projected cost of $9,987,960, which is roughly 1.8 times the cost of design and construction). As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified

SCMs. Figures 14 and 15 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 139 kg (306 lbs) TN and 56 kg (123 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/2-2/3 of the practices are implemented. Figure 16 shows what types of practices generally fall within the most cost effective range for TN for the Nance Avenue watershed.

As shown in Figure 16, the types of SCMs that proved to be most cost effective for TN removal included sand filters, bioretention and wetlands. Underground detention, water harvesting, permeable pavement, vegetated swales and streetsweeping were the least cost effective for TN removal, as they provided less water quality benefit with regard to the cost of implementation. This changed slightly for TP, with sand filters, streetsweeping for low density roads, wetlands and bioretention being most cost effective for the Nance Avenue watershed. Vegetated swales, water harvesting, permeable pavement, underground detention and streetsweeping for high density roads were the least cost effective (the cost effectiveness of streetsweeping would vary by road type due to the pollutant loading associated with each type of road and the relative amounts of each road type within the watershed). The vertical line displayed in Figure 16 indicates the 'break point' between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the Nance Avenue watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

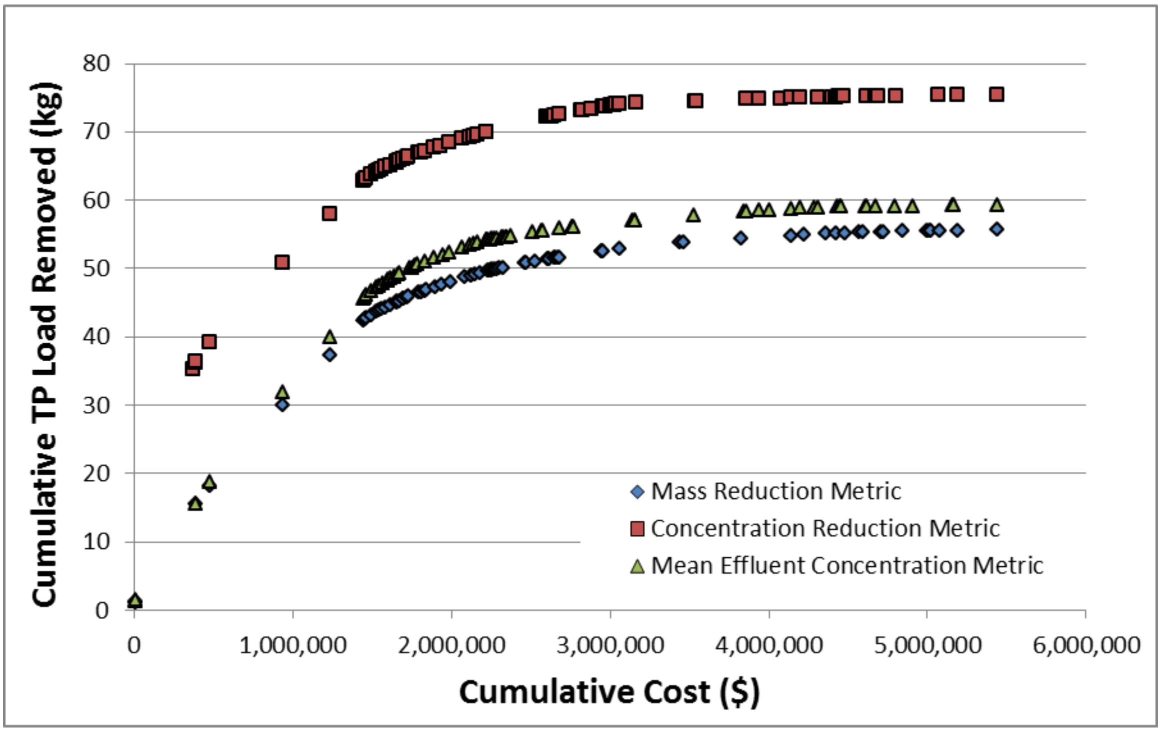

Figure 14. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Nance Avenue watershed, as sorted by the cost per kg of TP removed.

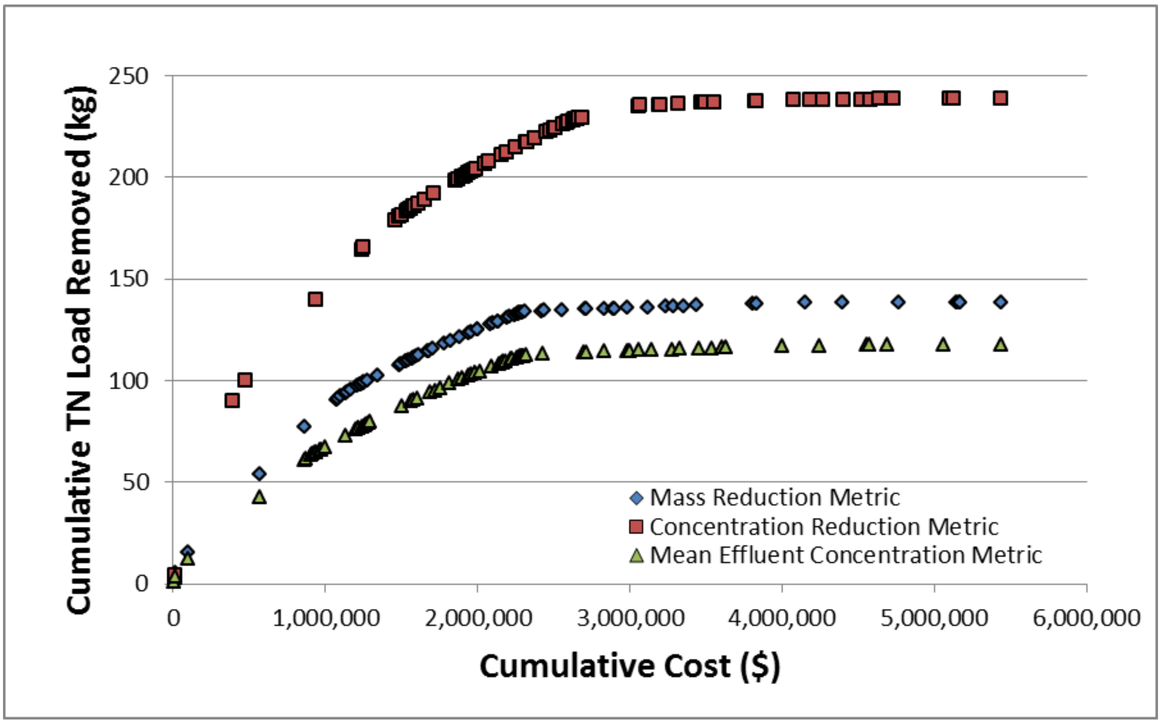

Figure 15. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Nance Avenue watershed, as sorted by the cost per kg of TN removed.

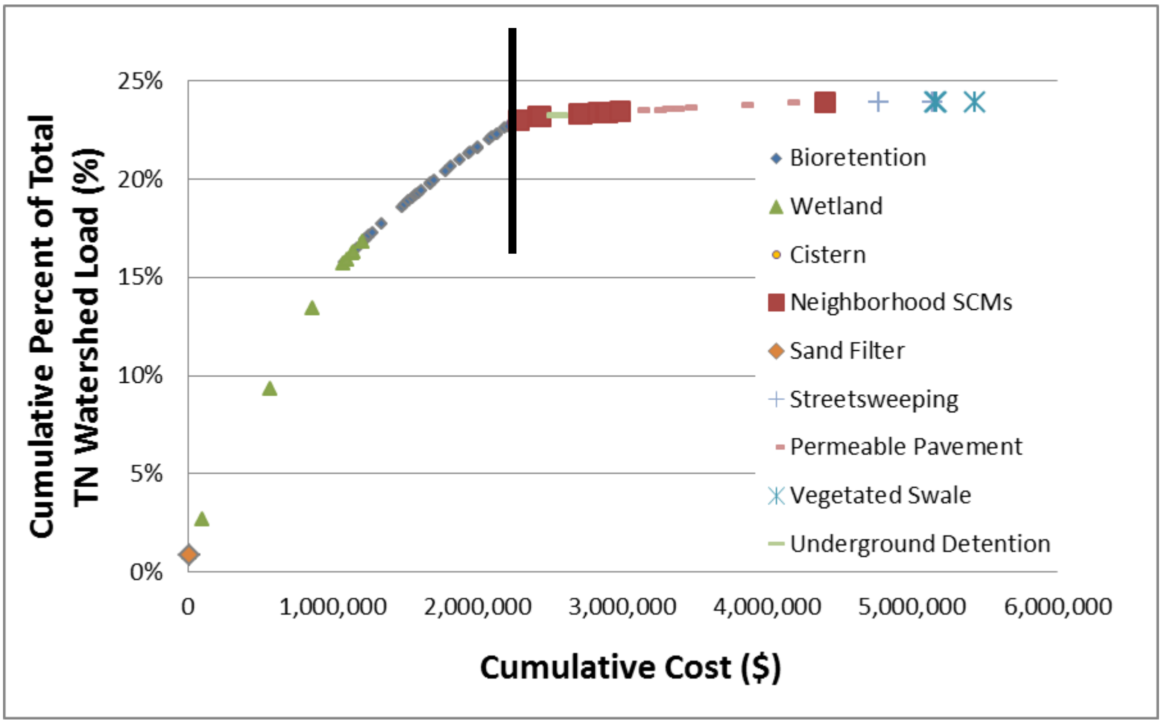

Figure 16. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.4 Individual Watershed Analyses – Greensboro (NB)

The NB watershed in the City of Greensboro encompasses 715 ac and is centered around the Cone Boulevard and Lawndale Drive intersection. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. The watershed is predominantly residential (63%) and a substantial amount of transportation land uses (21%). The remaining land uses are woods (8%), commercial (6%), maintained grass (1%), and pasture (1%). Figure 17 graphically displays the distribution of land uses throughout the watershed.

Four existing SCMs were identified for the NB watershed, including 2 retention ponds and 2 dry detention ponds. Combined, these SCMs treated a total of 10.7 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the Nance Avenue watershed, thus producing baseline values. These values are displayed in Table 11, as calculated via each of the 3 evaluation metrics. When normalized by the watershed size and calculated using the mass reduction metric, the NB watershed produces approximately 107 lbs/ac/yr TSS, 0.62 lbs/ac/yr TP and 3.15 lbs/ac/yr TN.

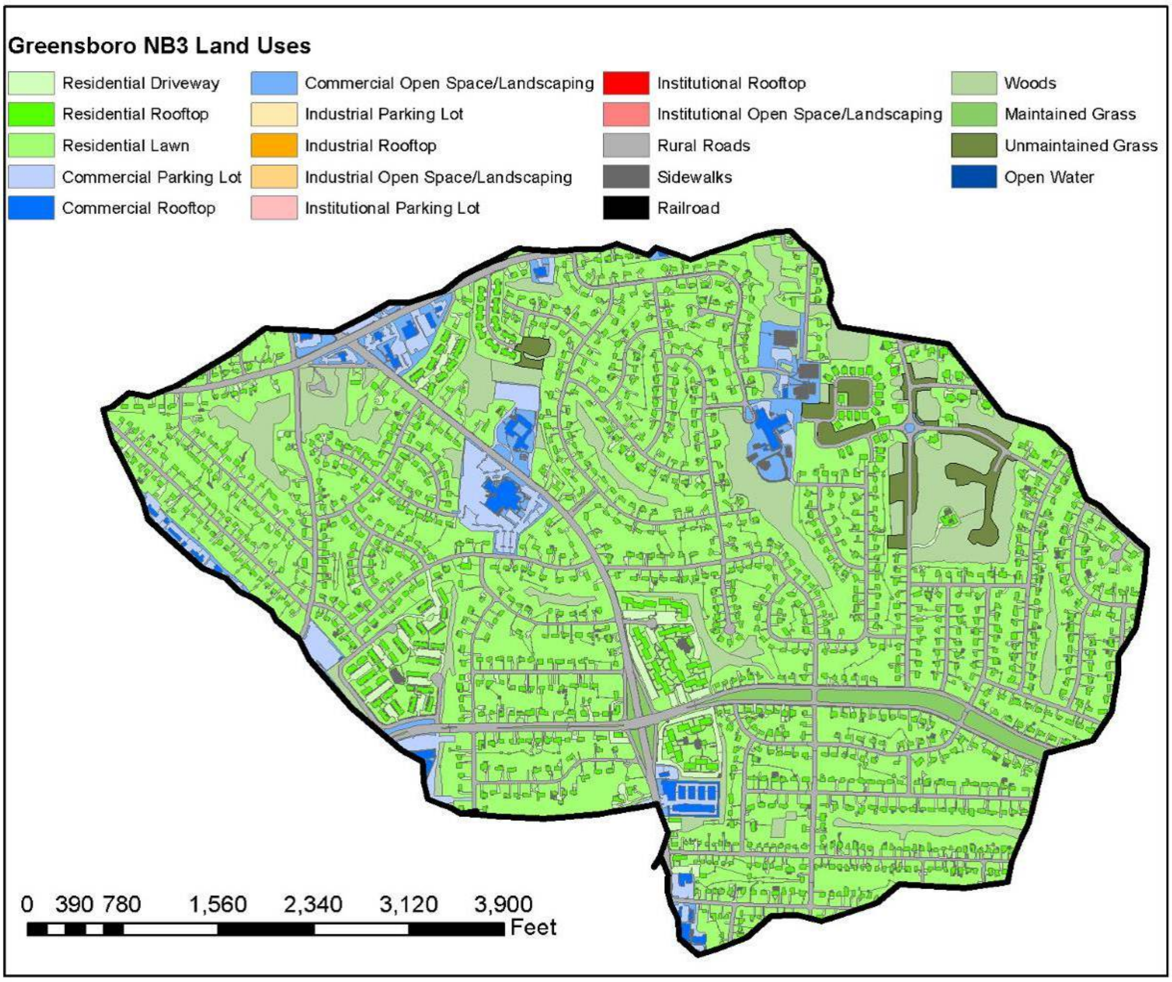

Figure 17. Greensboro NB watershed land uses, as classified based on 2008 aerial photography.

Table 11. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the NB watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	24,753,538	76,227	441	2,254
Percent Mass Reduction Metric	24,753,538	76,587	441	2,253
Percent Concentration Reduction Metric	24,753,538	76,592	441	2,252

Using GIS analyses, a total of 34 potential retrofit locations were identified. As with the Nance Avenue watershed, it is anticipated that this low number was due to residential land uses being the primary land use within the watershed. After performing site visits, this number increased slightly to 38. Permeable pavement was the most prominent type of SCM, with 20 retrofit opportunities identified. This was followed by bioretention (7), water harvesting (5), underground detention and wetlands (2 each) and a vegetated swale (1). Streetsweeping was also a potential retrofit in this watershed, and an additional 7 neighborhoods were identified as potential retrofit locations, the details of which are located in the accompanying excel file. The majority of these retrofits were concentrated within the commercial and maintained grass land uses, further indicating that residential areas are more difficult to retrofit than commercial areas, perhaps due to lack of open areas draining large catchments and/or the efficient routing of stormwater to regional retention ponds via curb/gutter and piping systems.

The individual implementation costs for the NB watershed ranged from $868 to $2,498,972. If all potential retrofit opportunities were realized, the total implementation cost would be approximately $17,691,233, with annual operation and maintenance costs of approximately $708,164. The 30-year maintenance cost ($21,244,920) is nearly 1.2 times that of the implementation cost. The cause of this relatively high maintenance cost is due to the amount of land use subject to streetsweeping and the resulting maintenance. Streetsweeping maintenance is based upon the area cleaned and this watershed had a substantially higher area of roadway subject to streetsweeping, thereby producing a higher annual maintenance cost. As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 18 and 19 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 157 kg (346 lbs) TN and 95 kg (209 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/3 – 1/2 of the practices are implemented. Figure 20 shows what types of practices generally fall within the most cost effective range for TN for the NB watershed.

As shown in Figure 20, the types of SCMs that proved to be most cost effective for TN removal included bioretention and wetlands. Underground detention, water harvesting, permeable pavement, vegetated swales and streetsweeping were the least cost effective for TN removal, as they provided less water quality benefit with regard to the cost of implementation. This changed slightly for TP, with streetsweeping, vegetated swales and wetlands being most cost effective for the NB watershed. Bioretention, water harvesting, permeable pavement and underground detention were the least cost effective. The vertical line displayed in Figure 20 indicates the 'break point' between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the NB watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

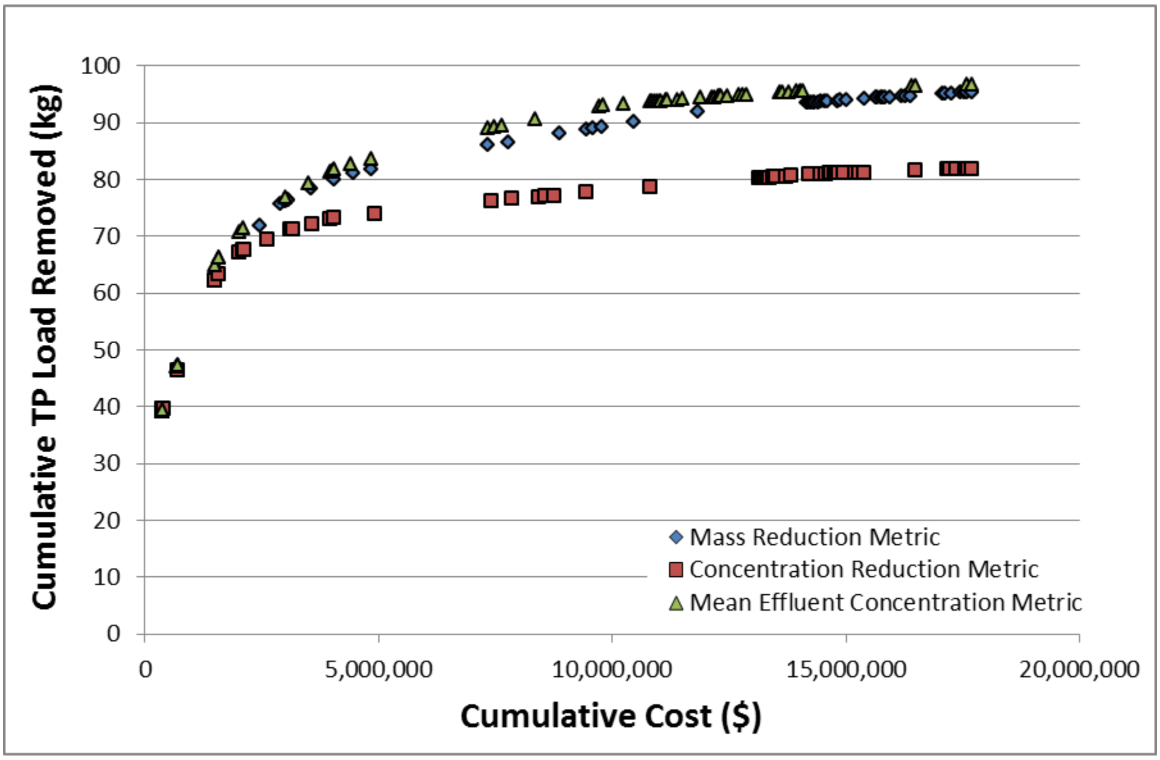

Figure 18. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the NB watershed, as sorted by the cost per kg of TP removed.

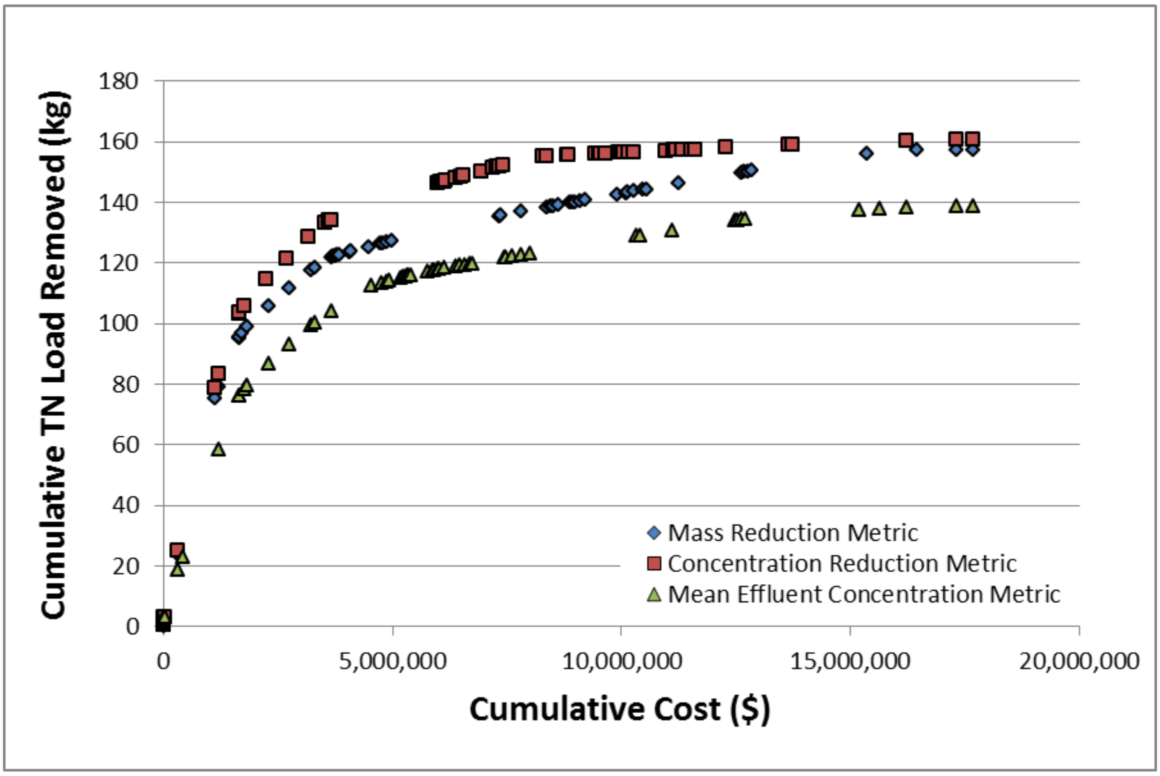

Figure 19. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the NB watershed, as sorted by the cost per kg of TN removed.

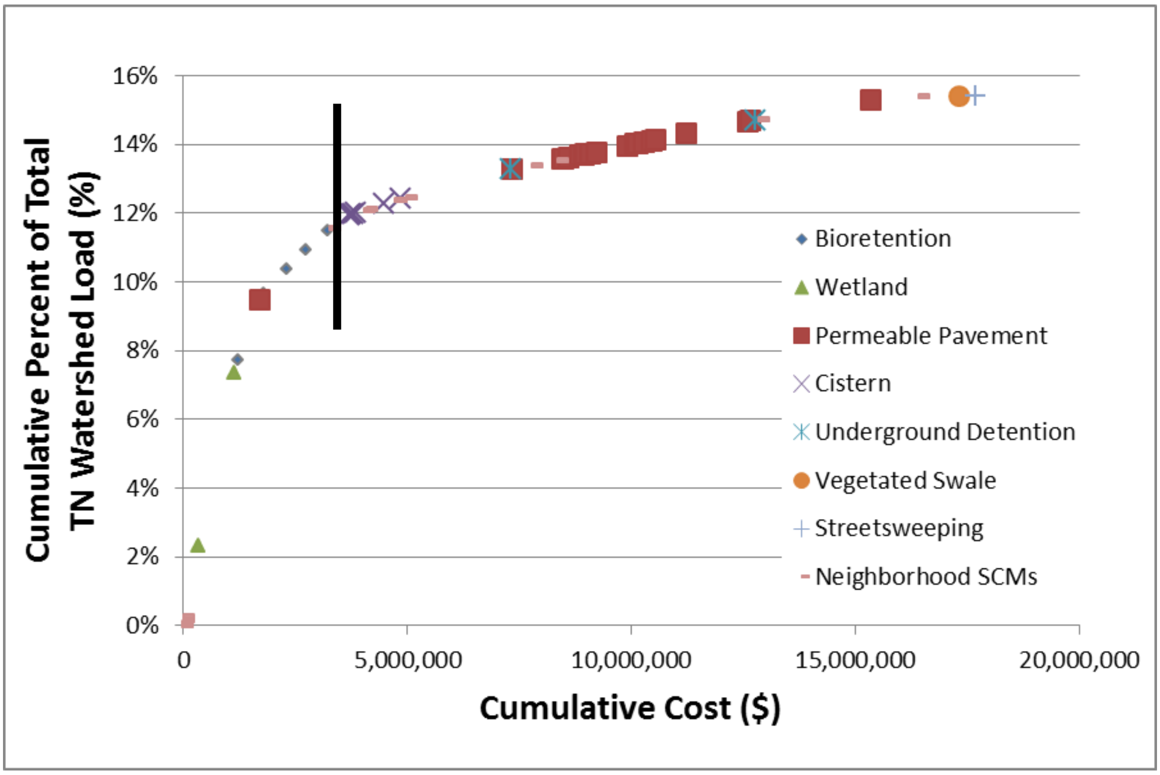

Figure 20. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.5 Individual Watershed Analyses – Greensboro (SB)

The second watershed selected from the City of Greensboro, South Buffalo or SB, contained approximately 748 ac of predominantly rural land and is centered around the I-40 and Elm-Eugene Street intersection. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. As shown in Figure 21, approximately 61% of the watershed was comprised of woods, maintained grass or pasture, with residential, commercial and transportation land uses comprising 24%, 8% and 7%, respectively. Most of the residential areas were not the typical urban subdivision and contained farms or large lots. Interstate I-40 runs through the middle of the watershed, adding a substantial amount of roadway and maintained grass. The watershed contains a moderately-sized commercial complex as well.

Five SCMs were already in place within the SB watershed: 2 dry detention basins, 1 underground detention facility and 2 wet retention ponds. Combined, these 5 practices treat approximately 34.7 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the SB watershed, thus producing baseline values. These values are displayed in Table 12, as calculated via each of the 3 evaluation metrics. When normalized by the watershed size and calculated using the mass reduction metric, the SB watershed produces approximately 183 lbs/ac/yr TSS, 0.50 lbs/ac/yr TP and 1.98 lbs/ac/yr TN.

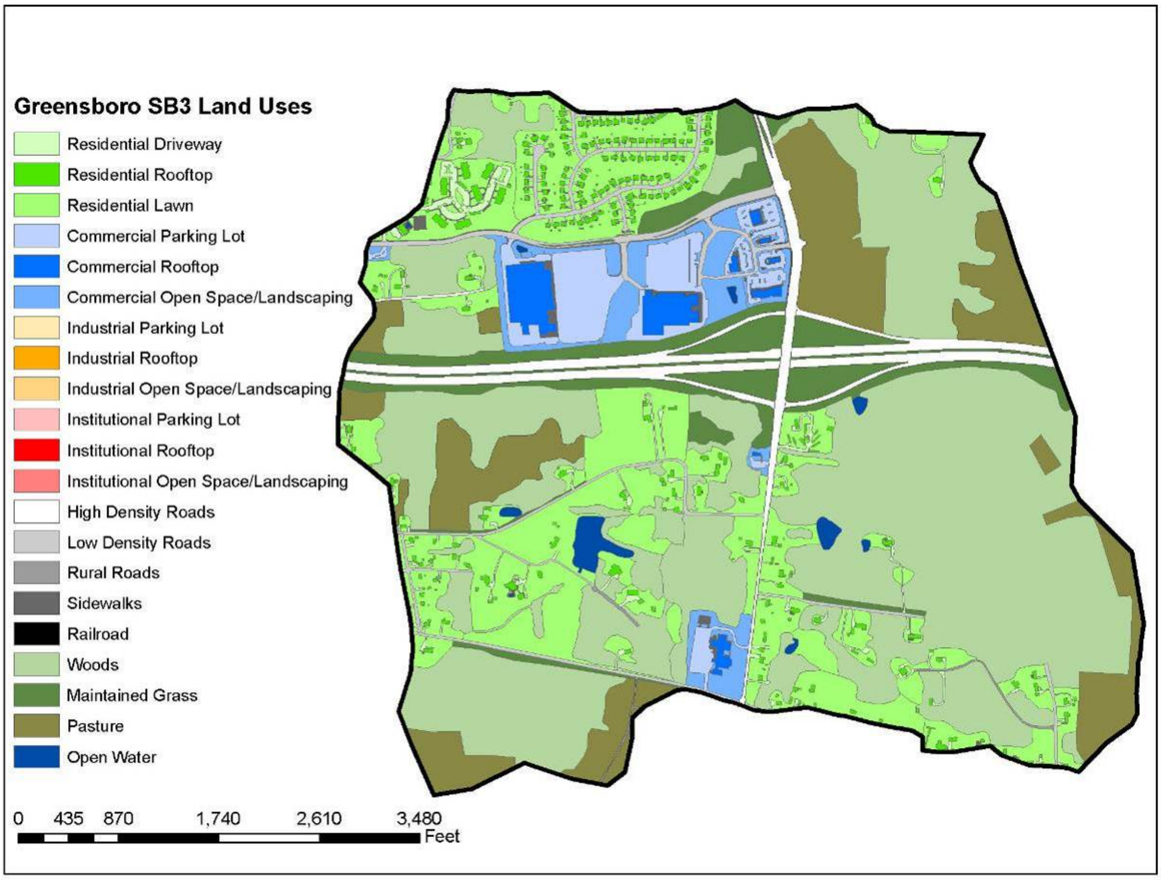

Figure 21. Greensboro SB watershed land uses, as classified based on 2008 aerial photography.

Table 12. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the SB watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	21,536,747	135,252	372	1,485
Percent Mass Reduction Metric	21,536,747	136,861	372	1,483
Percent Concentration Reduction Metric	21,536,747	136,900	371	1,473

Initially, only 25 retrofit possibilities were identified via GIS. This number was reduced to 19 after visiting the watershed. One neighborhood was identified for potential retrofit implementation, the details of which are located in the accompanying excel file. The low number of retrofit possibilities is due to the rural nature of the watershed and the presence of an interstate, as these types of land uses simply do not offer many possibilities for retrofit SCMs. This will be discussed in more detail in the "Overall Trends and Tendencies" section of the report. Of the SCMs identified, permeable pavement was the most numerous (8), followed by bioretention (5), water harvesting (3), vegetated swale (1) and streetsweeping. These retrofits were primarily located within the commercial area of the watershed or within the residential areas that represented an average subdivision layout (as opposed to rural, large lot section of land).

The individual implementation costs for the SB watershed ranged from $3,573 to $6,134,270. If all potential retrofit opportunities were implemented, the total implementation cost would be approximately $13,392,054, with annual operation and maintenance costs of approximately $383,714. The 30-year annual maintenance cost ($11,511,420) is approximately 80% of the implementation cost. As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 22 and 23 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 66 kg (146 lbs) TN and 37 kg (82 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/2 of the practices are implemented. Figure 24 shows what types of practices generally fall within the most cost effective range for TN for the SB watershed.

As shown in Figure 24, the types of SCMs that proved to be most cost effective for TN removal included permeable pavement and vegetated swales. Bioretention, water harvesting and streetsweeping were the least cost effective for TN removal. This changed slightly for TP, with bioretention, streetsweeping for low- and medium-density roads and vegetated swales being most cost effective for the SB watershed. Water harvesting and streetsweeping for high-density roads were the least cost effective. The vertical line displayed in Figure 24 indicates the ‘break point’ between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the SB watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

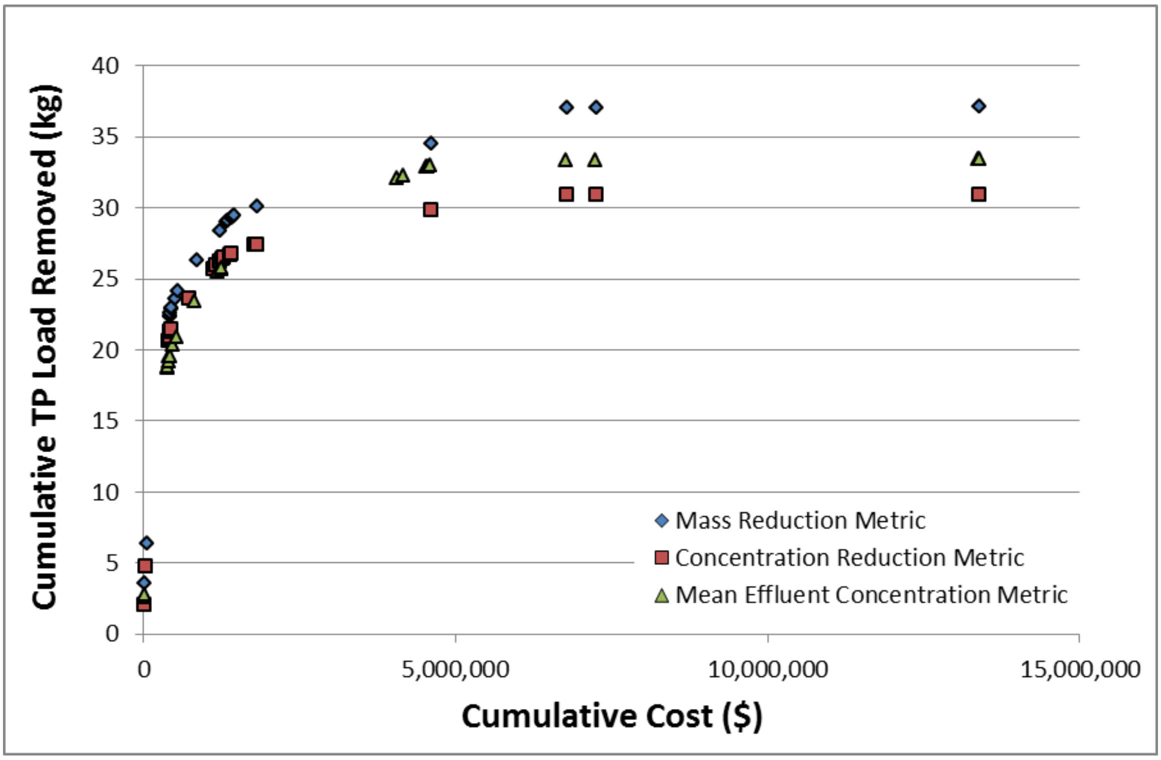

Figure 22. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the SB watershed, as sorted by the cost per kg of TP removed.

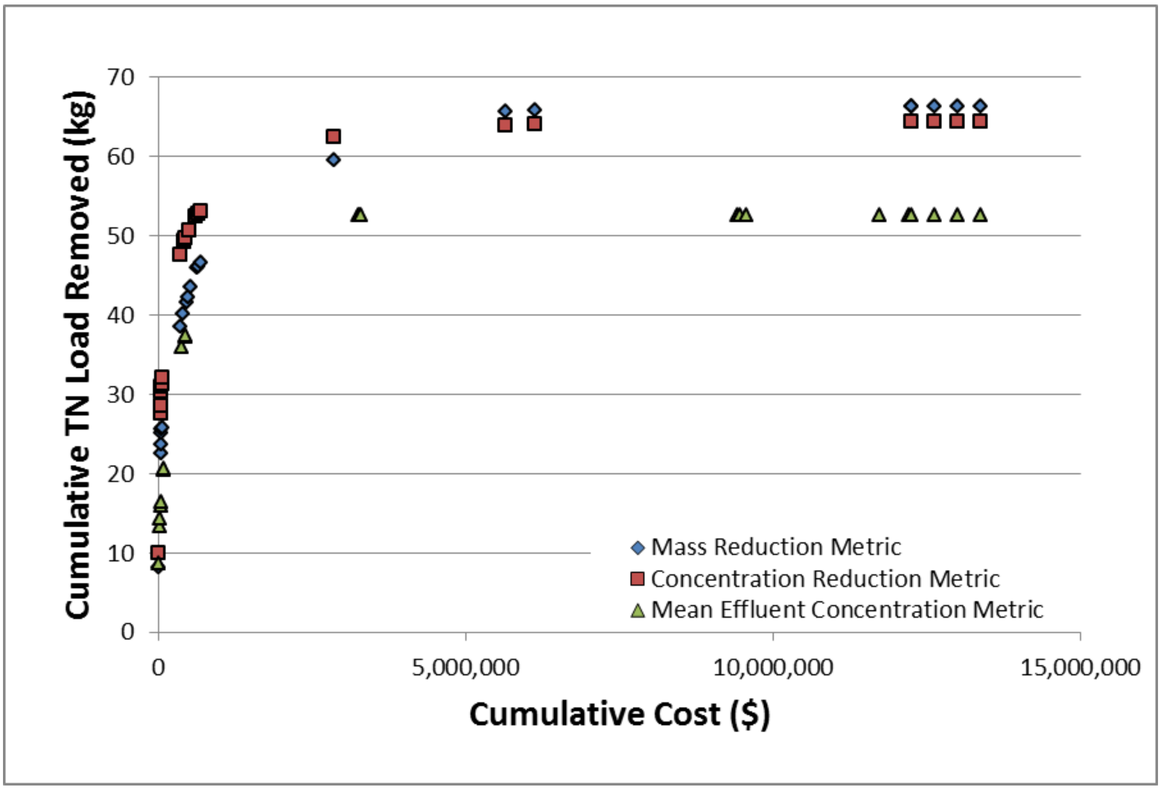

Figure 23. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the SB watershed, as sorted by the cost per kg of TN removed.

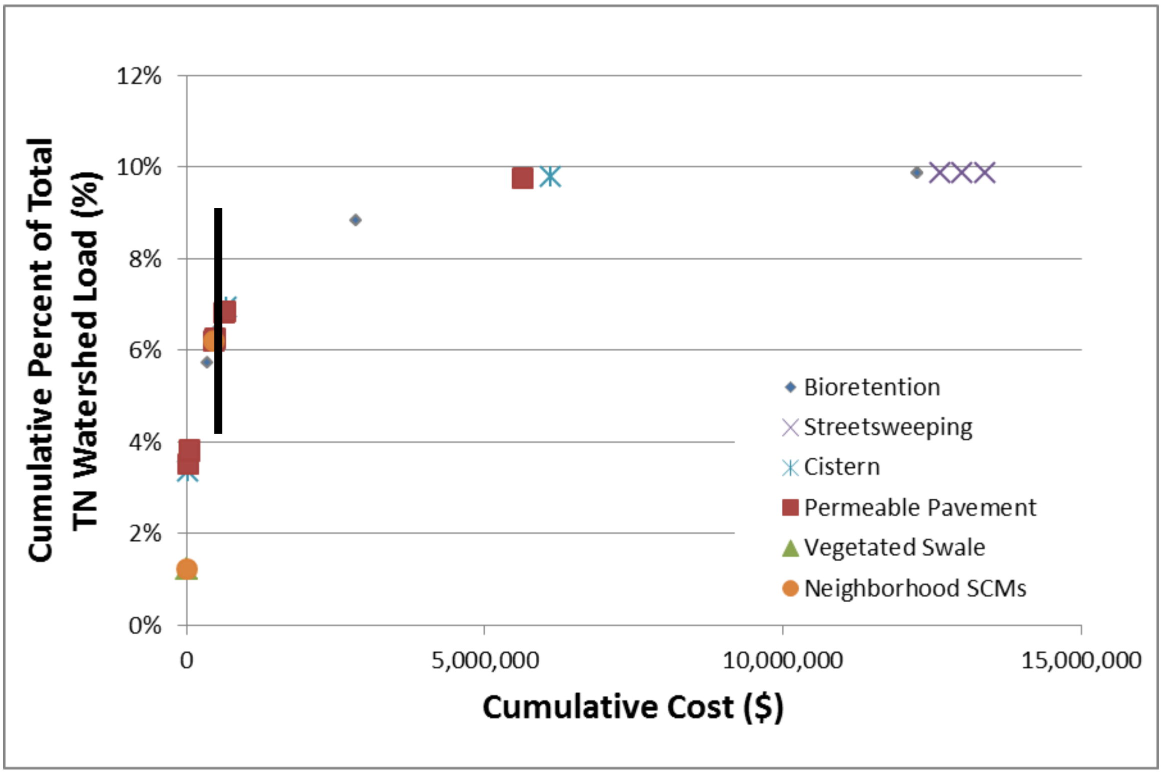

Figure 24. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.6 Individual Watershed Analyses – Raleigh (Marsh Creek)
The Marsh Creek watershed totaled 976 ac and was centered around where NC-401 (Louisburg Road) and US-1 (Capital Boulevard) diverge. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. The watershed was comprised of the following land uses: residential (36%), commercial (34%), transportation (13%), woods (11%), open water (3%), industrial (2%) and maintained grass (1%). Figure 25 shows the distribution and location of the various land use types within the Marsh Creek watershed.

Several SCMs were already in place within the Marsh Creek watershed, including 4 bioretention cells, 1 dry detention basin, 3 vegetated swales, 1 underground detention facility and 5 wet retention ponds. Combined, these 14 practices treated approximately 80.6 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the Marsh Creek watershed, thus producing baseline values. These values are displayed in Table 13, as calculated via each of the 3 evaluation metrics. When normalized by the watershed size and calculated using the mass reduction metric, the Marsh Creek watershed produces approximately 297 lbs/ac/yr TSS, 1.04 lbs/ac/yr TP and 5.97 lbs/ac/yr TN.

Table 13. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the Marsh Creek watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	63,267,600	287,947	1,019	5,800
Percent Mass Reduction Metric	63,267,600	290,127	1,020	5,827
Percent Concentration Reduction Metric	63,267,600	292,173	1,026	5,809

The individual implementation costs for the Marsh Creek watershed ranged from $1,673 to $3,504,838. If all potential retrofit opportunities were implemented, the total implementation cost would be approximately $30,387,374, with annual operation and maintenance costs of approximately $416,662. The 30-year operations and maintenance cost ($12,499,860) was less than one-half that of the implementation costs. As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 26 and 27 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 332 kg (732 lbs) TN and 145 kg (320 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/3 of the practices are implemented. Figure 28 shows what types of practices generally fall within the most cost effective range for TN for the Marsh Creek watershed.

As shown in Figure 28, the types of SCMs that proved to be most cost effective for TN removal included wetlands, water harvesting and bioretention. Permeable pavement, vegetated swales and streetsweeping were the least cost effective for TN removal. This changed slightly for TP, with streetsweeping, some bioretention practices, and wetlands being most cost effective for the Marsh Creek watershed. Water harvesting, permeable pavement and the majority of bioretention practices were the least cost effective. The vertical line displayed in Figure 28 indicates the ‘break point’ between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the Marsh Creek watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

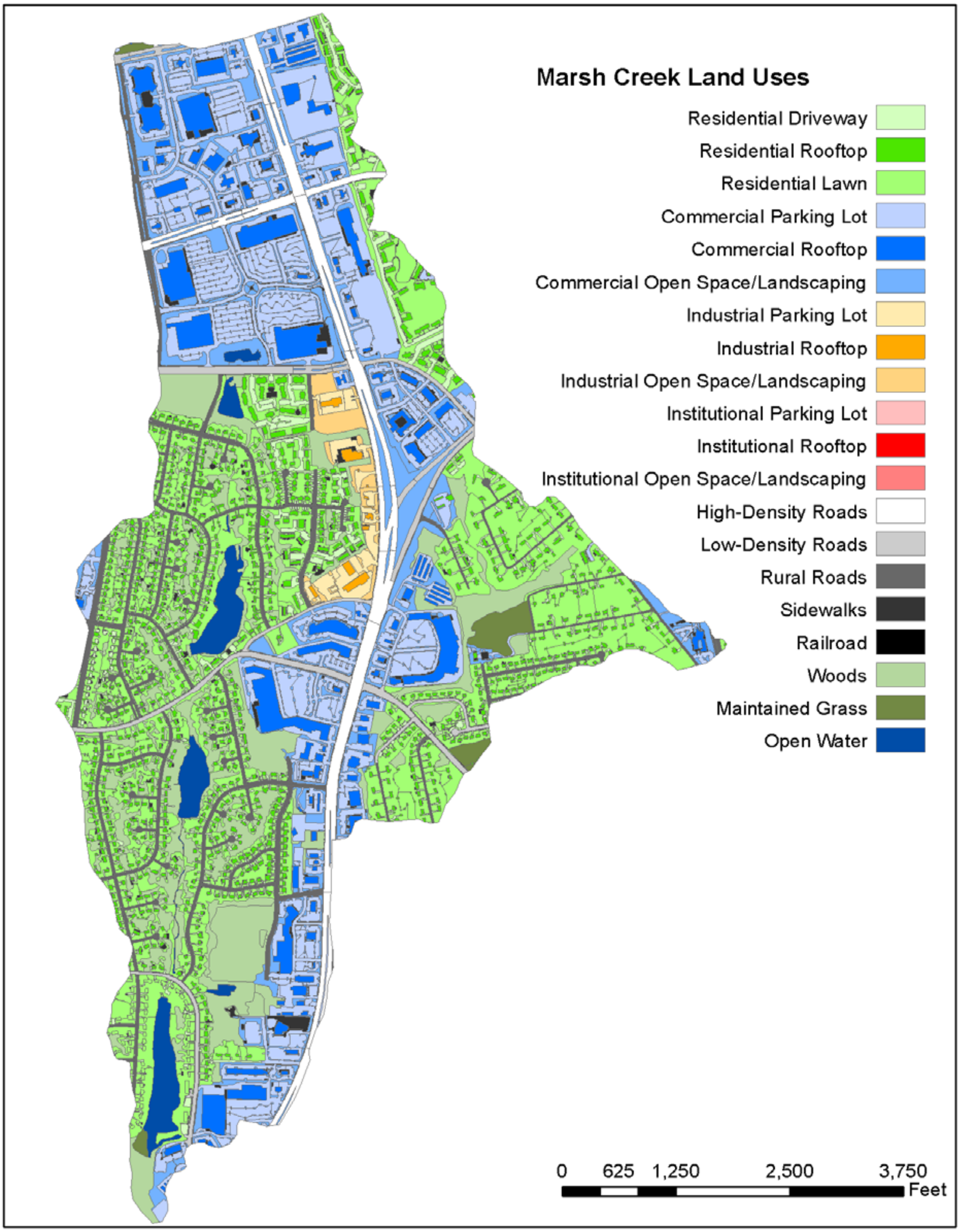

Figure 25. Marsh Creek watershed land uses, as classified based on 2005 aerial photography.

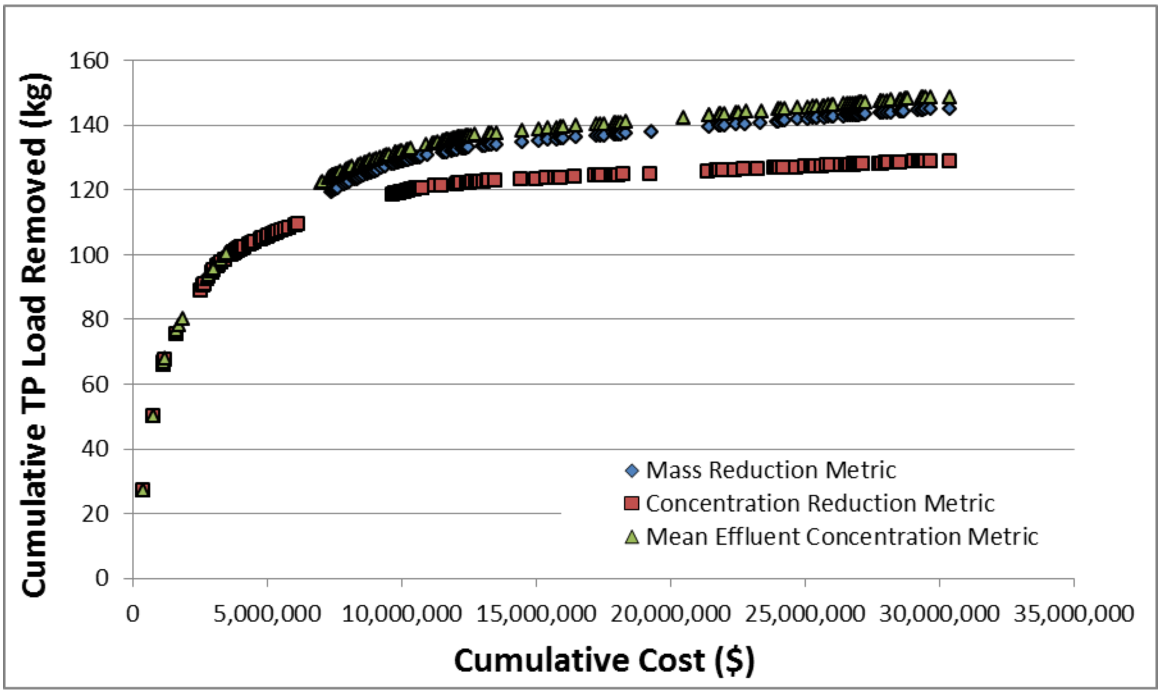

Figure 26. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Marsh Creek watershed, as sorted by the cost per kg of TP removed.

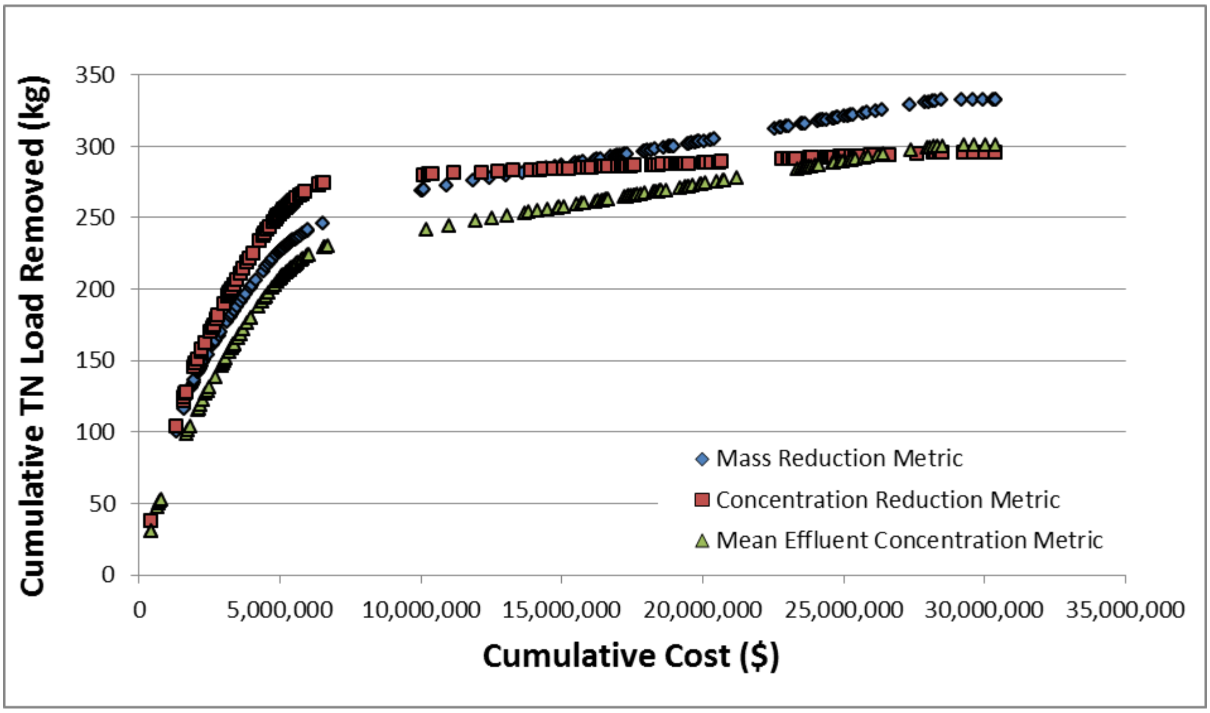

Figure 27. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Marsh Creek watershed, as sorted by the cost per kg of TN removed.

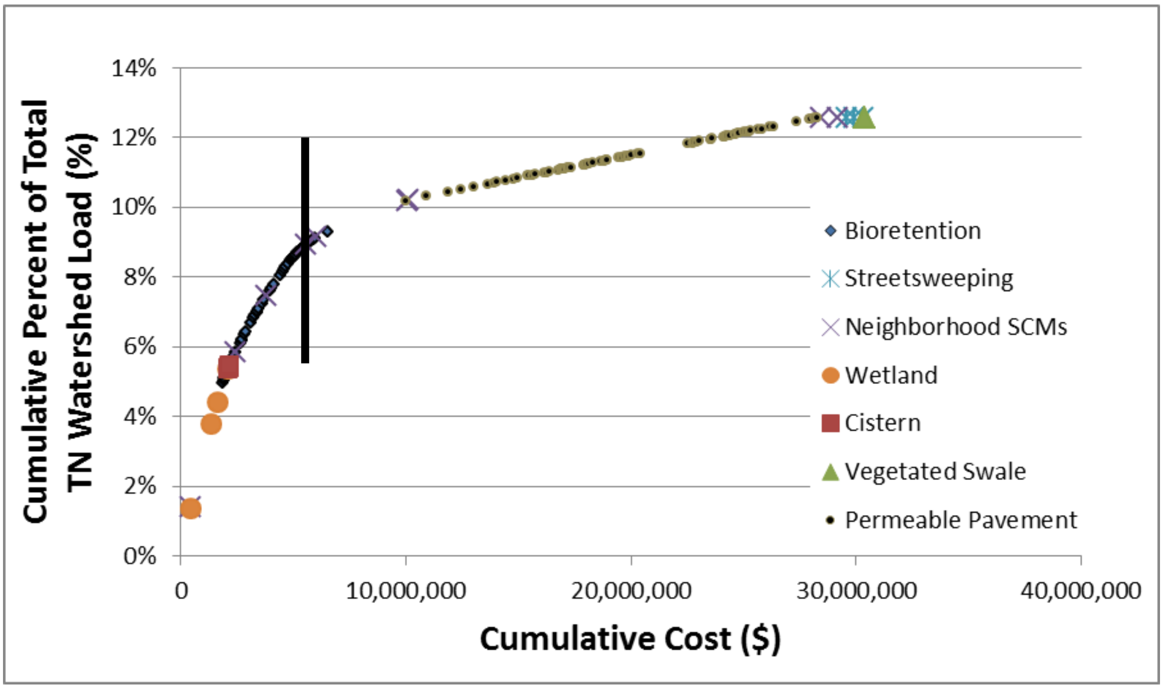

Figure 28. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.7 Individual Watershed Analyses – Wilmington (Downey Branch)

The Downey Branch watershed was centered around the intersection of Wrightsville Avenue and 39th Street and was approximately 335 ac in size. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. As shown in Figure 29, commercial and residential land uses dominated the watershed at 38% and 35%, respectively. Other land uses present included woods (15%), transportation (8%) and maintained grass (4%).

Two wet retention pond SCMs were already in place within the Downey Branch watershed and together treated approximately 4.1 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for this watershed, thus producing baseline values. These values are displayed in Table 14, as calculated via each of the 3 evaluation metrics. When normalized by the watershed size and calculated using the mass reduction metric, the Downey Branch watershed produces approximately 257 lbs/ac/yr TSS, 1.00 lbs/ac/yr TP and 5.86 lbs/ac/yr TN.

A total of 52 potential retrofit SCMs were identified with GIS analyses, although this number decreased to 49 once site visits were conducted. The majority of SCMs identified were permeable pavement (26) or bioretention (16). Three wetlands, 1 vegetated swale and streetsweeping were also identified. Almost all of the potential SCMs were located within commercial or open space land uses. Additionally, one neighborhood was identified as a potential retrofit location, the details of which are located in the accompanying excel file.

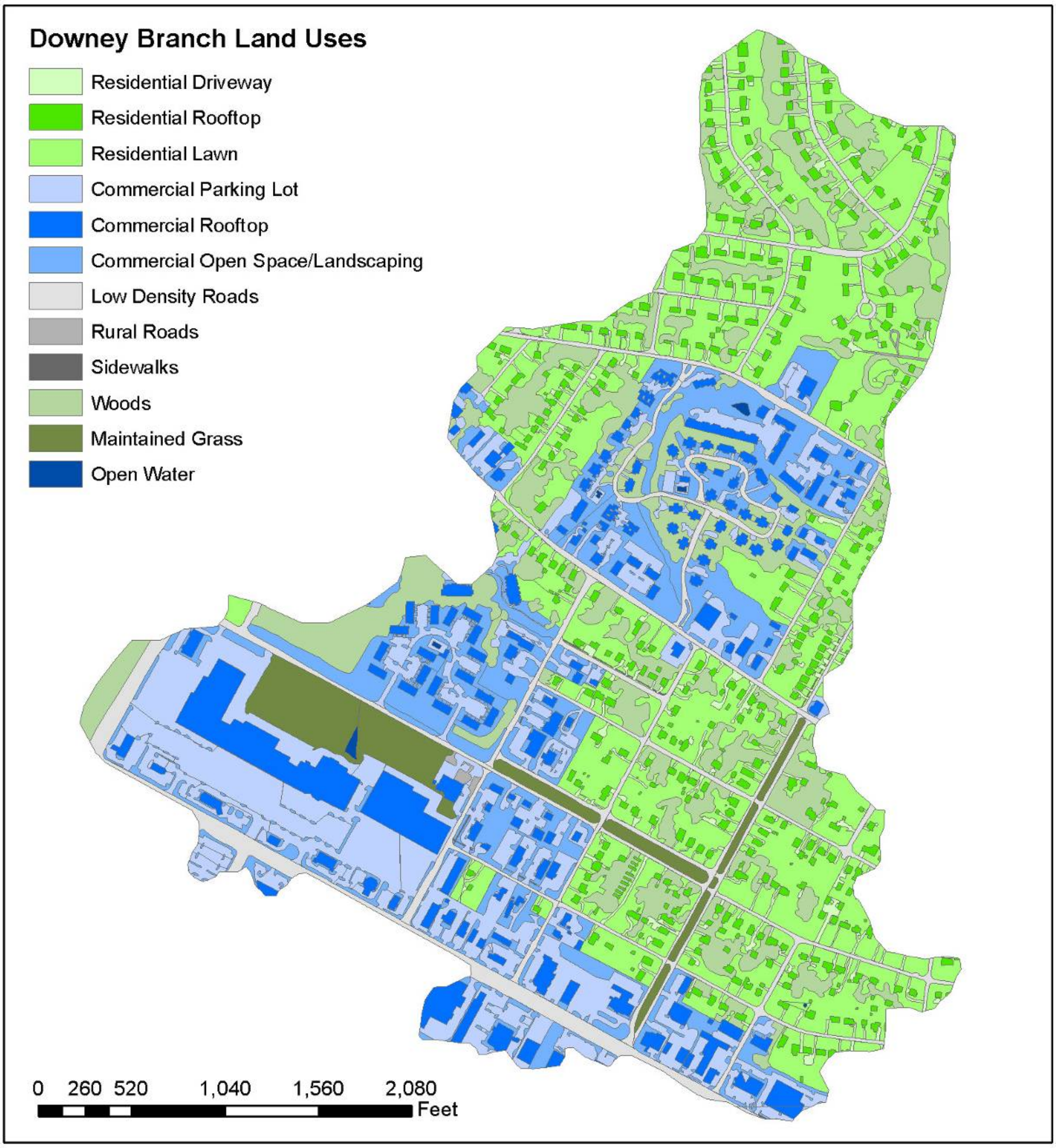

Figure 29. Downey Branch watershed land uses, as classified based on 2006 aerial photography.

Table 14. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the Downey Branch watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via the three SCM evaluation metrics discussed previously.

	Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
Mean Effluent Concentration Metric	21,690,819	85,869	336	1,961
Percent Mass Reduction Metric	21,690,819	86,008	336	1,962
Percent Concentration Reduction Metric	21,690,819	85,786	334	1,946

The individual implementation costs for the Downey Branch watershed ranged from $1,160 to $3,770,320. If all potential retrofit opportunities were implemented, the total implementation cost would be approximately $10,763,095, with annual operation and maintenance costs of approximately $278,204. The 30-year maintenance cost ($8,346,120) is slightly less than the cost of implementation. As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 30 and 31 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 145 kg (320 lbs) TN and 51 kg (112 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/3 of the practices are implemented. Figure 32 shows what types of practices generally fall within the most cost effective range for TN for the Downey Branch watershed.

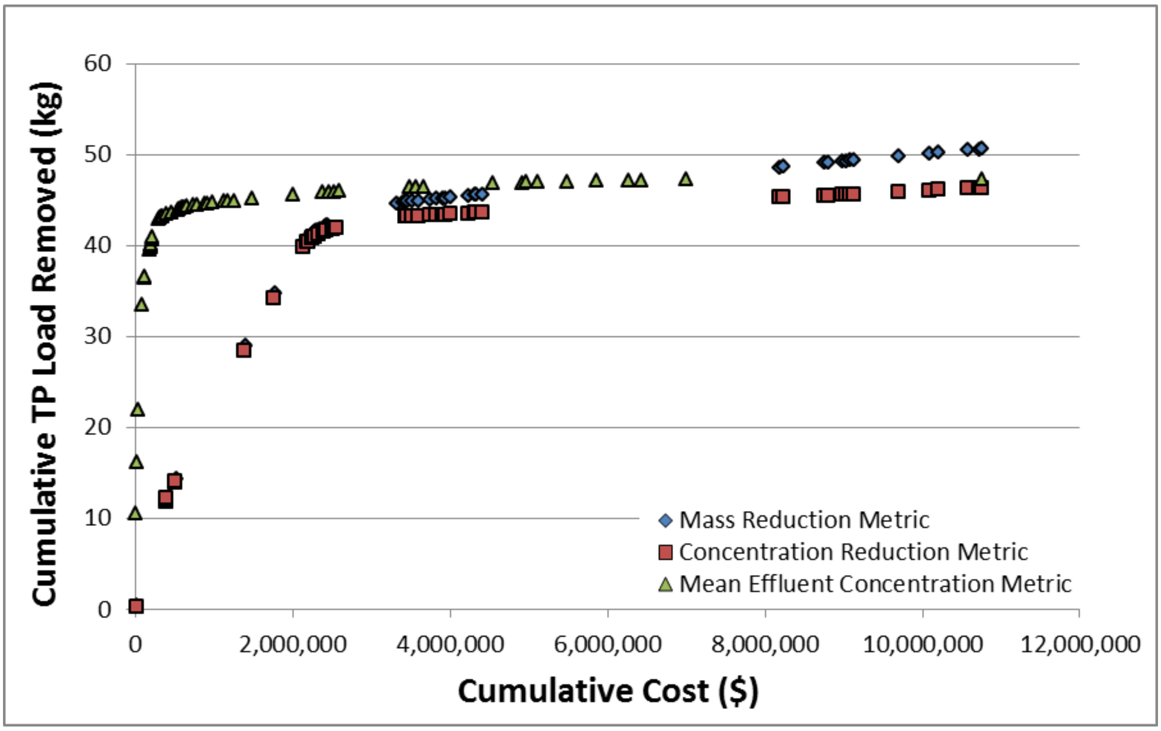

Figure 30. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Downey Branch watershed, as sorted by the cost per kg of TP removed.

As shown in Figure 32, the types of SCMs that proved to be most cost effective for TN removal included wetlands and the majority of bioretention practices. Permeable pavement, streetsweeping, vegetated swales and some bioretention practices were the least cost effective for TN removal. This changed slightly for TP, with streetsweeping, some bioretention practices, vegetated swales and wetlands being most cost effective for the Downey Branch watershed. Permeable pavement applications and the majority of bioretention practices were the least cost effective. The vertical line displayed in Figure 32 indicates the ‘break point’ between tier 1 (most cost effective) SCMs and tier 2 (least cost effective) SCMs. These first- and second-tier priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the Downey Branch watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

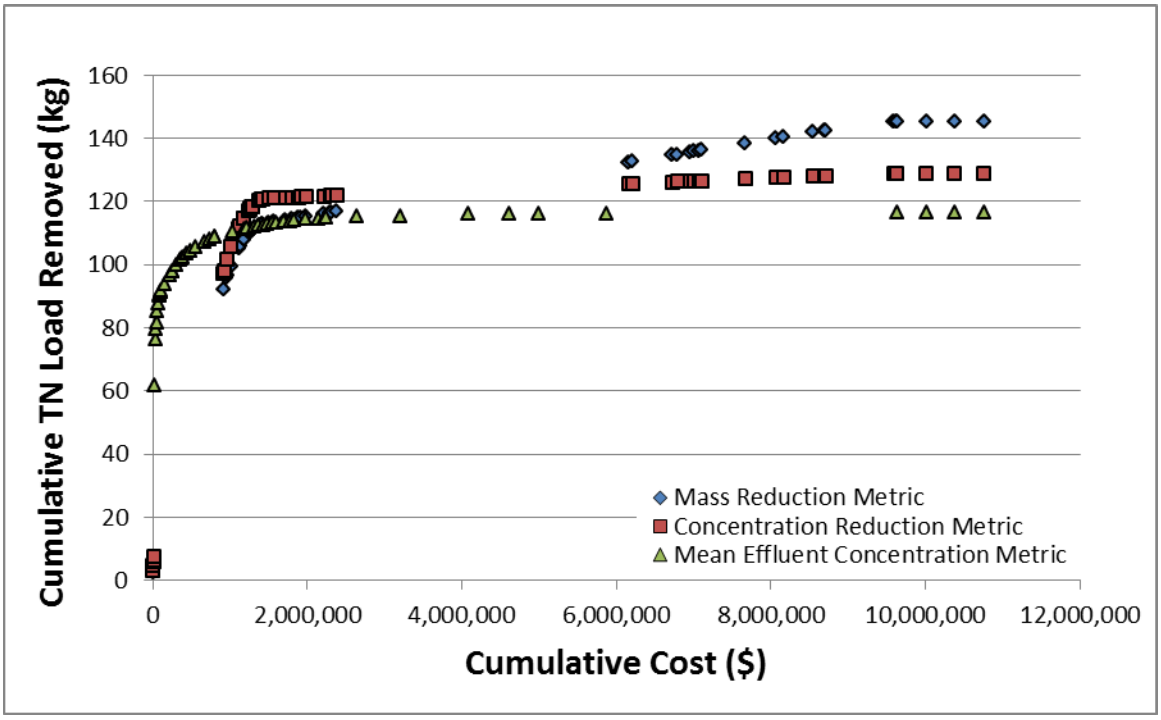

Figure 31. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Downey Branch watershed, as sorted by the cost per kg of TN removed.

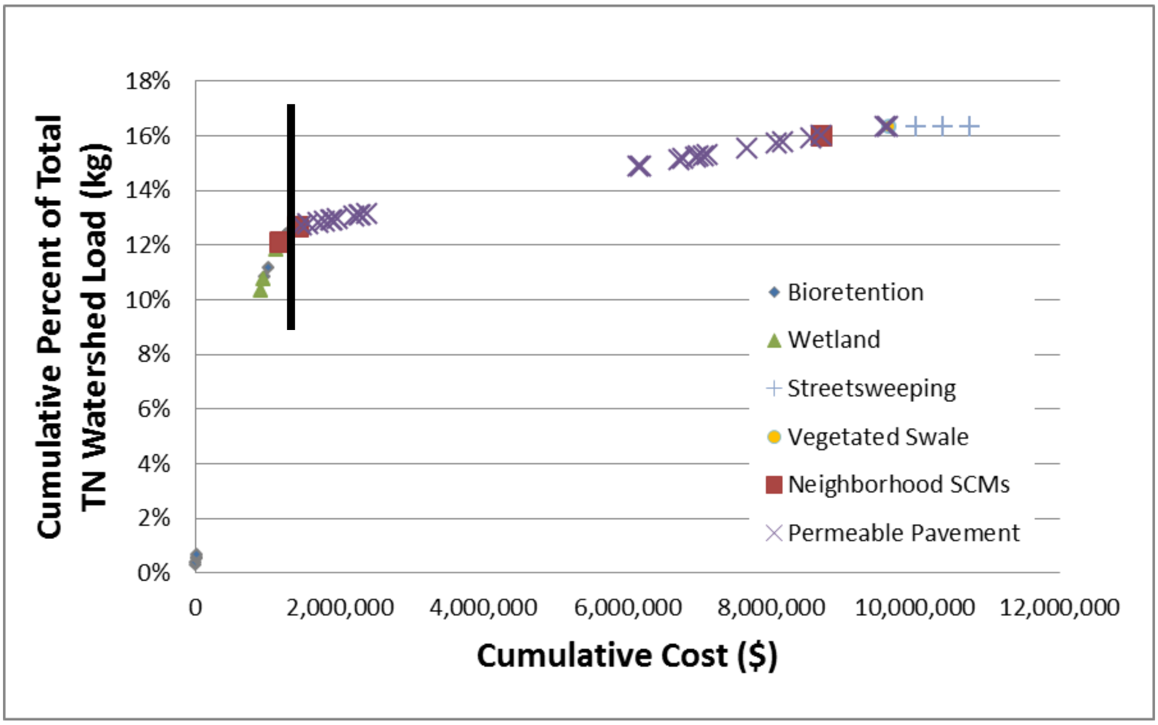

Figure 32. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.8 Individual Watershed Analyses – Winston-Salem (Tar Branch)

The Tar Branch watershed, located within the City of Winston-Salem, was approximately 413 ac. It encompassed a substantial amount of the downtown area of Winston-Salem, business route I-40 running through the middle of it. Latitude and longitude coordinates for the outlet of the watershed were determined and are included in the accompanying excel file. As downtown/ultra-urban land uses were included in the 'commercial' category, the majority of the watershed was comprised of commercial land uses (44%). As shown in Figure 33, residential and transportation uses made up 20% and 26%, respectively, and woods and maintained grass comprised 1% and 9% of the watershed area, respectively. Much of the area designated as residential was part of the historic district of Old Salem and was not reflective of a typical residential neighborhood.

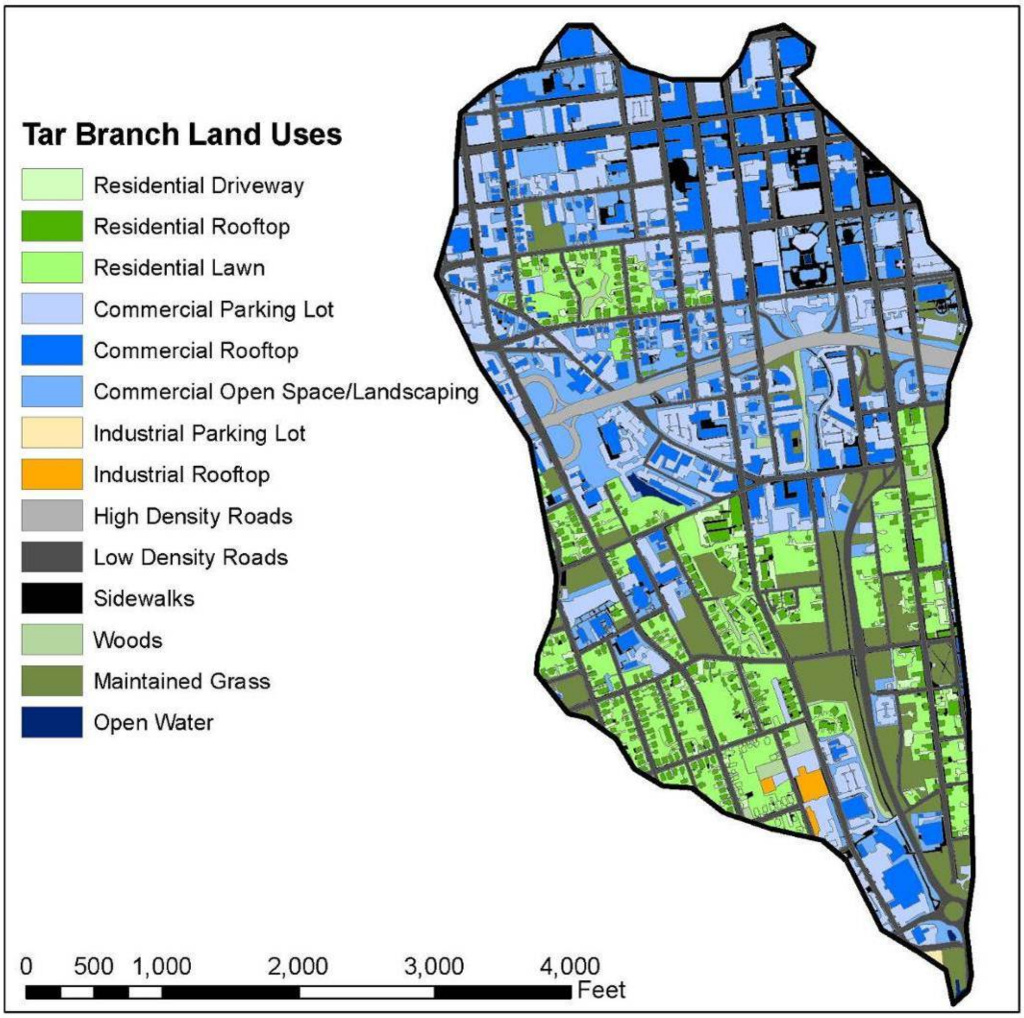

Figure 33. Tar Branch watershed land uses, as classified based on 2005 aerial photography.

There were no existing SCMs located within the watershed; thus the total annual volumes and loads calculated for the Tar Branch watershed served as the baseline values (and therefore evaluation metrics were not utilized). These values are displayed in Table 15. When normalized by the watershed size, the Tar Branch watershed produces approximately 235 lbs/ac/yr TSS, 1.33 lbs/ac/yr TP and 5.94 lbs/ac/yr TN.

Table 15. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the Tar Branch watershed prior to implementing retrofits.

Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
29,361,829	97,198	547	2,450

A surprisingly large number of potential SCMs (297) were identified via preliminary GIS analyses. After visiting the watershed, this number decreased slightly to 271. It was anticipated that the large number of retrofit opportunities was due to the large amount of commercial land use, the strategic placement of open space within these land uses, and the fact that the residential land uses were part of a historic district and contained more open space than typical newer, suburban-type residential land uses. The majority of the SCMs identified were either bioretention (83) or permeable pavement (67). Other SCMs included sand filters (28), water harvesting (24), downspout daylighting (23), green roofs (23), underground detention (8), wetlands (5), proprietary systems (5), level spreader/filter strips (3) and blue roofs (2). While the majority of SCM opportunities were located within the commercial/downtown areas, a substantial number were also located within the historic district of Old Salem, which is located in the bottom portion of the watershed (as shown in Figure 34). Additionally, five neighborhoods were identified as potential retrofit locations, the details of which are located in the accompanying excel file.

The individual implementation costs for the Tar Branch watershed ranged from $50 to $1,888,319. If all potential retrofit opportunities were implemented, the total implementation cost would be approximately $30,907,000, with annual operation and maintenance costs of approximately $783,889 (30-year projected maintenance costs of $23,516,670). This cost was approximately ¾ of the total implementation cost. As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 35 and 36 display the results of these analyses for TP and TN, respectively, as calculated using each of the 3 evaluation metrics discussed previously. As shown in the figures, a total of 164 kg (362 lbs) TN and 101 kg (223 lbs) TP can be removed if all identified retrofits were implemented. However, the water quality benefit provided compared to the cost decreased after approximately 1/2 of the practices are implemented.

As shown in Figure 37, the types of SCMs that proved to be most cost effective for TN removal included daylighting downspouts, level spreader/filter strips, and the majority of bioretention, water harvesting and wetland practices. Blue roofs, green roofs, streetsweeping and the majority of underground detention, permeable pavement and sand filter practices were the least cost effective for TN removal. For TP removal, daylighting downspouts, level spreader/filter strips, proprietary devices, and some bioretention practices proved to be most cost effective. Blue roofs, green roofs, streetsweeping, underground detention, wetlands and the majority of biotention, water harvesting, permeable pavement and sand filter practices were the least cost effective. The vertical lines displayed in Figure 37 indicate the ‘break points' between tiers 1 (most cost effective), 2 and 3 (least cost effective) SCMs. While data from the previous watersheds were easily divided into 2 priority groups, the data for this watershed necessitated the creation of three priority groups. These priority groups, as well as more details regarding size, design and specific location of each identified retrofit SCM for the Tar Branch watershed and can be found in the digitally attached spreadsheet file. Tables 18 and 19 summarize the estimated cost and pollutant removal if only Tier 1 SCMs were implemented.

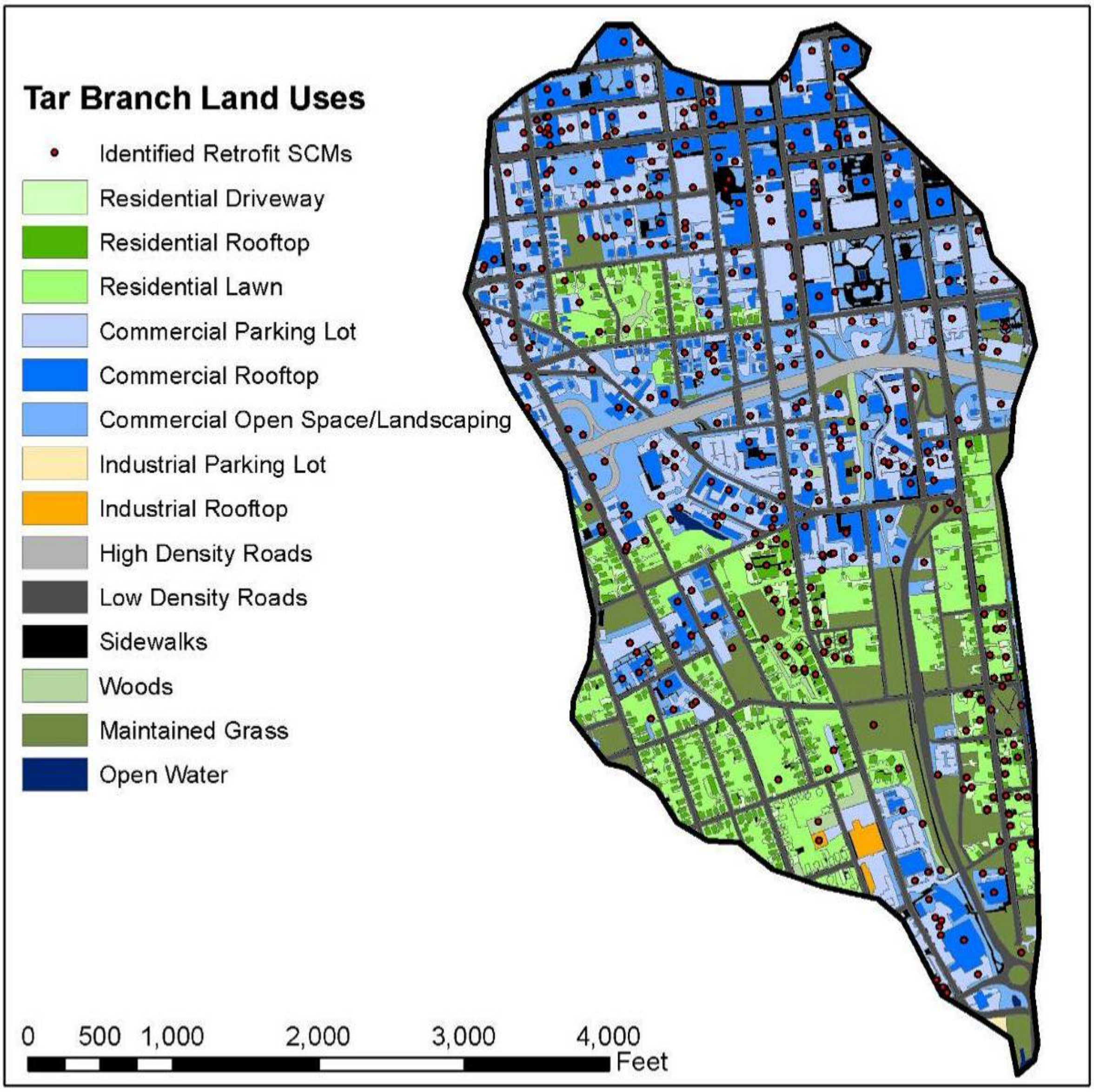

Figure 34. Locations of identified retrofit stormwater control measures (SCMs) within the Tar Branch watershed.

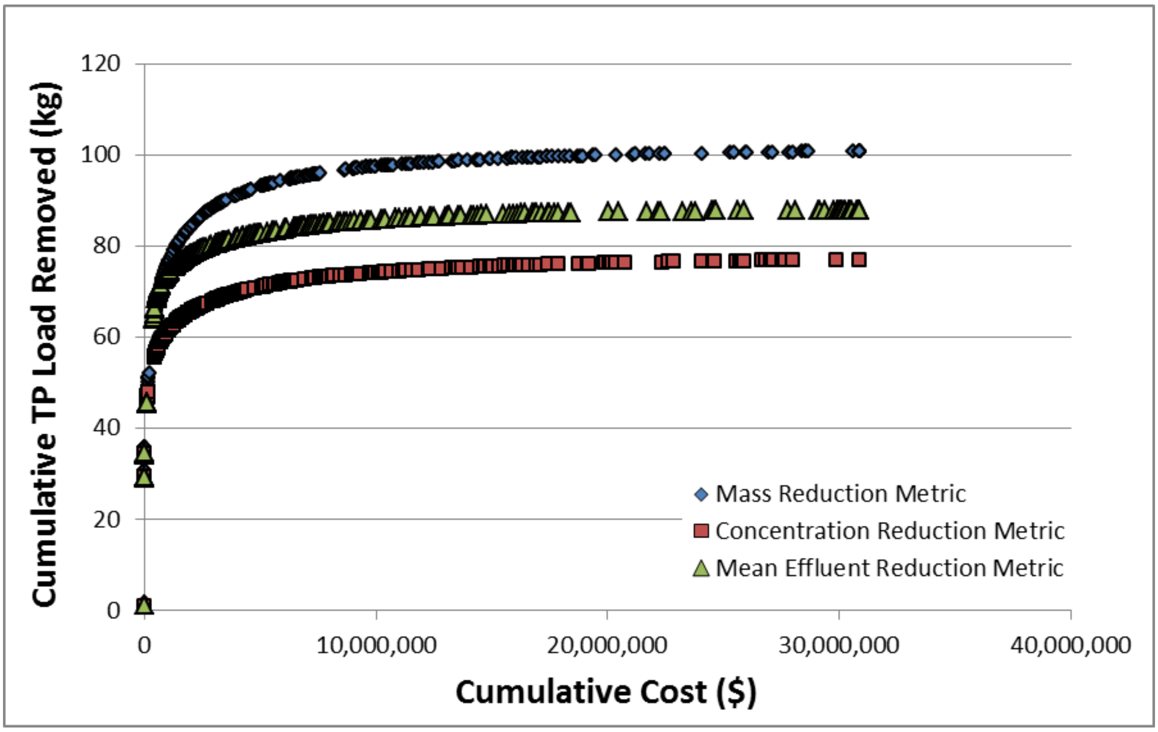

Figure 35. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Tar Branch watershed, as sorted by the cost per kg of TP removed.

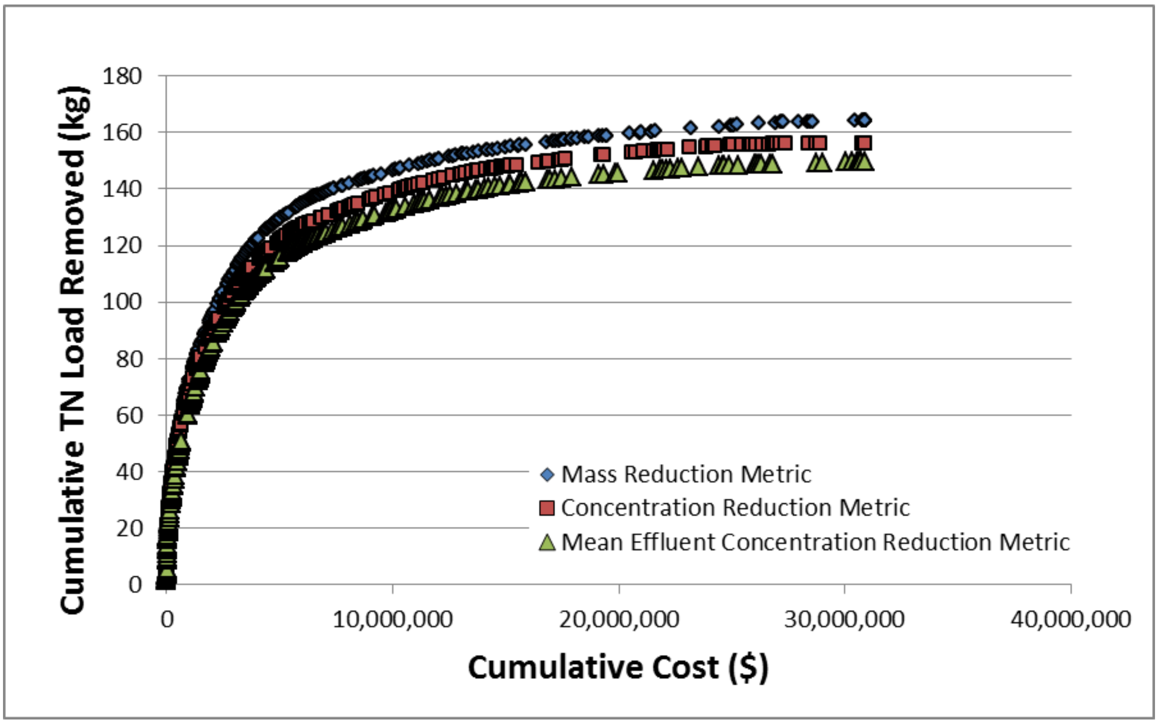

Figure 36. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Tar Branch watershed, as sorted by the cost per kg of TP removed.

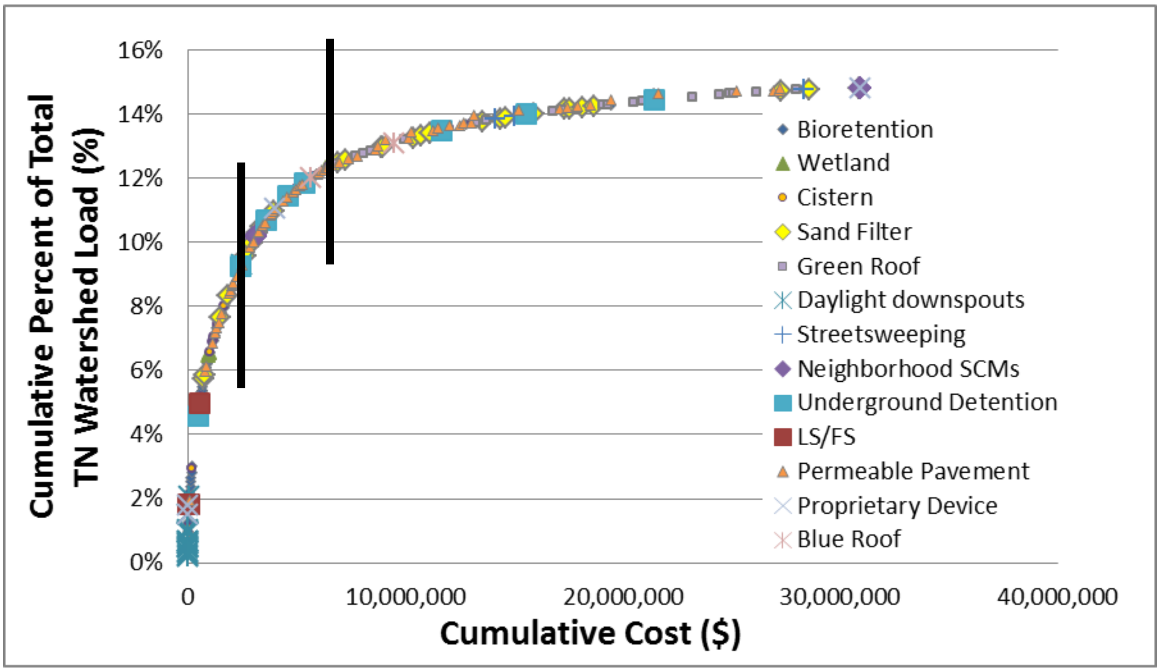

Figure 37. Cumulative percent of the baseline total nitrogen loading removed versus cumulative cost, as sorted by the cost per kg of TN removed (TN reduction calculated using the percent mass reduction metric). Type of stormwater control measure (SCM) is dictated by differing point styles. The vertical line indicates the 'break point' between tier 1 and tier 2 SCMs.

4.9 Large, Regional SCM Analyses

The watershed selected for the regional SCM analyses was located in the City of Raleigh and encompassed the Marsh Creek watershed previously discussed. This watershed was chosen because it was the only watershed submitted by the participating municipalities that met the criteria (8-10mi^2 in size with GIS data readily available). This watershed wholly encompassed the Marsh Creek watershed used for the site-specific BMP analyses. Latitude and longitude coordinates for the outlet of the watershed were 35°47'47.03"N 78°35'44.64"W. The watershed was 6,082 acres and was comprised of the following land uses: residential (40%), commercial (22%), woods (18%), transportation (11%), industrial (4%), institutional (2%), open water (2%), maintained grass (2%) and pasture (1%). Figure 38 shows the distribution and location of the various land use types within the large Marsh Creek watershed.

Numerous SCMs were already in place within the Large Marsh Creek watershed, including 8 bioretention cells, 15 dry detention basins, 2 level spreader/filter strips, 5 sand filters, 9 vegetated swales, 5 underground detention facilities, 15 wet retention ponds and 5 wetlands. Combined, these 64 practices treated approximately 361 ac. The runoff volume reduction and pollutant removal provided by these practices was subtracted from the total annual volumes and loads calculated for the Large Marsh Creek watershed, thus producing baseline values (displayed in Table 16). Only the mass reduction metric was applied to the Large Marsh Creek watershed; therefore all values are calculated using this method. When normalized by the watershed size, the Large Marsh Creek watershed produces approximately 227 lbs/ac/yr TSS, 0.84 bs/ac/yr TP and 4.4 lbs/ac/yr TN.

A total of 49 potential large retrofit SCMs were identified in the Large Marsh Creek watershed. Site visits and watershed reconnaissance decreased the number of feasible retrofits to 26. As the objective of these analyses was to evaluate the benefit of large, regional SCMs, only low-lying areas able to accommodate large wetland systems were considered. Wetlands were the only type of regional SCM considered, as they provide good water quality treatment and peak flow mitigation. Figure 39 shows the location of the identified SCMs.

Table 16. Annual runoff volumes, total suspended solids (TSS) loads, total phosphorus (TP) loads and total nitrogen (TN) loads leaving the Large Marsh Creek watershed prior to implementing retrofits, accounting for existing stormwater control measures (SCMs), and calculated via percent mass reduction metric.

Annual Runoff Volume (ft^3)	Annual TSS Load (lbs)	Annual TP Load (lbs)	Annual TN Load (lbs)
307,201,667	1,379,334	5,094	26,632

As the identified SCMs were located along streams of the watershed, many of them were in series with one another, receiving flow from one or more practices upstream. Several assumptions were made to calculate the flow reduction and pollutant removal of these practices. First, it was assumed that 20% of the volume entering a wetland was lost to evapotranspiration or exfiltration, 70% of the inflow volume was treated and 10% bypassed the system as untreated overflow. Secondly, any volume treated by an upstream practice was assumed to be improved as much as possible and therefore was not subject to additional treatment by any downstream practices. Finally, if there was not enough room for the wetland to be sized appropriately for the 1” storm event, runoff and pollutant reductions were reduced by the percent that the SCM was undersized. The volume remaining after the scaling was assumed to leave the system as overflow.

The individual implementation costs for the Large Marsh Creek watershed ranged from $182,875 to $27,974,029. If all potential retrofit opportunities were implemented, the total implementation cost would be approximately $82,205,708, with annual operation and maintenance costs of approximately $8,800,560 (30-year project maintenance cost of $264,016,800). As with the previous watersheds, graphs were created comparing the cost effectiveness of the identified SCMs. Figures 40 and 41 display the results of these analyses for TP and TN, respectively, as calculated using the mass reduction metric. As shown in the figures, a total of 4,151 kg (9,151 lbs) TN and 1,170 kg (2,579 lbs) TP can be removed if all identified retrofits were implemented. While not as pronounced as some of the other watersheds studied, an inflection point does exist for this watershed as well. Spending approximately $20-$35M for BMP implementation (not including recurring maintenance costs) in this watershed would achieve approximately 50% of the possible TN and TP removal. Municipalities would need to determine their own break points based on available finances and resources for building and maintaining the practices.

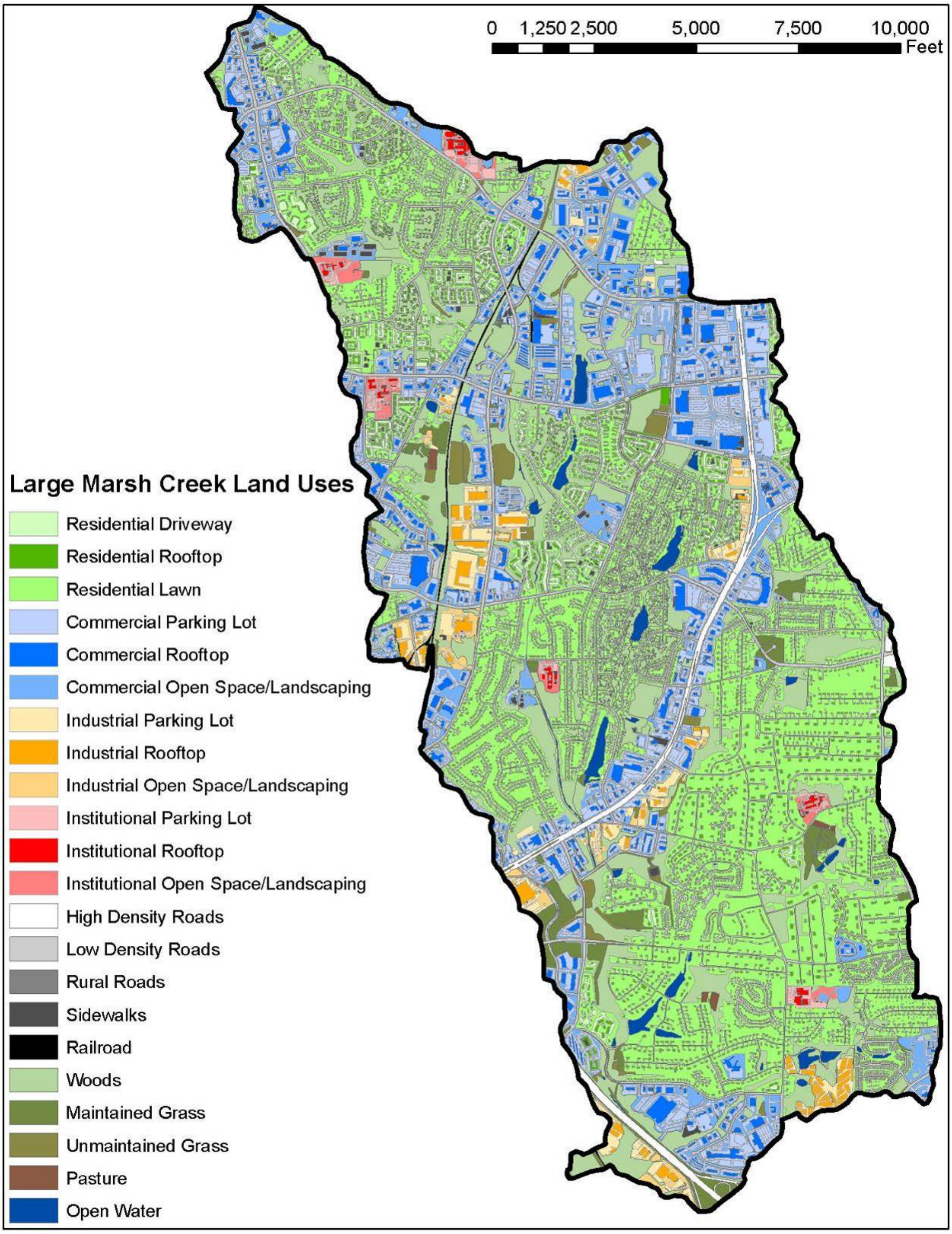

Figure 38. Large Marsh Creek watershed land uses, as classified based on 2005 aerial photography.

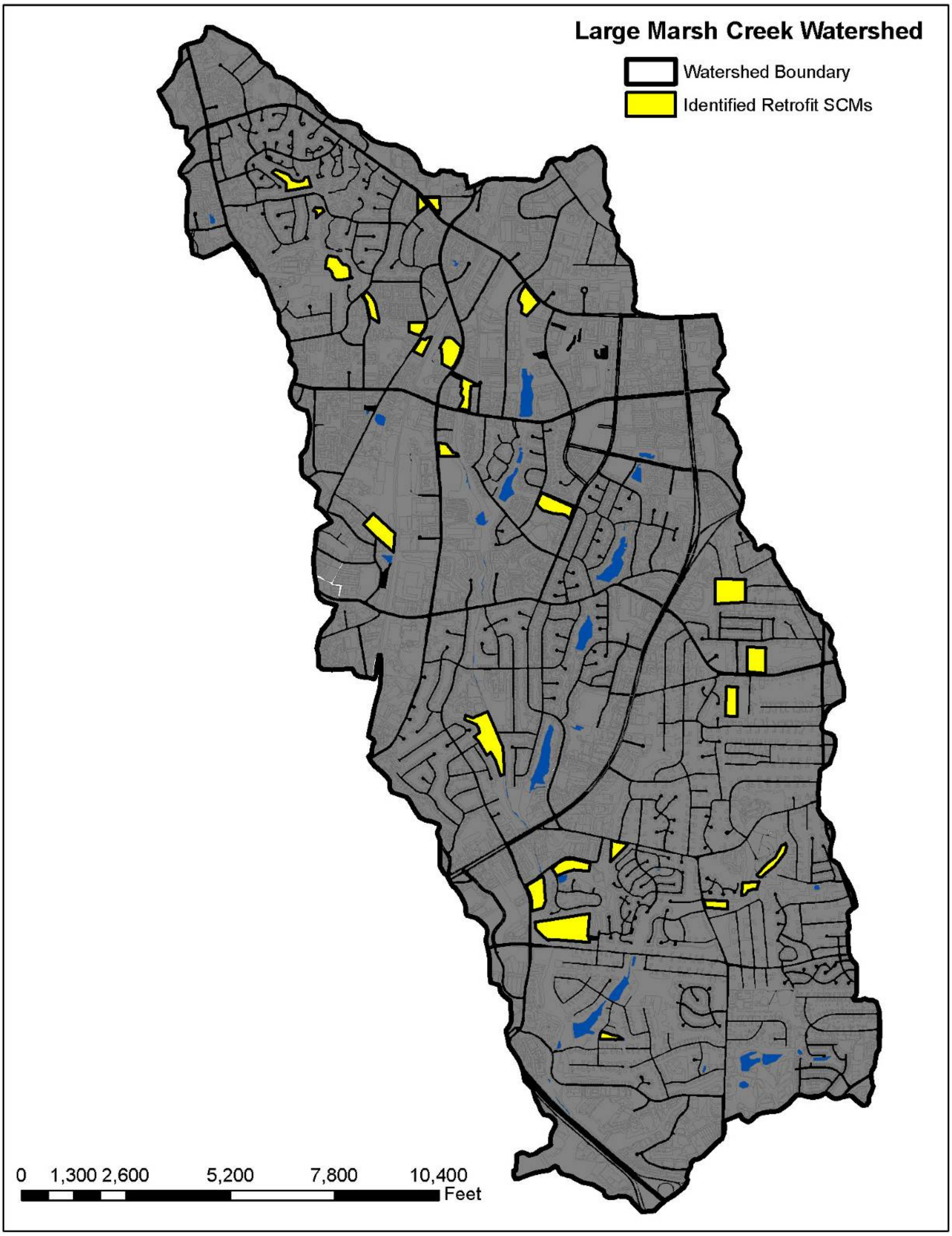

Figure 39. Locations of identified retrofit SCMs within the Large Marsh Creek watershed.

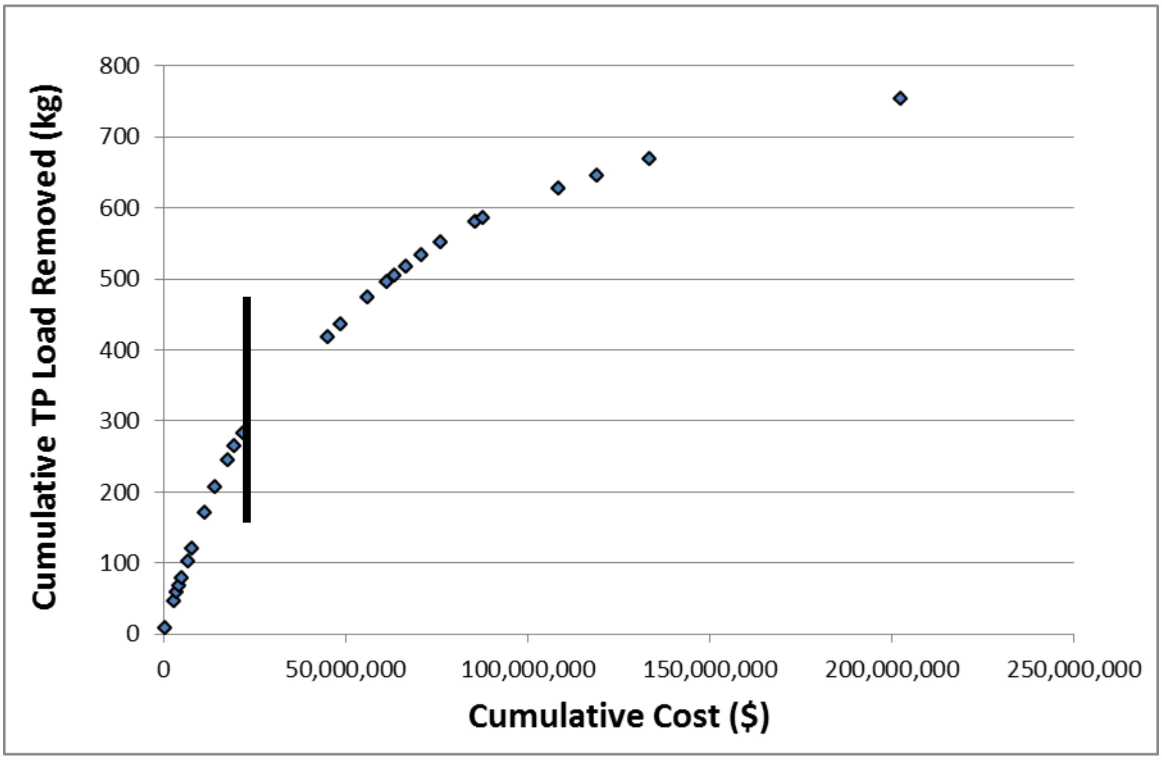

Figure 40. Cumulative total phosphorus (TP) removed annually versus cumulative cost for the Large Marsh Creek watershed, as sorted by the cost per kg of TP removed.

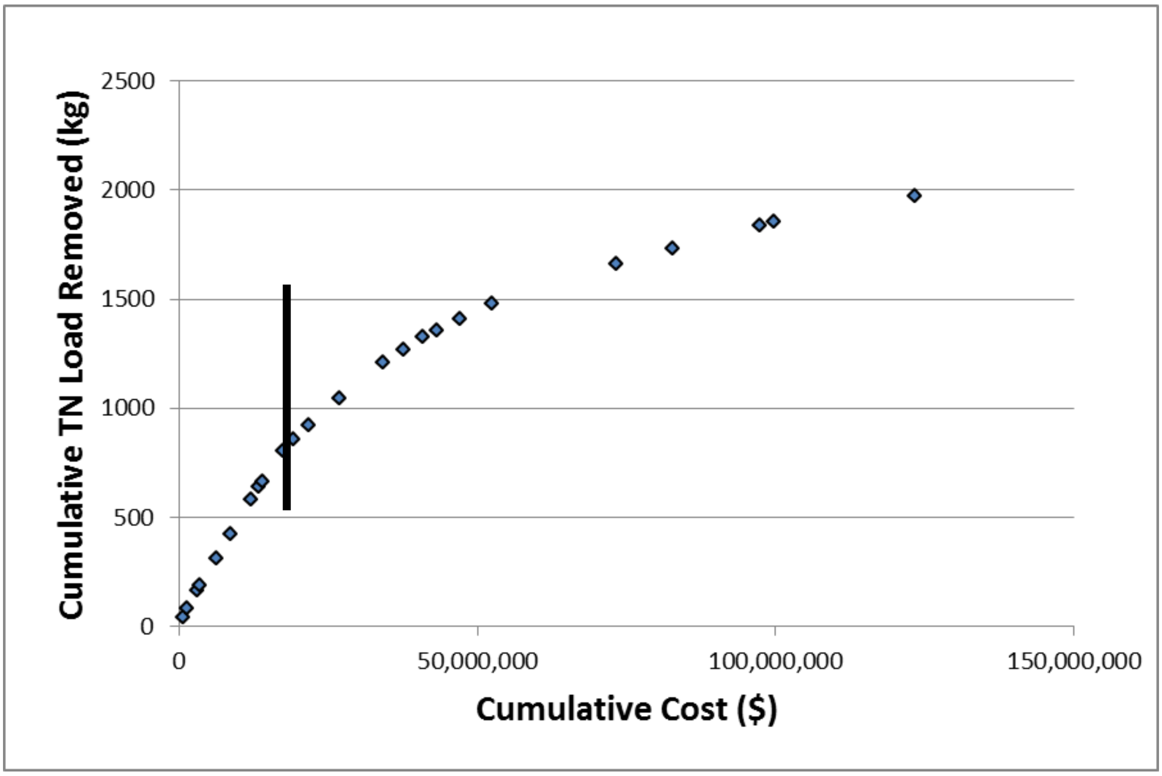

Figure 41. Cumulative total nitrogen (TN) removed annually versus cumulative cost for the Large Marsh Creek watershed, as sorted by the cost per kg of TN removed.

4.10 Overall Trends and Tendencies

The number of retrofit SCM opportunities identified within each watershed ranged widely, from 20 in one of the Greensboro watersheds to 273 in Winston-Salem. The number and type of retrofit opportunities in a given watershed proved to be a function of the type of land uses in that watershed. It was especially difficult to decrease the amount of TN and TP in stormwater runoff leaving undeveloped lands. This is due to the fact that many practices considered for stormwater management are often already employed in the rural landscape. Examples of these include vegetated swales alongside roadways (as opposed to curb and gutter) as shown in Figure 42a, minimal amounts of impervious surfaces (dirt/gravel roads and driveways, narrower paved roads) as shown in Figure 42b, increased grass heights, forestation, and wooded buffers along streams and regional ponds. Roadways were also difficult to retrofit, as they offer many constraints, notably the lack of space and the presence of utilities and sanitary sewers.

Figure 42. Photographs taken in Greensboro SB watershed depicting rural land use characteristics.

The feasibility of implementing retrofits in ultra-urban or downtown areas varied greatly. In the Ellerbe Creek watershed (Durham), these areas were highly impervious and offered a limited amount of space for SCMs, whereas in the Tar Branch watershed (Winston-Salem) there were many opportunities. Figures 43a, 43b and 43c depict locations in the Tar Branch watershed where permeable sidewalks, permeable pavement and sand filters could be implemented, respectively. Institutional land uses generally provided ample opportunity for retrofit SCMs, as the number of roadways was limited and open space was relatively plentiful (see Figure 44). While perhaps not intuitive, most commercial and industrial areas led to a higher number of retrofit opportunities than other land uses due to the prevalence of parking lots, most of which could be easily retrofitted with bioretention median strips or permeable pavement (see Figure 45). Most industrial areas were also rather easy to retrofit with SCMs. Large parking lots could be treated with bioretention or permeable pavement, and often there was ample open space surrounding industrial buildings to treat roof runoff with rain gardens or rainwater harvesting, as shown in Figure 46.

Figure 43. Photographs taken in Tar Branch (Winston-Salem) watershed depicting ultra-urban/downtown land use characteristics.

Figure 44. Photographs taken in the Ellerbe Creek (Durham) watershed depicting institutional land use characteristics.

Figure 45. Photographs a) and b), taken in the Marsh Creek (Raleigh) and Lower Toby (Charlotte) watersheds, respectively, depicting commercial land use characteristics.


Figure 46. Photographs taken in the Nance (High Point) watershed depicting industrial land use characteristics.

The feasibility of implementing retrofits varied greatly among residential land uses and was usually dictated by the age of the development. In the watersheds studied, newer developments (Figure 47a) often had more impervious space and less open space than older developments (Figure 47b), which decreased the amount of space available for retrofit practices in somewhat newer developments. Stormwater runoff was generally routed very efficiently via curb and gutter or underground pipes to large stormwater ponds at the edge of the development, leaving little to no opportunities for diversion or treatment. Older developments usually contained larger lot sizes, narrower roads and more open space. Roads were frequently drained with vegetated swales and many residences contained permeable driveways.

Figure 47. Photographs taken in the NB (Greensboro) watershed depicting newer (left) and older (right) residential land use characteristics.

Estimated annual load reductions varied somewhat among the eight watersheds (Figure 48). This is primarily due to the quantity and type of SCMs that are most prevalent for the land uses within a given watershed. There was no discernable relationship between watershed size and reduction in pollutants; however, the number of SCMs identified within a watershed was generally a factor of the predominant types of land uses, namely commercial and industrial. This indicates that focusing retrofit efforts on land uses that traditionally offer the most retrofit opportunities will most likely result in the highest pollutant load reductions.

Figure 48 also allows for the comparison of the site-specific SCM retrofitting approach applied to the eight small watersheds and the large, regional SCM retrofitting approach applied to the Large Marsh Creek watershed. As expected, the regional approach proved to cost less per square mile of watershed treated than seven of the eight watersheds where the site-specific approach was used. This indicates that economies of scale do exist when retrofitting watershed with SCMs.

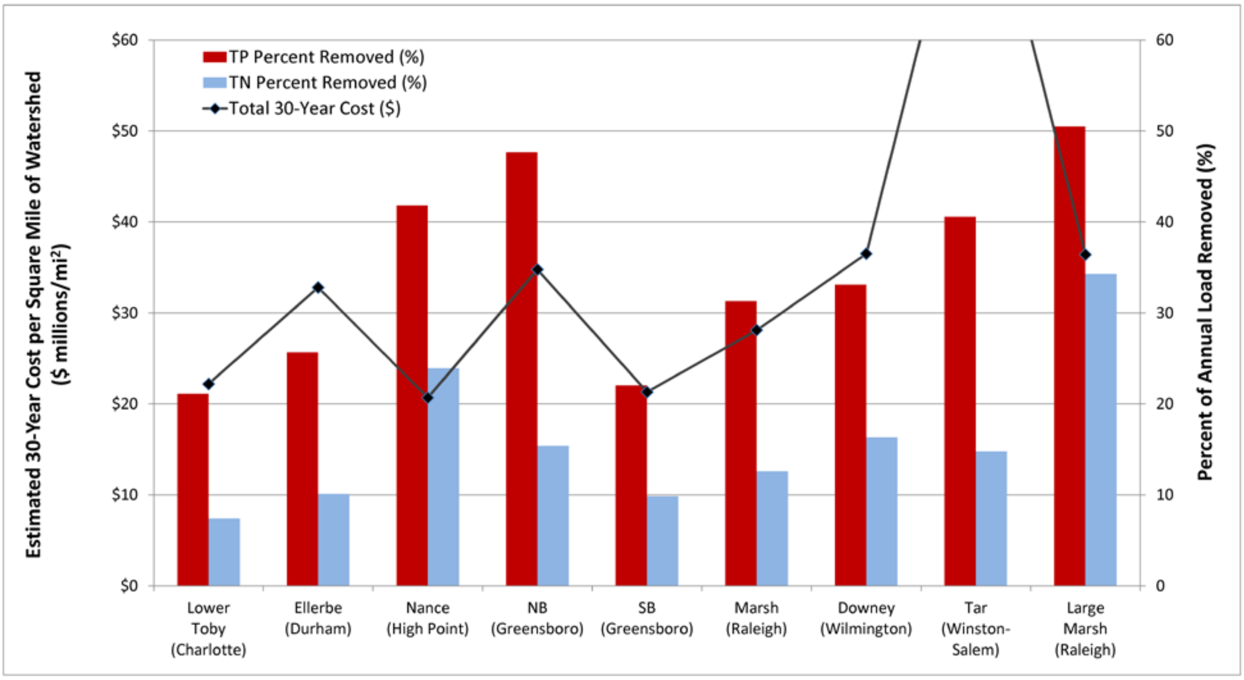

Figure 48. Nine studied watersheds in North Carolina, USA, their corresponding areas and the annual reduction of total nitrogen (TN) and total phosphorus (TP) loads expectedby retrofit stormwater control measures. Cost values include initial implementation cost and 30 years of annual maintenance costs.

The fraction of a pollutant removed was highly dependent on the proportion of watershed that was treated. Every watershed that had ~15% TN removal or better had at least 40% of its surface area receiving treatment by an SCM. An exception to this fact was the Downey Branch watershed in Wilmington, which is most likely due to the location of the watershed (in the coastal plain) and higher infiltration/removal by SCMs. Nevertheless, an important conclusion from this study was that in most cases, the larger the fraction of a given watershed that can be treated, the more a pollutant can be removed.

Table 17. Fraction of Watershed Treated by SCM

Location	Area treated by SCM (ac)	Total Watershed Area (ac)	% of Watershed Treated
Charlotte	248.8	1199.4	20.7%
Durham	170.0	464.8	36.6%
High Point	211.0	477.4	44.2%
Greensboro NB	326.2	715.1	45.6%
Greensboro SB	113.4	747.9	15.2%
Raleigh	367.2	976.4	37.6%
Wilmington	108.5	334.8	32.4%
Winston-Salem	196.7	412.7	47.7%
Large, Regional SCMs	2,832	6,082	46.6%

As discussed previously, there is a point in all watersheds studied where the marginal cost of implementing additional SCMs per the pollutant treatment provided may prove to be too high to justify implementation. This point is where Tier 1 SCMs end and Tier 2 SCMs begin. This point, as well as the SCMs included in Tiers 1 and 2 vary by the type of pollutant (TP or TN) being analyzed. Table 18 summarizes the estimated annual pollutant removal and associated costs if all Tier 1 SCMs were implemented to optimize TP removal. Table 19 summarizes the estimated pollutant removal and associated costs if all Tier 1 SCMs were implemented to optimize TN removal. As shown in these tables, a large portion of the potential total pollutant removal can be achieved within a watershed at a fraction of the total annual cost.

Table 18. Estimated annual costs and total phosphorus (TP) and total nitrogen (TN) removal achieved by implementing Tier 1 SCMs for optimum TP removal.

Watershed	Estimated Total Initial Cost ($)	Estimated Annual Operation & Maintenance Cost ($)	Annual TP Removed (lbs)	Annual TN Removed (lbs)
Charlotte	$2,442,345	$304,224	177.5 (75%)	260.4 (57%)
Durham	$2,582,788	$127,495	163.1 (88%)	195.8 (60%)
Greensboro NB	$2,469,443	$478,994	158.3 (75%)	174.2 (50%)
Greensboro SB	$1,327,034	$264,018	63.9 (78%)	96.8 (66%)
High Point	$1,659,070	$210,080	99.4 (81%)	220.9 (72%)
Raleigh	$3,674,409	$78,336	223.5 (70%)	343.0 (47%)
Wilmington	$2,198,285	$191,234	90.2 (81%)	223.5 (70%)
Winston-Salem	$1,156,353	$43,621	171.1 (77%)	138.0 (38%)
Large, Regional SCMs	$33,519,240	$3,381,059	2,002.5 (78%)	6,917.7 (76%)

*Values in parenthesis indicate the percent of total possible annual pollutant removal if all SCMs were implemented.

Table 19. Estimated annual costs and total phosphorus (TP) and total nitrogen (TN) removal achieved by implementing Tier 1 SCMs for optimum TN removal.

Watershed	Estimated Total Initial Cost ($)	Estimated Annual Operation & Maintenance Cost ($)	Annual TP Removed (lbs)	Annual TN Removed (lbs)
Charlotte	$2,442,345	$304,224	70.8 (30%)	278.2 (61%)
Durham	$2,582,788	$127,495	78.9 (43%)	259.3 (80%)
Greensboro NB	$2,469,443	$478,994	74.3 (35%)	259.0 (75%)
Greensboro SB	$1,327,034	$264,018	21.8 (27%)	101.2 (69%)
High Point	$1,659,070	$210,080	82.2 (67%)	291.9 (95%)
Raleigh	$3,674,409	$78,336	101.6 (32%)	520.7 (71%)
Wilmington	$2,198,285	$191,234	41.7 (37%)	242.3 (76%)
Winston-Salem	$1,156,353	$43,621	98.1 (44%)	261.7 (72%)
Large, Regional SCMs	$33,519,240	$3,381,059	1,497.8 (58%)	6,194.7 (68%)

*Values in parenthesis indicate the percent of total possible annual pollutant removal if all SCMs were implemented.

Finally, these analyses also highlighted the types of SCMs that, on average, are most cost effective in terms of pollutant removal. While these varied slightly from watershed to watershed, when examined across all eight watersheds studied, preferential SCMs were evident (Table 20). These SCMs were the types that most often appeared in Tier 1 for the watersheds. As stated previously, the efficiency of a SCM is different for TN and TP; therefore, the optimal SCMs for TN and TP are different as well. These lists can be helpful when retrofitting watersheds, as they highlight which SCMs will most likely provide the most benefit for the least amount of cost for a given pollutant of concern.

Table 20. Most cost effective stormwater control measures (SCMs) with respect to cost per kilogram of pollutant removed (cost effectiveness.

Most Cost Effective SCMs With Respect to TN Removal	Most Cost Effective SCMs With Respect to TP Removal
Daylighting Downspouts	Level Spreader/Filter Strips
Level Spreader/Filter Strips	Streetsweeping
Bioretention	Daylighting Downspouts
Stormwater Wetlands	Stormwater Wetlands
Water Harvesting	Vegetated Swales
Sand Filters	Bioretention

4.11 Differences Among the Three SCM Evaluation Metrics

In general, the mean effluent concentration predicted the most TP load removal, followed closely by the Mass Reduction and then by the Concentration Reduction metrics. The Mass Reduction metric projected the most TN removal, followed by the concentration metric and then the mean effluent metric. These were trends rather than absolute observations. The reason for a lack of consistency depended upon the types of practices selected. For example, permeable pavement would “score” very well using the mean effluent metric for Total Nitrogen, as the effluent concentration assigned to it was 0.95 mg/l, which was the 2nd lowest among SCMs. However, when looking at the mass reduction or concentration reduction metrics, permeable pavement had among the lowest reduction rates. So, in watersheds that were comprised of greater fractions of commercial and industrial land uses and consequently had a higher proportion of permeable pavement (Charlotte, Durham, Raleigh, and Winston-Salem), the mean effluent concentration predicted relatively more nitrogen loss than did the watersheds with higher fractions of residential development. By concentrating our discussion on the mass removal metric, the authors were choosing a metric that predicted either the most or second most pollutant load removal.

4.12 Implications for Urban Areas of North Carolina

The state-mandated nutrient reduction goals set forth by North Carolina require municipalities within the Jordan Lake watershed to reduce the annual export of TN and TP by 8% and 5%, respectively. Municipalities are expected to achieve these reductions by implementing retrofit stormwater BMPs, such as those investigated in this study. If water quality within the lake does not improve by an acceptable amount (criteria by which this is determined is detailed within the regulation, which can be found at http://portal.ncdenr.org/web/jordanlake) within a given time period, the TN reduction requirement will increase to 35%. When the estimated reduction in nutrients provided by retrofit SCMs was expressed as a percent of the pre-retrofit annual load leaving the watershed, 8 of the 9 watersheds met the initial reduction requirements in the new regulations. When compared to the possible TN reduction requirement of 35%, none of the nine watersheds study were in compliance. All watersheds met and exceeded the 5% TP reduction requirement set forth by the regulation.

5.0 OUTCOMES AND CONCLUSIONS

Due to new regulations regarding the management of stormwater, understanding the relationship between cost and pollutant removal is important for widespread implementation and water quality improvement. Municipalities installing SCMs throughout a watershed are most interested in knowing which practices are the most cost effective in terms of the pollutant reduction they provide. This study identifies those SCMs for 9 urban watersheds in the state of North Carolina, USA, and highlights trends that can aid municipalities in making informed and strategic decisions regarding retrofit SCM implementation. Perhaps most importantly, this study demonstrates that there is a point of diminishing returns when employing these practices in urban watersheds, although this point varies based on watershed characteristics, the number and types of retrofits and the pollutant of interest.

Certain SCMs did tend to provide more benefit than others. Namely level spreader-vegetated filter strips, stormwater wetlands and bioretention were uniformly the three practices to reduce nitrogen and phosphorus loads at the lowest cost. This appears to be the case because these practices have high removal effiencies and they both treat proportionally larger catchments than many of the other SCMs, such as permeable pavement and green roofs.

As expected, the use of larger, regional SCMs was a more cost-effective approach, based on cost per pollutant removal, than a site-specific approach. This verifies that economies of scale do exist when retrofitting watersheds with SCMs and municipalities should consider this type of approach to reduce the number of stakeholders, landowners, parcels and cost.

Readers are cautioned to not view the costs presented herein with 100% certainty. It is the authors' belief that they could be as much as 20% too low; however, there are not sufficient data to support that assertion. The amount of time dedicated to public involvement, for example, was unaccounted for and street sweeping maintenance costs did not include human time dedicated to the task.

Finally, the results presented herein indicate that achieving TN in excess of 20% and TP in excess of 50% via retrofit SCMs is very difficult in the urban watersheds studied; however, if "low hanging fruit" SCMs are chosen, a proportionally large fraction of the total potential pollutant removal can be achieved for less cost. Regardless of watershed size, location or characteristics, retrofitting urban areas with SCMs promises to be an expensive task.

6.0 RECOMMENDATIONS

This study illustrates the challenges of meeting nutrient reduction goals in watersheds that are built out by only employing stormwater retrofits. Findings of the work herein can generally be applied in communities across North Carolina and in surrounding states. Among these are:

1. Land uses most easily retrofit with stormwater practices were commercial and industrial. As communities search for locations to employ retrofits, these should probably be the first land use types examined.

2. Certain SCMs provide the most "bang for the buck." Communities and designers may initially target the use of level spreader-vegetated filter strips, stormwater wetlands and bioretention. Obviously, if the targeted pollutant for removal differs, so might the practices selected.

3. The study supports the use of larger watershed-scale SCMs, as economies of scale exist. Communities that inherit a maintenance burden with the addition of retrofit SCMs are recommended to strongly consider larger SCMs, such as constructed stormwater wetlands, as an initial retrofit option.

4. As communities proceed with selection and installation of SCMs, they must keep in mind the operation and maintenance costs associated with each. Thirty year O&M costs in many of the watersheds studied easily exceeded 3 times the cost of design and installation.

5. Perhaps most importantly, a cautionary recommendation is made regarding the requirement of communities to meet strict and far-reaching nutrient reduction goals solely from existing development. While modest reductions (e.g., 5%) of N and P loads certainly are attainable from existing development, aggressive 30% or greater nutrient reduction requirements are going to often be impossible without converting large amounts of impermeable surfaces and space to permeable and green landscapes.

7.0 BUDGET

The project came in under the proposed budget. The table below shows the requested versus actually spent totals (of Federal Funds) for the budgeted line items:

Table 21. Budget: Expected versus Realized.

Line Item	Requested	Actual
Personnel/ Salary	$57,793	$48,480
Fringe Benefits	$11,146	$13,126
Travel	$260	$0
Other (Tuition)	$5,410	$5,304
Total Direct	$74,609	$66,910
Indirect	$7,461	$6,289
Total	$82,070	$73,199

8.0 REFERENCES

Al-Hamdan A.Z., Nnadi F.N. and Romah M.S. (2007). Performance reconnaissance of stormwater proprietary best management practices. *J. Environ. Sci. Heal. A.*, **42**, 427-437.

Bannerman R.T., Owens D.W., Dodds R.B. and Hornewer N.J. (1993). Sources of pollutants in Wisconsin stormwater. *Wat. Sci. Tech*., **28**(3-5), 241-259.

Bass K. L. 2000. Evaluation of a small in-stream constructed wetland in North Carolina's coastal plain, M.S. thesis, North Carolina State University, Raleigh, NC, USA.

Brown R.B. and Hunt W. F. (2009). Internal water storage (IWS) for bioretention. North Carolina Cooperative Extension Service, Raleigh, NC, USA.

Center for Watershed Protection (CWP) (2007). Manual 3: Urban stormwater retrofit practices. Urban Subwatershed Restoration Manual Series. Ellicott City, MD, USA.

Erickson, A. J., J. S. Gulliver, P. T. Weiss and C. B. Wilson. (2009). Survey of stormwater BMP maintenance practices. Proc., Universities Council on Water Resources Annual Conference on Urban Water Management: Issues and Opportunities, UCOWR, Chicago, IL.

Hathaway J.M., Hunt W.F. and Johnson A. (2007). City of Charlotte pilot BMP monitoring program: Morehead Place dry detention basin, Final Monitoring Report, City of Charlotte, NC USA.

Hathaway J.M. and Hunt W.F. (2008). Field evaluation of level spreaders in the piedmont of North Carolina. *J. Irrig. Drain. E.*, **134**(4), 538-542.

Hunt, W. F. and W. G. Lord. (2003). Determining inspection and maintenance costs for structural BMPs in North Carolina. UNC-WRRI Report.

Hunt W.F. and Lord W.G. (2006). Bioretention performance, design, construction and maintenance. North Carolina Cooperative Extension Service, Raleigh, NC, USA.

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, N.C. *J. Environ. Eng.-ASCE*, **134**(5), 403-408.

Irish L.B., Jr., Lesso W.G., Barrett M. E., Malina J.F., Jr., and Charbeneau R. J. (1995). An evaluation of the factors affecting the quality of highway runoff in the Austin, Texas area, Technical Report No. CRWR 264, Center for Water Resources, Bureau of Engineering Research, Univ. of Texas, Austin, TX, USA.

Lenhart H.A. (2008). A North Carolina field study to evaluate the effect of a coastal stormwater wetland on water quality and quantity and nitrogen accumulation in five wetland plants in two constructed stormwater wetlands, M.S. Thesis, North Carolina State University, Raleigh, NC, USA.

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), 407.

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

Line D. E. and Hunt W.F. (2009). Performance of a bioretention area and a level spreader-grass filter strip at two highway sites in North Carolina. . *J. Irrig. Drain. E.*, **135**(2), 217-224.

Moran A.C. (2004). A North Carolina field study to evaluate greenroof runoff quantity, runoff quality, and plant growth, M.S. Thesis, North Carolina State University, Raleigh, NC, USA.

Natural Resources Conservation Service (NRCS). (1986). Hydrology for small watersheds, Technical Release 55, National Technical Information Service, Springfield, VA, USA.

North Carolina Department of Environment and Natural Resources (NCDENR) (2008). North Carolina stormwater best management practice (BMP) manual. North Carolina Department of Environment and Natural Resources website, http://h2o.enr.state.nc.us/su/bmp_forms.htm, visited 25 March 2011.

North Carolina Department of Environment and Natural Resources (NCDENR) (2009). Jordan Lake nutrient strategy. North Carolina Department of Environment and Natural Resources website, http://h2o.enr.state.nc.us/nps/JordanNutrientStrategy.htm#News, visited 25 March 2011.

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. *J. Irrig. Drain. E.*, **135**(4), 505-510.

Pitt, R., R. Field, M. Lalor and M. Brown. 2005. Urban stormwater toxic pollutants: assessment, sources and treatability. Water Environment Research. **67**(3):260-275.

Schueler T. (1987). Controlling urban runoff: A practical manual for planning and designing urban best management practices, Metropolitan Washington Council of Governments, Washington D.C.

Sharkey L.J. (2006). The performance of bioretention areas in North Carolina: A study of water quality, water quantity, and soil media, M.S. thesis, North Carolina State University, Raleigh, NC, USA.

Skipper G.M. (2008). Watershed-scale stormwater monitoring of a mixed land use watershed in the North Carolina Piedmont, M.S. thesis, North Carolina State University, Raleigh, NC, USA.

United States (U.S.) Census Bureau (2010). U.S. Census Bureau delivers North Carolina’s 2010 census population totals, 2010.census.gov/news/releases/operations/cb11-cn61.html, visited 25 March 2011.

Winston, R.J., Hunt, W.F., Osmond, D.L., Lord, W.G., and Woodward, M.D. (2011). Field evaluation of four level spreader – vegetative filter strips to improve urban stormwater quality. J. Environ. Eng.-ASCE, **137**(3), 170-182.

Wu J. S., Allan C. J., Saunders W. L. and Evett J. B. (1998). Characterization and pollutant loading estimation for highway runoff. J. Environ. Eng.-ASCE, 124(7), 584-592.

8.0 APPENDIX

Publications resulting from this project:

- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems. In Proc. 2011 International Conference on Urban Drainage, September 11-16, 2011, Porto Alegre, Brazil.
- DeBusk, K. M., W. F. Hunt, U. Hatch and O. Sydorovych. 2010. Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. Journal of Contemporary Water Research & Education, 146(1): 64-74.
- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. In Proc. EWRI-ASCE World Environmental and Water Resources Congress 2010, May 17-20, 2010, Providence, RI.

Presentations resulting from this project:

- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems. 2011 International Conference on Urban Drainage, September 11-16, 2011, Porto Alegre, Brazil.
- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. Water Resources Research Institute of North Carolina Annual Conference, March 22-23, 2011, Raleigh, NC.
- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. EWRI-ASCE World Environmental and Water Resources Congress 2010, May 17-20, 2010, Providence, RI.
- DeBusk, K. M. and W. F. Hunt. 2010. Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. Water Resources Research Institute of North Carolina Annual Conference, March 30-31, 2010, Raleigh, NC.
- DeBusk, K. M. and W. F. Hunt. 2009. Watershed Retrofit and Management Evaluation for Urban Stormwater Management Systems in North Carolina. Universities Council on Water Resources (UCOWR), July 6-9, 2009, Chicago, IL.