HYDROLOGICAL AND WATER QUALITY ASSESSMENT OF A RAPIDLY URBANIZING SOUTHEASTERN PIEDMONT WATERSHED

by

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ABSTRACT

VIJAYA GAGRANI. Hydrological and water quality assessment of a rapidly urbanizing Southeastern Piedmont watershed. (Under the direction of Dr. C. J. ALLAN)

The purpose of this dissertation research was to assess the change in hydrological and watershed processes influencing water quality in a rapidly urbanizing SE Piedmont watershed. Specifically, this dissertation research assessed the effectiveness of engineered stormwater control measures (SCMs) and stream restoration projects in a rapidly urbanizing watershed to maintain the pre development hydrologic and water quality regime in compliance with local stormwater and water quality regulations. The hydrologic and water quality benefits of a network of the existing engineered SCMs and alternative engineered SCMs that included distributed backyard rain-gardens and additional offline bio-retention basins were simulated in the most developed sub-watershed of the study watershed using the Model of Urban Stormwater Improvement Conceptualization (MUSIC). Model simulation results indicated that the post-development simulation with existing engineered SCMs network in comparison to without-engineered SCMs network lowered the annual load of total suspended sediment (TSS), total phosphorus (TP), and total nitrogen (TN) by 56.7%, 50.7%, and 9.5%, respectively. Model simulations indicated that mandatory 85% and 70% TSS and TP annual load reductions, respectively could be obtained by diverting runoff from 70% and higher of the contributing drainage area of the existing engineered SCMs into additional offline bio-retention basins.

The effectiveness of the existing engineered SCMs network in maintaining the predevelopment runoff hydrology of five developing sub-watersheds (10% to 54%

suburban development) was evaluated with the unit hydrograph, unit impulse response, and Mann-Kendall trend test approaches. The measured reduction in peakflow discharge and increase in direct runoff coefficient and runoff duration is attributed to the engineered SCMs in the most developed sub-watersheds, whereas little difference in runoff response could be attributed to the stream restoration projects. The three approaches applied to assess the change in hydrologic responses from different BDC sub-watershed provided similar results.

Finally, a residual mass balance approach was applied to assess the in stream transport and retention dynamics of sediment, nutrients, and organic carbon (OC) in two restored and two unaltered or "natural" stream reaches of the study watershed during different flow regimes. The restored stream reaches indicated a net retention of TSS, N (PN, TN, TDN, and DON), P (TP and PP), and OC during baseflow monitoring periods. Whereas, the restored stream reaches exhibited a net export of TSS, NO_3-N, TP, PP, and POC during storm events. The predominately forested and unaltered stream reach exhibited a net retention of ortho-P and a decline in per unit flux of most of the other water quality constituents during baseflow and storm runoff events. The suburban unaltered stream reach with significant engineered SCMs indicated the downstream mobilization of most of the water quality constituents during baseflow and storm events. Overall, this dissertation provided a comprehensive assessment of the alterations of the hydrological and biogeochemical processes in an urbanizing SE Piedmont watershed and an assessment of the effectiveness of current Stormwater Control and Stream Restoration practices through stormwater modeling, analytical, and field based monitoring approaches.

DEDICATION

To my family and friends.

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CHAPTER 1: INTRODUCTION

Urbanization modifies and impairs the natural hydrologic processes and water quality of a watershed due to increased runoff volumes, higher storm peakflow rates, and reductions in baseflow runoff often accompanied by elevated sediment, nutrients, and contaminants loading (e.g., Leopold 1968, Walsh et al. 2005, and O'Driscoll et al. 2010). In order to maintain the pre-development hydrologic and water quality conditions engineered Stormwater Control Measures (SCMs) such as wet and dry detention basins, bio-retention basins, rain-gardens, grass swales, constructed wetlands, amongst others are widely employed to comply with the local stormwater control regulations. Engineered SCMs are designed to diminish the peakflow and runoff volume by temporarily retaining the initial runoff and then gradually releasing it into streams as surface and/or subsurface runoff.

In addition to the stormwater quantity control, engineered SCMs can improve stormwater quality through processes such as sedimentation, adsorption of contaminants onto sediment particles, filtration, de-nitrification, and immobilization through uptake by plants and microorganisms (Lawrence 1996, Strecker et al. 2001, Hunt et al. 2006 and 2008, and Davis 2008). However, there are many instances where engineered SCMs have proven not to be effective in restoring the pre-development hydrologic and water quality regime due to excessive land cover disturbance in conjunction with inadequate location, design, type, and maintenance of these structures (Roesner et al. 2001, Booth et al. 2002, Hur et al. 2008, and NRC 2008).

The empirical stormwater design applications such as the Site Evaluation Tool (SET, Tetra Tech Inc. 2005) and the Integrated Design and Evaluation Assessment of Loadings (IDEAL, 2007) are used to design site specific engineered SCMs without considering the consequences of overall development at the watershed scale. That is they are applied on a development phase by phase approach and not on a comprehensive watershed scale basis. After reviewing the status of stormwater management practices in U.S., the National Research Council (NRC 2008) has recommended following a watershed scale approach for designing and installing engineered SCMs for new developments instead of phase-by-phase subdivision scale implementations. In old developments with existing engineered SCMs, but not meeting the required hydrologic and water quality standards, a basin wide performance assessment of the existing engineered SCMs network and retrofit engineered SCMs scenarios was recommended (Wong et al. 2006, Shuster et al. 2008, Gilroy and McCuen 2009, and Elliott et al. 2010).

The distributed watershed scale stormwater models such as the Model of Urban Stormwater Improvement Conceptualization (MUSIC, CRCCH 2005) provides the flexibility of evaluating existing and all the possible retrofit engineered SCMs scenarios to attain the mandatory reduction in runoff and fluxes of nutrients and sediment as well as simulating the pre-development hydrologic regime and water quality characteristics of a watershed. In urban watersheds with degraded water quality and altered hydrological regimes, the offline bio-retention basin retrofits have proved to be the optimal solution to attain the pollutant and hydrologic performance standards (USEPA 2006). The offline bio-retention basins disconnect impervious areas in a watershed from receiving surface waters and have demonstrated relatively high pollution removal efficiencies, requiring only 1% to 5% of the total drainage areas to install these structures.

In addition to the engineered SCMs, natural stream restoration practices are frequently implemented in an attempt to enhance physical, chemical, and biological activities to retain and degrade pollutants (e.g., Meyer et al. 2005, Groffman et al. 2005, Bukaveckas 2007, and Kaushal et al. 2008). Higher instream denitrification rates were observed in urban streams after the hydrologic reconnection of the channel to its floodplains and riparian buffers (Grimm et al. 2005, Kaushal et al. 2008, and Klocker et al. 2009). This was attributed to the increased opportunity for both biotic and abiotic uptake due to increased transient storage, increased travel time, and reduced flow velocities through enhanced complexity of the instream geomorphic structures. A 30 and 3 fold increase in the instream uptake of nitrogen (N) and phosphorus (P), respectively was reported in a restored stream channel receiving agricultural runoff during different flow regimes (Bukaveckas 2007). A mass balance study of the urban restored stream channels in Chesapeake Bay region, USA indicated an average 13% and 20% retention of N flux during baseflow and storm events, respectively (Filoso and Palmer 2011).

In urban watersheds, success in attaining the predevelopment hydrologic, water quality, and biological conditions through stream restoration is often limited due to constraints such as the elevated load of pollutants associated with sediment and stormwater runoff, the high cost of acquiring the necessary land for construction, and the proximity to the existing surface and sub-surface urban infrastructure (Booth 2005, Bernhardt and Palmer 2007, and Palmer et al. 2010). Moreover, the ecological recovery of a restored stream channel can also be affected by legacy sediment contamination and episodic metal releases (Harding et al. 1998, Walsh et al. 2005, and Clements et al. 2010).

In order to implement effective stormwater management practices it is important to assess the changes in the hydrologic regime due to urbanization. Hydrologic time series assessment approaches such as the construction of pre- and post-development unit hydrographs, auto regressive models, and statistical trend tests have been widely used to assess the change in watershed runoff responses following land use alteration (e.g., Zhang et al. 2001, Vicars and Williams 2007, and Farahmand et al. 2007). The unit hydrograph approach was previously used in a comparison of the pre- and post-development unit hydrographs of the urbanized White Rock Creek watershed in Texas, where a 49 minute shorter lag time and a doubling of the runoff volume for a 10 year rainfall event was observed (Vicars and Williams 2007). However, for an actively urbanizing watershed, determining "stable" pre- and post-development periods and averaging four to five unit hydrographs during sub-periods of the land development cycle can be problematic.

For an actively urbanizing watershed, the instantaneous assessment of the change in runoff response using continuous rainfall-runoff time series for sub-periods within the development cycle can provide information regarding alterations in hydrologic regime as they are occurring. In addition, such approaches can assess the effects of the implementation of mitigation measures such as engineered SCMs and stream restoration. The instantaneous change in runoff response approach known as the unit impulse response was proposed by Farahmand et al. (2007), where a unit impulse of rainfall can be used to assess the change in runoff response from the rainfall-runoff models of two consecutive land development periods. Limitations of this approach include a limited monitoring data available for model calibration and validation when applied in a rapidly developing watershed and the absence of a reference watershed to assess the impacts of other factors influencing runoff beyond land development.

Seasonality and climate change can also influence the hydrologic responses of a watershed. The Mann-Kendal non-parametric trend test has been widely used to assess the change in hydroclimatic trends (Zhang et al. 2001, Burn and Elnur 2002, Gratiot et al. 2009, and Sahoo and Smith 2009). The influence of climate change on the hydrologic response of 249 Canadian watersheds showed that the trends in streamflow were related to the trends in meteorological variables attributed to climate change (Zhang et al. 2001 and Burn and Elnur 2002). Using the same approach, Gratiot et al. (2009) examined an urbanizing watershed in Mexico, and found that the increased surface runoff was due to urbanization instead of increased precipitation.

In addition to assess the change in hydrologic regime through stormwater model application and analytical approaches, the reach scale assessment of retention and transport dynamics of sediment, nutrients, and organic carbon (OC) is necessary to understand the influence and benefits of stream restoration projects and engineered SCMs towards improving water quality in developing watersheds. The instream processing of nutrients, sediments and carbon can be significantly altered by changes in the channel flow regime as well as by seasonal climatic and vegetation dynamics. In the mixed land use River Swale watershed in the UK, the instream channel processes were characterized by assessing the P and dissolved silica (Si) dynamics for different flow regimes (Bowes and House 2001). Their results indicated net stream reach retention of both constituents during stable baseflow periods and during overbank flooding episodes due to instream processing and the deposition of sediment onto the floodplain. However, long duration flood events resulted in a net export of Si and P after floodwater receded and soil water and its dissolved constituents slowly drained back into the river channel.

The assessment of nutrient and sediment transport dynamics in a predominantly agricultural watershed during different seasons and flow regimes demonstrated that during low flow summer months 24% - 26% of the inorganic nitrogen and 9% - 19% of suspended sediment were retained within the monitored channel reach (Brunet and Astin 2000). Whereas, during higher flow autumn month, mobilization of all elements occurred, and in winter month, mobilization of soluble inorganic nitrogen and phosphorus occurred due to decreased biological activity. At the Hubbard Brook Experimental Forest, 80% - 140% higher instream nitrate retention was reported due to the increased light availability and a large input of woody debris after an ice storm disturbed the forest canopy (Bernhardt et al. 2005). A mass balance of nitrogen and DOC in a forest stream reach demonstrated up to 70% net retention of nitrate during baseflow conditions due to increased availability of DOC after the autumn leaf fall and was described as a "hot moment" for the denitification process (Sebestyen et al. 2008).

The purpose of this research is to assess the change in hydrological and biogeochemical processes due to urbanization and the effectiveness of stream restoration projects and installation of engineered SCMs to maintain the pre-development hydrologic and water quality regime to compliance with local stormwater and water quality regulations. This dissertation research utilizes stormwater modeling, analytical, and field-based monitoring approaches to meet the research objectives. Each chapter in this dissertation represents an independent and publication-style format research paper.

Chapter 2 assesses of an existing network of engineered SCMs at a watershed scale and simulates the distributed engineered SCMs retrofit scenarios by utilizing a spatially distributed stormwater model “the Model of Urban Stormwater Infrastructure Design Conceptualization” or MUSIC. The first step in the modeling exercise was to calibrate and validate the stormwater model for the existing conditions. The second step was to simulate the pre-development watershed condition (i.e., 99% pervious), and then compare with the present conditions and post-development simulations, and with an adjacent forested watershed to assess if the existing SCMs network was effectively maintaining the pre-development hydrologic and water quality characteristics of the study watershed. The final step was to simulate alternative distributed engineered SCMs retrofit scenarios that included backyard rain-gardens and offline bio-retention basins, with and without the inclusion of natural floodplains, for attaining mandatory 85% and 70% of TSS and TP annual load reductions.

Chapter 3 encompasses three separate analytical approaches to quantify the change in runoff responses of the five urbanizing sub-watersheds for evaluating the effectiveness of development regulations in maintaining the predevelopment runoff regime through the construction of multiple engineered SCMs and natural channel restoration. In this study, due to lack of a control watershed, ongoing development, a short pre-development period, and the implementation of stream restoration and engineered SCMs over an extended time period, the change in runoff response was assessed with three different analytical approaches: the unit hydrograph, the unit impulse response, and the Mann-Kendall statistical trend test.

Chapter 4 concerns the assessment of transport and retention dynamics of sediment, nutrients, and OC in two unaltered or “natural” and two restored stream reaches in a rapidly urbanizing SE Piedmont watershed by applying the residual mass balance approach during different flow regimes and seasons. The focus was also on assessing the influence of engineered SCMs on in-channel material processing in predominately suburban land use sub-watersheds in comparison to the predominately forested sub-watersheds.

CHAPTER 2: ASSESSING THE HYDROLOGIC AND WATER QUALITY BENEFITS OF A WATERSHED WIDE NETWORK OF STORMWATER CONTROL MEASURES

2.1 Abstract

The hydrologic and water quality benefits of an existing engineered stormwater control measures (SCMs) network, along with alternative engineered SCMs scenarios that included distributed backyard rain-gardens and additional offline bio-retention basins were assessed in a rapidly urbanizing, BD4 sub-watershed of the Beaverdam Creek (BDC) watershed by using the Model of Urban Stormwater Improvement Conceptualization (MUSIC). When compared to the simulated pre-development watershed conditions (i.e., 1% effective imperviousness), the post-development watershed condition (20.3% imperviousness) without engineered SCMs simulation indicated an increase of 77.4% runoff volume, an average of 202% higher peakflow for 1.5 to 3.2 cm 6-hour storm events, and 29.5, 12, and 2.7 times higher TSS, TP, and TN loadings, respectively. Model results indicated that the existing engineered SCMs network comprised by wet and dry detention basins and a bio-retention basin, in comparison to the post-developed watershed without engineered SCMs, reduced the average peakflow rates for 1.5 to 3.2 cm 6-hour storm events by 1.7 times, lowered the annual runoff volume by 2.6%, and lowered the total suspended sediment (TSS), total phosphorus (TP), and total nitrogen (TN) annual loads by 56.7%, 50.7%, and 9.5%, respectively. The backyard rain-garden simulation resulted in a minimal additional reduction of TSS (1.6%), TP (0.4%), and TN (4.2%) annual loads due to small areal

extent (3.2% of the BD4 sub-watershed area) and relatively low concentrations of nutrients and TSS in roof runoff. Model simulations indicate that mandatory 85% and 70% TSS and TP annual load reductions at the outlet of the single engineered SCMs, at the treatment trains, and at the long-term downstream monitoring station (J7 junction node) could be obtained by diverting runoff from 70% of the existing engineered SCMs contributing drainage areas into additional offline bio-retention basins.

Further, when downstream natural wetland/floodplain areas are incorporated into the model simulation as part of the water quality treatment train, mandatory TSS and TP reductions could be met by diverting 50% of the contributing drainage area runoff into the additional offline bio-retention basins. A scenario examining the effectiveness of natural floodplain/wetland areas alone in attenuating runoff, TSS, TP and TN loadings indicated a 5.4% runoff volume reduction, and a 61.4%, 61.0%, and 7.8% reduction of TSS, TP, and TN loading, respectively were obtained. The simulation of the downstream natural floodplain/wetland area in conjunction with the existing engineered SCMs and offline bio-retention basins scenarios lowered the additional loadings of the TSS, TP, and TN by 13.2%, 12.9%, and 3.2% and 4.5%, 6.5%, and 0.6%, respectively. The gradual reduction of the effectiveness of the downstream natural floodplain/wetland area was attributed to the fact that the existing engineered SCMs and retrofit offline-bio-retention basins treat and filter the runoff before the runoff reached into the natural floodplain/wetland area.

Keywords: Water quality, engineered SCMs network, MUSIC, Bio-retention basins, Rain-gardens, Stormwater model, and Floodplain/Wetland.

2.2 Introduction

Urbanization modifies and impairs the natural hydrologic processes and water quality of a watershed due to increased runoff volumes, higher storm peakflow rates, and reductions in baseflow runoff often accompanied by elevated nutrient and contaminant loading (e.g., Leopold 1968, Walsh et al. 2005, and O'Driscoll et al. 2010). In order to maintain the pre-development hydrologic and water quality conditions, engineered Stormwater Control Measures (SCMs) such as wet and dry detention basins, bio-retention basins, rain-gardens, grass swales, constructed wetlands, amongst others, are widely employed to comply with local stormwater control regulations. Engineered SCMs are designed to diminish the peakflow and runoff volume by temporarily retaining the initial runoff and then gradually releasing it into streams as surface and/or subsurface runoff. In addition to stormwater quantity control, engineered SCMs can improve stormwater quality through processes such as sedimentation, adsorption of contaminants onto sediment particles, filtration, de-nitrification, and immobilization through uptake by plants and microorganisms (Lawrence 1996, Strecker et al. 2001, Hunt et al. 2006 and 2008, and Davis 2008).

There are many instances where engineered SCMs have proven not to be effective in restoring the pre-development hydrologic and water quality regime due to excessive land cover disturbance in conjunction with inadequate location, design, type, and maintenance of the engineered SCMs (Roesner et al. 2001, Booth et al. 2002, Hur et al. 2008, and NRC 2008). In many cases, engineered SCMs are designed and implemented on a development-by-development basis without considering the consequences of overall development at the scale of the watershed. For example, empirical stormwater design applications such as the Site Evaluation Tool (SET, Tetra Tech Inc. 2005) and the Integrated Design and Evaluation Assessment of Loadings (IDEAL, 2007) are used to evaluate engineered SCMs on a site scale, but do not assess the overall water quality and hydrologic impact of basin wide development within a watershed.

After reviewing the status of stormwater management practices in the U.S., the National Research Council (NRC 2008) has recommended following a watershed scale approach for designing and installing engineered SCMs for new developments instead of phase-by-phase subdivision scale implementation. In old developments where existing engineered SCMs are not meeting the required hydrologic and water quality standards, a basin-wide performance assessment of the existing engineered SCMs network and retrofit engineered SCMs scenarios allows stormwater managers to evaluate a range of possible retrofit scenarios to attain the mandatory reduction in runoff and fluxes of nutrients and sediment (Wong et al. 2006, Shuster et al. 2008, Gilroy and McCuen 2009, and Elliott et al. 2010). Oftentimes offline bio-retention basin retrofits have proved to be the optimal solution. Offline engineered SCMs disconnect impervious areas in a watershed from receiving waters and demonstrate relatively high pollution removal efficiencies, requiring only 1% to 5% of the total drainage areas to meet pollutant and hydrologic performance standards (USEPA 2006).

In order to assess the changes in hydrologic and water quality responses of a watershed due to urban development with existing and alternate retrofit engineered SCMs scenarios, it is important to assess the hydrologic and water quality regime of the pre-development period. Distributed watershed scale stormwater models such as the Model of Urban Stormwater Improvement Conceptualization (MUSIC, CRCCH 2005) provide the flexibility of simulating the pre-development hydrologic regime and water quality characteristics of a watershed. The MUSIC model can also be used to examine existing and alternative retrofit engineered SCMs networks.

The overall goals of this study were to assess the effectiveness of the existing engineered SCMs network and secondly, to examine alternative distributed SCMs retrofit scenarios in order to maintain the hydrology and water quality integrity of a developing watershed by utilizing the capability of the MUSIC modeling tool to simulate spatially distributed engineered SCMs at a watershed scale. Additionally, we examine the importance of a downstream natural floodplain area as part of the developing watersheds "treatment train" in maintaining runoff hydrology and water quality. The first step was to simulate the pre-development watershed condition (i.e., 99% pervious), and compare with present and post-development conditions and an adjacent forested watershed to assess if the existing engineered SCMs network was effectively maintaining the pre-development hydrologic and the water quality characteristics of the study watershed. The second step was to simulate alternative distributed engineered SCMs retrofit scenarios that included backyard rain-gardens and offline bio-retention basins with and without the inclusion of natural floodplains for attaining mandatory 85% and 70% of TSS and TP annual load reductions

2.3 Study Area

The Beaverdam Creek (BDC) study watershed is located at approximately 35°10′11″N latitude and 80°59'16" longitude in southwest Mecklenburg County, North Carolina (Figure 2.1). The total drainage area of this watershed is 11.8 km^2. The BDC watershed lies in the humid subtropical climate zone (Cfa) in the Köppen climatic classification. The 30-year normal monthly mean, minimum, and maximum temperatures are 16.3°C, 5.4°C (January), and 26.8°C (July), respectively, and the mean annual precipitation is 110.4 cm. The BDC watershed drains into Lake Wylie, a water supply reservoir on the highly subscribed Catawba River System. Lake Wylie is classified as a eutrophic lake NCDENR (2003) and MCWQP (2008) due to excessive nutrient loading from urban and agricultural land uses in its watershed. In order to maintain and improve the existing water quality in Lake Wylie, new land development projects in the Western Catawba District under the Post Construction Control Ordinance (PCCO 2008), which includes the BDC watershed, require the implementation of engineered SCMs for subdivision and other land development with 12% and higher built upon areas (PCCO 2008).

This study focused on a 1.92 km^2 urbanizing sub-watershed of the BDC watershed (BD4 sub-watershed). Land use in 2003 for this sub-watershed was defined as 42.8% forest and pasture, 49% low-density residential (<12% built upon area), and 7.8% roads and highway (Buck Engineering, 2003). Since 2004, 54.3% of the total drainage area of the BD4 sub-watershed has been redeveloped, primarily as heavier density residential, with the land use now classified as 21.1% forest and pasture, 16.1% low density development, 50.7% high density development (>12% built upon area), 3.5% commercial and 7.8% roads and highway. The existing network of engineered SCMs was implemented with the phase-by-phase development of individual subdivisions, without considering the watershed scale stormwater impacts of overall watershed development. The engineered SCMs network in this sub-watershed included eleven wet-detention ponds, three dry-detention ponds, and one bio-retention basin occupying 15,200 m^2 or

0.79% of the watershed area (Figures 2.1 and 2.2). The network of existing engineered SCMs represents one cm of detention storage over the total BD4 sub-watershed area or 1.7 cm of detention storage in relation to the area of the new high-density development in the BD4 sub-watershed (Table 2.1).

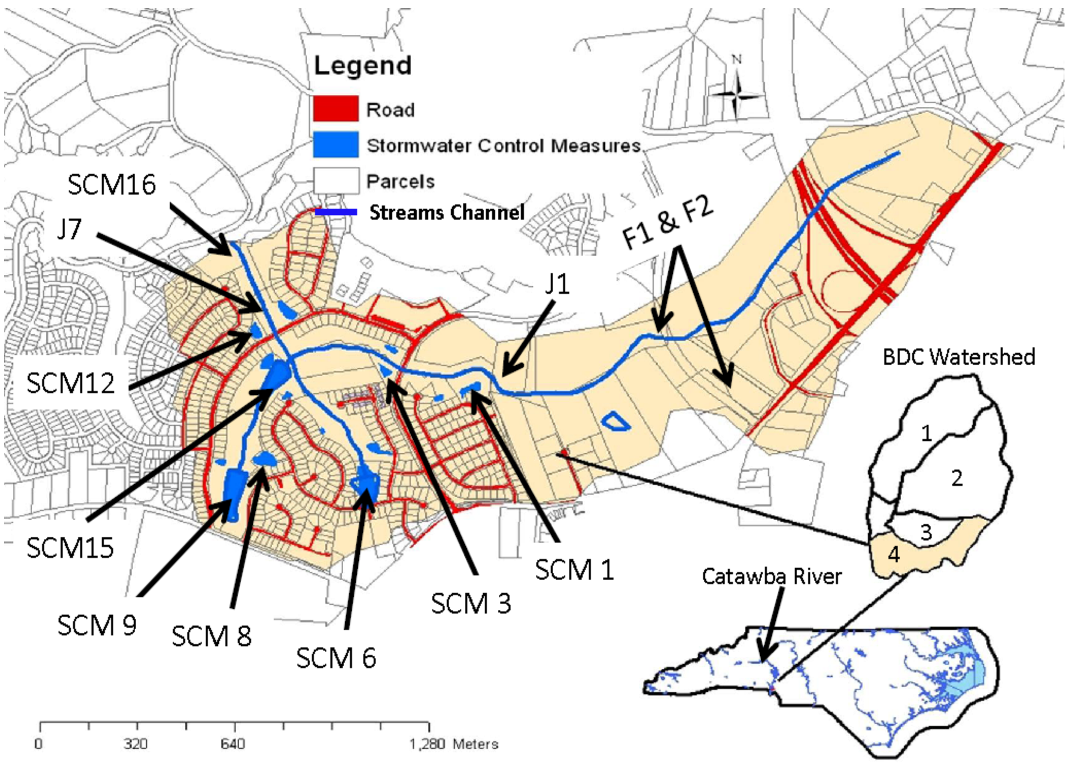

Figure 2.1: The BD4 sub-watershed of the Beaverdam Creek (BDC) watershed displaying the existing engineered Stormwater Control Measures (SCMs). Notes: The four BDC subwatersheds are displayed in the image. Subwatershed-1 is the predominately forested land use. The existing and retrofit SCMs scenarios were carried for the predominately suburban land use subwatershed-4.

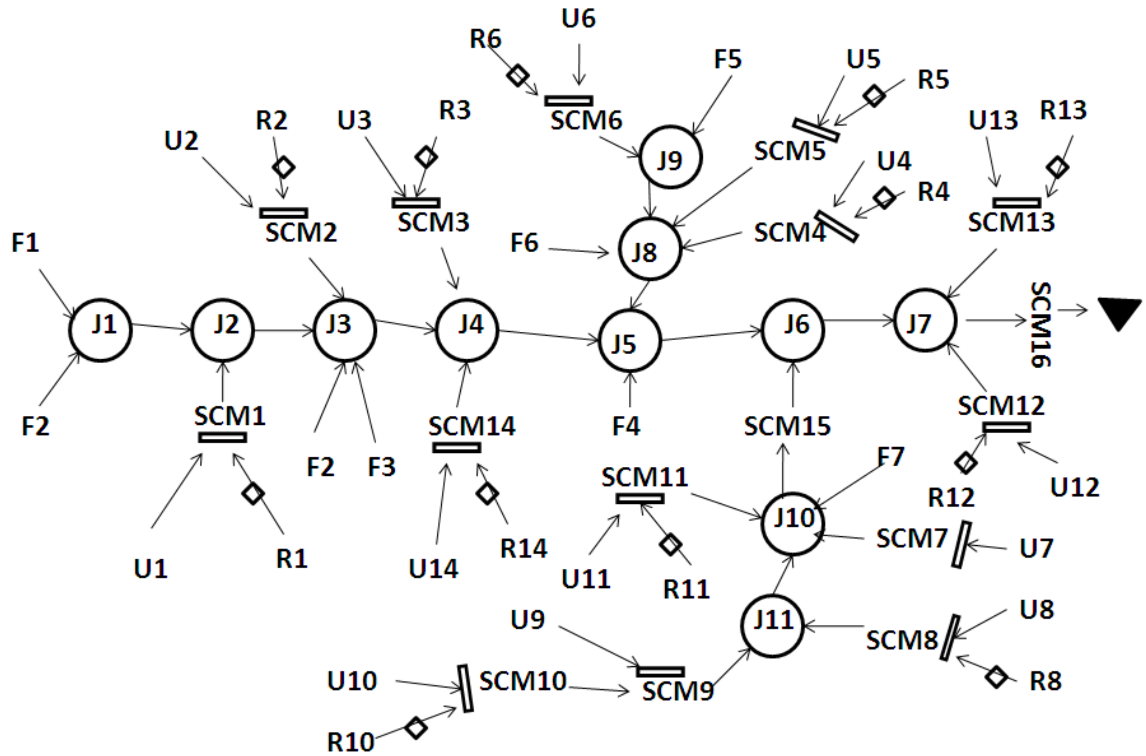

Figure 2.2 : The source, treatment, junction, and receiving nodes of the BD4 sub-watershed. Notes: 1) F: Forest source nodes; U: Urban source nodes; R: Roof only source nodes; SCM: Stormwater Control Measures and J: Junction nodes 2) Diamonds show the aggregated rain gardens, and rectangles are show the aggregated bio-retention basins and 3) SCM16 is the downstream natural wetland/floodplain area.

Table 2.1: Treatment node properties of the engineered SCMs network.
Notes: 1) *J7 is the long-term monitoring station, 2) SCM4, 10, and 14 are dry detention basins, and SCM13 is a bio-retention basin.

Junction Nodes	Contributing SCMs	Contributing Drainage Area to the node (ha)	Area served by SCMs (%)	Impervious Area (%)	"Roof only" Area (%)	Detention Depth (cm)
J1	0	101.29	0.00	8.20	0.00	0.00
J2	SCM 1	110.80	8.58	11.17	0.56	0.18
J3	SCM 1& 2	118.89	9.43	11.02	0.93	0.19
J4	SCM 1 to 3 & 14	129.39	16.78	13.58	1.36	0.35
J5	SCM 1 to 6 & 14	156.65	23.76	16.05	2.07	0.67
J6	SCM 1 to 11, 14 & 15	181.59	43.87	19.13	2.84	0.92
*J7	SCM 1 to 15	191.90	46.42	20.25	3.24	1.01
J8	SCM 4 to 6	19.45	79.74	37.55	7.79	3.03
J9	SCM 6	3.61	46.81	16.34	7.48	2.22
J10	SCM 7 to 11	24.94	85.08	38.45	7.70	2.01
J11	SCM 8 to 10	15.12	100.00	46.37	10.51	2.53

2.4 Methodology

2.4.1 BD4 Sub-watershed in MUSIC

The "watershed" in the MUSIC model is represented as a series of source, treatment, junction, and receiving nodes connected by drainage links (Figure 2.2). The BD4 sub-watershed is composed of a series of 9-forest, 15-urban, and 15-user defined roof source nodes; 16-treatment nodes; 11-juction nodes; and 1-receiving node, all connected by 64-drainage links (Table 2.2). The forest nodes were not considered to contribute to urban source stormwater treatment and were directly connected to the stream channel through the junction nodes.

The treatment nodes represented the existing 15-engineered SCMs and one natural floodplain/wetland. The engineered SCMs network of the BD4 sub-watershed has two treatment trains (SCM9 and SCM15). The SCM9 treatment train comprised of SCM9 and 10, and SCM10 flows into the SCM9 and the SCM15 treatment train comprised of SCM7, 8, 9, 10, 11 and 15, and flows into the SCM15, provided secondary and tertiary filtration (Figure 2.2). The J7 junction node is the long-term downstream monitoring station, used to calibrate and validate the MUSIC model for the BD4 sub-watershed. After leaving the newly developed area the stream flows through a natural floodplain/wetland, represented by treatment node SCM16, located downstream of the J7 junction node and readily accesses its floodplain during high flow events before discharging into the ultimate receiving node, Lake Wylie.

Table 2.2: Source node parameters of the engineered SCMs network.

Source Nodes	**Forest**	**Urban**	**Roof Area**
Field Capacity (mm)	35	35	NA
Pervious Area Infiltration Capacity coefficient - a	250	200	NA
Pervious Area Infiltration Capacity exponent - b	0.75	1	NA
Pervious Area Soil Storage Capacity (mm)	100	100	NA
Groundwater Daily Recharge Rate (%)	0.9	0.9	NA
Groundwater Daily Baseflow Rate (%)	0.7	0.7	NA
Stormflow TSS Mean / Standard Deviation(mg/L)	79/2.0	158/8.0	4.0/8.0
Stormflow TP Mean / Standard Deviation(mg/L)	8.0/3.2	0.2/8.0	0.6/5.0
Stormflow TN Mean / Standard Deviation(mg/L)	0.6/0.8	0.8/1.3	0.6/4.0
Baseflow TSS Mean / Standard Deviation(mg/L)	3.2/5.0	5.0/3.2	1.6/10.0
Baseflow TP Mean / Standard Deviation(mg/L)	0.1/2.0	0.1/5.0	0.01/5.0
Baseflow TN Mean / Standard Deviation(mg/L)	0.1/2.0	6.0/2.0	0.01/4.0

2.4.2 Rainfall Runoff and Engineered SCMs in MUSIC

The rainfall-runoff algorithm of the MUSIC model is based on the SimHyd model developed by Chiew and McMahon (1997). Rainfall on impervious areas generates runoff after meeting the initial abstraction. The pervious area runoff is modeled as the infiltration excess and saturated excess runoff, and baseflow as the liner recession of the groundwater storage. Soil types and characteristics of the BD4 sub-watershed obtained from the Mecklenburg County Soil Survey Report (USDA-NRCS 2010) were used to calculate the pervious area model parameters such as soil storage capacity, initial storage, field capacity, infiltration capacity coefficient and exponent, groundwater depth, and recharge and discharge rates, using the methods described by Macleod (2008). The pollutant removal capacity of different engineered SCMs was calculated by the first order kinetic decay (k-C*) model (where, k is the first order decay constant and C* is the background concentration) in a series of Continuously Stirred Tank Reactors (CSTRs) (Wong et al. 2006). The stormwater and pollutant routing between the nodes were computed using the Muskingum-Cunge method of streamflow routing. The selected values of the channel reach storage parameter (K) and relative weight of outflow and inflow (θ) were 6.0 minutes and 0.35, respectively for the drainage links connected from source to treatment and from treatment to the stream channel (MUSIC user manual 2005). The parameter θ affects the attenuation of the flood wave, a 0.5θ value indicates no attenuation. In this study θ was higher than the range (0-0.3) for a natural stream channel. The value of K for the stream channel was adjusted to the travel time between two junction nodes. In this study, the smallest available time step within the model, 6 minute was used.

2.4.3 Land Cover and Pollutant Concentrations

Land cover within the BD4 sub-watersheds was determined by digitizing a 2009 high-resolution aerial ortho photograph and annual field GPS land-cover change mapping. MUSIC input parameters of the engineered SCMs were compiled from individual stormwater plans provided by the Land Development Department of the City of Charlotte, NC and field surveys conducted in 2009. The average, minimum, and maximum impervious areas for different land development subdivisions were 41.9%, 28.4% (SCM2), and 52.2% (SCM9) for the BD4 sub-watershed (Table 2.1). For the urban source nodes, TSS, TP, and TN concentrations were obtained from a year-long sub-division scale study within the BD4 sub watershed (Barto et al. 2010). For the forest source nodes, TSS, TP, and TN concentrations were obtained from an adjacent forested sub-watershed and from MUSIC standard default values. The pollutant concentrations, used in this model, were finalized by running the model several times and comparing the plots of observed and modeled values (Wu et al. 2006), and by keeping the modeled annual load within ±10% range of the calculated load for the long-term monitoring station or J7 junction node (Figures 2.3). The final parameter values of the source nodes and treatment nodes are presented in the Tables 2.1 and 2.2. For the stormwater detention ponds, the first-degree decay rate (k) for TSS, TP, and TN were 300, 200, and 50 m/year, respectively. The mean baseflow concentration from an adjacent forested sub-watershed were used as the background concentrations (i.e. C*) for TSS, TP, and TN which were 13, 0.1, and 0.4 mg/L, respectively.

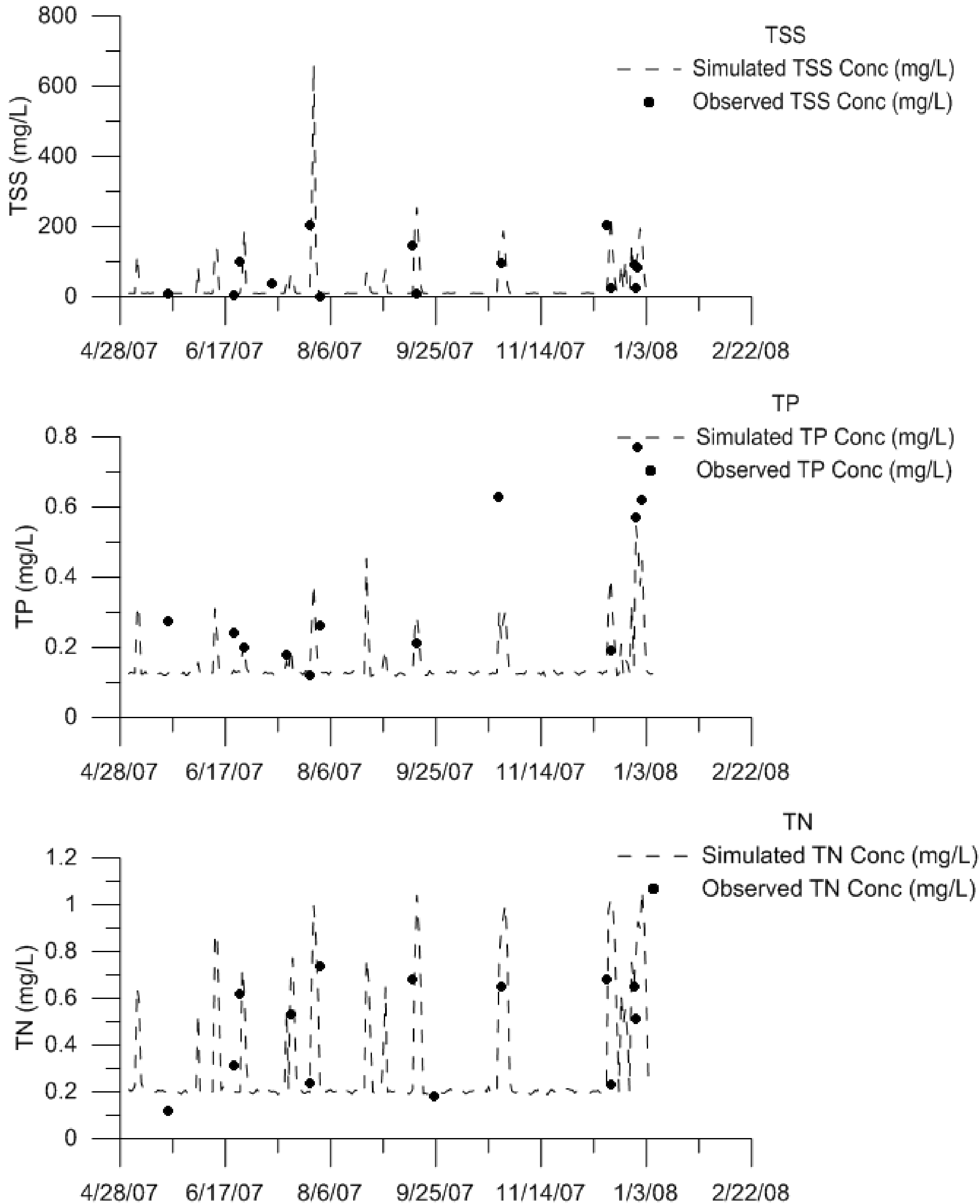

Figure 2.3: Simulated and observed concentrations of the TSS, TP, and TN.

2.4.4 Model Calibration and Validation and Scenario Run

The BD4 MUSIC model was calibrated with data from the May 2007 to December 2007 period and validated against January 2008 to May 2008 observed streamflow and water quality constituents at the J7 junction node. In the BD4 sub-watershed, 0.018 cm/day excess runoff was reported attributed to the delayed runoff from the existing engineered SCMs during baseflow conditions possibly due to irrigation of suburban lawns. The excess runoff in the study sub-watershed was quantified during four summer months in 2008 when the other three adjacent BDC sub-watersheds had ceased flowing (Allan et al. 2008). The stormwater model for the BD4 sub-watershed was calibrated and validated after removing the above excess runoff from the observed runoff.

The calibrated and validated stormwater model was used to evaluate the first objective by quantifying stormflow volume, peakflow, and pollutant load reduction through the existing network of engineered SCMs at the J7 junction node from June 2008 to May 2009 in comparison to the modeled pre-development hydrology and pollutant loading. In order to address the second goal, two separate retrofit scenarios were applied using the MUSIC modeling tool to see if they could maintain the hydrology and water quality of the developed watershed. In the first scenario, the individual backyard rain-gardens were modeled and in second scenario, the additional offline bio-retention basins were modeled. To simulate the backyard rain-garden scenario, the roof surfaces were separated from their urban source nodes and represented as the user defined “roof only” source nodes with 100% imperviousness (Figure 2.2). Aggregated backyard rain-gardens were linked to “roof only” source nodes during simulations where 0%, 10%, 30%, 50%, 70%, 90%, and 100% successive increase of contributing roof area runoff was diverted into the backyard rain-gardens.

Two sets of retrofit offline bio-retention basins simulations were run (Bio-I and Bio-II). In the first set of simulations, Bio-I, the offline bio-retention basins were incorporated to each urban source node during simulations where 0%, 10%, 30%, 50%, 70%, 90%, and 100% of contributing urban source area runoff diverted into the new retrofit offline bio-retention basins (Figure 2.2). The second set of simulations, Bio-II, was started with diverting runoff from 70% contributing source area nodes of the SCM9, the highest imperviousness, into a retrofit offline bio-retention basin followed by diverting runoff subsequently from the rest of the existing engineered SCMs contributing source area nodes into respective offline bio-retention basins in order of increasing source node imperviousness (i.e., engineered SCMs 9, 4, 14, 5, 12, 11, 10, 8, 1, 7, 13, 3, and 6).

The natural floodplain/wetland area, SCM16, located downstream of the J7 junction node was incorporated into all simulations. However, due to the absence of a permanent monitoring station at the outlet of the SCM16, all SCM16 simulation outputs are subject to an undetermined error and the results are informational only. For the scenario testing, an aggregated treatment node was assigned to each source node instead of incorporating rain-gardens in every backyard, and several offline bio-retention basins in each urban source node (Elliott et al. 2009). The design of the backyard rain-gardens and bio-retention basins were based on the Bio-Retention Design Manual for the City of Charlotte, NC (BDM of the COC 2010).

2.4.5 Sensitivity Analysis

A sensitivity analysis was performed by developing regression models to assess the influence of the recommended range of the given parameters in terms of flow, TSS, and TP annual load. For this purpose, one series of source, treatment, and receiving nodes from the detailed model was selected. Sensitivity of the rainfall-runoff model parameters such as the proportion of impervious and pervious areas, soil storage capacity, field capacity, infiltration capacity (coefficient "a" and exponent "b"), groundwater recharge rate, and baseflow discharge rate were evaluated. Sensitivity tests of a wet detention pond, a rain-garden, and a bio-retention basin were also carried out. The sensitivity test parameters and the resultant model results are presented in Table 2.3.

Table 2.3: Sensitivity test parameters and results.

Parameters	Sensitivity Equations	Correlation Coefficient (R^2)
Urban Source Node Area (% reduction in annual flow (Thousand L/yr))		
Effective Impervious area (35%)	0.1808x + 6.9617	(0.99)
Soil storage capacity (100 mm)	$35.2x^{-0.203}$	(0.95)
Field capacity (40mm)	$16.039x^{-0.048}$	(0.97)
Infiltration capacity coefficient, a (200)	-0.0002x + 13.461	(0.40)
Infiltration capacity exponent, b (1)	0.17x + 13.195	(0.71)
Daily groundwater recharge rate (0.9%)	0.035x + 13.801	(0.85)
Daily baseflow rate (0.7%)	1.1576x + 12.748	(0.77)
Treatment Node: Wet Detention Basin (% reduction in TSS,TP, and TN load (kg/yr))		
First order aerial decay rate for TSS (300 M/yr)	0.0009x + 87.601	(0.98)
Background conc. of TSS (13mg/L)	-0.1867x + 90.231	(1)
First order aerial decay rate for TP(200 M/yr)	0.0067x + 83.825	(0.99)
Background conc. of TP (0.1mg/L)	-10x + 86.4	(1)
First order aerial decay rate for TN (50 M/yr)	0.0037x + 40.752	(99)
Background conc. of TN (0.4mg/L)	-10.68x + 44.998	(0.99)
Number of CSTRs (2) (TSS)	-0.0694x + 88.012	(0.79)
Treatment Node: Bio-retention/Rain-garden (% reduction in TSS,TP, and TN load (kg/yr))		
First order aerial decay rate for TSS (8000 M/yr)	$42.9x^{0.078}$	(0.97)
Background conc. of TSS (20mg/L)	$95.572x^{-0.031}$	(0.94)
First order aerial decay rate for TP (6000 M/yr)	$21.391x^{0.1538}$	(0.99)
Background conc. of TP (0.13mg/L)	-15.287x + 84.578	(1)
First order aerial decay rate for TN (500 M/yr)	$49.577x^{-0.04}$	(0.96)
Background conc. of TN (1.0 mg/L)	-13.387x + 52.281	(1)
Number of CSTRs (1 to 10) (TSS)	$83.08x^{0.0219}$	(0.94)

2.5 Results and Discussion

2.5.1 Model Calibration, Validation, and Sensitivity Analysis

The calibration and validation results are presented separately for the rainfall-runoff model, TSS, TP, and TN in Figures 2.3 to 2.6. The rainfall-runoff model yielded an 81% and 82% correlation coefficient for the calibration and validation period, respectively (Figure 2.4). The root mean squared error (RMSE) of daily runoff for the calibration and validation period was 0.013 mm/day and 0.019 mm/day, which represents 7% and 5% of the daily average discharge, respectively. The sensitivity test results demonstrated that the stormwater model for the BD4 sub-watershed was most sensitive to the percent of effective impervious surface followed by soil storage capacity (Table 2.3). Dotto et al. (2009) also found that the MUSIC model was highly sensitive to impervious surface cover, soil storage capacity, and field capacity. The water quality output from the simulated wet detention basin and bio-retention basins were found to be particularly sensitive to the background concentration of TN. The bio-retention basin was found to be sensitive to the first order decay rates of TSS, TP, and TN, and the background concentration of TN (Table 2.3).

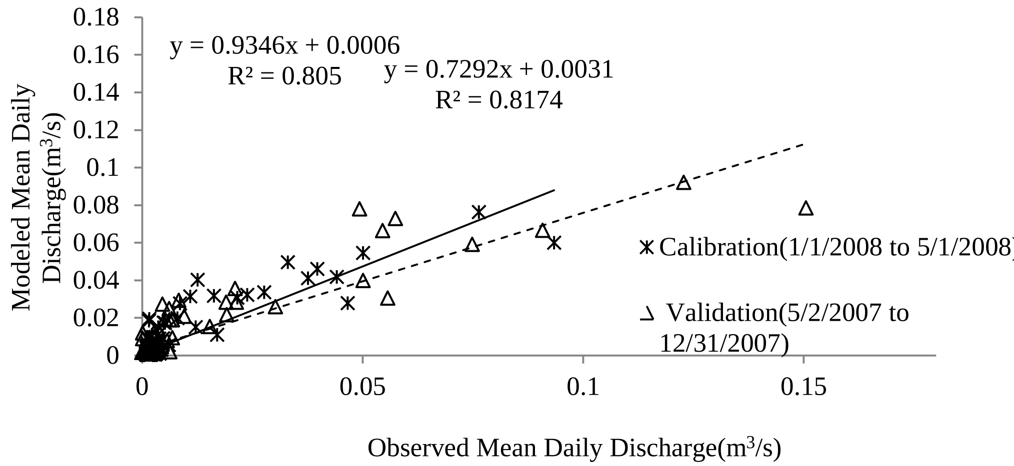

Figure 2.4: Calibration and validation results of the engineered SCMs network at the J7 junction node.

2.5.2 Effectiveness of the Existing Engineered SCMs Network: Hydrologic Benefits

During the simulation period, June 2008 to May 2009, the model input precipitation was 990 mm and the model output runoff depth was 290.5 mm or 29.3% of the total precipitation. An additional 65.9 mm or 6.7% of the total precipitation is attributed to the inter-storm runoff from engineered SCMs in the post-development period as discussed in the model calibration and validation section. The runoff depth in pre-development simulation was 205.3 mm or 20.7% of the total precipitation. The simulated runoff depth for the post-development state without the existing engineered SCMs network was 364.2 mm, calculated to be 77.4% higher than the pre-development simulation. In comparison, an adjacent relatively undeveloped BDC sub-watershed, BD1, where only 10% new land development occurred over the same period, 228 mm, or a 23% runoff yield, was directly measured. The existing engineered SCMs network at the downstream long-term monitoring station, the J7 junction node, provided a 2.6% or

7.8 mm of runoff depth reduction in comparison to the “developed without engineered SCMs” network scenario (Table 2.4). However, the runoff volume remained 1.7 times higher than the pre-development BD4 sub-watershed simulation.

The natural downstream floodplain/wetland, represented by SCM 16 in the model, along with the existing engineered SCMs network was estimated to reduce 5.4% or 16.1 mm of the total runoff depth in comparison to the “developed without engineered SCMs” network scenario where the SCM16 was the only SCM considered. For the simulation period, the runoff depths for all junction nodes (J1 to J11) ranged from 24 to 41 mm, demonstrating an increase with the increasing percent effective imperviousness (Table 2.1 and 2.5). In the BD4 sub-watershed, the relative effectiveness of the treatment trains in reducing runoff can be observed by comparing the percent runoff reduction at the following locations in the existing engineered SCMs network: 13 single engineered SCMs, the treatment train at SCM9 which includes runoff from SCM10 and U9, the treatment train at SCM15 which includes runoff from three single engineered SCMs and SCM9, junction node J7 which receives runoff from the complete stormwater control network, and the downstream natural floodplain/wetland (SCM16) (Figure 2.2). The median, minimum, and maximum percent runoff depth reduction by single engineered SCMs was 6.5%, 3.3%, and 11.9%, respectively (Table 2.4 and Figure 2.6). The percent runoff depth reduction, at the SCM9, SCM15, J7 junction node, and SCM16 was 5.3%, 6.4%, 2.6%, and 8.0%, respectively (Table 2.4). We are unable to observe any cumulative effect of the treatment trains established in the study watershed with the range in runoff reduction for the single engineered SCMs overlapping those of the engineered SCMs receiving runoff from upstream engineered SCMs. Rather the percent runoff reduction appears to be more related to the percent imperviousness in the drainage area of the individual engineered SCMs drainage area.

The Post Construction Control Ordinance for the Western Catawba District of the City of Charlotte, N.C. (PCCO 2008) requires that engineered SCMs in new developments maintain the 10 and 25-year, 6-hour storm events peak discharge at their pre-development levels. For the BD4 sub-watershed, the depths of these design storm events are 9 and 10.6 cm, respectively (NOAA 2011). An evaluation of eight 1.5 cm to 3.2 cm, 6-hour storm events, demonstrated an average three fold higher peakflow discharge in comparison to the pre-development simulation (range 2.5 to 3.6 times, Figure 2.5). Whereas, in comparison to the pre-development condition, the post-development state with existing engineered SCMs simulation demonstrated a 1.6 times higher average peakflow discharge (range 1.5 to 1.8 times) for these same rain events. The above evaluation of peakflow exhibits the failure of engineered SCMs to maintain the pre-development peakflow for smaller more frequent storm events. The two larger storm events, first occurred on 8/26/08 (10.1 cm in 6-hrs, 1.5 cm precedent precipitation in 10 hrs) and the second occurred 18 hours later on 8/27/08 (5.2 cm in 6-hrs) indicated similar peakflow discharge for pre and post-development simulations with and without engineered SCMs (Figure 2.5). The similar peakflow from the 0.5 times smaller event (8/27/08) was caused by prior saturated soil condition.

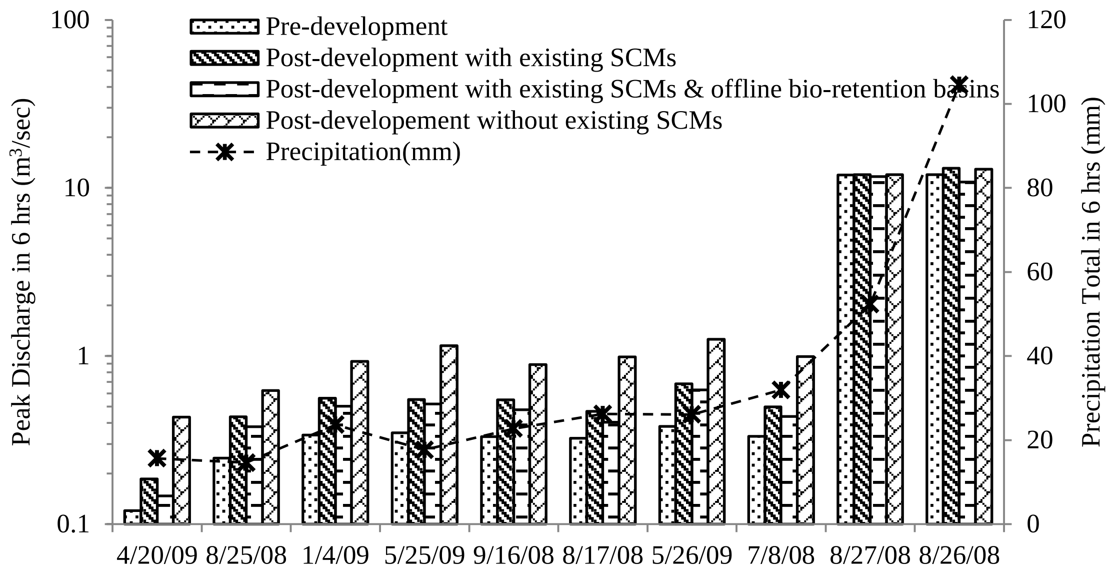

Figure 2.5: Peakflow discharges from the 12 simulated storm events.

Table 2.4: Reduction of runoff, TSS, TP, and TN inputs from the contributing source node areas at different locations on the SCMs network due to existing, backyard rain-garden, and offline bio-retention basins incorporated in different simulation in this study

Location	Parameters	Engineered SCMs Network Scenarios: Runoff (cm) & Source Area fluxes (kg/m^2)	Existing SCMs Network (%)	Backyard Rain-gardens (%)	50% Offline Bio-retention Basins (%)	70% Offline Bio-retention Basins (%)
Single 13 SCMs Median	Runoff	0.8	6.5	7.3	9.9	12.2
	TSS	378.4	50.5	55.7	78.6	87.4
	TP	0.5	41.1	54.7	75.3	81.6
	TN	0.3	12.9	15.1	28.1	36.9
At SCM9 (Treatment train SCM9 and 10)	Runoff	1.3	5.3	5.7	8.1	9.7
	TSS	552.6	42.1	42.9	79.2	87.7
	TP	0.7	45.2	48.0	68.1	79.9
	TN	0.4	18.9	18.9	33.0	42.2
At SCM15 (treatment train SCM7 to11, and 15)	Runoff	5.1	6.4	7.0	9.1	10.7
	TSS	443.3	60.7	63.7	81.1	88.4
	TP	0.6	49.9	61.8	74.5	81.1
	TN	0.3	14.3	14.3	26.6	35.0
At the long-term monitoring station (J7 junction node)	Runoff	29.8	2.6	3.1	4.0	4.7
	TSS	166.1	56.7	58.3	73.5	82.3
	TP	0.3	50.7	51.1	66.0	71.9
	TN	0.2	9.5	13.7	17.4	20.9
At downstream wetland or receiving node(SCM 16)	Runoff	29.8	8.0	8.9	9.7	10.4
	TSS	166.1	69.9	70.0	78.7	86.8
	TP	0.3	63.6	64.4	73.5	78.4
	TN	0.2	12.7	14.2	19.4	21.5

2.5.3 Effectiveness of the Existing Engineered SCMs Network: Water Quality

The 2008 PCCO requires 85% and 70% reductions in TSS and TP annual expected loading, for all new individual developments with greater than a 12% built upon area. Limits for total nitrogen (TN) in the study area are not included in the 2008 PCCO but are included in this analysis. An analysis of TSS, TP, and TN fluxes at all junction nodes (J1 to J11) demonstrated elevated fluxes from the high impervious junction nodes (Tables 2.1 and 2.5). Unit area fluxes from the upstream (J1) to downstream (J7) junction nodes, all located on the main stem of the BD4 stream channel increased in a downstream direction, which was attributed to increasing urbanization in the downstream portion of the BD4 sub-watershed (Figure 2.1 and Tables 2.1 and 2.5). Higher TSS, TP, and TN unit area fluxes at downstream monitoring stations in comparison to the upstream monitoring station on a stream reach of the BD4 sub-watershed were also measured during baseflow and stormflow sampling over discrete time periods (Gagrani unpublished data). During the simulation period, June 2008 to May 2009, the TSS, TP, and TN fluxes at the J1 junction node were 17.5 g/m^2, 0.05 g/m^2, 0.13 g/m^2, respectively. At the J7 junction node for this same period, the TSS, TP, and TN fluxes were 71.9 g/m^2 (+4.1x) g/m^2, 0.13 g/m^2 (+2.6x), and 0.16 g/m^2 (+1.2x), respectively.

Similar to the assessment of the percent runoff reduction at different locations on the BD4 sub-watershed engineered SCMs network in the “hydrologic benefits” section above, the relative effectiveness of the treatment trains in reducing TSS, TP, and TN loading was assessed (Table 2.4). From the 13 single engineered SCMs, the median (minimum and maximum) percent reductions of TSS 50.5% (37.4% and 65.5%), TP 41.1% (24.6% and 59.2%), and TN 12.9% (6.2% and 28.1%) were observed (Table 2.4

and Figure 2.6). The SCM9 treatment train lowered the TSS, TP, and TN loading by 42.1%, 45.2%, and 18.9%, respectively.

The SCM15 treatment train including SCM15 lowered the TSS, TP, and TN loading by 60.7%, 49.9%, and 14.3%, respectively (Table 2.4). At the SCM15, the TSS, TP, and TN incoming fluxes were 185.6 g/m^2, 0.31 g/m^2, 0.22 g/m^2 and the simulated outflow fluxes were 148.4, 0.26, and 0.21 g/m^2. The SCM15 itself provided 25.1%, 18.0%, and 2.3% additional reduction of TSS, TP, and TN fluxes, respectively (Table 2.4). The TSS, TP, and TN removal efficiency of the existing engineered SCMs network at the J7 junction node were estimated as 56.7%, 50.7%, and 9.5%, respectively. The total TSS, TP, and TN load reduction efficiencies after accounting for removal by the pre-existing downstream floodplain/wetland (at the SCM16) was estimated as 69.9%, 63.6%, and 12.7%, respectively.

Modeling results point to a 5.3x (70.93 g/m^2), 3.2x (0.16 g/m^2), and 1.4x (0.17 g/m^2) higher TSS, TP, and TN fluxes in the post-development state with existing engineered SCMs in comparison to the pre-development simulation at the J7 junction node (Table 2.4). Despite the site-by site installation of 15 engineered SCMs, the modeled BD4 sub-watershed runoff loading does not indicate that the required 85% TSS and 70% TP load reduction was met by the single engineered SCMs installed to receive runoff from the respective source node areas nor by the SCM9 treatment train, the SCM15 treatment train, the downstream J7 junction node, and at the SCM16. The reference concentration of TP for the rivers and streams of the S.E. eco-region IX is 0.037 mg/L and the boundary for the oligotrophic to mesotrophic is 0.025 mg/L and for the mesotrophic to eutrophic is 0.075 mg/L (USEPA 2000). The flow weighted daily mean, maximum and minimum TP concentrations at the J7 junction node for the simulation period were 0.18 mg/L, 1.2 mg/L, and 0.11 mg/L, respectively. These TP concentrations would categorize the BD4 stream channel as a mesotrophic to eutrophic stream based on USEPA (2000) criteria. We are unable to observe any cumulative effect of the treatment trains established in the study watershed on the range of TSS, TP and TN reduction for the single engineered SCMs, or for the engineered SCMs receiving runoff from upstream engineered SCMs, rather the percent loading reduction appears to be more related to the percent imperviousness in the individual engineered SCMs drainage area.

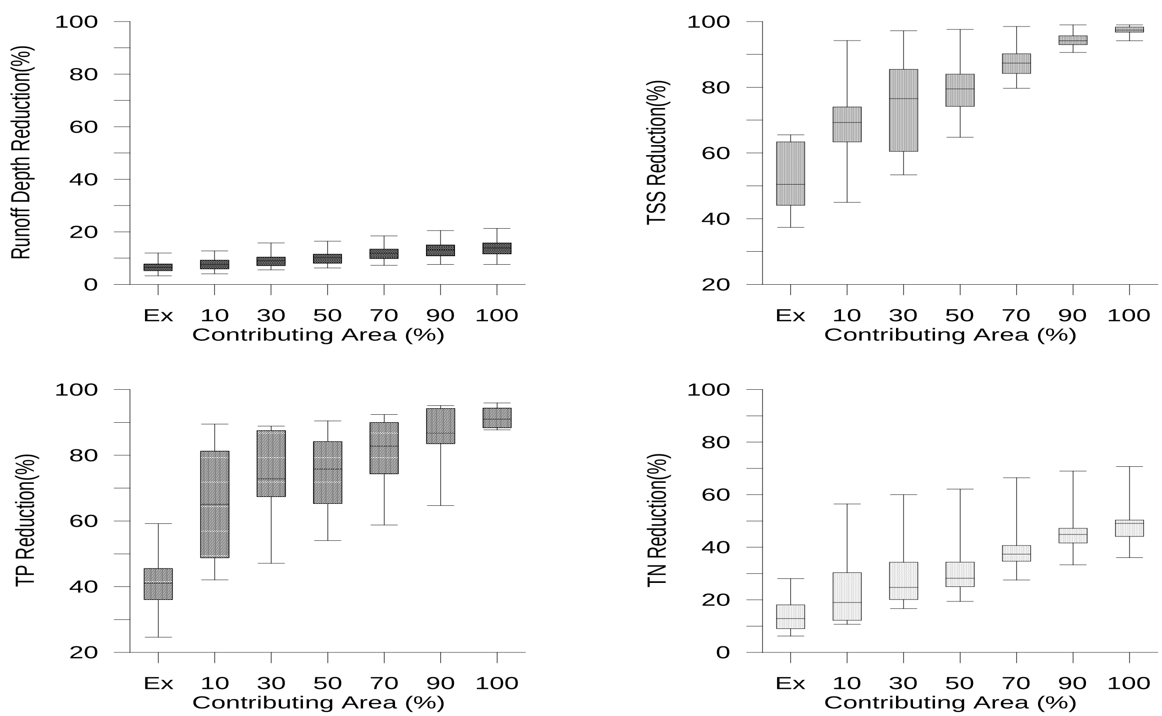

Figure 2.6: Reduction in runoff, TSS, TP, and TN from 13 primary SCMs from the existing SCMs network for the study sub-watershed (Bio-I scenario).
Notes: 1. Ex represents the existing SCMs network, rest simulations are in increasing order of runoff diverted into offline bio-retention basins from the contributing area of each SCM. 2. The primary SCMs are installed as the only treatment facility for the source area or without any treatment train

2.5.4 Backyard Rain Garden Scenario

In an attempt to examine the effect of potential retrofit solutions to control stormwater volumes and pollutant loading from developing source areas we simulated a backyard rain-garden scenario, where runoff from the existing suburban roof areas were diverted into onsite rain-gardens and then into engineered SCMs located in each subdivision of the BD4 sub-watershed (Figure 2.2). The assessment of simulated raingardens at different locations in the existing SCMs network of the BD4 subwatershed demonstrated the highest additional reduction at the outlet of single SCMs in comparison of the at the outlets of the SCM9, SCM15, J7 Junction node, and SCM16 (Table 2.4). The single SCMs exhibited 0.8% reduction in runoff volume and 5%, 14%, and 2 % of TSS, TP, and TN fluxes, respectively (Table 2.4).

In conjunction with the retention from the simulated existing engineered SCMs network of the BD4 sub-watershed, the backyard rain-garden simulation at the J7 junction node provided an additional 0.5% reduction in runoff depth and 1.6%, 0.6%, and 4.2% reduction in TSS, TP, and TN fluxes, respectively (Table 2.4). The relatively small reduction in pollutant loadings from the backyard rain-garden simulation is attributed to the small areal extent of the suburban roof areas (3.2% of the BD4 sub-watershed area) as well as the relatively low concentration of TSS (15.8 mg/L), TP (0.05 mg/L), and TN (0.03 mg/L) assigned to rooftop runoff. Field monitoring of a detention basin receiving runoff from a subdivision in the BD4 sub-watershed indicated that roofs accounted for only 1% of the annual TP flux received by the basin due to low roof runoff TP concentrations (0.01 to 0.07 mg/L) and the small areal extent represented by rooftops (9% of the study SCMs contributing area), whereas suburban lawns accounted for 94% of the annual TP flux to the basin due to high runoff TP concentrations (average 1.1 mg/L) and a greater areal extent (72% of the study SCMs contributing area) (Barto et al. 2010).

2.5.5 Offline Bio-Retention Basins Scenario (Bio-I and Bio-II Scenarios)

The simulated runoff, and sediment and nutrient loading outputs through adding additional retrofit offline bio-retention basins to each urban source node area in increasing increments of 10% up to 100% are presented in the Figure 2.7 (Bio-I Scenario). This analysis indicates that the mandated 85% TSS and 70% TP reduction for individual source node areas could be attained by diverting runoff from ≥70% of the source node areas into additional offline bio-retention basins (Table 2.4 and Figure 2.6). In order to attain the 85% TSS and 70% TP reduction at the J7 junction node, runoff from ≥70% of the source node areas need to be treated by additional offline bio-retention basins (Table 2.4 and Figure 2.7). However, the scenario of diverting runoff from 70% of the source node areas into offline bio-retention basins did not appreciably attenuate the peakflow runoff rates (Figure 2.5). When compared to the pre-development levels, even though the PCCO requirements are met after diverting runoff from 70% of urban source node areas into additional bio-retention basins, the post-developments TSS, TP, and TN annual loadings remained 1.8, 1.5, and 2.9 times higher than pre-development levels at the J7 junction node.

In a comparison to the calculated annual fluxes of nutrients and sediment from the adjacent forested BD1 sub-watershed, the urbanizing BD4 sub-watershed simulations demonstrated a two times lower TSS flux, a four times higher TP flux, and no change in the TN flux for the simulation period. The source node areas of the J8, J10, and J11 junction nodes, comprised the highest impervious coverage (37.5%, 38.4% and 46.4%,

Table 2.1), and demonstrated a higher reduction for average runoff, and TSS, TP, and TN fluxes (-4.7% and -72.2%, -60.3%, and -26.5%, respectively, Table 2.5) in comparison to the average for the other junction nodes (-1.6% and 38.7%, -27.4%, and -6.2%, respectively, Table 2.5). This can be attributed to the relatively high loadings into the SCM treatment trains (the existing engineered SCMs and simulated offline bio-retention basins) draining to these junction nodes (Table 2.1 and Figure 2.2).

The assessment of simulated offline bio-retention basins receiving runoff from 70% urban source node areas at different locations (13 single engineered SCMs, SCM9 treatment train, SCM15 treatment train, J7 junction node, and SCM16) demonstrated a significant increase in TSS, TP, and TN loading reductions in comparison to the existing engineered SCMs and backyard rain-garden scenarios (Table 2.4). For the 13 single engineered SCMs, the median reduction of the runoff depth was 12.2%, and the median reduction of the TSS, TP, and TN fluxes were 87.4%, 81.6%, and 36.9%, respectively (Table 2.4 and Figure 2.7). The simulation of diverting runoff from 70% of the urban source node areas at the SCM15 outlet lowered the TSS, TP, and TN by 88%, 81%, and 35%, respectively. At the J7 junction node the existing and the offline bio-retention basins jointly lowered the runoff depth by 5% along with the TSS, TP, and TN fluxes by 82%, 72%, and 21%, respectively (Table 2.4).

The simulation of downstream pre-existing natural floodplain/wetland area with the existing upstream SCMs in the BD4 sub-watershed indicated that the required TSS and TP annul load reductions could be attained by diverting runoff from >50% of urban surfaces instead of >70% (Table 2.4 and Figure 2.7). The effectiveness of the natural floodplain/wetland area in conjunction with the existing engineered SCMs in attenuating

TSS, TP, and TN loadings was 4.5%, 6.5%, and 0.6%, respectively. Further, the post-development scenario of incorporating the downstream floodplain/wetland, SCM16, without the existing upstream engineered SCMs demonstrated a runoff volume reduction of 5.6%, and TSS, TP, and TN load reductions of 61.4%, 61.0%, and 7.8%, respectively which are similar to the post-development simulation of exiting SCMs with downstream floodplain/wetland area (69.9%, 63.6%, and 12.7% TSS, TP, and TN, respectively). This demonstrated that natural downstream floodplain/wetland areas can play a significant role in reducing TSS, TP, and TN loading. Therefore pre-existing floodplain/wetland areas should be considered in the whole watershed post-development SCM assessment. The mean, maximum, and minimum concentration of TP at the long-term monitoring station (J7 junction node) under the 50% bio-retention scenario was 0.14 mg/L, 1.15 mg/L, and 0.07 mg/L, respectively. At the ultimate receiving node, Lake Wylie, the flow weighted daily mean, maximum, and minimum concentration of TP were 0.068 mg/L, 1.2 mg/L, and 0.0 mg/L. These concentrations still categorize the BD4 stream channel as a mesotrophic to eutrophic stream under the USEPA criteria (USEPA 2000).

The scenario of diverting runoff from 70% contributing source area nodes of the existing SCMs into retrofit offline bioretention basins in an incremental order of the source area imperviousness (Bio-II) demonstrated that the mandatory TSS and TP load reduction could be obtained only after diverting runoff from all urban source area nodes of the existing SCMs (Figure 2.8). Further, the simulation of downstream floodplain/wetland area, SCM16, demonstrated that the 85% reduction of the TSS could be obtained by diverting runoff from the contributing source area nodes of the first 12 existing engineered SCMs out of the 14 (excluding SCM 14 and 2) into the offline bio-retention basins (Figure 2.8). Whereas, the 70% TP reduction requires diverting the runoff from the contributing source area nodes of the first six existing engineered SCMs (SCM 8, 3, 13, 4, 11, and 10) into additional offline bio-retention basins (Figure 2.8). This simulation facilitates the prioritizing of the installation of the offline retrofit bio-retention basins in the BD4 sub-watershed source node areas to attain the mandatory reduction of the TSS and TP loadings at the watershed scale.

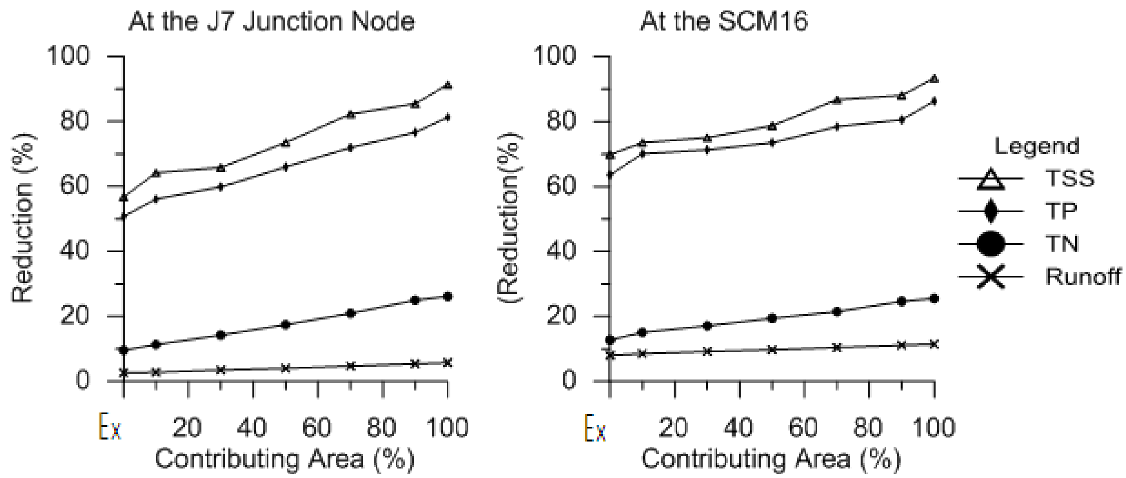

Figure 2.6: Reduction in runoff, TSS, TP, and TN at the J7 and SCM 16 (Bio-I Scenario)
Notes: Ex represents the existing SCMs network simulation. Rest simulations are in increasing order of runoff diverted into offline bio-retention basins from each source node area.

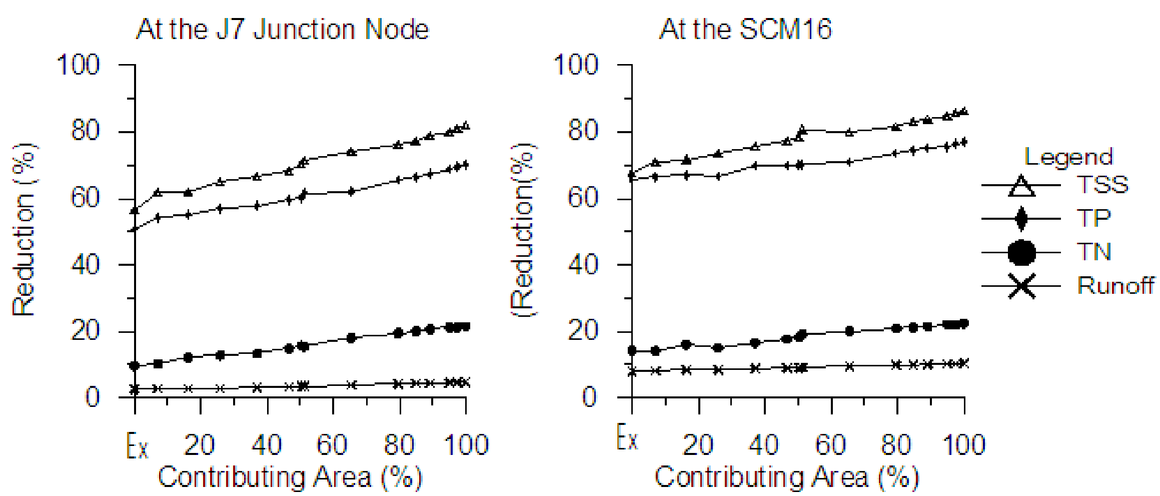

Figure 2.7: Reduction in runoff, TSS, TP, and TN at the J7 and SCM 16 (Bio-II Scenario)
Notes: Ex represents the existing SCMs network simulation. Rest other simulations are in increasing order of runoff diverted into offline bio-retention basins from the 70% contributing area starting from highest impervious to lowest imperviousness.

Table 2.5: Runoff depth and unit area fluxes of TSS, TP, and TN at different junction nodes.

Junction Nodes	Existing SCMs Simulation				Rain Garden Simulation				Bio-retention Basin Simulation			
	Runoff Depth (cm)	TSS (gm/m^2)	TP (gm/m^2)	TN (gm/m^2)	Runoff Depth (cm)	TSS (gm/m^2)	TP (gm/m^2)	TN (gm/m^2)	Runoff Depth (cm)	TSS (gm/m^2)	TP (gm/m^2)	TN (gm/m^2)
J1	0.24	17.47	0.05	0.13	0.24	17.67	0.05	0.13	0.24	17.87	0.05	0.14
J2	0.25	35.47	0.08	0.14	0.25	33.03	0.08	0.14	0.25	23.38	0.07	0.14
J3	0.25	35.66	0.08	0.14	0.25	33.14	0.08	0.14	0.25	23.80	0.07	0.14
J4	0.26	40.19	0.09	0.14	0.26	39.26	0.09	0.14	0.26	23.26	0.07	0.14
J5	0.27	55.03	0.10	0.15	0.27	54.71	0.10	0.15	0.27	25.60	0.07	0.14
J6	0.29	66.64	0.12	0.16	0.28	66.08	0.12	0.16	0.28	28.09	0.07	0.14
*J7	0.29	71.91	0.13	0.16	0.29	69.31	0.13	0.16	0.28	29.44	0.07	0.14
J8	0.36	148.6	0.21	0.21	0.36	146.5	0.20	0.21	0.35	45.30	0.09	0.16
J9	0.26	47.65	0.13	0.14	0.26	47.37	0.12	0.14	0.25	32.41	0.06	0.12
J10	0.37	193.7	0.28	0.22	0.37	169.2	0.23	0.22	0.35	53.33	0.11	0.16
J11	0.41	247.3	0.35	0.24	0.41	178.6	0.25	0.24	0.39	63.10	0.13	0.17

2.6 Summary and Conclusions

The BD4 sub-watershed is the most urbanized (54.3% developed) sub-watershed of the BDC watershed, and drains into the Lake Wylie, a water supply reservoir vulnerable to eutrophication on the heavily subscribed Catawba River system. In the BD4 sub-watershed, 15 engineered SCMs were installed in a phase-by-phase manner in line with ongoing sub-division development. Despite the installation of a network of 15-engineered SCMs the runoff volume, peakflow rates, and TSS, TP, and TN loadings were significantly higher than the pre-development state and for those of a nearby forested sub-watershed (10% developed). Simulated post-development TSS (56.7%) and TP (50.7%) load reductions fall short of those mandated by existing regulations, TSS (85%) and TP (70%). In order to meet these reduction targets for the peakflow and the TSS and TP loadings with the existing engineered SCMs network would require the diversion of at least 70% of the stormwater runoff into additional bio-retention basins. A retrofit scenario utilizing backyard rain-gardens in conjunction with the existing SCM network was found to be minimally effective in enhancing pollutant loading owing to the low nutrient concentrations in roof runoff and the relatively small areal percentage represented by rooftops in these subdivisions.

The BD4 sub-watershed contains an 8,443 m^2 downstream natural wetland/floodplain area, but it could not be included into the calibration and validation of the existing engineered SCMs network of the BD4 sub-watershed due to the absence of a monitoring station at that location. However, by using standard model parameters we can estimate the importance of this natural wetland/floodplain area in attenuating pollutant loading. The pre-existing downstream natural floodplain/wetland area simulation without engineered SCMs is estimated to reduce runoff volume by 5.4%, and lower the TSS, TP, and TN annual loadings by 61.4%, 61.0%, and 7.8%, respectively. However, ability of SCM 16 to trap TSS, TP, and TN was greatly reduced when it was simulated in conjunction with the existing engineered SCMs and offline bio-retention basins. This can be attributed to the floodplain/wetland area receiving pre-treated and filtered runoff from the existing SCMs and offline bio-retention basins, thereby leaving it less to do.

The traditional development approach of utilizing a phase-by-phase designing and implementation of engineered SCMs in land development of sub-divisions of the BD4 sub-watershed was not proven effective in attaining the mandatory reduction of peakflow volumes, TSS and TP loadings. Rather, additional offline bio-retention basins need to be installed to meet regulatory guidelines. Our modeling results indicate that the amount of additional bio-retention required in a retrofit might be reduced through the incorporation of existing natural bio-retention areas, including active floodplains and wetland areas, in the basin-wide treatment of sediment and nutrient transport.

CHAPTER 3: ASSESSING THE CHANGE IN RUNOFF RESPONSE IN A DEVELOPING SE PIEDMONT WATERSHED THROUGH THE UNIT HYDROGRAPH, UNIT IMPULSE RESPONSE, AND MANN-KENDAL STATISTICAL TREND TEST

3.1 Abstract

In this study, the change in the runoff hydrology of five developing SE Piedmont sub-watersheds (10% to 54% land use change) with a combination of engineered stormwater control measures and stream restoration was evaluated with the unit hydrograph, unit impulse response, and Mann-Kendall trend test approaches. The runoff response from the first sub-watershed (10% developed) demonstrated a decreasing average baseflow and streamflow trends as determined from the Mann-Kendall trend test and exhibited a decline in peakflow discharge (-13.2% to -28.4%) determined from the unit hydrograph and unit impulse response analyses. A second sub-watershed with a similar level of development but also impacted by a major stream restoration project experienced an increase in peakflow discharge (3.1% to 9.5%) and direct runoff coefficient (3.9%) using the same analytical methods. The third sub-watershed with 50% suburban development, constructed stormwater detention basins, and a 70% restored stream reach exprienced a decreasing trend in average baseflow and streamflow and a decline in peakflow discharges (-12.0% to -7.8%). The fourth sub-watershed with similar development and stormwater control detention indicated an increasing trend in average baseflow streamflow and a decline in peakflow (-15.8% to -4.4%). The fifth sub-watershed, which drains the first three sub-watersheds, demonstrated a significant

increase in the peakflow discharge (25.7% to 24.8%) attributed to a now more coincidental peakflow from its two larger contributing sub-watersheds in conjunction with an increase in peakflow from the one of these two sub-watersheds. The three approaches applied in this study indicated similar runoff responses from land development, stormwater detention structures, and stream restoration. Observed declines in peakflow discharge and increases in the direct runoff coefficient and runoff duration is attributed to the influence of stormwater detention basins in the most developed sub-watersheds whereas, little difference in runoff response could be attributed to the stream restoration projects.

Key Terms

Land use, Stormwater Control Measures, Stream Restoration, Unit Hydrograph, Unit Impulse, Mann-Kendall, Runoff Response

3.2 Introduction

Urbanization disrupts and alters the natural hydrologic regime of a watershed and is often characterized by increased runoff volume and peak discharges, and decreased basin lag times, groundwater recharge, and evapotranspiration (e.g., Leopold 1968, Barringer et al. 1994, Paul and Meyer 2001, and Booth et al. 2002). In order to maintain the hydrologic regime of an urbanizing watershed, excess event runoff from impervious surfaces is often diverted into engineered Stormwater Control Measures (SCMs) such as wet and dry detention basins, bio-retention basins, rain-gardens, grass swales, and constructed wetlands (e.g. Lawrence 1996, Strecker et al. 2001, Hunt et al. 2006 and 2008, and Davis 2008). In addition to the engineered SCMs, stream restoration practices are frequently implemented in an attempt to enhance channel stability, restore ecological functions, minimize flooding, and improve water quality (e.g., Meyer et al. 2005, Groffman et al. 2005, Bukaveckas 2007, and Kaushal et al. 2008).

However, in urban watersheds, success in restoring pre-development hydrologic and water quality regimes by installing engineered SCMs is often limited due to constraints such as excessive land cover disturbance in conjunction with inadequate location, design, type, and maintenance of these structures (Roesner et al. 2001, Booth et al. 2002, Hur et al. 2008, and NRC 2008). In urban watersheds, success in attaining the predevelopment hydrologic, water quality, and biological conditions through restoring stream reaches is often limited due to constraints such as elevated loading of pollutants associated with sediment and stormwater runoff, the high cost of urban land, and the proximity to the existing surface and sub-surface urban infrastructure (Booth 2005, Bernhardt and Palmer 2007 and 2011, and Palmer et al. 2010).

In urban watersheds, in order to implement effective stormwater management practices, it is important to assess the changes in hydrologic regime due to urbanization, and assess the effectiveness of existing engineered SCMs and stream restoration practices at the watershed scale. Hydrologic time series assessment approaches such as the construction of pre- and post- development unit hydrographs, auto regressive models, and statistical trend tests have been widely used to assess the change in watershed runoff responses following land use alteration (e.g., Zhang et al. 2001, Vicars and Williams 2007, and Farahmand et al. 2007). However, none of these previous studies has compared multiple assessment methods in terms of their outcomes. This study employs the above approaches in a comparative manner to assess the change in the runoff response in a rapidly developing watershed in the SE U.S. Piedmont.

The unit hydrograph approach has previously been used in a comparison of the pre- and post-development unit hydrographs of the urbanized White Rock Creek watershed in Texas, where a 49 minute shorter lag time and a doubling of the runoff volume for a 10 year rainfall event was observed (Vicars and Williams 2007). However, for an actively urbanizing watershed, determining "stable" pre- and post-development periods and averaging four to five unit hydrographs during sub-periods of the land development cycle can be problematic.

For an actively urbanizing watershed, the instantaneous assessment of the change in runoff response using continuous rainfall-runoff time series for sub-periods within the development cycle can provide information regarding alterations in a hydrologic regime as they are occurring. In addition, such approaches can assess the effects of the implementation of mitigation measures such as engineered SCMs and stream restoration. The instantaneous change in runoff response approach known as the unit impulse response was proposed by Farahmand et al. (2007), where a unit impulse of rainfall can be used to assess the change is runoff response from the rainfall-runoff models of two consecutive land development periods. Some limitations of this approach include a limited data period for model calibration and validation when applied in a rapidly developing watershed, and the absence of a reference watershed to assess the impacts of other factors influencing runoff beyond land development. In addition to land use changes through urbanization, seasonality and climate change can also influence the hydrologic responses of a watershed.

The Mann-Kendal non-parametric trend test has been widely used to assess the change in hydroclimatic trends (Zhang et al. 2001, Burn and Elnur 2002, Gratiot et al.

2009, and Sahoo and Smith 2009). The influence of climate change on the hydrologic response of 249 Canadian watersheds showed that the trends in streamflow were related to the trends in meteorological variables attributed to climate change (Zhang et al. 2001 and Burn and Elnur 2002). Using the same approach Gratiot et al. 2009 examined an urbanizing watershed in Mexico, and found that the increased surface runoff was due to urbanization instead of increased precipitation.

Multiple spatially distributed land development projects over prolonged periods are more often than not the norm in rapidly urbanizing watersheds. Because of the widespread regional occurrence of development, it is often difficult to identify a nearby "control" watershed to perform a paired watershed comparison. In addition, there is oftentimes little opportunity, or the resources necessary, to conduct a multi-year predevelopment monitoring program to establish robust regression relationships between the reference and experimental watersheds. In order to provide watershed managers information as to the effectiveness of development regulations in a timely manner it is also often not possible to wait until all development has ceased and land use has stabilized within the urbanizing area before performing a pre- and post-development analysis.

The goal of this research was to quantify the change in runoff response in a rapidly developing SE U.S. Piedmont watershed, where significant engineered SCMs infrastructure have been built to meet the stormwater control requirements within a drinking water supply watershed. Owing to the absence of a true reference watershed, a relatively brief pre-treatment monitoring period, ongoing land use changes throughout the study period, the construction activities and recovery periods following stream restoration projects, and variable engineered SCMs implementation, a variety of analytical approaches (i.e., unit hydrograph comparison, unit impulse response, and a statistical trend test) were used to assess the magnitude of change in runoff response of the five urbanizing sub-watersheds in order to evaluate the effectiveness of development regulations in maintaining the pre-development runoff regime.

3.3 Study Area

The Beaverdam Creek (BDC) watershed is located at 35°10′11″N latitude and 80°59'16" longitude in southwest Mecklenburg County, North Carolina (Figure 3.1). The BDC watershed drainage area is 11.8 km^2 and is comprised of five sub-watersheds: BD1, BD2, BD3, BD4, and BD5 (Figure 3.1). The BDC watershed drains into Lake Wylie, a water supply reservoir on the highly subscribed Catawba River system. The study watershed lies in the humid subtropical climate zone (Cfa) in the Köppen climatic classification. The 30-year normal monthly mean, minimum, and maximum temperatures are 16.3°C, 5.4°C (January), and 26.8°C (July), respectively, and the mean annual precipitation is 110.4cm (Charlotte Douglas International Airport 2011). Stream gauging stations are located in the downstream reaches of each of the five BDC sub-watersheds.

In 2003 at the initiation of our study, the BDC watershed was primarily undeveloped with land use classed as 61.3% mixed forest, 31.5% low-density residential (≤12% built upon area) and 5.2% transportation land uses (Buck Engineering Inc. 2003). However, by 2010, 16.2% of the pre-existing mixed forest and 5.3% of the low-density residential land use was converted into suburban single-family developments with a ≥12% built upon area (Table 3.1, Figure 3.2). The BD1 and BD2 sub-watersheds constituting 75% of the total BDC watershed drainage area remain relatively undeveloped in comparison to the BD3 and BD4 sub-watersheds. However, during this study the BD1 sub-watershed was impacted by the construction of an interstate highway (I-485) and expansion of the Charlotte Douglas International (CDI) airport, which resulted in the burying of two headwater tributaries and the construction of associated stormwater detention structures. In all, 10.7% of the BD1 sub-watershed area was altered (Figure 3.2). The headwater streams of the BD2 sub-watershed were also impacted from the construction of the same interstate highway and expansion of the CDI airport. In this sub-watershed 13.3% of the preexisting forested area was altered after 2003 (Figure 3.1 and Figure 3.2). In addition to these land cover changes, 1,663 meters of the downstream reach (52.8% of the channel mainstem length) of the BD2 sub-watershed was subject to a significant stream restoration project, which altered the channel pattern and slope of this tributary. The BD3 and BD4 sub-watersheds represent the most developed sub-watersheds, with only 36.3% and 21.1% of the original mixed forest cover remaining in 2010 (Table 3.1, Figure 3.2). The BD3 sub-watershed was not impacted by the construction of the I-485 highway corridor or the expansion of the CDI airport. Three fourths of the 3,228 meter stream reach of this sub-watershed was subject to stream restoration activities in 2006. Eight engineered SCMs were constructed to control runoff from the actively developing areas. These engineered SCMs provided 1.7 cm of detention depth over the total developed area in the BD3 sub watershed. As of 2010, 49.8% of the existing mixed forest has been cleared for urban development in the BD3 sub-watershed (Table 3.1, Figure 3.2). In the BD4 sub-watershed, residential development began in 2003. Current land use assessment shows a conversion of 54.3%

preexisting forest and low-density residential lands into high-density residential and commercial use buildings (Table 3.1, Figure 3.2). In this sub-watershed, 15 stormwater detention basins were constructed. The engineered SCMs in the BD4 sub-watershed provide 1.8 cm of detention depth over the total developed area.

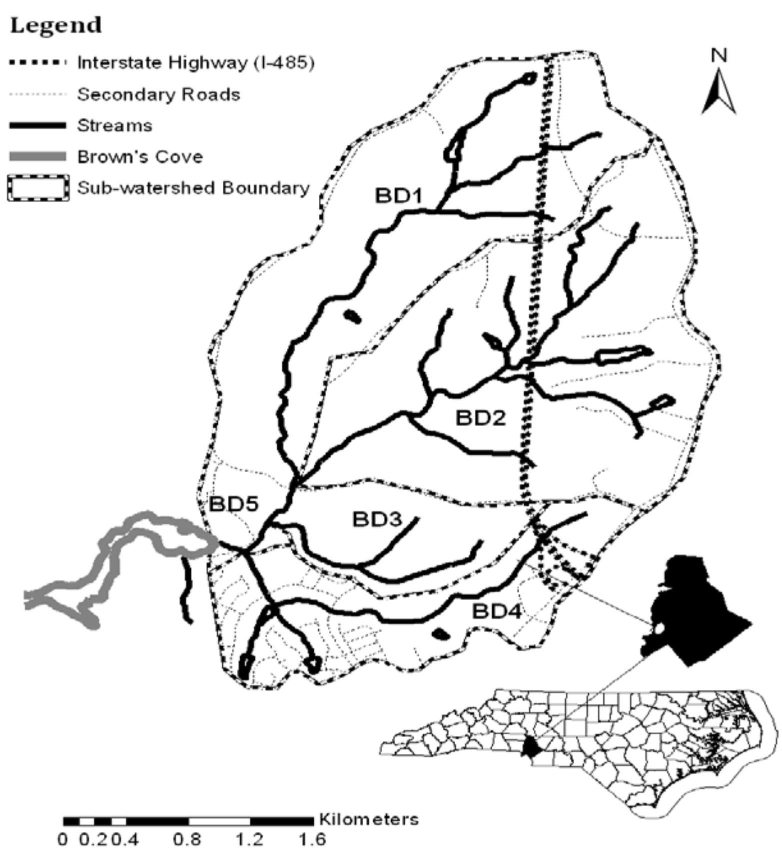

Figure 3.1: Locations of the BD1, BD2, BD3, BD4, and BD5 sub-watersheds in the Beaverdam Creek (BDC) watershed.

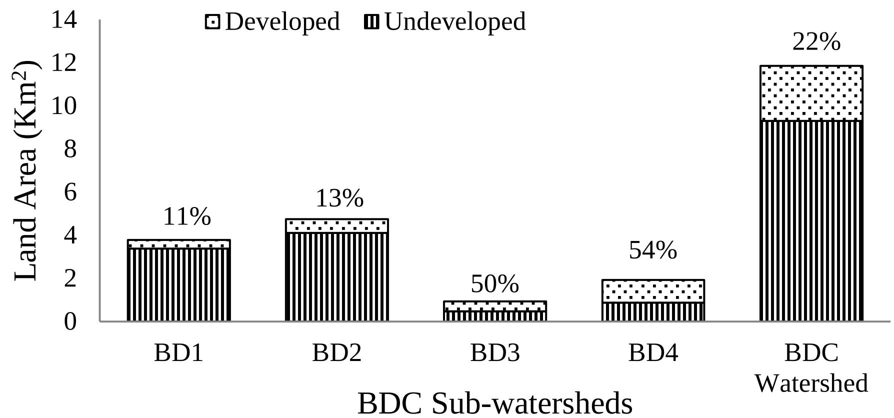

Figure 3.2 : Drainage area of the BDC sub-watersheds and percent land development as of 2010.

Table 3.1: Land use changes from 2003 to 2011 in the BDC sub-watersheds.

BDC sub-watersheds	BD1		BD2		BD3		BD4		BDC watershed	
Drainage Area (km^2)	3.78		4.74		0.93		1.92		11.85	
Years	2003	2010	2003	2010	2003	2010	2003	2010	2003	2010
Forest	61.00	50.32	60.30	46.96	86.10	36.29	42.80	21.07	61.32	45.15
Low density residential (≤12% built upon area)	31.88	31.88	31.38	31.38	11.80	11.80	48.70	16.11	31.54	26.26
High density residential (≥12% built upon area)	0.00	0.00	0.00	0.00	0.00	44.01	0.00	50.73	0.00	11.67
Transportation(I-485)	5.80	5.80	5.00	5.00	1.70	1.70	7.80	7.80	5.25	5.25
Institution	0.00	0.00	0.70	1.14	0.00	5.80	0.00	0.00	0.28	0.91
Airport	0.00	10.68	0.00	7.76	0.00	0.00	0.00	0.00	0.00	6.51
Commercial	0.02	0.02	0.02	4.16	0.00	0.00	0.00	3.59	0.01	2.25
Industrial	0.80	0.80	1.70	2.70	0.00	0.00	0.00	0.00	0.94	1.34
Water	0.50	0.50	0.90	0.90	0.40	0.40	0.70	0.70	0.66	0.66

3.4 Methodology

3.4.1 Precipitation and Stream Discharge Data

For the study sub-watersheds, 15 minute time interval precipitation and stream discharge data were compiled from July 2003 to December 2010. The average precipitation of the BDC sub-watersheds was calculated from the Thiessen polygon method using four USGS rain gauges located in the close vicinity of the study watershed (USGS 351247080592745, 350903081004545, 350842080572801, and 351132080562345 stations). Stream discharge data for the BD1, BD2, BD3, and BD4 sub-watersheds were measured directly by the authors as part of a long-term monitoring study of the watershed (Allan et al. 2010), whereas for the BD5 sub-watershed, stream discharge data were obtained from a USGS stream gauging station (USGS 0214297160).

3.4.2 Average Unit Hydrograph

The average unit hydrograph for each study sub-watershed was constructed as described by Viessman et al. (1998). Baseflow was separated by identifying the point of initial hydrograph rise, and from that point projecting a line with a slope of 0.0005 cubic meters per second per square km per hour until the line intersected the recession limb of the hydrograph (Hewlett and Hibbert 1967). Ordinates of a unit hydrograph were calculated by dividing the ordinates of the direct runoff hydrograph by the depth of infiltration excess precipitation. For the study sub-watersheds, the mean, median, minimum, and maximum duration of the excess rainfall or direct runoff were 0.90, 0.75, 0.25, and 4.0 hours, respectively, which were converted to the half an hour excess rainfall duration 1.0 cm unit hydrographs by the S-hydrograph method (Tauxe 1978). Three to five such unit hydrographs were averaged to obtain the average unit hydrographs for the pre- and post-development periods for each BDC sub-watershed. The storm events for the stable pre development period for the BD1, BD2, BD3, and BD5 sub-watersheds were selected from July 2003 to March 2005. However, due to an earlier initiation of land clearing in the BD4 sub-watershed, the pre-development storm events were selected from July 2003 to March 2004. The storm events for the post-development period for all the sub-watersheds were selected from March 2008 to December 2010. This study included only those storm events preceded by at least five dry days (i.e., less than 0.01cm precipitation per day) in order to reduce the influence of antecedent soil moisture on the runoff response. Effective rainfall, peak discharge, time to peak, losses or Φ index (i.e., storage, interception, and infiltration), direct runoff, duration of excess runoff, and runoff coefficient were determined for the pre- and post-development periods.

3.4.3 Unit Impulse Response

The unit impulse response method assesses the instantaneous runoff response change from an actively urbanizing watershed resulting from an input of a single impulse of known amplitude and duration of precipitation (unit storm event) (Farahmand et al. 2007). The System Identification Toolbox (SITB) of Matlab v.8 was used to develop the autoregressive with an exogenous variable (ARX) rainfall-runoff model, where rainfall is the exogenous component. The ARX model for a rainfall-runoff time series can be presented as follows:

$$y_t = \sum_{i=1}^{Na} a_i y_{t-i} + \sum_{j=1}^{Nb} b_j u(t - N_k - j + 1) + e_t \tag{3.1}$$

Where t= discrete time steps, y= stream discharge, u_t= precipitation, and e_t= external noise. The order of the autoregressive component, y_t is N_a, which is equal to the number of sampling intervals between the most-delayed and least-delayed outputs. The order of the exogenous component, u_t is N_k+N_b-1. Here, N_b is equal to the number of sampling intervals between the most-delayed and least delayed inputs and N_k is the number of samples before the input affects the output of the system, known as the delay or dead time of the system. The runoff (y_t) is modeled simply as a linear combination of the past values of runoff and precipitation. For the study sub-watersheds, the ARX rainfall-runoff time series models were developed by using 30 or more days of continuous 15-minute rainfall-runoff time series from the pre- and post-development periods. The ARX rainfall-runoff models were then employed to assess the change in runoff response of a triangulated unit impulse of 25.4 mm precipitation in 3.5 hours during the pre- to the post-development periods.

3.4.4 Mann-Kendal Non-Parametric Trend Detection Test

The trends in precipitation, baseflow, and quickflow time series for the five study watersheds were assessed with the rank-based Mann-Kendall (MK) non-parametric test (Mann 1945 and Kendall 1975). The Mann-Kendall statistic S is defined below:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \pm (X_i - X_j) \tag{3.2}$$

$$\pm (X_i - X_j) = \begin{cases} +1 & if\,(X_i - X_j) > 0 \\ 0 & if\,(X_i - X_j) = 0 \\ -1 & if\,(X_i - X_j) < 0 \end{cases} \tag{3.3}$$

Where X_i and X_j are the monthly values of the hydrologic parameter for all i =1 … (n-1) and j = (i+1)…n months. The standard deviation (σ_S) was calculated as:

$$\sigma_S = \sqrt{(n/18)(n-1)(2n+5)} \tag{3.4}$$

The standardized statistic test Z_s for more than 10 samples was calculated as:

$$Z_s = \begin{cases} \frac{S-1}{\sigma_S} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sigma_S} & if \quad S < 0 \end{cases} \tag{3.5}$$

A positive value of Zs indicates an increasing trend in the hydrologic variable, while a negative value of Zs indicates a decreasing trend. The monotonic trend for each hydrologic variable was tested at a significance level of 0.2, as used in similar studies (e.g. Zhang et al. 2001 and Sahoo and Smith 2009). The magnitude of the trend was determined using Sen's method of non-parametric statistics, which calculates the slope as a change in runoff per unit change in time. Magnitudes of change were obtained by calculating the median of the slopes over time (Hirsch et al. 1982):

$$\beta = median\left[\frac{(X_j - X_i)}{j-i}\right] \qquad \text{for all } i < j \tag{3.6}$$

Where, X_j and X_i were data points measured at times *j* and *i*, respectively. The Mann-Kendal test was used to assess monthly average and maximum values of the stormflow, quickflow, and baseflow for the growing and dormant seasons from July 2003 to December 2010 (Table 3). Streamflow was separated into baseflow and quickflow by filtering low frequency baseflow from high frequency quickflow signals by applying the recursive digital filter technique (Lyne and Hollick 1979, Nathan and McMohan 1990, and Arnold and Allen 1995 and 1999):

$$Q_t = q_t + b_t \tag{3.7}$$

$$q_t = \beta q_{(t-1)} + \left[(1+\beta)\bullet(Q_t - Q_{(t-1)})/2\right] \quad (3.8)$$

Where, Q_t, q_t, and b_t were the total streamflow, quickflow, and baseflow, respectively. The filter parameter was represented as β and the time step as *t*. In this study, the filter parameter was set to 0.92 (Nathan and McMohan 1990). Serial correlation in data can increase the number of false positive outcomes in the MK test (Hamed and Rao 1998 and Burn and Elnur 2001). Serial correlation was calculated using the Box-Ljung statistic at 5% significance levels and removed by following a pre-whitening procedure (Yue and Wang 2002).

$$yp_t = y_{(t+1)} - ry_t \quad (3.9)$$

Where, yp_t is the pre-whitened time series, r is the serial correlation, and y_t the original time series.

3.5 Results and Discussion

3.5.1 Unit Hydrograph Analysis

Results of the unit hydrograph analysis are presented in the Table 3.2 and Figure 3.3. The effective rainfall represents the rainfall depth produced during the period of direct runoff, which equals to the sum of direct runoff and losses or Φ index. The effective rainfall for the BD1, BD2, BD3, BD4, and BD5 sub-watersheds were increased by 0.65cm (49.8%), 0.76cm (31.9%), 0.74cm (68.5%), 0.08cm (6.1%), and 0.72cm (75.6%), respectively from pre- to post-development periods. The higher effective rainfall total in the post-development period demonstrates that to generate a 1cm unit hydrograph, more precipitation is required. The relatively small increase in the effective rainfall for the BD4 sub-watershed in comparison to the other sub-watersheds is attributed to the inter-storm runoff from engineered SCMs in the post-development period (Gagrani unpublished data).

For the least developed BD1 sub-watershed, the average unit hydrograph analysis of the pre and the post-development periods indicated a 2.2% increase in average rate of the Φ index and a 6.2% decline in direct runoff coefficient (Table 3.2 and Figure 3.3). For the BD1 sub-watershed, a one hour (≈2x) increase in the direct runoff duration, a 0.34 m^3/sec (13.2%) decline in peakflow, and a 0.75 hour (37%) increase in the time to peak were also reported. The increase in Φ index and direct runoff duration and decline in direct runoff coefficient could be attributed to the engineered SCMs installed to control the runoff from the interstate highway (I-485) and the new runway expansion for the CDI airport in the headwater tributary of the BD1 sub-watershed.

For the second least developed BD2 sub-watershed, the average unit hydrographs of the pre and post-development periods demonstrated a 19.8% increase in average rate of the Φ index and a 0.25 hours increase in time to peak (Table 3.2, Figure 3.3). The increasing infiltration rate and time to peak were attributed to both the construction of stormwater detention basins and a major stream restoration project. The stream restoration reconnected the stream channel with its floodplain and the re-patterning of the channel increased channel sinuosity and roughness and decreased the average channel slope. Despite the increase in floodplain storage due to stream restoration and stormwater detention storage in the post-development period, the direct runoff coefficient and peakflow rates were 3.9% and 3.1% higher than the pre-development and stream restoration periods, respectively.

The comparison of the average unit hydrographs of the pre- and post-development periods of the more developed BD3 sub-watershed demonstrated a 1.7% decline in average rate of the Φ index, a 6.0% increase in direct runoff coefficient, and a 0.03 m^3/sec or 12.0% decline in the peakflow discharge. The slight decline in infiltration and increase in direct runoff were attributed to the 50% land development since 2003, whereas the decline in peakflow discharge was attributed to the stream restoration and the construction of stormwater detention basins in the developed areas. The BD1, BD2, and BD3 sub-watersheds drain into the BD5 sub-watershed, the pre and post-development average unit hydrograph analysis of this sub-watershed demonstrated a 50.3% decrease in average rate of the Φ index, a 0.5% increase in direct runoff coefficient, a 1.3 m^3/sec or 25.7% increase in the peakflow discharges, and a 0.08 hours increase in the direct runoff duration.

The increased post-development peakflow in the BD5 sub-watershed is most likely due to the increased time to peak in the BD1 sub-watershed (Figure 3.3) making the time to peak coincident in the two largest sub-watersheds in this drainage basin. This may also be enhanced by a slight increase in peakflow of the BD2 sub-watershed. For the most urbanized BD4 sub-watershed, a 21.8% decrease in average rate of the Φ index, a 3.5% increase in direct runoff coefficient, a 15.8% decrease in peakflow discharges, and a 0.75 hour increase in time to peak were obtained through the comparison of the unit hydrographs of the pre and post-development periods. The decline in infiltration rate and increase in direct runoff is attributed to the conversion of forest and low density residential to high density residential and commercial land uses. The network of 15 engineered SCMs constructed in this sub-watershed has increased the time to peak discharge in the post-development period and lowered the peakflow discharges. The increase in runoff was also observed in direct measurement of runoff in a pre- and post-development water balance study of the BD4 sub-watershed (Allan et al. 2008).

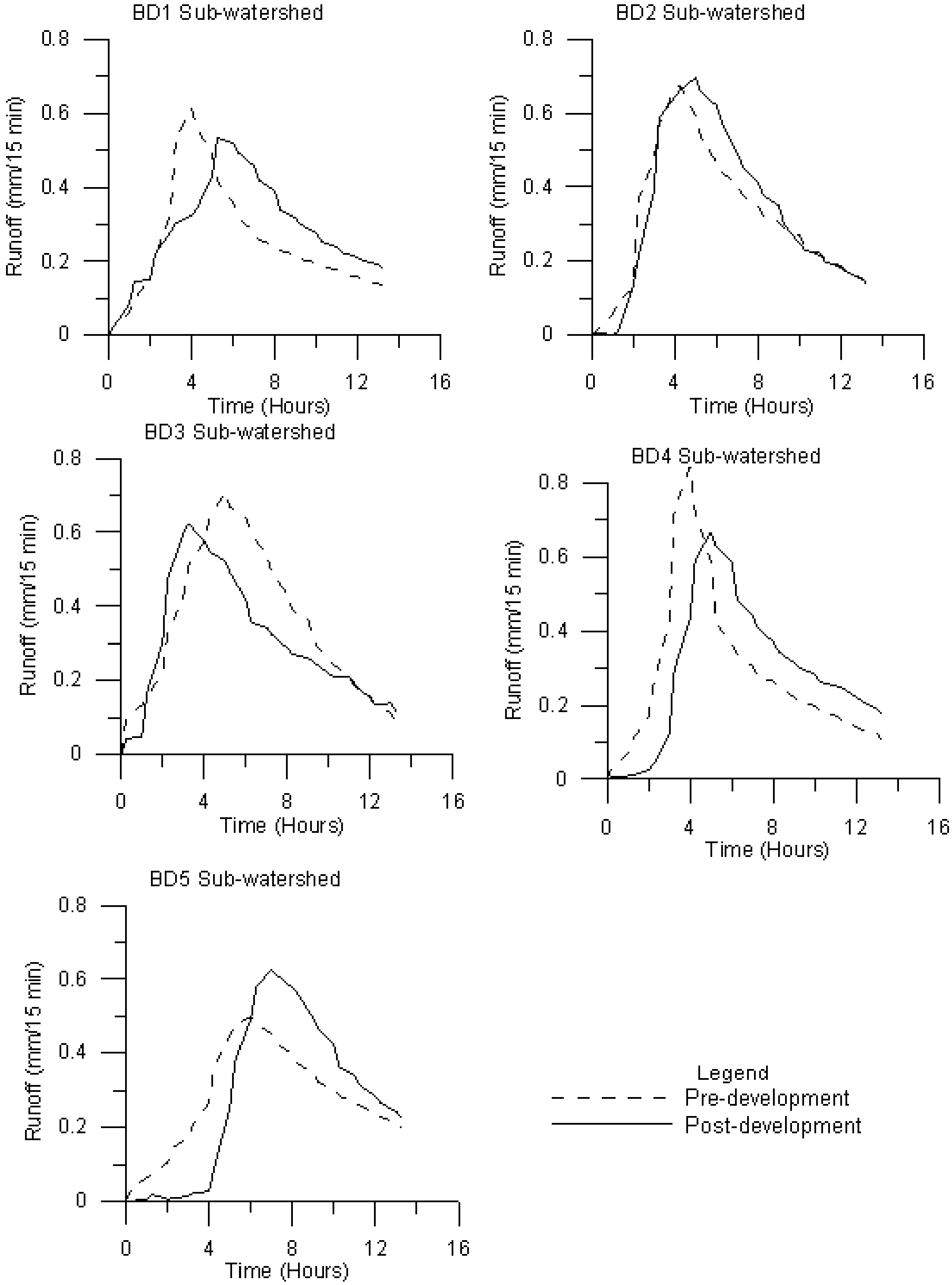

Figure 3.3: Pre- and post-development average unit hydrographs of the BDC sub-watersheds.

Table 3.2: Characteristics of the average unit hydrographs of the BDC sub-watersheds.

	BDC Sub-watersheds									
	BD1		BD2		BD3		BD4		BD5	
Unit Hydrograph Parameters	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Effective Rainfall(cm)	1.30	1.95	1.11	1.88	1.07	1.81	1.36	1.45	0.95	1.68
Peak Discharge (m^3/s)	2.56	2.22	3.55	3.66	0.28	0.24	1.70	1.43	5.05	6.35
Time to Peak (hours)	2.00	2.75	2.75	3.00	2.5	1.75	2.00	2.75	3.00	3.75
Duration of Direct Runoff (hrs.)	0.56	1.67	1.00	1.00	0.58	0.92	0.50	0.58	0.58	0.67
Rate of Φ Index (cm/15 min)	0.45	0.46	0.32	0.26	0.24	0.24	0.52	0.41	0.25	0.38
Total value of Φ Index (cm)	0.91	1.49	1.35	0.96	0.57	0.85	0.91	0.91	0.58	1.02
Φ Index Coefficient	0.70	0.76	1.21	0.51	0.53	0.47	0.66	0.63	0.61	0.61
Average Direct Runoff (cm)	0.39	0.46	0.50	0.92	0.50	0.96	0.46	0.54	0.37	0.66
Direct Runoff Coefficient	0.30	0.24	0.45	0.49	0.47	0.53	0.34	0.37	0.39	0.39

3.5.2 Unit Impulse Response Approach

The results of the unit impulse response analyses are presented in the Table 3.3 and Figure 3.4. The runoff response to the unit impulse (25.4 mm of precipitation over 3.5 hours and 3.5 mm peakflow) for the pre- and post-development periods demonstrated a 4.7% and 1.2% decline in runoff coefficient for the BD1 and BD5 sub-watersheds, respectively, whereas increase in runoff coefficient were indicated for the BD2 (4.2%), BD3 (2.3%), and BD4 (4.0%) sub-watersheds. The decline in runoff coefficient from the BD1 and increase from the BD2, BD3, and BD4 sub-watersheds were similar to the direct runoff coefficients obtained from the unit hydrograph approach whereas, for the BD5 sub-watershed, opposite but minimal differences from the pre to post-development periods were observed from the unit hydrograph and unit impulse response approaches.

The peakflow depth from the BD1, BD3, and BD4 sub-watersheds declined by (0.05 mm) 28.4%, (0.01 mm) 7.8%, and (0.01mm) 4.4%, respectively, whereas peakflow from the BD2 and BD5 sub-watersheds increased by (0.02 mm) 9.5% and (0.04 mm) 24.8%, respectively. The peakflow changes assessed by this method were similar to the unit hydrograph analysis for all the sub-watersheds. Differences in the changes in the time to peak are evident between the unit hydrograph and the unit impulse methodologies. The time to peak appeared to decline by 0.25 hour, 0.50 hours for the BD2 and BD5 sub-watersheds, whereas it increased by 0.25, 0.75, and 0.25 hours for the BD1, BD3, and BD4 sub-watersheds using the unit impulse approach. Opposite results were obtained for the BD2, BD3, and BD 5 sub-watersheds.

The correlation coefficients between the calibrated model output and data used to validate the model for the pre- and post-development periods ranged from 0.52 to 0.73

for all the BDC sub-watersheds (Table 3.3). The middling correlation coefficients observed for the BDC sub-watersheds are attributed to significant variations in storage resulting in a non-linear relationship between rainfall and runoff that are not effectively captured in the unit impulse approach. The model uncertainty somewhat limits the confidence in the estimated modification of the hydrologic responses to land use change predicted by this method.

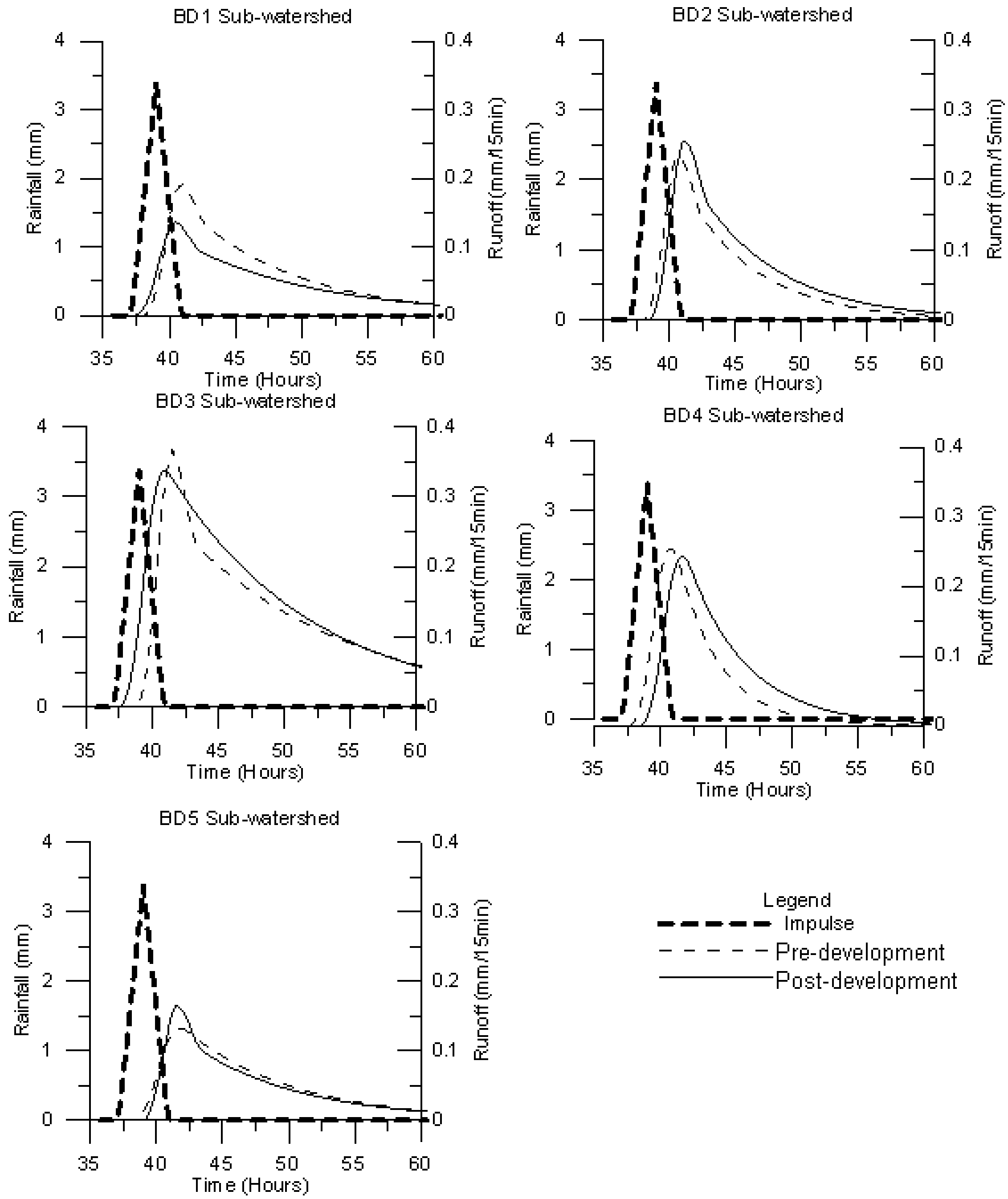

Figure 3.4: Pre and post-development unit impulse response hydrographs of the BDC sub-watersheds.

Table 3.3: Characteristics of the unit impulse response of the BDC sub-watersheds

Unit Impulse Parameters	BDC sub-watersheds									
	BD1		BD2		BD3		BD4		BD5	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
ARX Model	164	171	1 4 4	156	117	112	113	116	144	117
Correlation coefficient of the Model	0.63	0.52	0.53	0.53	0.58	0.73	0.60	0.58	51.54	56.50
Total Rainfall(mm)	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40
Runoff Depth (mm)	6.53	5.35	5.76	6.84	5.86	6.44	5.07	6.09	5.40	5.09
Runoff Coefficient	0.26	0.21	0.23	0.27	0.23	0.25	0.20	0.24	0.21	0.20
Peak Runoff(mm)	0.19	0.14	0.23	0.25	0.35	0.32	0.25	0.24	0.13	0.17
Time to Peak (hours)	2.75	3.00	2.50	2.25	2.50	3.25	2.75	3.00	2.75	2.25

3.5.3 Mann-Kendall Approach

The results of the Mann-Kendall trend test are provided in Table 3.4 and Figure 3.5. The Mann-Kendall non-parametric trend test for the monthly average and maximum precipitation time series for the dormant season demonstrated an increasing trend (Figure 3.5). All of the BDC sub-watersheds also demonstrated an increasing trend in the total streamflow, maximum baseflow, and quickflow for the dormant season. The positive precipitation trend in the dormant season obscures the actual trend for the total streamflow, baseflow, and quickflow that might be attributed to land use changes in each sub-watershed (Table 3.4).

For the growing season, the monthly average and maximum precipitation of the BD1, BD2, BD3, BD4, and BD5 sub-watersheds demonstrated no obvious temporal trend (Table 3.4 and Figure 3.5). Therefore, the trends found in total streamflow, baseflow, and quickflow most likely reflect land use alterations in each sub-watershed. The average growing season baseflow of the BD1, BD3, and BD5 sub-watersheds demonstrated a declining trend. The magnitude of the Sen's slopes in baseflow of the BD1, BD3, and BD5 sub-watersheds were -0.003, -0.004, and -0.002, respectively (Table 3.4). The BD2 sub-watershed demonstrated no trend in the average baseflow and the BD4 sub-watershed demonstrated an increasing trend with a 0.002 magnitude of the Sen's slope. Similar to the baseflow, the average streamflow of the BD1, BD3, and BD5 sub-watersheds indicated a decreasing trend. The magnitude of the Sen's slopes in streamflow for these sub-watersheds were -0.004, -0.003, and -0.003, respectively (Table 3.4).

The BD2 sub-watershed demonstrated no trend in the average streamflow and the BD4 sub-watershed demonstrated an increasing trend with a 0.004 magnitude of the Sen's slope (Table 3.4). For the BD1 sub-watershed, the decline in average baseflow and total streamflow can be attributed to the land development in two headwater tributaries and construction of stormwater detention basins associated with airport and interstate highway (I-485) development. The unit hydrograph and unit impulse response analyses indicated a decline in quickflow yield and peakflow. The average baseflow and average streamflow trend of the BD3 sub-watershed with 50% development, stormwater detention basins, and restored stream reach, also exhibited declines. A decline in quickflow yield and peakflow was also indicated from the unit hydrograph and unit impulse analyses from this sub-watershed. The increasing trend for the average baseflow and streamflow with an increase in quickflow yield from the unit hydrograph and unit impulse response analyses form the BD4 sub-watershed is attributed to the excess runoff generated from the inter-storm runoff from the engineered SCMs (Gagrani unpublished data).

The declining trend in the average streamflow of the BD5 sub-watershed is also consistent with the results from the unit impulse response analysis for this sub-watershed. Little or no change in runoff coefficient was indicated by the unit hydrograph analysis. The Mann-Kendall trend analysis for quickflow of all the BDC sub-watersheds demonstrated no trend for the growing season. This result is consistent with the relatively small changes in the direct runoff coefficients obtained from the unit hydrograph analysis (-6.2% to 6%) and the relatively consistent pre- and post-development runoff coefficients (-4.6% to 4.2%) observed from the unit impulse analyses for all five sub-watersheds (Table 3.5).

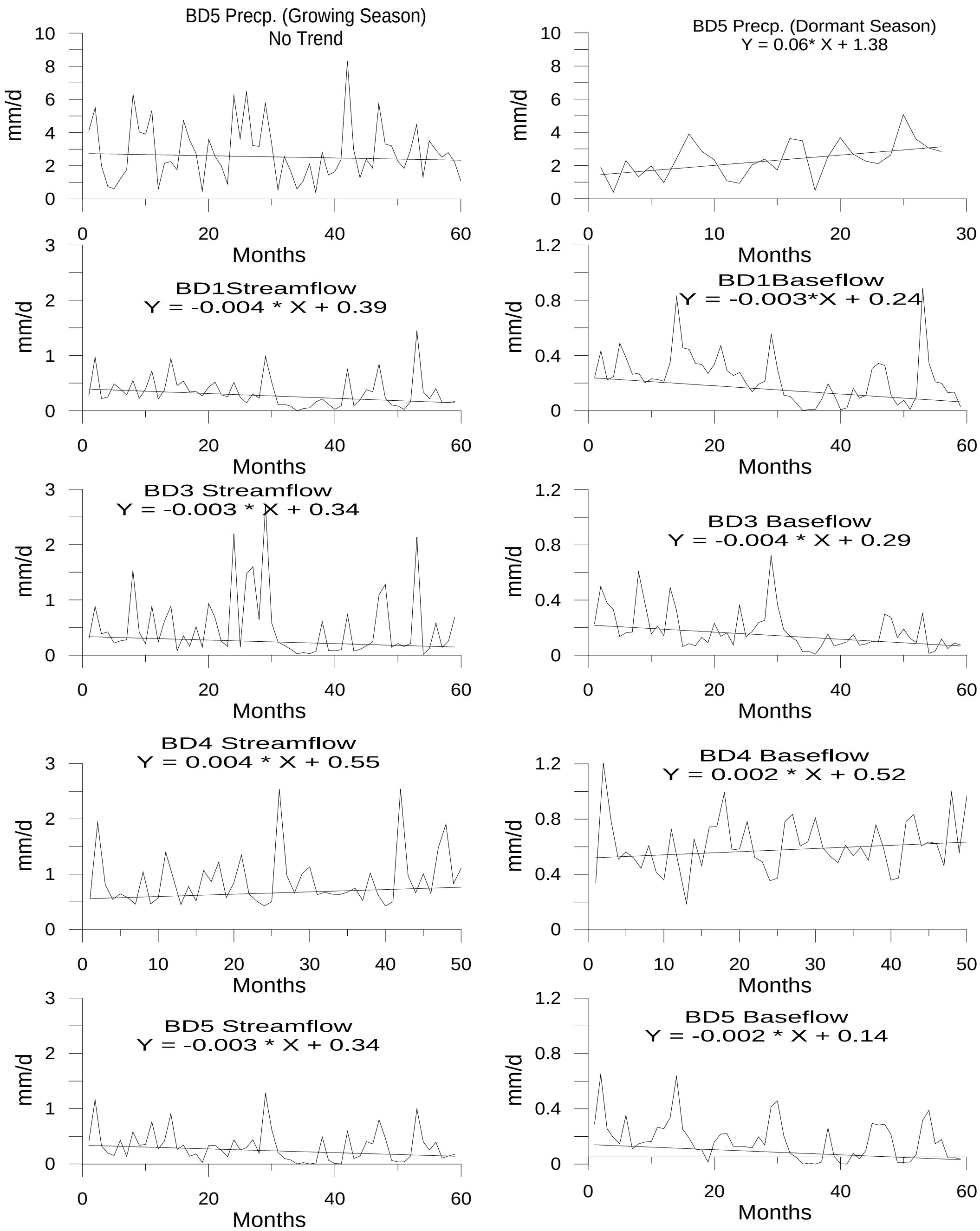

Figure 3.5: Mann-Kendall trend plots for precipitation during growing and dormant seasons and total streamflow and baseflow during growing season only for the BDC sub-watersheds. Note: BD2 indicated no trend, therefore is not included in this figure

Table 3.4: Sen's slope and Tau values of Mann-Kendall trend test of the BDC sub-watersheds. Note: precipitation for each sub-watershed was calculated applying the Thiessen approach (1911) for four nearby USGS rain gauges.

BDC Sub-watersheds		BD1		BD2		BD3		BD4		BD5	
MK Statistics		Sen's Slope (mm)	Tau	Sen's Slope (mm)	Tau	Sen's Slope (mm)	Tau	Sen's Slope (mm)	Tau	Sen's Slope (mm)	Tau
Dormant Season (Precipitation)	Average	0.06	0.32	0.07	0.39	0.06	0.37	0.06	0.33	0.06	0.35
	Max.	0.85	0.35	0.16	0.27	0.68	0.29	0.71	0.30	0.79	0.37
Dormant Season (Streamflow)	Average	0.23	0.32	0.02	0.29	0.02	0.30	NT		0.02	0.24
	Max.	0.23	0.32	0.24	0.25	0.23	0.30	0.23	0.23	0.18	0.35
Dormant Season (Baseflow)	Average	NT		NT		0.004	0.23	NT		NT	
	Max.	0.03	0.22	0.04	0.29	0.05	0.41	0.03	0.30	0.03	0.28
Dormant Season (Quickflow)	Average	0.01	0.37	0.01	0.32	0.01	0.30	NT		0.02	0.33
	Max.	0.22	0.31	0.16	0.34	0.23	0.30	0.22	0.20	0.17	0.35
Growing Season (Precipitation)	Average	NT		NT		NT		NT		NT	
	Max.	NT		NT		NT		NT		NT	
Growing Season (Streamflow)	Average	-0.004	-0.27	NT		-0.003	-0.15	0.004	0.16	-0.003	-0.17
	Max.	NT		NT		NT		0.04	0.17	NT	
Growing Season (Baseflow)	Average	-0.003	-0.30	NT		-0.004	-0.31	0.002	0.14	-0.002	-0.25
	Max.	-0.004	-0.14	NT		-0.0004	-0.15	0.005	0.15	-0.005	-0.15
Growing Season (Quickflow)	Average	NT		NT		NT		NT		NT	
	Max.	NT		NT		NT		NT		NT	

Table 3.5: Comparing outputs of the unit hydrograph, unit impulse, and Mann-Kendall approaches.

Parameters	BDC Sub-watersheds	Change Unit Hydrograph	Change Unit Impulse Response	Mann-Kendall Analysis (For the growing season only)
Average Streamflow	BD1	NA	NA	Decreasing
	BD2	NA	NA	NT
	BD3	NA	NA	Decreasing
	BD4	NA	NA	Increasing
	BD5	NA	NA	Decreasing
Average Baseflow	BD1	NA	NA	Decreasing
	BD2	NA	NA	NT
	BD3	NA	NA	Decreasing
	BD4	NA	NA	Increasing
	BD5	NA	NA	Decreasing
Quickflow Yield	BD1	-6.20%	-4.60%	NT
	BD2	3.90%	4.20%	NT
	BD3	6%	2.30%	NT
	BD4	3.50%	4.00%	NT
	BD5	0.50%	-1.20%	NT
Peakflow	BD1	-13.2%	-28.4%	NA
	BD2	3.1%	9.5%	NA
	BD3	-12%	-7.8%	NA
	BD4	-15.8%	-4.4%	NA
	BD5	25.7%	24.8%	NA
Change Time to Peak (Hours)	BD1	0.75	0.25	NA
	BD2	0.25	-0.25	NA
	BD3	-0.75	0.75	NA
	BD4	0.75	0.25	NA
	BD5	0.75	-0.50	NA
Direct Runoff Duration (Hours)	BD1	1.1	NA	NA
	BD2	0	NA	NA
	BD3	0.34	NA	NA
	BD4	0.8	NA	NA
	BD5	0.9	NA	NA

3.6 Summary and Conclusions

We present a summary of the changes between pre- and post-development for streamflow, peakflow, and baseflow as quantified by our three comparative methods (Table 3.5). Three of the five sub-watersheds BD1, BD3, and BD5 indicated decreasing trends in average streamflow and baseflow during the growing season. No trend is evident for the BD2 sub-watershed and increasing trends are indicated for the BD4 sub-watershed in average baseflow and average streamflow for the growing season. Changes in the average post-development storm event runoff yields varied between the sub-watersheds dependent upon the method of analysis. No trends in average post-development quickflow runoff of the growing season are indicated for all of the sub-watersheds when analyzed with the Mann Kendall trend test. Both the unit hydrograph and unit impulse approaches indicate a decline in quickflow yield for the BD1 sub-watershed. These same two approaches indicate small increases in quickflow yield for the BD2, BD3, and BD4 sub-watersheds. These same analyses for the BD5 sub-watershed indicate small changes in quickflow yield in opposite directions. However, the magnitude of the change in quickflow yield averages <5.4% indicating little or no change in post-development stormwater runoff for any of the sub-watersheds examined in this study.

The decline in baseflow and average streamflow combined with little or no indication for significant increases in quickflow yield for three of the five sub-watersheds suggest that a greater proportion of runoff is returned to the atmosphere through evaporation. We suggest that the capture of most runoff from smaller precipitation events in engineered stormwater retention structures and the subsequent evaporation of this stored water are largely responsible for these trends. The increasing trend in average streamflow for the BD4 sub-watershed is attributed to the inter-storm runoff from the engineered SCMs (Gagrani unpublished data).

The average unit hydrographs and the hydrographs generated from a triangulated unit impulse of precipitation for the pre- and post-development period allow one to assess changes in peakflow discharge, time to peak, and the duration of direct runoff. The decline in peakflow from the BD1 (-13.2% to -28.4%), BD3 (-12.0% to -7.8%), and BD4 (-15.8% to -4.4%) sub-watersheds were indicated from the unit hydrograph and unit impulse response analyses, respectively. The results are attributed to the stormwater detention basins in the most developed BD3 and BD4 sub-watersheds (50% and 54% developed) and the least developed BD1 sub-watershed. The above two analyses indicated an increase of 25.7% and 24.8% in peakflow discharge for the largest (BD5) sub-watershed, respectively. The significant increase in peakflow of the BD5 sub-watershed is attributed to the change in time to peak of the contributing sub-watersheds as well as to a 3.1% to 9.5% increase in peakflow of the BD2 sub-watershed.

Our analysis of the change in runoff response from pre- to post-development periods is consistent with the generally accepted phenomenon that urbanization results in reduced baseflow. However, the engineered SCMs constructed in the developed sub-watersheds appeared to largely control stormwater releases, lowered the magnitude of quickflow and spread the quickflow over a longer time duration. An examination of the results from the sub-watersheds with and without restored stream reaches demonstrated minimal differences, suggesting that the stream restoration projects did not appreciably affect the runoff responses of the developing watersheds.

The results of this study demonstrated that the unit hydrograph, unit impulse response, and Mann-Kendall trend test approaches generally indicated similar changes in runoff response from the pre- to post-development periods. The unit hydrograph and unit impulse response are fairly comparable approaches and both provide information pertaining to changes in the timing of the event runoff response as well as changes in the magnitude of the runoff response. However, to use effectively the unit hydrograph approach effectively one needs to divide the rainfall-runoff time series into “stable" pre- and post-development periods. Often times, the stable pre-development period is short or does not exist and it is often difficult to obtain a sufficient number of suitable hydrographs for shorter periods of interest (e.g. post engineered SCMs implementation) during the development cycle. The unit impulse response approach facilitates the assessment of the instantaneous change in runoff response by utilizing only 15-30 days of continuous rainfall-runoff time series for two sub-periods of an active development cycle. However, the utility of this approach is limited when non-linear rainfall to runoff relationships exists, resulting in lower model correlation coefficients and thereby reducing the confidence in the results of the analysis. The Mann-Kendall trend test can be used to elucidate increasing or decreasing trends in runoff over time, but it requires long-term monitoring data and does not provide any information about changes in the timing of the event runoff response.

CHAPTER 4: ASSESSING THE INSTREAM TRANSPORT AND RETENTION DYNAMICS OF SEDIMENT, NUTRIENTS, AND ORGANIC CARBON IN A S.E. PIEDMONT URBANIZING WATERSHED

4.1 Abstract

In this study, a residual mass balance approach was applied to assess the instream transport and retention dynamics of sediment, nutrients, and organic carbon (OC) in two restored and two unaltered or “natural”, stream reaches of an urbanizing SE Piedmont watershed during different flow regimes. For each combination of channel types one of each pair drained a predominantly forested land cover and the other a recently developed suburban land cover. The baseflow monitoring indicated that the restored stream reaches were hydrologically losing reaches and the unaltered stream reaches were gaining reaches under dry antecedent moisture conditions. Net retention of TSS, N (PN, TN, TDN, and DON), P (TP and PP), and OC was measured for restored stream reaches during the baseflow monitoring periods. The suburban land use and unaltered stream reach demonstrated mostly positive residual mass balances or net exports of sediment, nutrients, and OC during the baseflow monitoring periods. This is largely attributed to groundwater inputs supplemented with the inter-storm runoff from engineered SCMs between the upstream and downstream monitoring stations. In contrast, the other unaltered but predominately forested stream reach mostly demonstrated greater hydrologic flux increases over any increases in the nutrient and OC flux indicating a decline in unit area inputs into the study stream reach, with all upstream ortho-P inputs completely retained in that study stream reach.

The residual mass balance for the restored stream reaches indicated a net export of TSS, NO_3-N, TP, PP, and POC during storm events. Similar to the baseflow monitoring periods, a 100% net retention of ortho-P occurred for the forested and unaltered stream reach during high flow periods. For the forested and unaltered stream reach, a decline in TSS, N, P, and OC input between the up and downstream monitoring stations were measured. In contrast for the suburban unaltered stream reach, mobilization of DON, TDN, ortho-P, DOP, TOC, and POC was measured. The unit area flux analysis from the downstream monitoring station for all stream reaches indicated lower fluxes from the restored stream reaches in comparison to the suburban unaltered stream reach as well as lower fluxes during the growing season in comparison to the dormant season during both baseflow and storm events. Overall, our study indicated that the land use, stream restoration, and installation of engineered SCMs significantly influence instream sediment and nutrient retention and export dynamics in Piedmont streams.

Keywords: Channel Processes, Organic Carbon, Nutrients, Residual Mass Balance, Retention, and Sediment.

4.2 Introduction

The instream transport and retention dynamics of sediment, nutrients, and organic carbon during different flow regimes and seasons is dependent upon the hydrological, biological, and geochemical processes taking place within the stream channel, floodplains, and associated riparian buffers. In urban watersheds the instream transport and retention dynamics can be altered due to increased runoff volumes, reductions in baseflow, severed hydrologic connections between the stream channel and floodplain/riparian buffer, and elevated nutrient and contaminant loadings (e.g., Leopold

1968, Walsh et al. 2005, and O'Driscoll et al. 2010). In an attempt to enhance physical, chemical, and biological activities to retain and degrade pollutants natural stream restoration projects have been increasingly employed (e.g., Meyer et al. 2005, Groffman et al. 2005, Bukaveckas 2007, and Kaushal et al. 2008). Higher instream denitrification rates were observed in urban streams after the hydrologic reconnection of the channel to its floodplains and riparian buffers (Grimm et al. 2005, Kaushal et al. 2008, and Klocker et al. 2009). A 30 and 3 fold increase in the instream uptake of nitrogen (N) and phosphorus (P), respectively was reported in a restored stream channel receiving agricultural runoff during different flow regimes (Bukaveckas 2007). A mass balance study of the urban restored stream channels in Chesapeake Bay region, USA indicated an average 13% and 20% retention of N flux during baseflow and storm events, respectively (Filoso and Palmer 2011).

In urban watersheds, success in attaining the predevelopment hydrologic, water quality, and biological conditions through restoring stream reaches is often limited due to constraints such as the elevated load of pollutants associated with sediment and stormwater runoff, the high cost of urban land, and the proximity to the existing surface and sub-surface urban infrastructure (Booth 2005, Bernhardt and Palmer 2007 and 2011, and Palmer et al. 2010). Moreover, the ecological recovery of a restored stream channel can also be affected by legacy sediment contamination and episodic metal releases (Harding et al. 1998, Walsh et al. 2005, and Clements et al. 2010).

In addition to stream restoration projects, engineered Stormwater Control Measures (SCMs) such as wet and dry detention basins, bio-retention basins, rain-gardens, grass swales, constructed wetlands, amongst others are often mandated and widely employed to control stormwater runoff in developing areas. In addition to controlling runoff volume and peakflow discharges, engineered SCMs can also improve stormwater runoff quality through processes such as sedimentation, filtration, denitrification, and immobilization through uptake by plants and microorganisms (e.g. Lawrence 1996, Strecker et al. 2001, Hunt et al. 2006 and 2008, and Davis 2008). In urban watersheds, similar to the stream restoration, success in restoring pre-development hydrologic and water quality regimes by installing engineered SCMs is often limited due to excessive land cover disturbance in conjunction with inadequate location, design, type, and maintenance of these structures (Roesner et al. 2001, Booth et al. 2002, Hur et al. 2008, and NRC 2008).

Seasonal and climatic dynamics can also significantly alter the riparian/floodplain and channel interactions. The assessment of nutrient and sediment transport dynamics in a predominantly agricultural watershed during different seasons and flow regimes demonstrated that during low flow summer months 24% - 26% of the inorganic nitrogen and 9% - 19% of suspended sediment were retained within the monitored channel reach (Brunet and Astin 2000). In comparison, during higher flow autumn months, mobilization of all elements occurred, and in winter months, mobilization of soluble inorganic nitrogen and phosphorus occurred due to decreased biological activity. At the Hubbard Brook experimental forest, 80% - 140% higher instream nitrate retention was reported due to the increased light availability and a large input of woody debris after an ice storm disturbed the forest canopy (Bernhardt et al. 2003). A mass balance of nitrogen and DOC in a forest stream reach demonstrated up to a 70% net retention of nitrate during baseflow conditions due to increased availability of DOC after the autumn leaf fall and was described as a "hot moment" for in stream denitrification (Sebestyen et al. 2008). In the mixed land use River Swale watershed in the UK, the instream processes were characterized by assessing the P and dissolved silica (Si) dynamics for different flow regimes (Bowes and House 2001). Their results indicated net stream reach retention of both constituents during stable baseflow periods and during overbank flooding episodes due to instream processing and the deposition of sediment onto the floodplain. However, long duration flood events resulted in a net export of Si and P after floodwater receded and soil water and its dissolved constituents slowly drained back into the river channel.

The assessment of instream transport and retention dynamics of sediment, nutrients, and other chemical constituents under different land uses, seasons, and during different flow regimes is necessary to understand the influence and benefits of stream restoration projects and engineered SCMs towards improving water quality in developing watersheds. Previous studies have measured significant improvements in nutrient retention after stream restoration during different flow regimes (Bukaveckas 2007, Kaushal et al. 2008, and Filoso and Palmer 2011). We would expect to see nutrients and OC processing during baseflow and high flow periods in restored channels owing to significantly longer travel times, greater geomorphic complexity, and the reestablishment of hydrologic connectivity with the floodplain in the re-engineered stream channels examined in this study. We would also expect to see higher unit area fluxes of nutrients in watersheds with a predominantly suburban land use in comparison to the forested watersheds. The presence of engineered SCMs could be expected to retain sediment during high flow periods but their effectiveness in maintaining stream water quality is unclear. Previous studies have indicated a wide range of nutrient retention rates associated with these structures (e.g., Bartone and Uchrin 1999, Carleton et al. 2000, Weiss et al. 2007, and Li and Davis 2009). In the current study, the residual mass balance approach initially proposed by Bowes and House (2001) was utilized to quantify the instream transport and retention dynamics of sediment, nutrients, and OC during the dormant and growing seasons in a developing S.E. U.S. Piedmont watershed during different flow regimes. We specifically focus on the influence of stream restoration projects and the influence of engineered SCMs on in-channel material processing in the study watershed.

4.3 Study Area

The Beaverdam Creek (BDC) watershed is located at 35°10′11″N latitude and 80°59'16" longitude in southwest Mecklenburg County, North Carolina (Figure 4.1). This watershed lies in the humid subtropical climate zone (Cfa) in the Köppen climatic classification. The 30-year normal monthly mean, minimum, and maximum temperatures are 16.3°C, 5.4°C (January), and 26.8°C (July), respectively and the mean annual precipitation is 110.4 cm (Charlotte Douglas International Airport 2011). This Piedmont watershed is characterized by gentle slopes in upland areas, steep-walled valleys produced by incised stream channels in the mid-section, and slightly-to-moderately incised stream channels with broad floodplains towards the watershed outlet. Vegetation in the watershed is dominated by a mixed deciduous canopy that has become established after multiple agricultural and logging disturbances in the study watershed (Eckardt 2003). The watershed is underlain by metamorphosed quartz diorite and tonalite, gabbro, gabbronorite, and granodiorite (Goldsmith et al. 1988). The lithology comprises acidic to strongly acidic soils including the Mecklenburg fine sandy loam, Cecil sandy loam, and Enon sandy loam (USDA NRCS 2010).

4.3.1 Watershed Land Cover Modifications and Distribution

Two study stream channels (Forested Reach (FR) and Forested Restored Reach (FRR) drain predominantly forested land and two other stream channels (Suburban Restored Reach (SRR) and Suburban Reach (SR)) drain predominantly suburbanized areas (Figure 4.1, Table 4.1). The FR and SR are unaltered "natural" channels while FRR and SRR were subject to extensive engineered channel reconstruction projects in 2006 that included channel repatterning, the installation of instream structures and the replanting of the riparian zone with native vegetation. Although the unaltered channels were not subject to stream channel reconstruction and are located in predominantly forested watersheds these channels reflect significant alterations (incising and over widening) owing to legacy agricultural and logging activities in these sub-watersheds (Eckderdt 2003)

While each of the study stream reaches drains predominantly either forest or suburban land uses the distribution of land cover classes are not uniform. The upstream drainage area of FR and FRR includes an interstate highway (I-485) and a portion of the newly expanded Charlotte Douglas International (CDI) airport. This has resulted in the upstream contributing area of FR now only containing 12% residual forest cover. The forest cover of the contributing drainage area increases to approximately 50% in the downstream contributing area of the FR (Table 4.1). Both the upstream and downstream contributing area of FRR on average consists of 45% forest cover (Table 4.1). In addition, two engineered SCMs (detention basins) drain into the stream between the upstream and downstream monitoring stations of the FRR.

The percent forest cover increases significantly when comparing the upstream and downstream contributing areas for both SRR monitoring stations, but both stations primarily drain high-density (12% and higher built upon area) suburban land uses. The SRR stream channel also receives runoff from two engineered SCMs between the upstream and downstream monitoring stations (Table 4.1). The percent forest cover is relatively similar between the upstream and downstream monitoring stations on SR (Table 4.1). However, land use in the developed portion of this sub-watershed changes significantly between the upstream and downstream monitoring stations, with the density of housing increasing in the downstream segment.

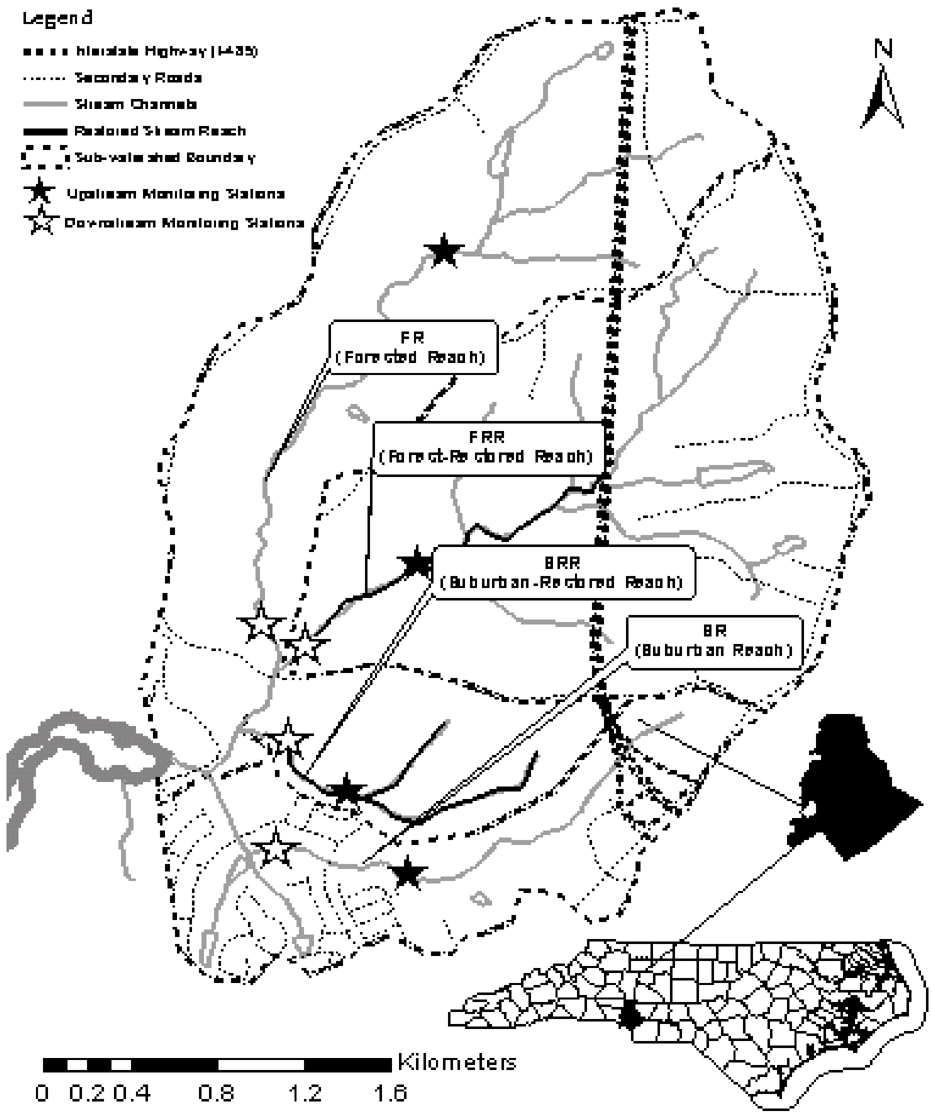

Figure 4.1: The Beaverdam Creek (BDC) watershed, showing upstream and downstream monitoring locations of the four stream reaches.

Table 4.1: Land use classification and other characteristics of the four study stream reaches in the BDC watershed.

Monitoring Stations	FR		FRR		SRR		SR	
	Up	Down	Up	Down	Up	Down	Up	Down
Drainage Area (km^2)	1.3	3.8	4.1	4.7	0.7	0.9	1.0	1.2
Forest (%)	12.0	50.3	44.2	47.2	25.3	36.2	46.5	42.2
Low density residential (≤12% built upon area) (%)	36.2	31.9	32.4	31.1	0.0	0.0	31.8	25.1
High density residential (≥12% built upon area) (%)	0.0	0.0	0.0	0.0	63.7	55.9	0.0	14.2
Transportation (I-485) (%)	17.2	5.8	5.7	5.0	2.4	1.7	14.4	12.2
Airport (%)	31.7	10.7	8.9	7.8	0.0	0.0	0.0	0.0
Commercial (%)	0.0	0.0	4.8	4.2	0.0	0.0	6.6	5.6
Institution (%)	0.0	0.0	0.0	1.1	8.2	5.8	0.0	0.0
Industrial (%)	2.4	0.8	3.1	2.7	0.0	0.0	0.0	0.0
Water (%)	0.5	0.5	0.9	0.9	0.4	0.4	0.7	0.7
Engineered SCMs (Number)	2.0	2.0	2.0	4.0	6.0	8.0	3.0	7.0
Stream Restoration	Unaltered		Restored		Restored		Unaltered	

4.4 Methodology

4.4.1 The Residual Mass Balance

The residual mass balance approach originally employed by Bowes and House (2001) was used to assess the instream retention and transport dynamics of sediment, nutrients, and OC in four stream reaches, FR, FRR, SRR, and SR located in the BD1, BD2, BD3, and BD4 sub-watersheds, respectively (Figure 4.1). This approach is based on the comparison of the flux entering the upstream site with the flux leaving at the downstream site of a stream reach. The difference in flux between the upstream and downstream monitoring stations is referred to as the residual mass. The upstream and downstream monitoring timing was individually adjusted to the water parcel travel time, which is the time required for a water parcel to move from the upstream monitoring station to the downstream monitoring station of a stream reach (Table 4.2). Baseflow travel time was calculated by the timing of multiple salt dilution trials in stream segments of the four stream reaches in the BDC watershed. For storm flow events, the travel time for each stream reach during each event was quantified through the directly measured upstream to downstream peakflow lag time for each event (Table 4.2). The detailed procedure to calculate the residual mass balance is described below.

First, the runoff volume (R_i) was calculated by multiplying stream discharge (Q_i) and time interval ($t_i \pm 0.5t_i$) for the i^{th} time period (equation 4.1):

$$R_i = Q_i \times (t_i \pm 0.5t_i) \qquad (4.1)$$

The flux of a particular water quality constituent transported through a gauging station for a given time interval ($t_i \pm 0.5t_i$) was calculated by multiplying runoff volume and concentration (equation 4.2):

$$F_i = (R_i) \times (C_i) \qquad 4.2)$$

where, F_i is the flux over the time and C_i is the concentration. The total cumulative flux for each sampling site is determined using equation 4.3

$$M_j = \sum_{i=1}^{j} F_i \qquad (4.3)$$

Where, M_j is the cumulative flux over time period j. The total cumulative flux (M_j) for each sampling site is used to calculate the residual mass balance ($M_{j,\ residual}$) for a particular stream reach. The $M_{j,\ residual}$ is the mass balance residual at the time period j and is a net measure of instream and floodplain processes that are occurring within that particular stream reach of the watershed.

For each stream reach, the mass-balance residual ($M_{j,\ residual}$) is calculated separately. The mass balance residual of the FR, FRR, SRR, and SR stream reaches is assessed through following equations 4.4 to 4.7.

$$M_{j(Residual\ FR)} = M_{j(FR_{DS})} - M_{j(FR_{US})} \quad (4.4)$$

$$M_{j(Residual\ FRR)} = M_{j(FRR_{DS})} - M_{j(FRR_{US})} \quad (4.5)$$

$$M_{j(Residual\ SRR)} = M_{j(SRR_{DS})} - M_{j(SRR_{US})} \quad (4.6)$$

$$M_{j(Residual\ SR)} = M_{j(SR_{DS})} - M_{j(SR_{US})} \quad (4.7)$$

If there is no instream, floodplain, and riparian buffer processing, then the flux of a chemical constituent at the upstream and the downstream station will be the same. However, a negative mass balance residual is obtained if the observed flux of a chemical constituent at the downstream monitoring station is lower than the upstream station, whereas a positive mass balance residual is obtained if the observed flux of a chemical constituent at the downstream monitoring station is higher than the upstream station.

Uncertainties in stream discharge and chemical fluxes were estimated as the percentage error at one standard deviation for measured values. An estimated 12% uncertainty for stream discharge measurement was derived from the literature (Winter et al. 1981 and Harmel et al. 2006). The analytical uncertainties were assessed through quintuplet replicates of the chemical constituents measured in the lab and varied from 2.3% to 16%. The root mean square error propagation method was used to estimate cumulative probable uncertainties of stream discharge and water quality constituents (Barry et al. 1978, Devito et al. 1982, Allan et al. 1993, Harmel et al. 2006).

4.4.2 Monitoring Procedures

An intensive spatial monitoring program of four stream reaches was undertaken for this study. Multiple baseflow and storm events were monitored during the growing and dormant seasons (Table 4.2). Eight monitoring stations were established at the upstream and downstream locations of the four stream reaches in the BDC watershed (Figure 4.1). To assess the mass balance for each storm event, water samples from the upstream and downstream monitoring stations were collected by offsetting the travel time for all the stream reaches. For the baseflow regime, a 30 minutes time interval was used to collect water samples throughout the monitoring period, with samples matched according to the directly determined travel times. For storm events, a variable time interval sampling protocol was followed with the sampling interval varying between 30 to 45 minutes for the rising limb and between 30 to 240 minutes for the recession flows. The variable time interval was required to sample peak flows more intensively as water quality constituent concentration and fluxes can change rapidly during this period of the hydrograph.

4.4.3 Field and Laboratory Procedures

Water samples, from each site were collected using ISCO 6712 automatic water samplers. The collected water samples were stored temporarily in Nalgene® 250 ml bottles for transporting back to the Hydrology and Biogeochemistry Laboratory at UNC Charlotte for analysis. In addition to collecting water samples, continuous stage height measurements were made with Odyssey capacitance water level loggers on a five to ten minute time step. Stage heights were converted to discharge with stage-discharge rating curves determined for each monitoring station.

Water samples, collected in the field were analyzed for turbidity, total suspended solids (TSS), total phosphorus (TP), total dissolved phosphorus (TDP), ortho-P (PO_4^{3-}), total nitrogen (TN), total dissolved nitrogen (TDN), nitrate (NO_3-N), total organic carbon (TOC), dissolved organic carbon (DOC) and ammonium (NH_4-N) at the UNC Charlotte Hydrology and Biogeochemistry Lab. Turbidity was measured with a Lamotte 2020 turbidimeter, calibrated with standards of 1 NTU and 100 NTU and specific conductance was measured with a HI 9033 multi range conductivity meter as soon as the samples arrived in the lab. Samples were then suction filtered through a pre-weighed 0.45µm filter paper. The filter paper and its accumulated sediment were oven dried and weighed to calculate TSS (APHA 1992). After filtration, the filtered and unfiltered samples were frozen for later analysis. Ortho-P, NO_3-N and NH_4-N, were determined with a Dionex DX-500 ion chromatograph using appropriate analytical columns, TDN and DOC were analyzed with a Shimadzu TOC-V with a TN module. Total phosphorus (TP) was determined manually by the ascorbic acid method following a digestion step (Hach Inc. 1997). The total dissolved phosphorus (TDP) was determined with a Lachat QuickChem® 8500 auto analyzer using the same ascorbic acid method (Hach Inc. 2011). Particulate phosphorus concentration was calculated as the difference between TP and TDP concentrations. Dissolved organic phosphorus (DOP) was calculated as the difference between TDP and ortho-P concentrations. Particulate N (PN) was calculated as the difference between TN and TDN concentrations. Dissolved organic nitrogen (DON) concentration was estimated by subtracting nitrate and ammonia concentration from the TDN concentration. Particulate organic carbon (POC) concentration was calculated as the difference between TOC and DOC concentrations.

4.5 Results

The residual mass balance approach was applied to assess the instream transport or retention dynamics of sediment, nutrients, and OC by monitoring two growing season baseflow periods (B1 and B2), three growing season storm events (GS1, GS2, and GS3), and two dormant season storm events (DS1 and DS2, Table 4.2). The growing season from April through November was defined by a daily mean temperature of 32^{o}F and higher (USDA 2003). The dormant season from December through March was characterized with a daily mean temperature of lower than 32^{o}F. Retention or export of sediment, nutrients, and OC was considered significant when the residual mass balance exceeded the analytical and hydrologic uncertainties for each chemical constituent. In stream processing was indicated when the change in the residual mass balance exceeded the measured change in the hydrologic flux.

Table 4.2: Meteorologic and hydrologic details of the monitored baseflow and storm events.

			Precipitation (mm)			BDC Stream Reaches (Length in meters)			
				Antecedent		FR (2316.5)	FRR (918.1)	SRR (438.9)	SR (681.5)
Event Date	Type	Season	Event	5 days	15 days	Travel Time (Hours)			
2/28/2011	Storm Event	Dormant	24.3	0.6	0.6	0.7	0.3	0.2	0.5
3/30/2011	Storm Event	Dormant	27.7	31.3	34.8	NA	NA	0.3	0.3
4/16/2011	Storm Event	Growing	31	0.26	42.4	0.8	0.3	0.5	0.6
5/17/2011	Storm Event	Growing	48.3	21.6	43.2	0.7	0.4	0.4	0.2
9/6/2011	Storm Event	Growing	37.8	1.5	6.6	0.7	0.3	0.5	0.5
6/8/2011	Baseflow	Growing	0	4.3	30	10.1	6.6	12.7	6.1
7/12/2011	Baseflow	Growing	0	25.8	80.8	10.1	6.6	12.7	6.1

4.5.1 Residual Mass Balance of the Baseflow Monitoring Events

The monitored baseflow events 6/8/2011 (B1) and 7/12/2011 (B2) were characterized by 4.3 mm and 25.8 mm 5-day antecedent precipitation (A5D), respectively (Table 4.2). The downstream monitoring time was adjusted to a 10.1, 6.6, 12, and 6.1 hour travel time for the FR, FRR, SRR, and SR stream reaches, respectively (Table 4.2).

The baseflow discharge at the downstream monitoring station of the unaltered and predominately forested land use FR during the B1 and B2 monitoring period was 252% and 164% higher in comparison to their upstream stations, respectively (Table 4.3). A similar trend was observed for the other unaltered and predominately suburban land use SR indicating a measured 73% and 146% increase during the B1 and B2 monitoring events, respectively (Table 4.3). The increased baseflow in FR could be attributed to the groundwater input from 192% increase in downstream drainage area of primarily forested land cover. In comparison, for the SR, the elevated downstream baseflow could be attributed to both groundwater inputs and delayed stormwater runoff from engineered SCMs situated between the upstream and downstream monitoring stations. In the SR, the downstream drainage area increased by 20% and three wet-detention basins and one bio-retention basin drain into the SR between the upstream and downstream monitoring stations. Direct discharge measurements from engineered SCMs indicated that the largest detention basin in this stream reach could contribute at least 7% of the downstream baseflow discharge during inter-storm periods after 0.00 mm of A5D precipitation (Gagrani unpublished data). The contribution from the other two smaller SCMs is much lower and likely occurs intermittently during dryer inter-storm periods.

The restored and predominately forested land use FRR demonstrated an 8% (non-significant) and a 21% decline in runoff between upstream and downstream monitoring stations during the B1 and B2 monitoring periods, respectively (Table 4.3). The restored and predominately suburban land use SRR demonstrated a 22% decline and 48% increase in runoff during the B1 and B2 monitoring periods, respectively (Table 4.3). The drainage area of the downstream monitoring stations of the FRR and SRR stream reaches increased by 15% and 29%, respectively. The decline in water flow is attributed to increased evapotranspiration demands of the riparian vegetation on the now hydrologically reconnected floodplain/riparian zones of the restored stream reaches. However, the increase in downstream baseflow in SRR exhibited during the B2 monitoring period is attributed to the wetter antecedent conditions and delayed stormwater runoff from SCMs supplementing streamflow (Table 4.2).

The average runoff depth during the B1 and B2 monitoring events at the downstream monitoring stations for the restored stream reaches, FRR and SRR, was 38% and 73% lower than the averages for the unaltered stream reaches, FR and SR, respectively. Overall, the baseflow monitoring indicated that the unaltered stream reaches were gaining reaches, and the restored stream reaches were losing reaches under dry antecedent moisture conditions.

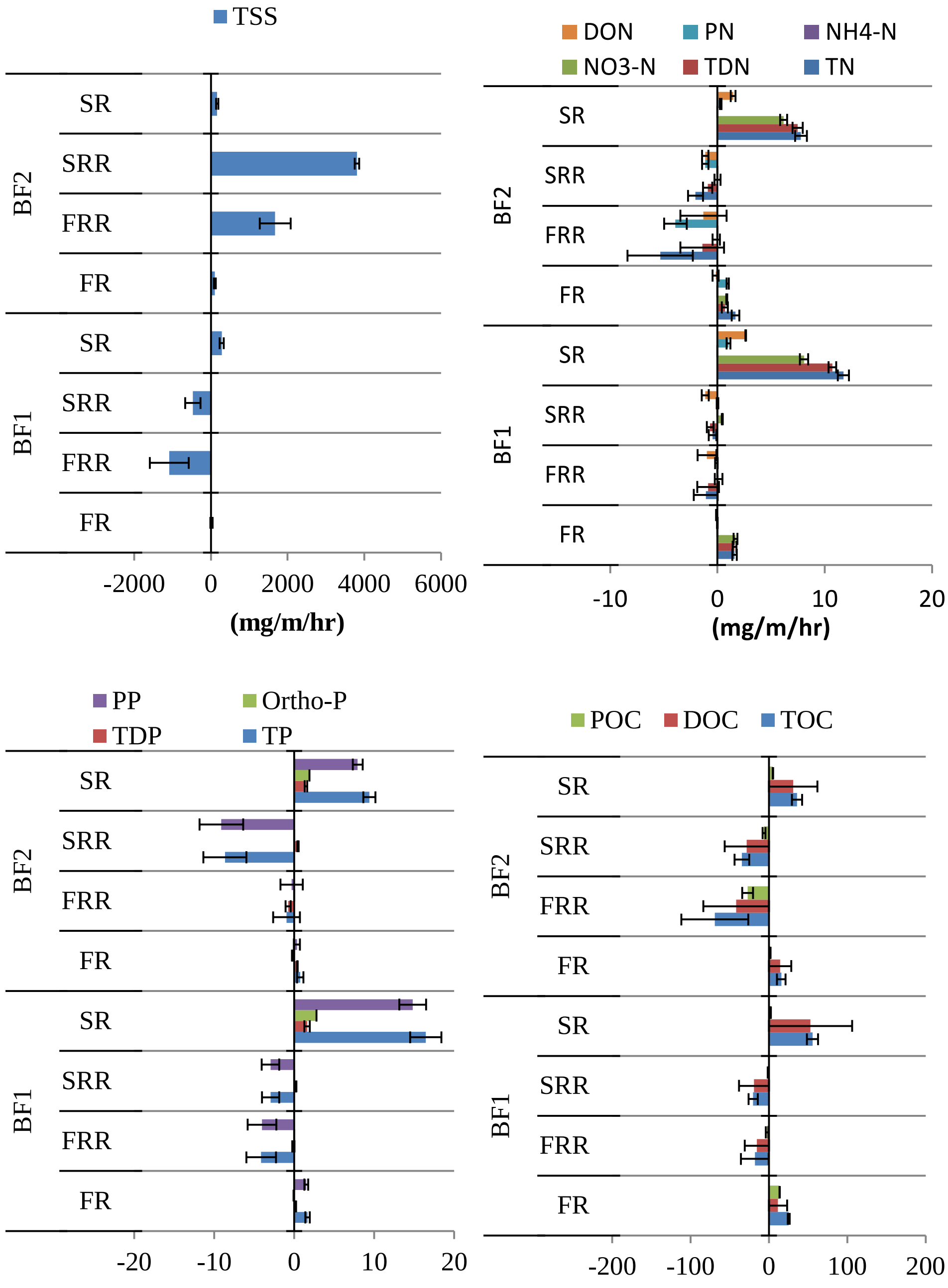

Figure 4.2: Downstream transportation of TSS, nitrogen, phosphorus, and organic carbon during baseflow monitoring periods (± 1 SD estimated hydrologic and analytical uncertainties). Note: The net transport or retention is presented as per linear meter of stream channel.

Table 4.3: Residual mass balance of the baseflow events (± 1 SD estimated hydrologic and analytical uncertainties)
Note: Significant changes over the hydrologic flux are in bold

BDC Stream Reaches		FR		FRR		SRR		SR	
Event	Para meters	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)
(B1 Event) 6/8/11	Runoff (m^3/hr)	26.1 ± 3.0	**252 ± 16**	26.2 ± 3.1	-8 ± 16	3.0 ± 0.3	**-22 ± 16**	30.9 ± 3.6	73 ± 16
	TSS	82.5 ± 16.9	**16 ± 29**	119.9 ± 24.5	**-62 ± 29**	114.3 ± 23.4	**-69 ± 29**	259.4 ± 53.1	**38 ± 29**
	Turbidity (NTU)	7.1 ± 0.4	-3 ± 8	26.4 ± 1.6	-2 ± 8	20.6 ± 1.2	-6 ± 8	9.8 ± 0.6	32 ± 8
	TN	2.1 ± 0.3	-12 ± 17	1.0 ± 0.1	-16 ± 17	0.8 ± 0.1	**-30 ± 17**	8.2 ± 1.0	**5 ± 17**
	TDN	2.0 ± 0.2	-10 ± 17	0.9 ± 0.1	-16 ± 17	0.6 ± 0.1	**-36 ± 17**	7.1 ± 0.9	**-2 ± 17**
	NO_3-N	1.9 ± 0.3	**-4 ± 20**	0.3 ± 0.0	5 ± 20	0.3 ± 0.0	**195 ± 20**	5.6 ± 0.8	**154 ± 20**
	NH_4-N	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	0.1 ± 0.0	-39 ± 18	0.1 ± 0.0	**-21 ± 18**	0.2 ± 0.0	-4 ± 18	1.1 ± 0.1	**96 ± 18**
	DON	0.1 ± 0.0	-44 ± 21	0.6 ± 0.1	**-25 ± 21**	0.2 ± 0.0	**-70 ± 21**	1.5 ± 0.2	**-71 ± 21**
	TP	2.3 ± 0.3	-15 ± 19	1.0 ± 0.1	**-42 ± 19**	1.5 ± 0.2	**-51 ± 19**	14.8 ± 1.9	**117 ± 19**
	TDP	0.3 ± 0.0	-22 ± 18	0.1 ± 0.0	-10 ± 18	0.2 ± 0.0	**43 ± 18**	2.0 ± 0.2	**-10 ± 18**
	Ortho-P	0.0 ± 0.0	-100 ± 18	0.0 ± 0.0	0 ± 18	0.0 ± 0.0	0 ± 18	1.5 ± 0.2	**100 ± 18**
	PP	2.0 ± 0.3	-14 ± 20	0.9 ± 0.1	**-45 ± 20**	1.3 ± 0.2	**-55 ± 20**	12.8 ± 1.6	**177 ± 20**
	DOP	0.3 ± 0.0	-12 ± 21	0.1 ± 0.0	-10 ± 21	0.2 ± 0.0	**43 ± 21**	0.4 ± 0.1	**-62 ± 21**
	TOC	24.4 ± 2.9	**4 ± 17**	15.7 ± 1.9	**-17 ± 17**	7.2 ± 0.9	**-60 ± 17**	54.1 ± 6.4	**-47 ± 17**
	DOC	13.1 ± 1.6	-5 ± 17	14.5 ± 1.7	-16 ± 17	5.5 ± 0.7	**-65 ± 17**	52.1 ± 6.2	**-48 ± 17**
	POC	11.3 ± 1.3	**16 ± 17**	1.3 ± 0.2	**-26 ± 17**	1.7 ± 0.2	-22 ± 17	1.9 ± 0.2	**210 ± 17**

Table 4.3 (Continued)

(B2 Event) 7/12/11	Runoff (m^3/hr)	28.6 ± 3.3	**164 ± 16**	26.2 ± 3.1	**-21 ± 16**	6.7 ± 0.8	**48 ± 16**	22.6 ± 2.6	**146 ± 16**
	TSS	135.7 ± 27.8	-7 ± 29	557.8 ± 114.2	**121 ± 29**	2113.1 ± 432.5	**1582 ± 29**	144.2 ± 29.5	**2 ± 29**
	Turbidity (NTU)	13.6 ± 0.8	-6 ± 8	59.6 ± 3.6	-2 ± 8	15.5 ± 0.9	-8 ± 8	5.3 ± 0.3	-1 ± 8
	TN	2.8 ± 0.3	-15 ± 17	2.3 ± 0.3	**-30 ± 17**	1.1 ± 0.1	**-70 ± 17**	6.1 ± 0.7	**-24 ± 17**
	TDN	1.7 ± 0.2	-24 ± 17	1.9 ± 0.2	-12 ± 17	0.9 ± 0.1	**-70 ± 17**	5.7 ± 0.7	**-27 ± 17**
	NO_3-N	0.8 ± 0.1	**23 ± 20**	0.3 ± 0.0	-8 ± 20	0.8 ± 0.1	-15 ± 20	4.3 ± 0.6	**123 ± 20**
	NH_4-N	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	1.1 ± 0.1	1 ± 18	0.4 ± 0.0	**-67 ± 18**	0.2 ± 0.0	**-72 ± 18**	0.4 ± 0.1	52 ± 18
	DON	0.9 ± 0.1	-43 ± 21	1.6 ± 0.2	-12 ± 21	0.2 ± 0.0	**-92 ± 21**	1.4 ± 0.2	-76 ± 21
	TP	2.1 ± 0.3	-27 ± 19	1.4 ± 0.2	-12 ± 19	2.9 ± 0.4	**-63 ± 19**	7.4 ± 1.0	**117 ± 19**
	TDP	0.4 ± 0.1	0 ± 18	0.2 ± 0.0	**-37 ± 18**	0.5 ± 0.1	**-3 ± 18**	1.3 ± 0.2	**-23 ± 18**
	Ortho-P	0.0 ± 0.0	**-100 ± 18**	0.0 ± 0.0	0 ± 18	0.0 ± 0.0	0 ± 18	1.1 ± 0.1	**100 ± 18**
	PP	1.7 ± 0.2	-32 ± 20	1.2 ± 0.2	-5 ± 20	2.4 ± 0.3	**-67 ± 20**	6.1 ± 0.8	**256 ± 20**
	DOP	0.4 ± 0.1	**55 ± 21**	0.2 ± 0.0	**-37 ± 21**	0.5 ± 0.1	**86 ± 21**	0.3 ± 0.0	**-62 ± 21**
	TOC	35.5 ± 4.2	-22 ± 17	33.1 ± 4.0	**-27 ± 17**	10.6 ± 1.3	**-78 ± 17**	40.8 ± 4.9	-60 ± 17
	DOC	32.7 ± 3.9	-23 ± 17	30.6 ± 3.7	-20 ± 17	8.2 ± 1.0	**-81 ± 17**	37.3 ± 4.4	-63 ± 17
	POC	2.8 ± 0.3	-16 ± 17	2.5 ± 0.3	**-66 ± 17**	2.5 ± 0.3	**-57 ± 17**	3.5 ± 0.4	**366 ± 17**

4.5.1.1 TSS and Turbidity

The residual mass balance of TSS for the unaltered FR and SR was positive during the B1 and B2 monitoring periods indicating a net export of sediment (Table 4.3 and Figure 4.2). However, during the B2 monitoring period, the TSS flux increase in FR was smaller than the hydrologic flux increase indicating a slight reduction in the unit area sediment flux whereas, the increases in TSS flux in SR was within the range of the hydrologic flux increase (Table 4.3 and Figure 4.2). For the restored FRR and SRR, the B1 monitoring period indicated negative residual or net instream sediment deposition, whereas during the B2 monitoring event, net TSS export was observed for both channels (Table 4.3 and Figure 4.2). The channel cross sectional areas of both FRR and SRR have narrowed considerably during the post construction period suggesting significant sediment retention during base flow periods (Baker Engineering unpublished data). The increase in TSS flux during the second baseflow monitoring period in both restored stream reaches can be attributed to the wetter A5D moisture conditions for that event. The average turbidity level in baseflow did not change significantly between monitoring stations with the exception of a 32% increase measured for SR during the B1 monitoring period (Table 4.3 and Figure 4.2).

The unit area flux of TSS from the downstream monitoring stations for the restored FRR and SRR was 120 gm/km^2/hr and 114 gm/km^2/hr, respectively during the B1 monitoring period, or 42% higher than for the unaltered forested FR and 55% lower than the unaltered suburban SR (Table 4.3 and Figure 4.2). During the B2 monitoring period, a similar pattern was evident between the two restored stream reaches and FR, but with significantly higher sediment fluxes and greater differences observed between the restored stream reached and SR. Long term post construction monitoring indicated that the average turbidity levels during baseflow in the downstream stations of the restored stream reaches averages 33 NTU (FRR) and 28 NTU (SRR) in comparison to the 11 NTU (FR) and 10 NTU (SR) in unaltered stream reaches (Allan et al. 2011). The elevated baseflow turbidity in the restored channels in relation to the unaltered channels is a common observation in the post stream- restoration period some six years after the completion of the channel restoration projects.

4.5.1.2 Nitrogen

The particulate N (PN) fraction comprised 6% to 39% (mean 21%) of the TN export for all monitoring stations during both baseflow monitoring periods (Table 4.3). The residual mass balance of PN in the restored FRR and SRR during the B1 (non-significant for SRR) and B2 monitoring periods was negative indicating net instream sedimentation (Table 4.3 and Figure 4.2). The suburban unaltered SR indicated positive residual mass balance of PN during the B1 and B2 monitoring periods. However, during the B2 monitoring period the export was lower than the hydrologic flux increase indicating reduced inputs of PN between the upstream and downstream monitoring locations (Table 4.3 and Figure 4.2). The residual mass balance of PN for FR during the B1 monitoring period was not-significantly different from a zero net change. For the B1 monitoring period PN export at the downstream monitoring station was lower than the hydrologic flux increase indicating that PN input was lower per unit area in the downstream portion of the watershed than that received in the upstream portion of the watershed (Table 4.3 and Figure 4.2).

A negative residual mass balance of TN and TDN was measured in the restored FRR and SRR during both monitoring periods indicating instream retention (Table 4.3 and Figure 4.2). TN and TDN fluxes increased less than the hydrologic flux during both monitoring periods in the predominately forested land use and unaltered FR indicating a net reduction of the unit area input of TN and TDN between the upstream and downstream monitoring locations (Table 4.3 and Figure 4.2). However, in the suburban land use and unaltered SR, net flux of TN and TDN increased significantly more than the hydrologic flux for both baseflow monitoring periods likely from groundwater inputs supplemented with inter-storm runoff from the engineered SCMs.

Ammonium was not detected at any monitoring stations during both baseflow monitoring periods meaning that the dissolved N fraction consisted of variable proportions of DON and NO_3-N. DON dominated the dissolved N fraction (63% to 85%) in FRR during both monitoring periods (Table 4.3 and Figure 4.2). The importance of DON and NO_3-N was variable between monitoring periods for the FR, SRR, and SR stream reaches. The residual mass balance of NO_3-N in the unaltered FR and SR was positive during both baseflow monitoring periods (Table 4.3 and Figure 4.2). However, during the B1 monitoring period the increased export of NO_3-N for FR was not significantly different from the hydrologic flux increase. Nitrate export increased significantly for the SR during both monitoring periods and for the FR during the second monitoring period (Table 4.3 and Figure 4.2). The source of exported NO_3-N in FR during the B2 monitoring period is attributed to the flushing of nitrate from the soil profile between the upstream and downstream monitoring stations due to a higher A5D moisture condition in the second monitoring period. The residual mass balance of NO_3-N in restored FRR and SRR was generally not significantly different from zero except for SRR during the B1 monitoring period (Table 4.3 and Figure 4.2).

The residual mass balance of DON for all stations except for the SR was negative during both monitoring periods (Table 4.3 and Figure 4.2). Net instream retention of DON was indicated for the SRR in both events while the reduced flux of DON in the FRR was within the range of the reduced water flux in both baseflow events. The retention of TDN and DON in the FR and SRR could be attributed to the assimilation by microbial bio-films and/or benthic algae present in the stream channels (Grim et al. 2005, Bukaveckas 2007, Craig et al. 2008, and Sebestyen et al. 2008). Measured DON fluxes for the SR indicated net export during both monitoring periods with the B2 flux increase within range of the hydrologic flux increase and a significant increase in the export of DON from the downstream stream reach during the B1 monitoring period (Table 4.3 and Figure 4.2).

The unit area flux of TN from the downstream monitoring stations of the restored stream reaches during the B1 and B2 monitoring events was 0.9 $gm/km^2/hr$ and 1.7 $gm/km^2/hr$, respectively (Table 4.3 and Figure 4.2). For both events, the downstream unit area flux of TN in the restored channels averaged 2X and 6.3X lower than the fluxes measured for the unaltered FR and SR, respectively. Similar trends for TDN and NO_3-N were also observed (Table 4.3 and Figure 4.2). Elevated fluxes of N from the suburban dominated SR in comparison to the other stream reaches is largely attributed to delayed runoff entering the stream channel from engineered SCMs although elevated levels of N in groundwater entering the between the upstream downstream monitoring station cannot be ruled out. Nitrate and TDN levels in runoff from the engineered SCMs in this sub-watershed were found to average 2.9X and 1.5X higher than the stream water concentrations for that same period during a 2010 monitoring study (Barto 2010).

4.5.1.3 Phosphorus

The particulate P (PP) fraction comprised 78% to 97% (mean 86%) of the TP export during the B1 and B2 monitoring events for all monitoring locations (Table 4.3 and Figure 4.2). The residual mass balance of PP for the restored FRR and SRR was negative (non-significant retention in the FRR during B2 monitoring periods) indicating net retention (Table 4.3 and Figure 4.2). The instream retention of PP in FRR and SRR indicates sedimentation of particulate bound P. The residual flux of PP from the forested unaltered FR during both monitoring periods was positive but lower than the increased hydrologic flux indicating reduced inputs of PP from downstream areas of the watershed in comparison to the more urbanized upstream reach in this sub-basin (Table 4.3 and Figure 4.2). A positive residual mass balance of PP was measured during both baseflow monitoring periods for the suburban unaltered SR. A potential source for P is the engineered SCMs draining into this stream channel or re-suspension and transport of particulate material from the stream channel.

Ortho-P was detectable at the urban land use dominated upstream monitoring station of FR and at the downstream monitoring station of SR during both monitoring periods (Table 4.3 and Figure 4.2). Ortho-P in the FR upstream station comprised 33% - 100% and in the SR downstream station 79% - 81% of the TDP fluxes during the B1 and B2 monitoring periods, respectively (Table 4.3 and Figure 4.2). The forested unaltered FR retained 100% of the ortho-P transported from the upstream station during both baseflow events likely through a combination of biological assimilation and sorption to sediments (e.g., Meyer and Likens et al. 1978, Reddy et al. 1999, and Smith 2009). In comparison, in the suburban land use dominated SR, the source of ortho-Pwithin the lower stream reach can be attributed to desorption from the bed-sediment as well as the delayed runoff from the engineered SCMs. An analysis of bed sediment collected from the streambed of the FR, SRR, and SR indicated 0.07 mg/L equilibrium phosphorus concentration or EPC^0 , which was significantly higher than the adjacent FR and SRR stream reaches (Gagrani unpublished data 2011). The results suggest that when overlying waters have a <0.07 mg/L concentration of ortho-P streambed sediments desorbs P in contrast, bed sediments of the other stream channels continues to absorb P even when the concentration of the ortho-P is less than 0.07 mg/L. The average event mean concentration or EMC of the ortho-P was 0.06 mg/L in the SR during both baseflow monitoring periods indicating desorption as a potential source of P within that stream reach.

Dissolved organic P comprised 100% of TDP in downstream monitoring stations of the FR, FRR, and SRR and only 20% for SR. The FRR and SR stream reaches retained DOP during the B1 (non-significant in FRR) and B2 monitoring periods possibly through biological uptake by macrophytes, phytoplankton, and benthic algae within the stream channel (Reddy et al. 1999 and Smith 2009).

The average unit area flux of TP from the downstream monitoring station of the restored stream reaches during the B1 and B2 monitoring events was 1.2 gm/km^2/hr and 2.2 gm/km^2/hr, respectively (Table 4.3 and Figure 4.2). For both events, the average unit area TP fluxes of the two restored stream reaches was on average 7.6X lower than the suburban dominated unaltered SR. The TP flux for the unaltered FR was significantly greater (84%) than the restored streams during the B1 monitoring period and not significantly different during the B2 monitoring period (Table 4.3 and Figure 4.2). The average TDP flux for the restored FRR and SRR was 1.2X and 8.5X lower than the flux measured for the unaltered FR and SR, respectively, during the B1 and B2 monitoring events (Table 4.3 and Figure 4.2). The higher flux of P from the SR in comparison to the other stream reaches was likely due to the runoff from the P-fertilizer application in suburban lawns draining into the stream channel through SCMs in this watershed (Barto 2010).

4.5.1.4 Organic Carbon

Particulate organic carbon (POC) comprised 3% to 46% (mean 14%) of the TOC for all monitoring stations during both baseflow events (Table 4.3 and Figure 4.2). A net retention of POC occurred in the restored FRR and SRR during the B1 (within the measured hydrologic flux decline for SRR) and B2 monitoring events. The retention of POC in these stream reaches could be attributed to sedimentation within the stream channel. A positive residual mass balance of POC for FR and SR during the B1 and B2 monitoring periods was observed (Table 4.3 and Figure 4.2). However, except for SR during the B1 monitoring period, the increase was lower than the hydrologic flux increase. Similar trends for DOC were also obtained in all stream reaches during both monitoring periods (Table 4.3 and Figure 4.2). The net retention of DOC within the stream channel could be attributed to uptake by microbial biofilms lining the stream channel (e.g., Meyer et al. 1980, Newbold et al. 1982, and Vidon et al. 2009). The export of DOC during both baseflow periods from the SR could be attributed to the inter-storm runoff from engineered SCMs. The average observed instream concentration of DOC was 2.6 mg/L, whereas the average SCMs outlet concentration was found to be 5.9 mg/L for the same period during a 2010 monitoring study (Barto 2010). The higher outlet concentration of the engineered SCM indicates that the delayed stormwater runoff from these SCMs structures are a potential source of elevated in stream inter-storm DOC concentrations in this watershed.

The average unit area flux of TOC from the downstream monitoring station of the restored stream reaches during the B1 and B2 monitoring events was 11.5 gm/km^2/hr and 21.9 gm/km^2/hr, respectively (Table 4.3 and Figure 4.2). The average downstream unit area fluxes for the two restored stream reaches was lower for TOC (1.9X and 3.3X), DOC (1.5X and 3.6X), and POC (4.3X and 1.3X) in comparison to the FR and SR (Table 4.3). It was also observed that the downstream unit area flux of OC of restored and suburban dominated SRR was consistently lower than the other sites possibly because of the small area of remaining forest cover in the headwaters of this watershed.

4.5.2 Residual Mass Balance of High Flow Events

In this study, two dormant season storm events 2/28/2011(DS1 for all stream reaches) and 3/30/2011(DS2 for the SRR and SR only) were monitored (Table 4.2 and Figure 4.3). The total event precipitation recorded at the nearby Charlotte Douglas International Airport for the DS1 and DS2 storm events were 24.3 mm and 27.7 mm with a 0.6 mm and 31.3 A5D, respectively (Table 4.2). In addition to the dormant season storm events, three growing season storm events 4/16/2011(GS1), 5/17/2011(GS2), and 9/6/2011(GS3) were monitored for all stream reaches (Table 4.2 and Figure 4.3). For these three growing season storm events, the total event precipitation recorded at the Charlotte Douglas International Airport were 31.0 mm with a 0.26 mm A5D, 48.3 mm with a 21.6 mm A5D precipitation and, 37.8 mm with a 1.5 mm A5D, respectively (Table 4.2). The DS2 and GS2 precipitation events resulted in out-of-bank flooding for the restored FRR and SRR. The per hour runoff volume from the upstream to downstream monitoring stations increased during each runoff event between 47% to 138% in the FR, 8% to 63% in the FRR, 6% to 43% in the SRR, and 15% to 96% in the SR (Table 4.4 and 4.5).

Temporal patterns of the chemographs varied between storm events and locations for most of the constituents examined in this study. However, a relatively consistent pattern of dilution with increasing discharge was observed during most storm events. The observed dilution pattern is depicted by plotting the conductivity measured at the downstream monitoring station with upstream and downstream hydrographs of each stream reach for all monitored events (Figure 4.3).

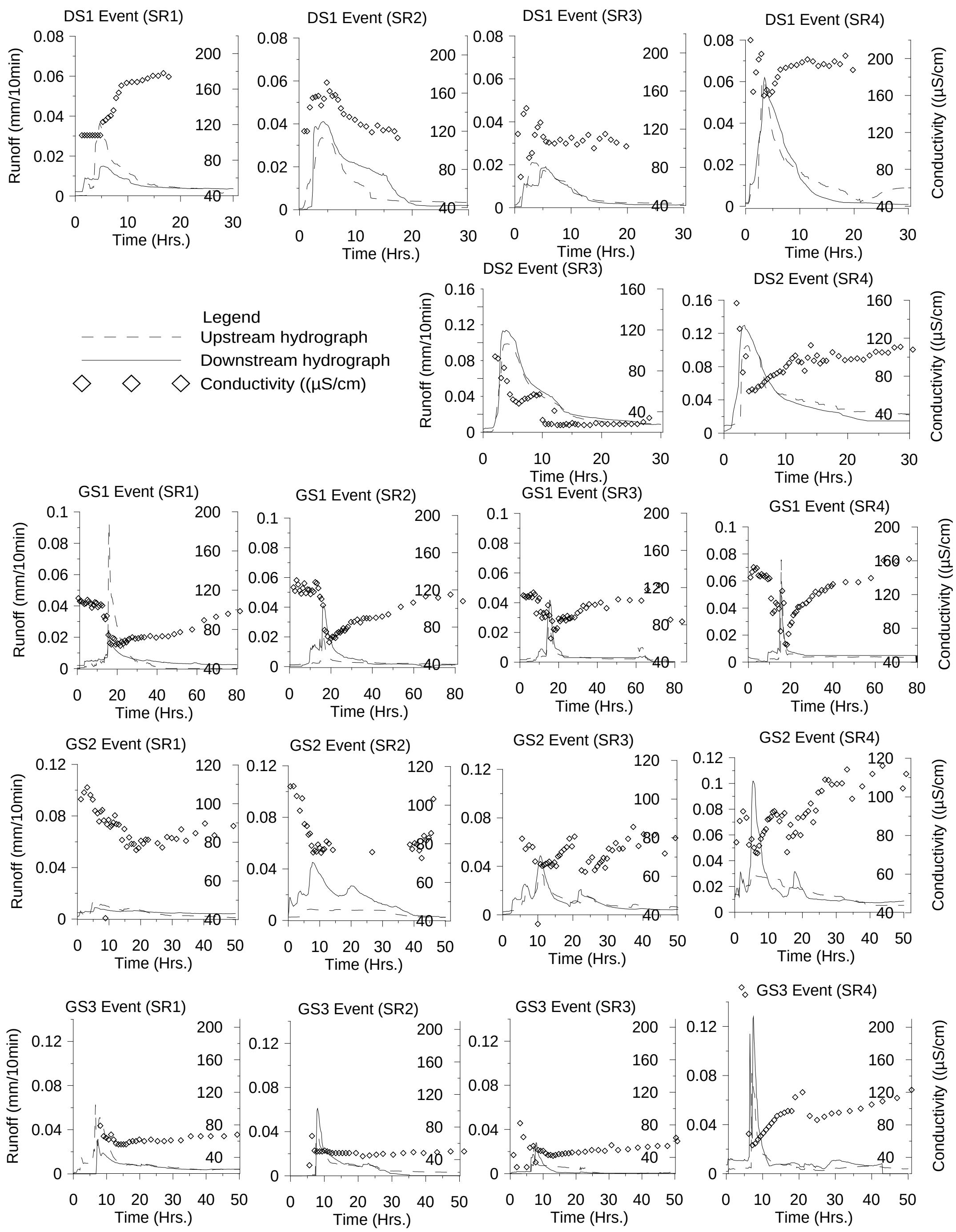

Figure 4.3: Upstream and downstream hydrographs of monitored storm events with temporal patterns of downstream specific conductance.

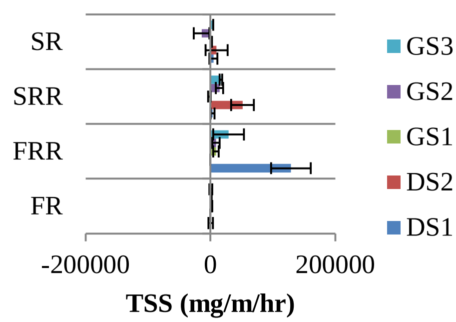

Figure 4.4A: Downstream transport of TSS during storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: The net transport or retention is presented as per linear meter of stream channel.

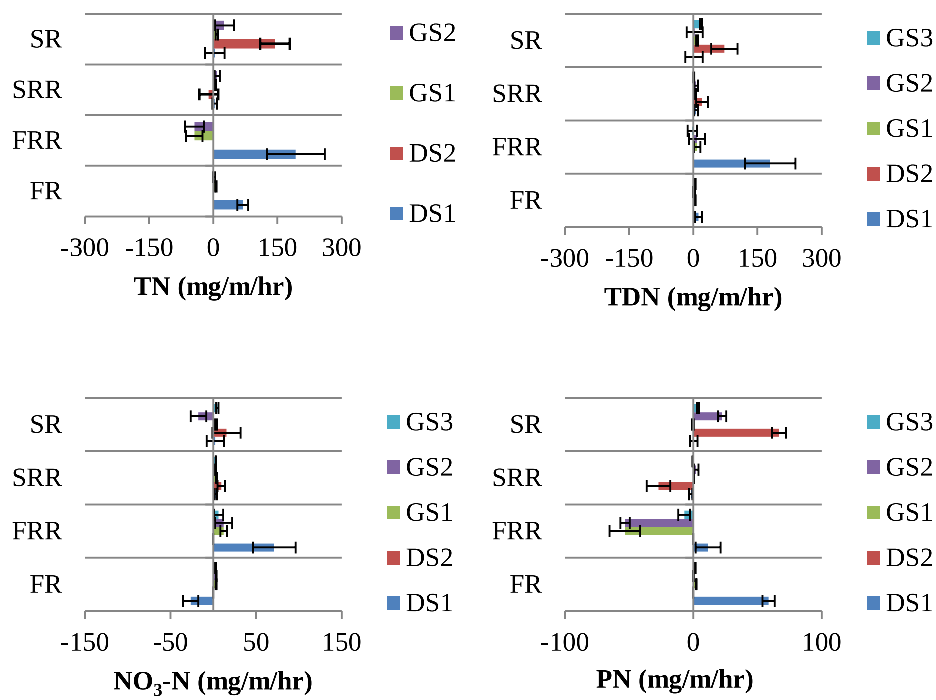

Figure 4.4B : Downstream transport of different N species during storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: The net transport or retention is presented as per linear meter of stream channel.

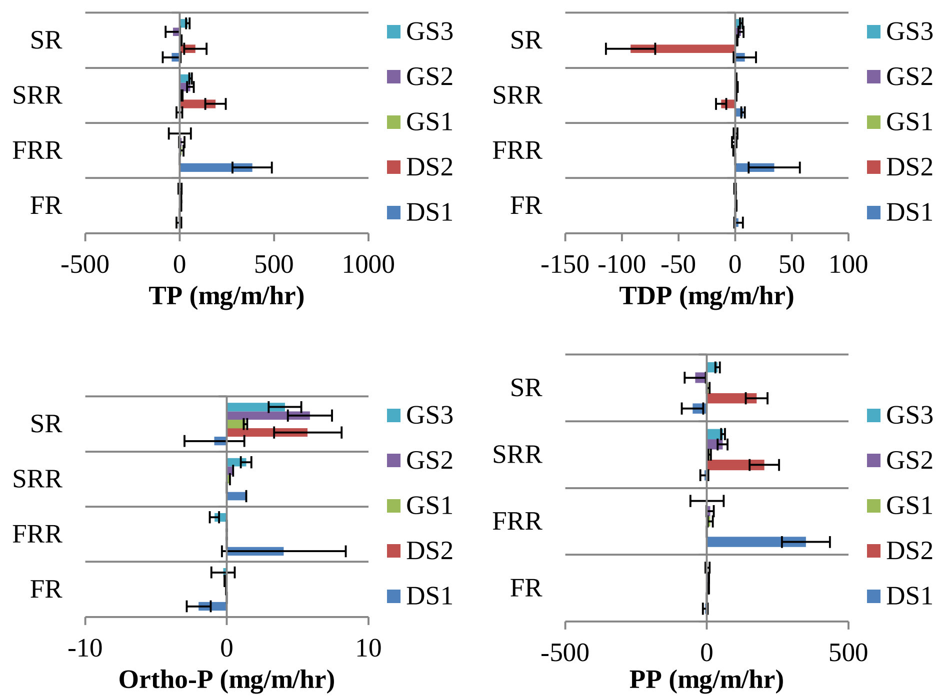

Figure 4.4C: Downstream transport of different P species during storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: The net transport or retention is presented as per linear meter of stream channel.

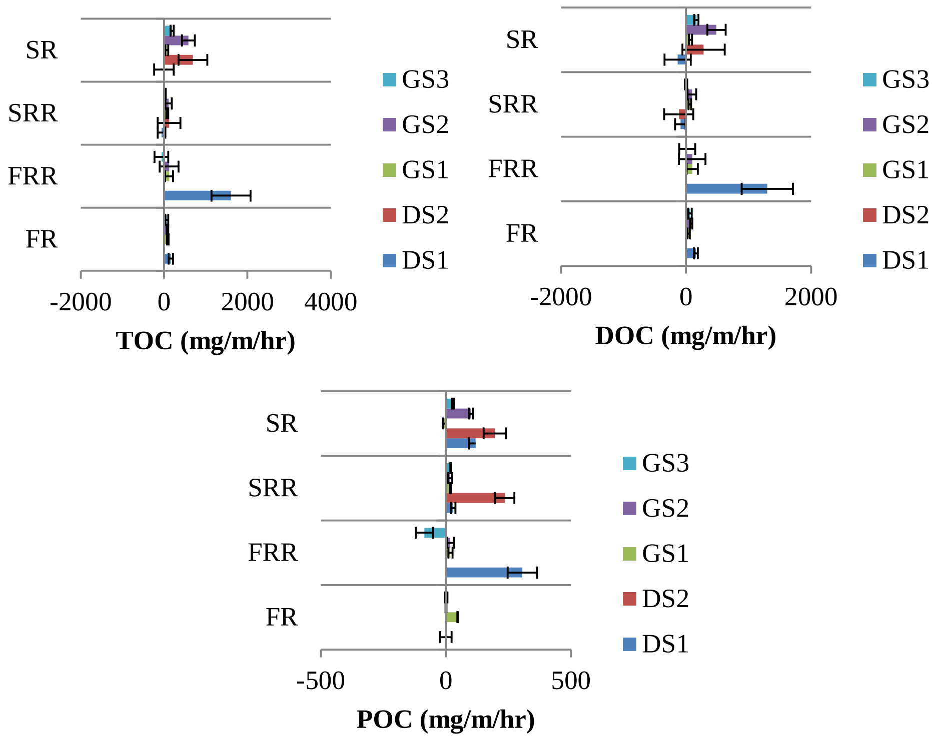

Figure 4.4D: Downstream transport of different organic carbon species during storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: The net transport or retention is presented as per linear meter of stream channel.

Table 4.4: Residual mass balance of the dormant season storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: 1) Significant changes over the hydrologic flux are in bold, 2) NA: Not monitored.

BDC Stream Reaches		FR		FRR		SRR		SR	
Events	Parameters	Downstream ($gm/km^2/hr$)	Residual (%)	Downstream ($gm/km^2/hr$)	Residual (%)	Downstream ($gm/km^2/hr$)	Residual (%)	Downstream ($gm/km^2/hr$)	Residual (%)
(DS1 Event) 2/28/11	Runoff (m^3/hr)	132.1 ± 15.4	**71 ± 16**	566.2 ± 66.0	**63 ± 16**	0.878 ± 0.1024	9 ± 16	2.122 ± 0.2475	**18 ± 16**
	TSS	8646.2 ± 1769.9	-4 ± 29	43278.9 ± 8859.2	**119 ± 29**	7207.4 ± 1475.4	**32 ± 29**	15102.9 ± 3091.6	22 ± 29
	Turbidity (NTU)	7.1 ± 0.9	**-66 ± 8**	26.4 ± 3.5	37 ± 8	20.6 ± 2.7	31 ± 8	9.8 ± 1.3	**-23 ± 8**
	TN	106.9 ± 12.9	**93 ± 17**	107.6 ± 13.0	48 ± 17	18.9 ± 2.3	10 ± 17	76.5 ± 9.2	3 ± 17
	TDN	45.4 ± 5.5	26 ± 17	95.7 ± 11.5	52 ± 17	16.4 ± 2.0	**25 ± 17**	67.5 ± 8.1	1 ± 17
	NO_3-N	13.4 ± 1.9	**-59 ± 20**	35.6 ± 4.9	57 ± 20	5.4 ± 0.7	**41 ± 20**	29.5 ± 4.1	4 ± 20
	NH_4-N	0.0 ± 0.0	0 ± 17	23.8 ± 2.8	**119 ± 17**	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	62.9 ± 7.6	**225 ± 18**	11.9 ± 1.4	21 ± 18	3.0 ± 0.4	**-26 ± 18**	9.1 ± 1.1	3 ± 18
	DON	32.0 ± 4.4	**907 ± 21**	36.8 ± 5.1	25 ± 21	11.0 ± 1.5	19 ± 21	38.0 ± 5.3	-1 ± 21
	TP	45.5 ± 6.0	-5 ± 19	170.3 ± 22.3	70 ± 19	41.9 ± 5.5	-2 ± 19	113.4 ± 15	-17 ± 19
	TDP	18.3 ± 2.3	14 ± 18	29.1 ± 3.6	28 ± 18	8.5 ± 1.1	**82 ± 18**	35.3 ± 4.4	15 ± 18
	Ortho-P	2.0 ± 0.3	**-42 ± 18**	5.2 ± 0.7	16 ± 18	0.7 ± 0.1	**100 ± 18**	6.0 ± 0.8	-8 ± 18
	PP	28.1 ± 3.5	-13 ± 20	141.2 ± 17.6	**83 ± 20**	33.4 ± 4.2	-12 ± 20	78.1 ± 9.7	**-26 ± 20**
	DOP	16.3 ± 2.0	30 ± 21	24.0 ± 3.0	30 ± 21	7.8 ± 1.0	**67 ± 21**	29.3 ± 3.7	**22 ± 21**
	TOC	353.1 ± 42.1	51 ± 17	796.0 ± 94.9	58 ± 17	250.7 ± 29.9	-12 ± 17	764.0 ± 91	0 ± 17
	DOC	253.4 ± 30.2	**88 ± 17**	677.2 ± 80.8	54 ± 17	211.5 ± 25.2	**-18 ± 17**	612.3 ± 73	-11 ± 17
	POC	99.6 ± 11.9	0 ± 17	118.8 ± 14.2	88 ± 17	42.7 ± 5.1	**56 ± 17**	154.3 ± 18.4	**74 ± 17**

Table 4.4 (Continued)

(DS2 Event) 3/30/11	Runoff (m^3/hr)	NA	NA	NA	NA	5.056 ± 0.5896	13 ± 16	6.441 ± 0.7512	15 ± 16
	TSS	NA	NA	NA	NA	60106.0 ± 12303.7	**82 ± 29**	39225.4 ± 8029.4	16 ± 29
	Turbidity (NTU)	NA	NA	NA	NA	20.6 ± 2.7	**-23 ± 8**	9.8 ± 1.3	**-23 ± 8**
	TN	NA	NA	NA	NA	63.1 ± 7.6	-8 ± 17	193.0 ± 23.3	**71 ± 17**
	TDN	NA	NA	NA	NA	52.3 ± 6.3	**26 ± 17**	140.0 ± 16.9	**40 ± 17**
	NO_3-N	NA	NA	NA	NA	16.9 ± 2.3	**42 ± 20**	53.8 ± 7.5	19 ± 20
	NH_4-N	NA	NA	NA	NA	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	NA	NA	NA	NA	13.0 ± 1.6	**-52 ± 18**	53.2 ± 6.4	**227 ± 18**
	DON	NA	NA	NA	NA	35.4 ± 4.9	20 ± 21	86.1 ± 12.0	**55 ± 21**
	TP	NA	NA	NA	NA	250.0 ± 32.8	**67 ± 19**	219.9 ± 28.8	**27 ± 19**
	TDP	NA	NA	NA	NA	6.9 ± 0.9	**-48 ± 18**	15.9 ± 2.0	**-76 ± 18**
	Ortho-P	NA	NA	NA	NA	0.0 ± 0.0	0 ± 18	10.5 ± 1.4	**43 ± 18**
	PP	NA	NA	NA	NA	243.1 ± 30.3	**79 ± 20**	204.0 ± 25.4	**92 ± 20**
	DOP	NA	NA	NA	NA	6.9 ± 0.9	**-48 ± 21**	5.4 ± 0.7	**-91 ± 21**
	TOC	NA	NA	NA	NA	906.0 ± 108.1	8 ± 17	1507.9 ± 179.8	**34 ± 17**
	DOC	NA	NA	NA	NA	660.9 ± 78.8	-8 ± 17	1254.5 ± 149.6	14 ± 17
	POC	NA	NA	NA	NA	245.8 ± 29.3	**101 ± 17**	253.3 ± 30.2	**75 ± 17**

Table 4.4: Residual mass balance of the growing season storm events (± 1 SD estimated hydrologic and analytical uncertainties). Note: significant changes over the hydrologic flux are in bold.

BDC Stream Reaches		FR		FRR		SRR		SR	
Event	Para meters	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)	Down stream ($g/km^2/hr$)	Residual (%)
(GS1 Event) 4/16/11	Runoff (m^3/hr)	92.5 ± 10.8	**138 ± 16**	144.7 ± 16.9	14 ± 16	20.7 ± 2.4	**39 ± 16**	43.8 ± 5.1	**59 ± 16**
	TSS	2909.3 ± 595.5	**149 ± 29**	4421.7 ± 905.1	**59 ± 29**	2780.9 ± 569.3	-24 ± 29	2438.7 ± 499.2	**56 ± 29**
	Turbidity (NTU)	7.1 ± 0.9	**-36 ± 8**	26.4 ± 3.5	7 ± 8	20.6 ± 2.7	-15 ± 8	9.8 ± 1.3	-34 ± 8
	TN	11.6 ± 1.4	70 ± 17	12.2 ± 1.5	**-40 ± 17**	7.7 ± 0.9	**52 ± 17**	13.1 ± 1.6	49 ± 17
	TDN	9.1 ± 1.1	48 ± 17	9.7 ± 1.2	**21 ± 17**	7.0 ± 0.8	**51 ± 17**	11.5 ± 1.4	**73 ± 17**
	NO_3-N	4.6 ± 0.6	107 ± 20	5.7 ± 0.8	**64 ± 20**	3.7 ± 0.5	**101 ± 20**	5.0 ± 0.7	54 ± 20
	NH_4-N	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	2.6 ± 0.3	**266 ± 18**	2.5 ± 0.3	-80 ± 18	0.8 ± 0.1	28 ± 18	2.0 ± 0.2	-10 ± 18
	DON	4.4 ± 0.6	14 ± 21	4.0 ± 0.6	-12 ± 21	3.2 ± 0.5	18 ± 21	6.5 ± 0.9	**73 ± 21**
	TP	10.7 ± 1.4	105 ± 19	11.0 ± 1.4	**23 ± 19**	19.0 ± 2.5	**42 ± 19**	17.9 ± 2.3	26 ± 19
	TDP	1.5 ± 0.2	114 ± 18	0.5 ± 0.1	**-20 ± 18**	1.2 ± 0.1	**53 ± 18**	2.2 ± 0.3	**67 ± 18**
	Ortho-P	0.0 ± 0.0	**-100 ± 18**	0.0 ± 0.0	0 ± 18	0.1 ± 0.0	**100 ± 18**	1.1 ± 0.1	**162 ± 18**
	PP	9.2 ± 1.2	103 ± 20	10.5 ± 1.3	**26 ± 20**	17.8 ± 2.2	**41 ± 20**	15.7 ± 2.0	22 ± 20
	DOP	1.5 ± 0.2	126 ± 21	0.5 ± 0.1	**-20 ± 21**	1.1 ± 0.1	**43 ± 21**	1.1 ± 0.1	21 ± 21
	TOC	139.4 ± 16.6	91 ± 17	124.8 ± 14.9	**21 ± 17**	114.4 ± 13.6	**58 ± 17**	139.3 ± 16.6	35 ± 17
	DOC	101.0 ± 12.0	46 ± 17	113.0 ± 13.5	**19 ± 17**	98.2 ± 11.7	**50 ± 17**	122.2 ± 14.6	47 ± 17
	POC	38.4 ± 4.6	**986 ± 17**	11.8 ± 1.4	**39 ± 17**	16.2 ± 1.9	**140 ± 17**	17.1 ± 2.0	-16 ± 17

Table 4.5 (Continued)

(GS2 Event) 5/17/11	Runoff (m^3/hr)	101.2 ± 11.8	**174 ± 16**	466.7 ± 54.4	**87 ± 16**	54.1 ± 6.3	**31 ± 16**	128.0 ± 14.9	**39 ± 16**
	TSS	1798.5 ± 368.2	**225 ± 29**	17002.4 ± 3480.4	**359 ± 29**	18479.4 ± 3782.7	**72 ± 29**	16291.0 ± 3334.8	**-33 ± 29**
	Turbidity (NTU)	7.1 ± 0.9	9 ± 8	26.4 ± 3.5	7 ± 8	20.6 ± 2.7	-8 ± 8	9.8 ± 1.3	-27 ± 8
	TN	11.9 ± 1.4	15 ± 17	47.0 ± 5.7	**100 ± 17**	23.7 ± 2.9	26 ± 17	85.9 ± 10.4	20 ± 17
	TDN	10.7 ± 1.3	15 ± 17	42.7 ± 5.1	**115 ± 17**	17.6 ± 2.1	27 ± 17	63.4 ± 7.6	3 ± 17
	NO_3-N	4.2 ± 0.6	152 ± 20	16.7 ± 2.3	83 ± 20	3.4 ± 0.5	**56 ± 20**	15.9 ± 2.2	**-38 ± 20**
	NH_4-N	0.0 ± 0.0	**-100 ± 17**	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.5 ± 0.1	**100 ± 17**
	PN	1.1 ± 0.1	9 ± 18	4.3 ± 0.5	19 ± 18	6.1 ± 0.7	23 ± 18	22.4 ± 2.7	**126 ± 18**
	DON	6.6 ± 0.9	170 ± 21	26.0 ± 3.6	**144 ± 21**	14.2 ± 2.0	21 ± 21	46.9 ± 6.5	29 ± 21
	TP	9.6 ± 1.3	174 ± 19	31.3 ± 4.1	**126 ± 19**	78.1 ± 10.2	**63 ± 19**	91.5 ± 12.0	-18 ± 19
	TDP	1.2 ± 0.1	74 ± 18	3.2 ± 0.4	70 ± 18	3.0 ± 0.4	**37 ± 18**	9.7 ± 1.2	**41 ± 18**
	Ortho-P	0.0 ± 0.0	**-100 ± 18**	0.0 ± 0.0	0 ± 18	0.2 ± 0.0	**100 ± 18**	8.0 ± 1.0	**69 ± 18**
	PP	8.4 ± 1.0	**197 ± 20**	28.1 ± 3.5	**135 ± 20**	75.1 ± 9.4	**64 ± 20**	81.8 ± 10.2	-22 ± 20
	DOP	1.2 ± 0.1	108 ± 21	3.2 ± 0.4	70 ± 21	2.8 ± 0.4	28 ± 21	2.8 ± 0.3	30 ± 21
	TOC	149.2 ± 17.8	70 ± 17	524.9 ± 62.6	**115 ± 17**	296.4 ± 35.4	25 ± 17	830.3 ± 99.0	**64 ± 17**
	DOC	141.0 ± 16.8	77 ± 17	478.4 ± 57.1	**109 ± 17**	261.5 ± 31.2	24 ± 17	746.2 ± 89.0	**57 ± 17**
	POC	8.1 ± 1.0	2 ± 17	46.5 ± 5.5	**201 ± 17**	34.9 ± 4.2	**33 ± 17**	84.1 ± 10.0	**194 ± 17**

Table 4.5 (Continued)

(GS3 Event) 9/6/11	Runoff (m^3/hr)	108.3 ± 12.6	**47 ± 16**	194.6 ± 22.7	8 ± 16	11.0 ± 1.3	6 ± 16	43.3 ± 5.1	**96 ± 16**
	TSS	6641.6 ± 1359.5	8 ± 29	20645.0 ± 4226.0	**34 ± 29**	12462.0 ± 2551.0	**245 ± 29**	3880.8 ± 794.4	**100 ± 29**
	Turbidity (NTU)	7.1 ± 0.9	**-22 ± 8**	26.4 ± 3.5	-5 ± 8	20.6 ± 2.7	**65 ± 8**	9.8 ± 1.3	**-25 ± 8**
	TN	15.9 ± 1.9	25 ± 17	14.6 ± 1.8	-10 ± 17	4.8 ± 0.6	5 ± 17	22.7 ± 2.7	**114 ± 17**
	TDN	12.1 ± 1.5	23 ± 17	11.1 ± 1.3	-4 ± 17	4.5 ± 0.5	16 ± 17	18.5 ± 2.2	**116 ± 17**
	NO_3-N	5.9 ± 0.8	46 ± 20	6.1 ± 0.8	**23 ± 20**	2.6 ± 0.4	**159 ± 20**	6.1 ± 0.8	78 ± 20
	NH_4-N	0.0 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17	0.2 ± 0.0	0 ± 17	0.0 ± 0.0	0 ± 17
	PN	3.8 ± 0.5	30 ± 18	3.4 ± 0.4	**-27 ± 18**	0.5 ± 0.1	**-33 ± 18**	4.2 ± 0.5	**104 ± 18**
	DON	6.2 ± 0.9	8 ± 21	5.0 ± 0.7	**-24 ± 21**	1.8 ± 0.3	**-38 ± 21**	13.3 ± 1.9	**158 ± 21**
	TP	32.7 ± 4.3	6 ± 19	56.0 ± 7.3	0 ± 19	51.0 ± 6.7	**152 ± 19**	49.4 ± 6.5	**97 ± 19**
	TDP	2.9 ± 0.4	1 ± 18	1.8 ± 0.2	4 ± 18	1.6 ± 0.2	**37 ± 18**	6.6 ± 0.8	**82 ± 18**
	Ortho-P	3.2 ± 0.4	-6 ± 18	0.2 ± 0.0	**-48 ± 18**	1.8 ± 0.2	**58 ± 18**	5.9 ± 0.8	64 ± 18
	PP	29.8 ± 3.7	7 ± 20	54.2 ± 6.8	0 ± 20	49.4 ± 6.2	**159 ± 20**	42.8 ± 5.3	**97 ± 20**
	DOP	0.3 ± 0.0	**278 ± 21**	1.6 ± 0.2	16 ± 21	0.1 ± 0.0	**-40 ± 21**	2.5 ± 0.3	**1084 ± 21**
	TOC	195.6 ± 23.3	34 ± 17	162.5 ± 19.4	-7 ± 17	69.6 ± 8.3	**18 ± 17**	230.1 ± 27.4	**88 ± 17**
	DOC	172.5 ± 20.6	39 ± 17	140.5 ± 16.8	3 ± 17	54.1 ± 6.4	0 ± 17	199.8 ± 23.8	**85 ± 17**
	POC	23.2 ± 2.8	6 ± 17	21.9 ± 2.6	**-42 ± 17**	15.5 ± 1.8	**196 ± 17**	30.3 ± 3.6	**110 ± 17**

4.5.2 1 TSS and Turbidity

The positive residual mass balance of TSS during all storm events (non-significant for SRR during the GS1 event) in the restored FRR and SRR indicated a net export of sediment (Table 4.4 and 4.5 and Figure 4.4A). For the unaltered FR and SR, the residual mass balance of TSS during most of the storm events was either not-significantly different from zero change or positive, but within the range of the hydrologic flux increase, indicating no significant differences between similar unit area TSS fluxes in the upstream and downstream monitoring stations (Table 4.4 and 4.5 and Figure 4.4A). We attribute the positive residual mass balance of sediment to the mobilization of channel sediment whose original source was active suburban residential and institutional development projects between the upstream and downstream monitoring stations of the FRR and SRR. Whereas, in unaltered FR and SR the land use was stable during the study period.

The unit area flux of TSS from the downstream monitoring stations of all stream reaches during the DS1 event was compared with the GS3 event. The two events had similar runoff magnitudes and antecedent rainfall conditions but occurred in different seasons (Table 4.2). The analysis indicated a 23%, 52%, and 74% lower TSS flux from the FR, FRR and SR, respectively, whereas a 73% higher TSS flux was measured for SRR during the GS3 event in comparison to the DS1 event (Table 4.4 and 4.5 and Figure 4.4A). The higher TSS flux from the FR, FRR, and SR during the dormant season is attributed to increased erosion losses from stream banks and hillslopes in the absence of a leafed overstory (Gray and Sotir 1996, Dougherty et al 2006). The increase in TSS flux during the GS3 event in SRR is attributed to excess sediment discharged into the stream channel through an unstable SCM within an actively developing sub-division (Gagrani personal observation). The restored stream reaches FRR and SRR on average transported 2.2X higher suspended sediment per unit area in comparison to the unaltered stream reaches FR and SR during all storm events in both seasons (Table 4.4 and 4.5 and Figure 4.4A).

During over-bank flooding events sediment and P storage on floodplains was observed in a residual mass balance study of the suburban land use dominated River Swale, UK (Bowes and House 2001). In contrast, we observed a net export of TSS, TDN, NO_3-N, TP, PP, and POC with other constituents not indicating a consistent pattern of retention or export during the two overbank events (DS2 and GS2). Although, the restored stream reaches now have access to their floodplains, the flooding onto the floodplains did not result in significant retention of these water quality constituents.

The average downstream turbidity levels exhibited a declining trend in the unaltered FR and SR, whereas in the restored FRR and SRR, the change in volume weighted average turbidity levels between monitoring stations was mostly non-significantly different in comparison to upstream sites or did not exhibit consistent patterns of change (Table 4.4 and 4.5 and Figure 4.4A). In part, this might be attributed to the unstable land use in SRR during this study. The measured average volume weighted turbidity during monitored storm events for the downstream locations of FR, FRR, SRR, and SR was 850 NTU, 1038 NTU, 402 NTU, and 613 NTU, respectively during 2010-2011. The average turbidity in the two suburban land use dominated stream reaches with engineered SCMs is typically lower than the primarily forested FR and FRR in this stage of watershed development (Allan et al. 2011).

4.5.2 2 Nitrogen

For the dormant and growing season storm events, the particulate N (PN) fraction comprised 9% to 60% (mean 22%) of the TN export. The residual mass balance of the PN in the restored FRR and SRR was generally negative indicating sedimentation within the study reach. For the GS2 event the downstream PN fluxes increased but the increase was lower than the observed increase in the hydrologic flux possibly indicating a reduction in the unit area inputs from the downstream contributing area in comparison to the upstream contributing area (Table 4.4 and Table 4.5 and Figure 4.4B). For FR and SR the sign and magnitude of the residual mass balance of PN varied between events and streams in no predictable manner (Table 4.4 and 4.5 and Figure 4.4B).

The residual mass balance of TN and TDN during all storm events in the predominately forested and unaltered FR was mostly either characterized by net exports lower than the observed increase in hydrologic flux or exhibited no change between the two monitoring stations. The residual mass balance in FR indicated similar or declining unit area fluxes of TN and TDN in downstream monitoring station in comparison to the upstream monitoring station (Table 4.4 and 4.5). The sign and magnitude of the residual mass balance for the FRR, SRR, and SR for TN and TDN varied between events and streams in no predictable manner (Table 4.4 and 4.5 and Figure 4.4B).

Ammonium concentrations were generally below detection levels during the monitored runoff events at all upstream and downstream monitoring stations. However, NH_4-N was detected in the downstream monitoring station of the suburban SRR (GS3) and SR (GS2) but only comprised 5% and 1% of the TDN flux, respectively. Ammonium comprised 51% of the TDN flux at the upstream monitoring station of the

FR during the GS2 event but was completely retained within the study stream reach. Possible mechanisms for retention include adsorption onto suspended or channel margin particulate matter and/or immobilization by biological communities within the study reach. The only significant transport of NH_4-N occurred during the DS1 event for the FRR, comprising 25% of the TDN loads (Table 4.4). The source of NH_4-N is most likely from N-fertilizer applications within the study watersheds. In all other runoff events, the TDN fraction consisted of variable proportions of DON and NO_3-N. The residual mass balance of NO_3-N in the restored FRR and SRR was mostly positive, indicating a net export during stormflow events. The source of the NO_3-N is believed to be the riparian soils of the restored stream channels. In the restored stream channels, the water table is much closer to the soil surface as compared to the unaltered FR and SR channels. It is likely that NO_3-N produced by the nitrification process was mobilized from riparian soils by shallow runoff pathways activated over the course of individual runoff events.

The downstream unit area fluxes were significantly higher for TN (70% to 85%), PN (54% to 94%), TDN (73% to 88%), NO_3-N (52% to 83%), and DON (65% to 86%) during the dormant season DS1 event in comparison to the growing season GS3 event for all stream reaches (Table 4.4 and 4.5 and Figure 4.4B). We also observed, higher unit area fluxes of TN (1.4 to 3.3times), PN (0.8 to 3.8 times), TDN (1.2 to 3.1 times), NO_3-N (1.1 to 3.3 times), and DON (1.8 to 3.0 times) in the downstream monitoring station of the unaltered SR in comparison to the average downstream unit area fluxes from the other three stream reaches during all storm events (Table 4.4 and 4.5 and Figure 4.4B). We attribute the higher N fluxes in SR to the mobilization from the impervious surfaces and lawns receiving N-fertilizer in the suburbanized area of the catchment (Craig et al. 2008, Bernhardt et al. 2008, Barto 2010, and Filoso and Palmer 2011). However, the observed lower unit area flux of N in the SRR in comparison to other stream reaches during most of the storm events is believed not to be attributable to stream restoration, but rather the incomplete state of the suburban development within this sub-watershed at the time of the study. The remaining unbuilt lots represent an earlier and unstable stage of suburban development in the SRR sub-watershed resulting in a lower percentage of impervious cover and a lower unit area application of landscape fertilizer as compared to the more built out SR sub-watershed.

4.5.2.3 Phosphorus

The particulate P (PP) fraction comprised 61% to 97% (mean 87%) of the TP export during the dormant and growing season storm events. Particulate P was mostly mobilized from the restored FRR and SRR in association with increased TSS fluxes, however for the unaltered FR and SR, the residual mass balance of PP varied unpredictably between runoff events (Table 4.4 and 4.5 and Figure 4.4C). For all monitoring locations, the fraction of ortho-P and DOP as a proportion of the TDP fraction was variable during each event. Ortho-P was generally retained in the forested land use dominated FR and FRR, although ortho-P was not detected in FRR during the GS1 and GS2 runoff events (Table 4.4 and 4.5). During storm events, ortho-P retention most likely occurred through sorption to sediments retained in the stream channel or deposited onto the flood plain (Reddy 1999, Bowes and House 2001, and Smith 2009). The residual mass balance of ortho-P in the suburban SRR and SR was mostly positive indicating a net export (Table 4.4 and 4.5 and Figure 4.4C).

A recent study of assessing nutrient cycling within a subdivision in the SR watershed indicated runoff draining suburban lawns as the primary source of ortho-P (Barto 2010). The increases in ortho-P observed between the upstream and downstream monitoring stations in the suburban SRR and SR is most likely due the leaching losses of P-fertilizer applied onto suburban lawns in the suburban watersheds. This study also found that the TDP and ortho-P concentrations at the engineered SCMs outlets draining to SR were 1.9X and 2.5X higher than the mean stream channel concentrations during the 2010 monitoring period. This indicates that the engineered SCMs are a potential source of elevated P in the stream channel. Moreover, desorption of P from the bed sediments of the SR stream channel is also a potential source due to higher EPC^0 (0.07 mg/L) than the runoff EMC for this watershed during storm events.

Similar to the TSS unit area flux analysis, the unit area flux of TP in downstream monitoring stations for all stream reaches was 28%, 67%, and 56% lower from the FR, FRR, and SR, respectively, whereas a 21% higher TP flux was measured for SRR during the GS3 event in comparison to the DS1 event (Table 4.4 and 4.5 and Figure 4.4C). In the FR, FRR, and SR, the decline in downstream unit area flux of TP during the GS3 event in comparison to the DS1 event is mainly attributed to the sedimentation of PP because DOP and ortho-P comprised only 0.2% to 12% of the TP flux at these sites (Table 4.4 and 4.5 and Figure 4.4C). Whereas, in the SRR, the PP fraction of TP was mobilized with TSS as indicated by a 47% increase in downstream unit area flux of PP during the GS3 event when compared to the DS1 event (Table 4.4 and 4.5). The downstream unit area flux of PP was 1.8X higher in the suburban SRR and SR in comparison to the forested FR and FRR (Table 4.4 and 4.5 and Figure 4.4C). The downstream unit area flux of ortho-P was 4.7X higher in SR in comparison to the rest of stream reaches whereas, the unit area flux of DOP indicated no trend between monitoring stations (Table 4.4 and 4.5 and Figure 4.4C).

4.5.2 4 Organic Carbon

Particulate organic carbon comprised 6% to 35% (mean 15%) of the TOC for upstream and downstream monitoring stations of all stream reaches during storm events (Table 4.4 and 4.5 and Figure 4.4D). The predominately forested land use and unaltered FR indicated no change in flux of POC between upstream and downstream monitoring stations (Table 4.4 and 4.5 and Figure 4.4D). A net export of POC occurred for the majority of runoff events in FRR, SRR, and SR (Table 4.4 and 4.5 and Figure 4.4D). In the restored FRR and SRR, the concurrent mobilization of POC occurred with PP and TSS. However, in the suburban and unaltered SR mobilization of POC occurred without concurrent increases in the TSS flux. The magnitude and sign of the residual mass balance of DOC was not consistent between storm events for the study stream reaches (Table 4.4 and 4.5 and Figure 4.4D).

Similar to the unit area fluxes of N, the downstream unit area fluxes of OC demonstrated an elevated unit area fluxes of POC (32% to 79%) and DOC (64% to 82%) in the dormant season DS1 storm event in comparison to the growing season GS3 storm event for all study stream reaches (Table 4.4 and 4.5 and Figure 4.4D). The elevated OC during DS1 event could be attributed to the greater availability of leaf litter within the stream channel during the dormant season (DS1 event) in comparison to the growing season (GS3 event) in all monitored stream reaches.

4.6 Discussion and Conclusions

It could be expected to observe increased instream TSS, nutrients, and OC retention during baseflow and high flow periods in the restored FRR and SRR resulting in negative residual mass balances or increases that are less than the increase in hydrologic fluxes. We observe significant negative residual mass balances of TSS, TP, PP, TN, TDN, PN, DON, TOC, and POC during baseflow monitoring periods indicating instream retention in the restored FRR and SRR (Table 4.3). Whereas, the predominately forested land use and unaltered FR generally demonstrated decline in per unit area inputs into the stream channel resulting in positive residual mass balances but less than the hydrologic flux increase for these same constituents. A positive residual mass balance was found for the predominately suburban land use unaltered SR during baseflow monitoring periods (Table 4.3 and Figure 4.2). The source of this material is attributed to delayed runoff from engineered SCMs that drain pervious and impervious suburban surfaces and/or mobilization from the stream channel itself. We do not observe net retention for TSS, NO_3-N, TP, PP, and POC during high flow events in our two restored stream reaches (Table 4.4 and 4.5 and Figure 4.2A to D). In fact positive residual mass balances or net export were measured. In contrast, the residual mass balance of the same species in both the unaltered FR and SR was characterized by net exports lower than the observed increase in hydrologic flux or exhibited no significant change between the upstream and downstream monitoring stations (Table 4.4 and 4.5).

A second major trend we had expected to observe was that of elevated unit area fluxes of nutrients and OC from the predominately suburban land use SRR and SR in comparison to the predominately forested land use FR and FRR during baseflow and storm events. In addition, we also expected to observe that the engineered SCMs in the suburban SRR and SR retaining TSS, nutrients, and OC during highflow events, resulting in downstream unit area fluxes similar to forested stream reaches. Our baseflow unit area analysis mostly confirms this expectation with elevated unit area fluxes of N, P, and OC for the suburban SRR and SR receiving runoff from multiple engineered SCMs draining stable and developing suburbanized land cover in comparison to the forested FR and FRR (Table 4.3 and Figure 4.2).

The unit area fluxes of TN, PN, NO_3-N, DON, PP, and ortho-P were higher during storm events for the unaltered suburban SR in comparison to the other three stream reaches (Table 4.4 and 4.5). The SR unit area fluxes for DOC and POC, DOP, and NH_4-N did not exhibit any noticeably different trends in comparison to the other stream reaches. The sources of nutrients in suburban SR are attributed to delayed stormwater runoff detained in the SCMs enhanced by P and N fertilizer applications in lawns entering the stream channel from groundwater and engineered SCMs, and P-desorption from channel sediments. Lower unit area fluxes for most constituents were found for the other suburban dominated stream reach SRR (Tables 4.3, 4.4, and 4.5). The difference in behavior of the SRR was not entirely attributed to the stream restoration, but more attributed to the greater surface area of incompletely developed residential lots in this sub-watershed resulting in a lower percentage of impervious cover and a lower unit area application of fertilizer as compared to the built out BD4 sub-watershed.

We initially expected to observe higher net exports of sediments, nutrients, and OC during dormant season runoff events. Our storm events monitoring indicated no seasonal trends in instream retention and of sediment, nutrients, and OC. However, we measured higher per unit fluxes of TSS, N, P, and OC at most sites during the dormant season in a comparison of events with similar A5D condition and runoff magnitude. This could be attributed to higher mobilization of sediment due to lack of leafy canopy cover and relatively higher availability of leaf litter during dormant season in comparison to the growing season storm events.

4.6.1 Linear and Aerial Uptake and Export Rates

In order to compare our results with previous reach scale studies, we calculated instream linear and aerial retention and export rates of TN, TP, and DOC for the study stream reaches (Table 4.6). We estimated lateral inputs of groundwater and delayed runoff from the engineered SCMs located between the upstream and downstream monitoring stations of the study stream reaches to calculate the linear and aerial retention and export rates during baseflow monitoring periods. The groundwater input was calculated as the increase in baseflow discharge from upstream to the downstream monitoring stations of the study stream reaches. In FRR during both baseflow monitoring periods and SRR during B1 monitoring period, no lateral input was added because the downstream baseflow runoff declined. In the predominately forested land use FR, the lateral input was comprised of groundwater only as no engineered SCMs exist between the upstream and downstream monitoring stations. In comparison, in the predominately suburban land use SRR and SR stream reaches, the lateral inputs comprised both groundwater and delayed runoff from the engineered SCMs located between the upstream and downstream monitoring stations. The concentrations of TP, TN, and DOC for groundwater were estimated to be the same as stream baseflow concentrations. The concentrations of TP, TN, and DOC for engineered SCMs draining to the stream channels were derived from an ongoing monitoring program in the study watershed (Allan unpublished data). We partitioned the contributions from each source by making the assumption that little if any groundwater recharge occurred from suburban areas draining to the engineered SCMs and proportioned the measured increase in downstream runoff by the surface area represented by both forested and suburban land uses.

The linear and aerial retention rates of TN in the restored FRR during the B1 monitoring period was not-significantly different from zero and during the B2 monitoring period equated to 0.13 g $N.m^{-1}.d^{-1}$ and 1.77 mg $N.m^{-2}.h^{-1}$, respectively (Table 4.6). The average linear and aerial TN retention rates during baseflow monitoring periods for the restored SRR were 0.07 g $N.m^{-1}.d^{-1}$ and 0.93 mg $N.m^{-2}.h^{-1}$, respectively (Table 4.6). In restored stream reaches N uptake was dominated by DON. A mass balance study in the urbanized coastal plain of western Maryland found values of 0.38 g $N.m^{-1}.d^{-1}$ for the linear uptake of TN and 1.39 mg $N.m^{-2}.h^{-1}$ aerial uptake in urban restored stream reaches (Filoso and Palmer 2011). The aerial uptake rate of N in both restored stream reaches in this study was similar to the 2 mg $N.m^{-2}.h^{-1}$ average aerial denitrification rates observed for urban/suburban streams measured by Mulholland et al. (2009) in eight different locations in USA assessed by the $^{15}N\text{-}NO_3$ tracer addition approach. Following the same analysis we do not observe any significant retention of TN in the predominately forest land use and unaltered FR (Table 4.6). However, in the predominately suburban land use unaltered SR a not-significantly different from zero export was measured during the B1 monitoring period, whereas 0.09 g $N.m^{-1}.d^{-1}$ and 1.84 mg $N.m^{-2}.h^{-1}$ linear and aerial retention rates, respectively were measured during the B2 monitoring period (Table 4.6).

The linear and aerial retention rates of TP in the restored FRR during the B1 monitoring period were 0.10 g $P.m^{-1}.d^{-1}$ and 1.36 mg $P.m^{-2}.h^{-1}$, respectively and during the B2 monitoring period were not-significantly different from zero change (Table 4.6). The average linear and aerial retention rates during baseflow monitoring periods for the restored SRR were 0.15 g $P.m^{-1}.d^{-1}$ and 2.02 mg $P.m^{-2}.h^{-1}$, respectively (Table 4.6). In addition, the linear and aerial retention rates in the predominately forest land use and unaltered FR were not-significantly different from 0% change during the B1 monitoring period and 0.03 g $P.m^{-1}.d^{-1}$ and 0.35 mg $P.m^{-2}.h^{-1}$ during the B2 monitoring period. In contrast, the predominately suburban land use and unaltered SR indicated an average 0.26 g $P.m^{-1}.d^{-1}$ and 5.85 mg $P.m^{-2}.h^{-1}$ linear and aerial export during baseflow monitoring periods. The measured linear retention rate for P in the study restored stream reaches were similar to the 0.38 g $P.m^{-1}.d^{-1}$ to 1.0 g $P.m^{-1}.d^{-1}$ measured for forested stream reaches in Tennessee and North Carolina, as measured by injecting and observing uptake of $^{33}PO_4$ (Mulholland and Marzolf 1997). While, the predominately forested land use and unaltered FR exhibited generally lower linear and aerial retention rates despite the similar unit area fluxes of TP. The relatively low retention efficiencies for TP could be due limited lower geomorphic complexity within the unaltered FR channel and 2X higher stream velocities in comparison to the restored stream reaches.

The linear and aerial retention rates of DOC in the restored FRR during the B1 monitoring period were not-significantly different from zero change and during the B2 monitoring period was 1.01 g $C.m^{-1}.d^{-1}$ and 13.9 mg $C.m^{-2}.h^{-1}$, respectively (Table 4.6). The average linear and aerial retention rates estimated during baseflow for the restored SRR were 1.0 g $C.m^{-1}.d^{-1}$ and 13.97 mg $C.m^{-2}.h^{-1}$, respectively and for the suburban land use and unaltered SR were 2.45 g $C.m^{-1}.d^{-1}$ and 52.73 mg $C.m^{-2}.h^{-1}$, respectively (Table 4.6). In contrast, our estimates of the linear and aerial retention rates indicated that the predominately forested and unaltered FR during the B1 monitoring period was not-significantly different from a zero net change whereas during the B2 monitoring period the linear and aerial retention rates were 0.32 g $C.m^{-1}.d^{-1}$ and 4.38 mg $C.m^{-2}.h^{-1}$, respectively. The linear and aerial C retention rates in study stream reaches were similar to those observed in previous studies. An assessment of instream heterotrophic uptake of C assessed by releasing ^{13}C-acetate into two forested stream reaches at the Coweeta Hydrologic Laboratory, NC indicated uptake rates of 0.51 g $C.m^{-1}.d^{-1}$ and 0.65 g $C.m^{-1}.d^{-1}$ (Hall and Meyer 1998). Whereas, a study of using ^{13}C-labelled tree tissues found retention rates of 1.7 to 11.3 mg $C.m^{-2}.h^{-1}$ during baseflow periods in unaltered forested stream reaches in Pennsylvania, U.S.A (Kaplan et al. 2008).

We also observed that only restored stream reaches in our study indicated net retention of PP and TP during low flow periods. The results were similar to the suburban land use river Swale, UK receiving runoff from a sewage treatment works (STWs), which the authors largely attributed to the instream sedimentation and adsorption on bed-sediment measured by utilizing the residual mass balance approach (Bowes and House 2001). In addition, we measure a net export of TP and PP during in bank high flow events similar to the River Swale study. However, unlike the River Swale study, we have not observed significant sediment and associated P deposition onto floodplains of restored stream reaches during overbank storm events. We also, observed similar to or greater (30% to 70%) TN retention in restored stream reaches during baseflow conditions than the 23% N retention reported by Filoso and Palmer (2011) in restored stream reaches. That same study measured on average 24% TN retention during high flow events, whereas during our monitored high flow events we measured a 26% to 100% net export of N occurred from the restored stream reaches examined in this study.

Our results contribute to the growing body of literature of instream retention and processing of TSS, nutrients, and OC (e.g. Meyer et al. 2005, Groffman et al. 2005, Bukaveckas 2007, Kaushal et al. 2008, and Filoso and Palmer 2011) suggesting that the restored stream reaches retain and process the TSS, N, P, and C to a greater degree than unaltered channels impacted by legacy landcover alterations during baseflow conditions. However, these restored stream channels exhibited elevated turbidity and significantly higher losses of TSS, NO_3-N and P during high flow episodes. These trends appeared to be exacerbated during overbank flooding episodes and during dormant season high flow events. Our results further indicate that in the restored Piedmont stream channels the linear and aerial retention rates of N, P, and C assessed through the residual mass balance approach during baseflow periods are generally comparable to previous studies measuring linear and areal uptake rates by a variety of methods. We also demonstrated that an unaltered stream reach receiving runoff from suburban dominated land uses with a significant SCMs network generally exhibited a net export of TSS, P, N, and OC due to increased loadings from the engineered SCMs draining the suburban lawns and impervious land cover and P desorption from the instream bed sediment. In contrast, our study mostly indicated a decline in per unit area input of TSS, P, N, and OC with all upstream ortho-P inputs completely retained in an unaltered stream reach receiving runoff from predominately forested land uses.

Table 4.5: Linear and areal uptake of N, P, and DOC from the study stream reaches. Note: significant change in rates is in bold.

Stream Reaches	Retention/Export Rates	6/8/2011 (B1Mmonitoring Period)			7/12/2011 (B2 Monitoring Period)		
		TP	TN	DOC	TP	TN	DOC
SR1	Linear ($g.m^{-1}.d^{-1}$)	-0.01 ± 0.02	-0.01 ± 0.01	-0.02 ± 0.07	**-0.03 ± 0.02**	**-0.02 ± 0.02**	**-0.32 ± 0.23**
	Aerial ($mg.m^{-2}.h^{-1}$)	-0.19 ± 0.23	-0.13 ± 0.18	-0.28 ± 1.04	**-0.35 ± 0.24**	**-0.23 ± 0.26**	**-4.38 ± 3.23**
SR2	Linear ($g.m^{-1}.d^{-1}$)	**-0.10 ± 0.04**	**-0.03 ± 0.03**	-0.37 ± 0.39	-0.02 ± 0.04	**-0.13 ± 0.07**	**-1.01 ± 0.85**
	Aerial ($mg.m^{-2}.h^{-1}$)	**-1.36 ± 0.61**	**-0.35 ± 0.37**	-5.15 ± 5.36	-0.34 ± 0.55	**-1.77 ± 1.02**	**-13.97 ± 11.85**
SR3	Linear ($g.m^{-1}.d^{-1}$)	**-0.07 ± 0.03**	**-0.02 ± 0.01**	**-0.46 ± 0.12**	**-0.22 ± 0.07**	**-0.12 ± 0.03**	**-1.55 ± 0.33**
	Aerial ($mg.m^{-2}.h^{-1}$)	**-0.97 ± 0.35**	**-0.22 ± 0.12**	**-6.38 ± 1.67**	**-3.07 ± 0.91**	**-1.64 ± 0.40**	**-21.56 ± 4.53**
SR4	Linear ($g.m^{-1}.d^{-1}$)	**0.35 ± 0.05**	0.02 ± 0.06	**-2.12 ± 0.74**	**0.17 ± 0.03**	**-0.09 ± 0.06**	**-2.77 ± 0.74**
	Aerial ($mg.m^{-2}.h^{-1}$)	**7.45 ± 0.76**	0.37 ± 0.80	**-45.69 ± 10.29**	**3.72 ± 0.38**	**-1.84 ± 0.83**	**-59.76 ± 10.31**

CHAPTER 5: CONCLUSIONS

The objective of this research was to gain a better understanding of the hydrological and biogeochemical processes in an actively urbanizing S.E. Piedmont watershed known as the Beaverdam Creek (BDC) Watershed and to translate these results other urbanizing watersheds. The specific focus was to assess the effectiveness of stream restoration projects and engineered SCMs installations to maintain the pre-development hydrologic and water quality regime under the local stormwater and water quality regulations. The land development projects in the BDC watershed are spatially and temporally distributed and comprised of highway construction, airport runway construction, and suburban residential development with associated institutional and commercial developments. The BDC watershed contain two restored (FRR and SRR) and two unaltered or "natural" (FR and SR) stream channels. In addition, several engineered SCMs have been installed under the local stormwater management regulations to maintain the pre-development flow and water quality regime in the BDC watershed. The hydrological and biogeochemical processes in the BDC sub-watersheds were assessed by following three approaches: (1) The existing network of engineered SCMs in a stable suburban land use sub-watershed was assessed through a distributed catchment scale stormwater model application, (2) The change in runoff responses in the urbanizing BDC sub-watersheds was assessed through multiple analytical approaches, and (3) The instream retention and transport dynamics of sediment, nutrients, and OC was assessed through a residual mass balance approach.

Chapter 2 was a examined the effectiveness of an existing network of 15-engineered SCMs installed through the phase-by-phase sub-division development approach in the suburban watershed (54% development) by utilizing a spatially distributed stormwater model application, MUSIC. The results indicated that the runoff volume, peakflow rates, and TSS, TP, and TN loadings were significantly higher than the pre-development levels as well as the levels from an adjacent watershed (10% developed) despite the existing engineered SCMs network. It was also indicated the mandatory requirement of maintaining the pre-development peak discharge of the 10 and 25-year, 6-hour storm events at their pre-development levels and reducing the TSS and TP annual loading by 85% and 70%, respectively were not attained through the existing engineered SCMs.

Two separate retrofit scenarios of aggregated backyard rain-garden and offline bio-retention basins were modeled to assess their potential to meet mandatory for attaining the mandatory hydrologic and water quality targets. The first simulation of diverting 100% existing roof area runoff into backyard rain-gardens provided minimal reduction of runoff, and TSS, TP, and TN loadings, which can be attributed to small areal extent of the roof area and relatively low concentrations of sediment and nutrients in roof runoff. The second simulation of diverting runoff in a range from 10% to 100% contributing urban source node areas into offline bio-retention basins indicated that the mandatory reductions of TSS and TP could be met by diverting runoff from the 70% and higher percent of the contributing source node area of the suburban watershed. The final simulation of the existing natural floodplain/wetland area downstream of the calibration and validation monitoring station indicated on average a 61% TSS and TP annual load reduction. However, the load reduction efficiency was significantly reduced when the existing floodplain/wetland area was simulated in conjunction with the existing SCMs and offline bio-retention basins scenarios, which can be attributed that to the existing floodplain/wetland area receiving treated and filtered runoff from the existing and offline bio-retention basins in upstream locations in the watershed.

Chapter 3 examined the change in runoff hydrology in five developing SE Piedmont sub-watersheds (10% to 54% conversion of forest/farmland to suburban development) with a combination of engineered SCMs and stream restoration to meet the stormwater control requirements within a drinking water supply watershed. Three different analytical approaches, the Mann-Kendall statistical trend test, the unit hydrograph comparison, and unit impulse response were applied to assess the change in runoff response. The Mann-Kendal trend test indicated a declining trend in average streamflow and baseflow during the growing season for the BD1, BD3, and BD5 sub-watershed, no trend for the BD2 sub-watershed, and an increasing trend for the BD4 sub-watershed. The same approach also indicated no trends in average post-development quickflow runoff of the growing season for any of the sub-watersheds.

The unit hydrograph and unit impulse approaches indicate a decline in quickflow yield for the BD1 and BD5 sub-watersheds. These same two approaches indicate small increases in quickflow yield for the BD2, BD3, and BD4 sub-watersheds. However, the magnitude of the change in quickflow yield averages <5.4% indicating little or no change in post-development stormwater runoff for any of the sub-watersheds examined in this study. The decline in baseflow and average streamflow combined with little or no indication for significant increases in quickflow yield for three of the five sub-watersheds suggest that a greater proportion of runoff is returned to the atmosphere through evaporation. Moreover, the engineered SCMs captured the runoff from smaller precipitation events and subsequent evaporation of this stored water is largely responsible for these trends. The increasing trend in average streamflow for the BD4 sub-watershed could be attributed to the groundwater input supplemented with the runoff from the engineered SCMs. The unit hydrograph and unit impulse approaches also indicated an increase of 25.7% and 24.8% in peakflow discharge for the largest, BD5 sub-watershed. The significant increase in peakflow of the BD5 sub-watersheds is attributed to the change in time to peak of the contributing sub-watersheds as well as to a 3.1% to 9.5% increase in peakflow of the BD2 sub-watershed. The engineered SCMs constructed in the developed sub-watersheds appeared to largely control stormwater releases, lowered the magnitude of quickflow, and spread the quickflow over a longer time duration.

Chapter 4 involved an assessment of the instream transport and retention dynamics of sediment, nutrients, and OC during different flow regime and seasons by applying the residual mass balance approach in the urbanizing study watershed. The specific focus was given to evaluate the instream transport and retention dynamics in two restored and two unaltered or “natural” stream reaches with engineered SCMs during different flow regimes. One of the each restored and unaltered stream reach pair drained a predominately suburban and the other forested dominated land use. A negative residual mass balances indicating instream retention of TSS, TP, PP, TN, TDN, PN, DON, TOC, and POC was obtained during the baseflow monitoring periods in the restored FRR and SRR. In comparison, the predominately forested land use and unaltered FR generally demonstrated decline in per unit area inputs into the stream channel resulting in positive residual mass balances but less than the hydrologic flux increase for these same constituents. A positive residual mass balance was found for the predominately suburban land use unaltered SR during baseflow monitoring periods.

During high flow events, a positive residual mass balance indicating net export was observed for TSS, NO_3-N, TP, PP, and POC in two restored stream reaches. In contrast, the residual mass balance of the same species in both the unaltered FR and SR was characterized by net exports lower than the observed increase in hydrologic flux or exhibited no significant change between the upstream and downstream monitoring stations. The baseflow unit area analysis indicated elevated unit area fluxes of N, P, and OC for the suburban SRR and SR receiving runoff from multiple engineered SCMs draining stable and developing suburbanized land cover in comparison to the forested FR and FRR. In comparison, the highflow unit area analysis indicated elevated nutrients and OC fluxes in comparison to the forested stream reaches and restored suburban stream reach.

The three chapters presented in this dissertation research expand our understanding of the hydrological and biogeochemical processes due to land development, installation of engineered SCMs, and stream restoration projects in predominately forested and suburban land use SE Piedmont watersheds. The stormwater modeling, rainfall-runoff analytical methods, and reach scale water quality monitoring approaches utilized in this study to evaluate the effectiveness of existing engineered SCMs and stream restoration projects implemented under the local stormwater and water quality regulations can also be utilized to evaluate and implement stormwater management projects in other urbanizing watersheds for improving hydrologic and water quality regimes.

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