# ABSTRACT

Title of Document: HYDROGRAPH SEPARATION ANALYSES TO DETERMINE RUNOFF SOURCES IN A LARGE, URBAN WATERSHED

Marcie Elizabeth Occhi, Master of Science, 2011

Directed By: Dr. Karen L. Prestegaard,
Department of Geology

Hydrograph separation techniques were used to determine contributions of old and new water during storm events at four sites within the urban Anacostia River watershed. Multiple storm hydrographs were successfully separated with electrical conductivity as a tracer. Total runoff correlated to rainfall, but most runoff ratios were significantly less than the percentage of impervious surfaces. Old water was a significant component of runoff at each site. Peak contributions of old water occurred earlier new water peaks, which suggests rapid transmission of groundwater to streams. New water runoff was the dominant contribution for storm events greater than 2-3 cm. Watershed topography influenced patterns of urbanization and runoff pathways. Riparian buffers along Piedmont streams appeared to be sites of infiltration of overland flow. These results indicate that electrical conductivity is an effective tracer for the evaluation of streamflow sources within large urban watersheds.

# HYDROGRAPH SEPARATION ANALYSES TO DETERMINE RUNOFF SOURCES IN A LARGE, URBAN WATERSHED

By

Marcie Elizabeth Occhi

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2011

Advisory Committee:
Professor Karen L. Prestegaard, Chair
Professor Michael Evans
Professor Wenlu Zhu

# Acknowledgements

I would first like to thank the members of my committee, Dr. Michael Evans and Dr. Wenlu Zhu for helping me to broaden my perspective on my research and pushing me to make my research more accessible to those outside of my field. Secondly, I would like to thank my committee chair, graduate and undergraduate thesis advisor, Dr. Karen Prestegaard who has helped invigorate my creative thinking and fostered an ever growing "tool box" of critical thinking and problem solving skills that I will use throughout my career. Her endless patience and astounding enthusiasm for research has shaped both the research that I present here, and will have enormous impact on the research I do going forward. For this, I thank her deeply.

I would also like to thank the geology department at the University of Maryland for requiring a year-long undergraduate research project of their undergraduate students. This research project taught me how to think critically about scientific problems and begin to learn the correct way to effectively present data. While the faculty of the entire geology department was involved in shaping the senior undergraduates into critical thinkers, I would like to thank Dr. Phillip Candela specifically for his comments, suggestions and support through the senior thesis process.

The administrative staff at the University of Maryland, department of Geology was also a key to my success at this University. I would like to thank Ms. Dorothy Brown, Ms. Sharon Tazelaar, and Ms. Suzanne Martin for helping me through the logistics of the graduate program.

Help in the field was another key to success in this graduate program. I sincerely thank Erik Hankin, Zachary Blanchet, Emily Seldomridge, Lisa Walsh, and Dorothy Lundberg for donating time out of their lives to help me collect field data.

Last, but most certainly not least, I would like to thank my family for their never-ending support and unwavering, unconditional love during this time in my life. Without my family, I would not be where I am today. I would also like to thank my partner David Lapides for providing me with love and support, helping me collect data in the cold rain, editing posters and draft upon draft of this document without the slightest complaint. I love you, and none of this would be possible without you.

Portions of this research was funded by grants from The Environmental Protection Agency, The Anacostia Watershed Society and The Geological Society of America.

# Table of Contents

Acknowledgements…………………………………………………………..…ii
Table of Contents……………………………………………………………iv
List of Tables………………………………………………………………..vi
List of Figures……………………………………………………………....vii

Chapter 1: Introduction and Approach…………………………………………...1
  1.1 Introduction – Statement of the Problem……………………………...1
  1.2 Research Approach and Hypotheses………………………………….4
  1.3 Previous Work………………………………………………………...5
    1.3.1 Stream Hydrograph……………………………………….5
    1.3.2 Rainfall-Runoff Relationships…………………………….7
    1.3.3 A Review of Runoff Processes…………………………...8
    1.3.4 Identification of Surface and Subsurface Sources to Stream Hydrographs……………………………………………………...10
    1.3.5 Hydrograph Separation Analyses and Their Application to Urban Watersheds……………………………………………….11
    1.3.6 Predictive Models for Runoff Volumes and Peak Discharges in Urban Watersheds……………………………………………..13
    1.3.6 Connectiveness of Impervious Surfaces and Overland Flow Runoff………………………………………………………14
  1.4 Design and Approach of the Study…………………………………..16
  1.5 Organization of Thesis……………………………………………….17

Chapter 2: Study Site…………………………………………………………19
  2.1 Anacostia Watershed………………………………………………...19
  2.2 Geological Setting of the Anacostia Watershed……………………..21
  2.3 Location of Stream Gauging Stations………………………………..22
    2.3.1 USGS Gauged Sites……………………………………..23
    2.3.2 UMD Gauged Sites……………………………………...25
  2.4 Location of Precipitation Gauges…………………………………….26

Chapter 3: Methods…………………………………………………………...28
  3.1 Field Measurements………………………………………………….....28
    3.1.1 In Situ Field Probes……………………………………...28
    3.1.2 Discharge Rating Curves………………………………...29
    3.1.3 Electrical Conductivity as a Tracer……………………....31
    3.1.4 Comparison of Overland Flow Field Samples and Precipitation Conductivity……………………………………….33
    3.1.5 Measurement of Stream Specific Conductivity……………35
  3.2 Electrical Conductivity Determination of End-Member Samples…...36
    3.2.1 Baseflow (Groundwater) End-Member Characterization….36
    3.2.2 Precipitation (Surface Flow) End-Member Conductivity….37
  3.3 Hydrograph Separation Procedures…………………………………37
  3.4 Analysis of Error in Hydrograph Separation Analysis………………39

3.5 Analysis of Error in Precipitation Measurements……………………40
3.6 Limitations of Hydrograph Separation Procedures…………………..40

Chapter 4: Hydrograph Separation Analyses……………………………………43
4.1 Introduction……………………………………………………………..43
4.2 Objectives and Hypotheses……………………………………………..47
4.3 Storm Selection for Hydrograph Separation Analyses………………47
4.4 Conductivity of End-Member Samples…………………………….....52
4.5 Hydrograph Separation Results: Percent of New Water in Runoff….55
4.6 Error Calculations for Hydrograph Separation Analyses……………60
4.7 Rainfall Runoff Relationships…………………………………………62
4.7.1 Total Rainfall Runoff Relationships………………………62
4.7.2 Relationship of New and Old Water Runoff to Rainfall…..65
4.7.3 Error Analysis of Rainfall Runoff Coefficients……………70
4.8 Discussion………………………………………………………………71
4.9 Evaluation of Hypotheses……………………………………………72
4.10 Conclusions……………………………………………………………73

Chapter 5: Investigation of Storm Flow Delivery Processes……………………75
5.1 Introduction……………………………………………………………..75
5.2 Hypotheses and Objectives……………………………………………..79
5.3 Timing of Peak New and Old Water Contributions to Hydrographs…………………………………………………………...80
5.4 Seasonal Variations in Baseflow Conductivity………………………83
5.5 Baseflow Dilution by Storm Events…………………………………88
5.6 Alternative Hydrograph Separation Analysis………………………..91
5.7 Comparison of Traditional and Alternative Hydrograph Separation Results – Mixed Water Component……………………………………...97
5.8 Conceptual Model of Runoff for NW and NE Branch Watersheds – Synthesis of Field Observations and Data Analysis…………………....101
5.8.1 The NW Branch Model…………………………………...101
5.8.2 The NE Branch Model……………………………………107
5.9 Discussion and Evaluation of Hypotheses…………………………111
5.9.1 Rise Time Analysis……………………………………….....111
5.9.2 Baseflow Dilution and Alternative Hydrograph Separation Analyses…………………………………………………...112
5.10 Conclusions…………………………………………………………..113

Chapter 6: Conclusions…………………………………………………...……114
6.1 Summary……………………………………………………………114
6.2 Implications…………………………………………………………116

References……………………………………………………………………118

# List of Tables

Table I:  Stream gauge characteristics…………………………………………...23
Table II:  September 26th, 2008 overland flow runoff samples………………….34
Table III:  October 26th, 2008 overland flow runoff samples……………………35
Table IV:  Storm event characteristics…………………………………………...52
Table V:  Percentage of new water in streamflow hydrographs…………………59
Table VI:  Rainfall – runoff equations…………………………………………...64
Table VII:  Average runoff expressed as percent of total rainfall……………….69
Table VIII:  Percent of new water in alternative hydrograph separations……….93
Table IX:  Alternative separation average runoff………………………………..96
Table X:  Cherry Hill old, new and mixed water proportions…………………...98
Table XI:  Paint Branch old, new and mixed water proportions………………...99
Table XII:  NW Branch old, new and mixed water proportions…………………99
Table XIII:  NE Branch old, new and mixed water proportions………………..100
Table XIV:  NW Branch culvert field measurements…………………………..103

# List of Figures

Figure 1: Storm Hydrograph, NE Branch, Anacostia River. ……………………6
Figure 2: Air photos of University Park, MD………..…………………………15
Figure 3: Land use map of the North East Branch Anacostia Watershed………20
Figure 4: Piedmont – Coastal Plain transition within the Anacostia Watershed……………………………………………………………………..21
Figure 5: Watershed map with stream and rain gauge locations……….………24
Figure 6: Hach Hydrolab MS5 field probe…………………………………...28
Figure 7: Cherry Hill discharge rating curve…………………………………30
Figure 8: Discharge and specific conductivity with time for July 9th, 2008 storm event at the NW Branch USGS gauge………………………..……….......32
Figure 9: Average daily discharge and conductivity for the NE and NW Branch gauges…………………………………………………………………………49
Figure 10: Daily total precipitation values, USDA Beltsville site, 2008-2009………………………………………………………………………………51
Figure 11: Average conductivity values of baseflow, precipitation and overland flow runoff samples…..……………………………………………………53-54
Figure 12: Separated hydrograph for 6/27/2008 storm hydrograph…………….56
Figure 13: Separated hydrograph for 9/6/2008 storm hydrograph……………...57
Figure 14: Error envelope for 7/23/2008 NW Branch storm hydrograph………61
Figure 15: Total rainfall – runoff relationships…………………………………63
Figure 16: Coastal Plain and Piedmont old and new water rainfall – runoff diagrams………………………………………………………………………66-67
Figure 17: Cartoon of runoff processes…………………………………………75
Figure 18: Hydrograph rise time vs. drainage area…………………………71-82
Figure 19: Specific conductivity normalized by drainage area……………...84-85
Figure 20: Specific conductivity normalized by unit discharge………………...87
Figure 21: Discharge and conductivity of July 28th, 2008 storm……………….89
Figure 22: Pre and post storm conductivity…………………………………..…90
Figure 23: Old water conductivity decrease with time…………………….……92
Figure 24: Coastal Plain and Piedmont old and new water rainfall-runoff using alternative hydrograph separation analyses…...……………………………...94-95
Figure 25: Air photo of NW Branch…………………………………...…102
Figure 26: Riparian width measurements of the NW Branch…………………105
Figure 27: Schematic cross section of NW Branch (A - A')…………………..106
Figure 28: Air photo of NE Branch gauge locations…………………………...108
Figure 29: Schematic cross section of NE Branch gauges (B – B') and (C – C')……………………………………………………………………110

# Chapter 1: Introduction and Approach

## 1.1 Introduction – Statement of the Problem

Runoff ratios and hydrographic peak discharges are often significantly higher in urban streams than non-urban streams in same geographic area (Brutsaert, 2005). This increase in runoff has been measured in small urban watersheds (Pellerin et al., 2008) and it is primarily due to increased overland flow runoff from impervious surfaces (Rodriguez et al., 2003; Brutsaert, 2005). Increases in flood discharges and volumes are also observed in large, urban watersheds and are also thought to be caused by increases in overland flow runoff. It is difficult to measure actual runoff processes in large watersheds, therefore, runoff behavior in large systems is often estimated from models rather than direct or proxy measurements (e.g. Moglen and Beighley ,2002). Large urban watersheds can have complex patterns of impervious surfaces that provide multiple opportunities for infiltration between initial overland flow generation and the stream channel. Although hydrograph characteristics can be estimated effectively through calibration of parameters in rainfall-runoff models (Logue and Freeze, 1985), an understanding of the actual processes that generate streamflow is important for determining contaminant transport and developing designs for the efficient mitigation of runoff and contaminant loads in urban areas (Hewlett and Hibbert, 1967; Thurston et al., 2003; Berkowitz et al., 2004).

The terms "runoff" or "storm flow generation" processes refer to the multiple physical mechanisms that can deliver water from hillsides to stream channels and they include a variety of surface and subsurface pathways (Dunne and Leopold, 1978). Between storm events, in perennial streams, there is no overland flow to streams. Therefore, most watersheds dominated by overland flow runoff during storm events experience subsurface flow runoff as well, including during the storms. Research in the past 40 years indicates a variety of physical processes that convey water to stream channels and has revealed the important contributions of subsurface flow processes to storm hydrographs (Sklash, 1990).

Field studies to identify storm runoff generation processes were initially conducted in small, agricultural watersheds as part of the effort to understand runoff and soil erosion from agricultural areas (e.g. Horton, 1945). Measurements indicated that overland flow runoff occurred when the infiltration capacity (cm/hr) of the soil was exceeded by storm intensity (cm/hr), thus producing infiltration-excess overland flow (Horton, 1945; Brutsaert, 2005). Subsequent research has demonstrated that infiltration-excess overland flow is rare in undisturbed humid temperate watersheds; instead, overland flow generally results from direct precipitation on saturated areas or from subsurface flow returning to the surface in convergent areas (Dunne and Black, 1970; Dunne 1978; Beven and Kirkby, 1979).

Urbanization partially covers permeable surfaces with impervious ones, resulting in infiltration excess overland flow. This overland flow runoff is efficiently transmitted to stream channels by storm sewer systems (Thurston et al., 2003). Detailed studies of urban runoff have been conducted primarily in small watersheds with small riparian zones (Brun, 2000). Overland flow runoff is often the dominant runoff mechanism identified in these studies of small urban watersheds (Lee and Heaney, 2003). Increased impervious surfaces within a watershed cause a proportional increase in the amount of runoff as a response to storm events (Carlson, 2004) and net soil infiltration (precipitation – runoff) proportionally decreases (Schiff and Benoit, 2007). Relationships among storm characteristics, runoff, and infiltration obtained from studies of small watersheds have been used to develop models of urban runoff.

Large urban watersheds can have complex patterns of urbanization that are overlain on watersheds that are also more complex than small zero or first order streams. Therefore, overland flow runoff from impervious surfaces may be added to or replace the original watershed hydrological processes. Patterns of urban development are also important. In some regions, storm sewers convey runoff directly to major streams in others; there are opportunities for infiltration of surface runoff between sites of overland flow generation and major stream channels. Therefore, the assumption that overland flow is the dominant runoff mechanism in large watersheds is not necessarily valid. The hydrologic behavior of these watersheds must be determined by physical or chemical measurements, which can then be used to develop conceptual models and to test quantitative models of hydrological processes.

Various isotopic and geochemical methods have been developed to identify sources of water to streamflow hydrographs. These hydrograph separation techniques are used to identify surface and subsurface water sources.

These methods can be applied to both urban and non-urban watersheds of varying sizes (Rice and Hornberger, 1998, Gremillion et al, 2000)

## 1.2 Research Approach and Hypotheses

In this study, stream runoff responses to precipitation are examined at several scales in two large, urban watersheds. Preliminary research (Occhi, 2009) indicated that electrical conductivity values for overland flow and precipitation are similar and significantly different from baseflow values in the Anacostia watershed. Therefore, electrical conductivity can be used in a two-component mixing model to determine proportions of “old” water (water stored in the system prior to the storm event) and “new” water (water introduced by the storm event) contributions to storm hydrographs. The main goal of this research is to quantify and compare subsurface and surface contributions to streamflow hydrographs in Piedmont and Coastal Plain subwatersheds of the Anacostia River and to see how these proportions vary with storm characteristics. Rainfall-runoff ratios, hydrograph separation analyses, lag time analysis, and watershed evaluation were all used to evaluate hydrological processes in these watersheds.

### Hypotheses:

1. The percentage of “new” water in stream hydrographs is directly proportional to the percentage of impervious surface in large (>10 $km^2$) urban watersheds.

2. Due to less permeable bedrock, thin soils, and narrow floodplains, Piedmont watersheds will contribute proportionally larger amounts of overland flow runoff to streamflow than Coastal Plain watersheds.

3. New water runoff occurs earlier in storm flow hydrograph than the groundwater runoff at all spatial scales.

4. Pressure changes in the groundwater system contribute "old" water rapidly to the stream. Therefore, "old" water components that arrive prior to or along with the flow runoff provide estimates of this end member.

5. Traditional methods of hydrograph separation analyses underestimate subsurface flow contributions to storm runoff due to mixing of "old" and new sources in shallow groundwater.

## 1.3 Previous work

### 1.3.1 Stream hydrograph

Stream discharge during storms can be easily monitored by measurement of gauge height and empirical calibration of gauge height to discharge from field measurements of channel area and velocity (Buchanan and Somers, 2005). Figure 1 is a hydrograph for the USGS North East Branch stream gauge (ID 01651000). The rises in discharge are caused by storm events, followed by a gradual return to baseflow. A hydrograph is a measure of the integrated response of the watershed upstream to a storm event.

Analysis of a storm hydrographs is used to determine peak discharge, hydrograph lag time, and total runoff volume (Dunne and Leopold, 1978). If precipitation data are available for the watershed, it can be used to evaluate the amount of rainfall that appears as storm runoff (Dunne and Leopold, 1978). Historically, storm hydrographs were interpreted as being composed entirely of overland flow runoff from the precipitation event, and this bias is still present in some recent hydrology texts (Hewlett and Hibbert, 1967; Brutsaert, 2005). In the past several decades, significant advances have been made in understanding stormflow generation (Hewlett and Hibbert, 1967; Dunne and Black, 1970; Dunne and Leopold, 1978, McDonnell et al., 1991).

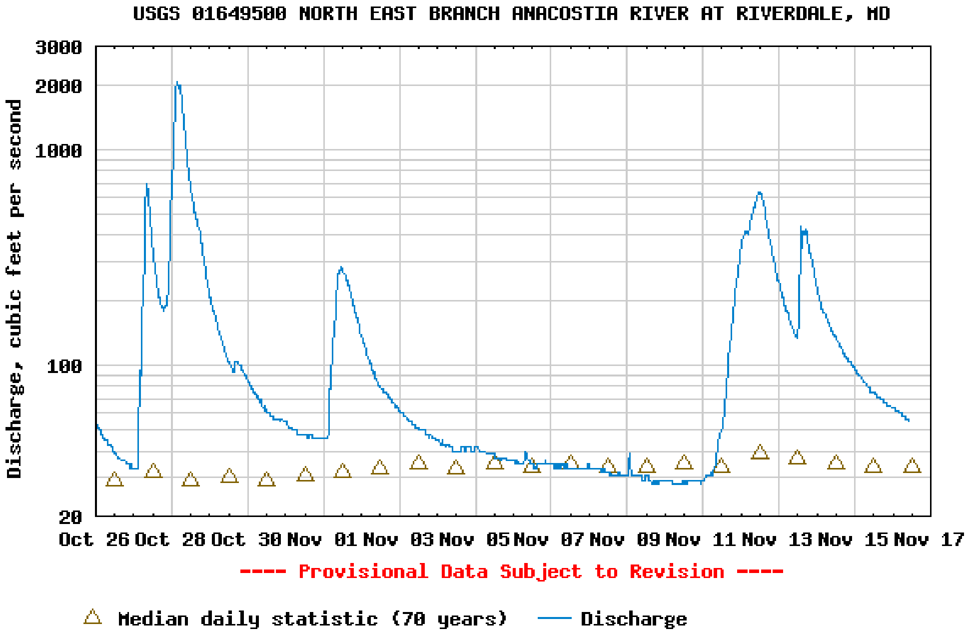


**Figure 1: Storm flow hydrographs are represented by peaks in discharge and are followed by receding limbs and periods of low flow (baseflow) for the NE Branch Anacostia River. Figure taken from USGS website.**

Even though stream channel discharge is easily measured at established gauging locations, it is difficult to measure individual flow paths of storm runoff and their various contributions to the storm hydrograph (e.g. Dunne and Black, 1970). Conservative tracers coupled with mass balance equations are used to quantify the contribution of dominant storm flow pathways (Sklash and Farvolden, 1982; Rice and Hornberger, 1998; Gremillion et al., 2000). This method of analysis is called hydrograph separation, and it is the primary method I will use to assess hydrologic behavior in the Anacostia Watershed.

### 1.3.2 Rainfall - Runoff Relationships

In the previous section, I introduced streamflow hydrographs and total storm runoff as integrative measures of watershed behavior. Runoff terms are expressed in units of length (m or cm) and it is calculated by dividing runoff volume ($m^3$) by watershed area ($m^2$). Comparison of storm runoff values to total rainfall for each storm event is used to evaluate the relationship between runoff and rainfall for a watershed.

Rainfall-runoff relationships are calculated in a number of different ways depending upon the purpose of the study (Blume et al., 2007). In this study, total storm runoff is considered to be the total hydrograph volume minus the baseflow volume for a storm event. A more detailed explanation of baseflow separation is in Chapter 4. Comparison of runoff to rainfall for a storm event provides information about watershed response, and these responses can be evaluated for their sensitivity to storm magnitude, intensity and to antecedent moisture conditions. These relationships inform on possible runoff processes (e.g. Dingman, 1994), but they are unable to tell us the specific flow paths taken by water to the stream channel. Identification of major flow paths within a watershed is essential for prediting the fate of various contaminants and designing mitigation measures. Rainfall-runoff ratios are a major component of unit hydrograph analysis (e.g. Rodriguez et al., 2003) and runoff ratios are a major parameter in many runoff models (Blume et al., 2007).

### 1.3.3 A Review of Runoff Processes

Water can take a variety of paths to a stream channel during a storm event (Sloan and Moore, 1984). The path easiest to observe is overland flow; water that flows over impervious, compacted, or saturated surfaces to stream channels without spending much, if any time in the subsurface (Hewlett and Hibbert, 1967). This type of runoff can be further subdivided into two major categories: infiltration-excess overland flow (aka Hortonian overland flow) and saturated overland flow (Dunne and Black, 1970; Dunne, 1978).

Hortonian overland flow is defined as water in excess of the infiltration capacity of the soil due either to high intensity rainfall or low infiltration capacity of the soils. In urban areas it is associated with the runoff derived from impervious surfaces and compacted surfaces (Horton, 1933). Hortonian overland flow is common in arid to semi-arid regions and is thought to be rare in non-disturbed humid temperate watersheds, except for regions with low permeability soils (Horton, 1933). It can be introduced by disturbances due to agriculture, compaction by roads and trails, and in urban areas by placement of impervious surfaces (Sloan and Moore, 1984; Pearce et al., 1986). Hortonian overland flow is generated due to surface conditions present in the watershed, thus areas of occurrence can be determined from land-use and soils maps of watersheds.

Saturated overland flow is runoff derived from areas that become saturated during the storm event due to shallow water tables or convergent subsurface flow. It is different from Hortonian overland flow in that saturated overland flow can be generated from regions with permeable soils (Dunne and Black, 1970). Saturated overland flow is found to be common in humid temperate watersheds, but antecedent moisture conditions and long duration storm events are most effective at producing this type of runoff (Dunne, 1978). Saturated overland flow is related to water table depths and topographic convergence and is not entirely dependent upon surface conditions (Beven and Kirkby, 1979). Thus, it is often modeled with these topographic parameters, but rarely calibrated with field measurements in large watersheds (Wood, 1994).

Subsurface contributions to storm runoff have received considerable attention over the past six decades and the literature on this topic covers two main categories of subsurface flow: groundwater discharge and throughflow (shallow subsurface flow). Although both of these categories are technically groundwater flow, the term "groundwater discharge" is reserved for Darcian flow and does not include rapid flow through pipes and macropores. Rapid groundwater discharge during storm events is difficult to explain and is thought to be a response to changes in pressure and total hydraulic head caused rapid infiltration of precipitation to the capillary fringe that changes the pressure distribution in this region (Beven and Germann, 1982; Abdul and Gillman, 1984; Berkowitz et al., 2004). This capillary fringe response primarily involves old, stored water to be discharged to the stream channel (Pearce et al., 1986). This response can be rapid because it is transmitted as a pressure wave, not as the slow movement of water through the soil.

Shallow subsurface flow is the rapid transmission of water through series of interconnected macropores or through saturated layers within the unsaturated zone to the stream channel (Pearce et al., 1986). This runoff process has been documented in field plots and in experimental studies (Weyman, 1970). The water that is transmitted through permeable soil lenses, large macropores, or subsurface pipes is a combination of new precipitation and older, stored water (Beven and Germann, 1982; Sloan and Moore, 1984).

### 1.3.4 Identification of surface and subsurface sources to stream hydrographs

Previous studies of runoff processes in urban watersheds have mainly focused on the effects of impervious surfaces on the overland flow runoff component of storm hydrographs (Schiff and Benoit, 2007). In order to quantify the amount of overland flow and groundwater runoff in large watersheds, total runoff must be measured from storm hydrographs, and a method for distinguishing overland flow from subsurface flow components must be used.

There have been a variety of methods developed to identify water sources in storm hydrographs (e.g. Pilgrim et. al. 1979, Weiler et al., 1998, Gremillion et al., 2000, and Heppel and Chapman, 2006). There are two main approaches to the determination of water sources: physical measurements of event water and pre-event water that are primarily conducted in small catchments (e.g. Dunne and Black, 1970), and geochemical tracer studies that can be applied to watersheds of various sizes (Huth et al., 2004; Joerin et al., 2002). Some studies also combine physical and geochemical measurements (O'Connell, 1998).

Hydrograph separation procedures have previously been used to determine runoff sources in large watersheds (Gremillion et al., 2000; Bhote et al., 2010). Hydrograph separation techniques have been used since the early 1970's in order to determine the quantity of contributing sources of storm runoff by using mass balance equations coupled with a conservative tracer (Ladouche et al., 2001). Most research that utilizes hydrograph separation procedures has focused on small to large natural catchments, but there is no reason to assume that the procedures are not applicable to large urban watersheds (Pellerin et al., 2008).

Hydrograph separation analyses can provide information about sources of streamflow from a watershed for a particular storm event. These results can be influenced by many variables, including storm intensity, spatial variability of rainfall, and soil antecedent moisture condition (Gremillion et al., 2000). Therefore, evaluation of multiple storm hydrographs at various watershed locations should provide an opportunity to examine sources of storm discharge under a variety of conditions and provide insight into the dominant streamflow generation mechanics in urban watersheds.

### 1.3.5 Hydrograph Separation Analyses and their Application to Urban Watersheds

Geochemical components of water, including the stable isotopes of oxygen and hydrogen or conservative ions such as chloride, sodium and silica, and physical parameters like temperature and electrical conductivity (Rice and Hornberger, 1998; Hoeg et al., 2000; Ladouche et al., 2001) have all been used as tracers for hydrograph separation analyses. Suitable tracers have several required characteristics: values chosen to represent the endmembers must be significantly different from one another and stream water values must fall between the end-member values over the course of the storm hydrograph (for the two component system). Tracer compositions are assumed to be homogeneous throughout the water source reservoirs, (e.g. groundwater or rainwater) or to vary in a predictable manner (e.g. linear changes in precipitation concentrations). Simple mass balance equations are then used to separate the components of stream discharge into contributions from endmember components (Gremillion et al., 2000). This process of dividing the storm hydrograph into its components is called hydrograph separation (Weiler et al, 1999).

Ladouche et al. (2001) presents a widely-used mass balance equation for hydrograph separation analysis:

$$Q_t = Q_a + Q_b \qquad (1)$$

$$Q_tC_t = Q_aC_a + Q_bC_b \qquad (2)$$

where $Q_t$ is total stream discharge, $Q_a$ is the discharge from source a and $Q_b$ is the discharge from source b. $C_t$ is the total tracer concentration of the stream, $C_a$ is the tracer concentration from point source a, and $C_b$ is the tracer concentration from point source b. Given the concentrations of $C_a$ and $C_b$ known along with $Q_t$ and $C_t$, equation (2) can be solved for $Q_a$ and $Q_b$.

These equations require several assumptions for their use that must be examined for validity to properly use the hydrograph separation procedures. The concentrations designated to represent the two end-member tracers (event water and pre-event water) must represent the average concentration of their respective reservoir. The end-member concentrations must be significantly different from one another and represent average values for their respective reservoirs (Gremillion et al., 2000), and all stream concentration values must fall between the two end-members over the course of the storm hydrograph (for two component mixing).

### 1.3.6 Predictive Models for Runoff Volumes and Peak Discharge in Urban Watersheds

Measurement of overland flow runoff in small watersheds has lead to both simple and complex models of runoff that are based on the following data: storm intensity, watershed area, soil characteristics, land cover, and a method to convert land use and soil characteristics into a runoff parameter. Simple runoff models include the rational method (Chow, 1964; Guo, 1999), SCS curve number method (USDA,1986; Mishra and Singh, 1999), TR55 (USDA, 1986; Thurston et al., 2003), and other commonly-used empirically-derived methods (Molgen and Beighley, 2002). For example, peak discharge can be calculated from the rational method expressed as:

$$Q_d=\alpha C I_d A$$

where $Q_d$ is the peak runoff discharge, $\alpha$ is a unit conversion factor, C is a runoff coefficient, $I_d$ is the rainfall intensity in inches per hour, and A is the watershed area in acres (Guo, 1999). This peak runoff rate equation does not account for antecedent conditions and soil infiltration rates, all of which will have a large effect on the peak discharge (Gremillion et al., 2000). The runoff coefficient, C is directly proportional to the amount of impervious cover (Schuler, 1994) or other land use parameters (Guo, 1999). The rainfall intensity, $I_d$ may also be affected by seasonality, and spatial distribution of rainfall, and the effect of the rainfall may be influenced by antecedent rainfall. These variables can have a net effect on the effective precipitation in the watershed (Molgen and Beighley, 2002). Although these equations were derived from and should be used for small watersheds, they are often used for larger catchments due to their simplicity and the availability of estimated values for equation parameters.

### 1.3.7 Connectiveness of Impervious Surface and Overland Flow Runoff

The patchiness of urban development in large watersheds suggests that impervious surface and overland flow connectivity may be an important factor in watershed hydrological response. Impervious surface connectivity refers to the connection between various impervious surfaces such as roof-tops, roadways, and storm sewer systems. Recent studies evaluated the effect of impervious surface connectivity on the quantity of overland flow runoff (Lee and Heaney, 2003, Roy and Schuster, 2009, Konrad and Booth, 2005). These studies suggest that connected impervious surfaces generate overland flow runoff in proportion to the impervious surface area, but that disconnected impervious surfaces do not. A common example of high connectivity is a parking lot that is directly connected to storm sewer systems that have outfalls in perennial stream channels (Fig. 2B). Impervious surfaces that drain to pervious surfaces produce an opportunity for infiltration and they may generate less runoff. This suggests that two watersheds with similar impervious surface areas can generate different amounts of overland flow runoff depending upon impervious connectivity.

The connectivity of impervious surfaces in suburban developments might decrease with time. Lawn permeability probably increases with time due to the growth of vegetation and biological expansion of soil compacted during construction. Rooftops, driveways, and streets are all considered to be impervious surfaces. Rooftops (8% of the impervious surface in Fig. 2A) can be disconnected from streets and may not contribute runoff during storms. Tree cover can also provide significant interception of rainfall. These changes in watersheds occur over time after initial development. Thus, the age of a development can affect its hydrologic response.

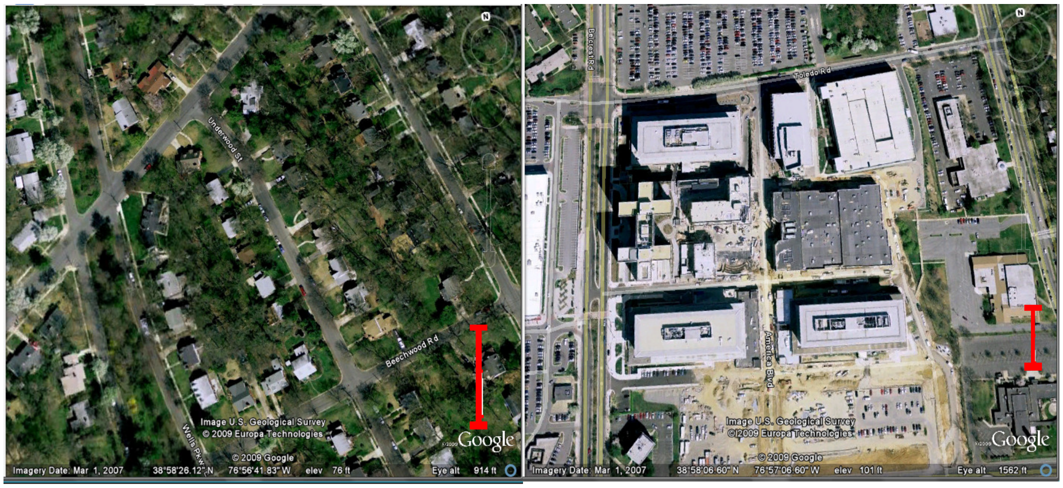


**Figure 2: Left (A), 60-year old suburb in University Park, MD. Note mature trees that partially cover roofs, roadways, and driveways. Right (B), an adjacent shopping center with connected impervious surfaces. 2007 USGS air photo. Scale bar shows 300 m.**

The connectivity of impervious surfaces that generate overland flow can affect total runoff to stream channels. Impervious surfaces may be disconnected from perennial stream channels by: a) storm sewer connections to ephemeral stream channels that can serve as infiltration corridors, b) storm sewer connections to unchannelized, usually grassed landscapes, c) storm sewer connections to ponds, and d) impervious surface runoff to pervious land without storm sewer systems. Ephemeral stream channels do not have perennial flow and are usually in the unsaturated portion of the soil. Therefore, infiltration can take place in these stream channels prior to or during delivery to the main channel. Thus, urban runoff may serve to recharge the riparian groundwater and increase groundwater flow to the stream when urban runoff is directed into ephemeral channels. The concept of connectivity of impervious surfaces directly to stream channels will be assessed in Chapter 5.

### 1.4 Design and Approach of the Study

Multiple storm hydrographs were obtained from six gauged locations in the Anacostia River Watershed. Electrical conductivity is used as a tracer in hydrograph separation analyses to quantify the contributions of “new” and “old” water sources to storm runoff. The usefulness of this hydrograph separation procedure to urban runoff in large watersheds is examined. The relationship between runoff and rainfall is investigated for a variety of storm events with different characteristics. Comparison of hydrological response to various storm events is conducted for watersheds of various sizes and from Piedmont and Coastal Plain Physiographic provinces. This analysis of multiple storm hydrographs at multiple watershed locations should provide insight into major stormflow paths within this large urban watershed.

## 1.5 Organization of Thesis

This thesis has been divided into six chapters that are organized into introductory materials, study site and methods, two main results chapters and a conclusion. Chapter 2 is used to provide an overview of the study sites and background information on the geology, topography, and climatic setting. In Chapter 3, the field and analytical methods are discussed along with methods for error calculation and propagation. Hydrograph separation results are presented in Chapter 4 and analysis of these results to interpret sources of subsurface flow are presented in Chapter 5, including conceptual models explaining NE and NW watershed behavior. Synthesis and discussion of all results are presented in Chapter 6.

Multiple terms are used in the literature to discuss similar concepts in hydrograph separation analysis. The terms “old” and “new” water are used to describe “pre-event” and “event” water. These terms will all be used synonymously throughout this document (Rice and Hornberger, 1998; Gremillion et al., 2000; Ladouche et al., 2001). The interpretation of these water sources as surface and subsurface water is more complex, and will be discussed in the discussion of the results.

# Chapter 2: Study Site

## 2.1 Anacostia Watershed

The Anacostia River Watershed is a large (464 $km^2$) complex urban-suburban watershed with spatially variable amounts of urbanization and land use. The watershed is located within Washington D.C., Montgomery County and Prince Georges County of Maryland with each contributing 17%, 34% and 49% of the watersheds drainage area, respectively (MDNR, 2005). The watershed is located within a humid temperate climate zone. The state of Maryland receives 45 inches of annual precipitation (Miller et al., 2007).

The lower most portions of the watershed are tidally influenced just downstream of where the North East and North West Branch rivers meet, however, most of the watershed is characterized by non-tidally infulenced stream flow (MDNR, 2005). This study will focus on the upper portions of the Anacostia watershed, including the non-tidally influenced North East (NE) and North West (NW) Branch watersheds, which are both located within Montgomery and Prince Georges County, Maryland.

Land use within the Anacostia is a mixture of agricultural, urban, forested and other areas (Prestegaard and Deveraux, 2008). Figure 3 shows the land use within the NE Branch of the Anacostia. The magnitude of urbanization is similar in some respects for both the NE and NW branches: the older urban/suburban developments have extensive impervious cover (30-35%) and are located near the mouths of both watersheds. Upstream tributary watersheds were developed later and are predominantly suburban with 17-19% impervious cover (Council of Governments, 2008).

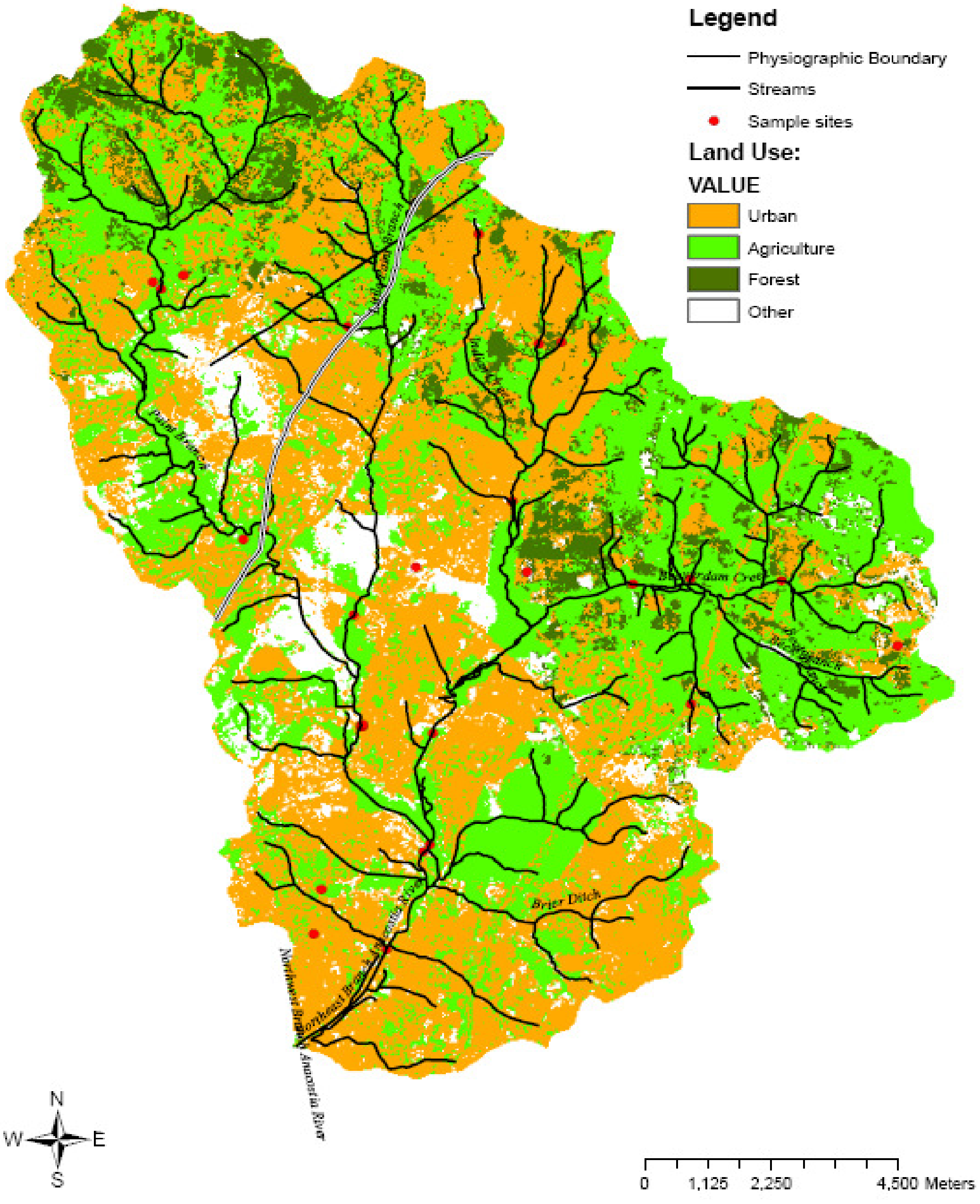


**Figure 3: Land use map of the NE branch of the Anacostia watershed. (From Devereux et al., 2010).**

## 2.2 Geological Setting of the Anacostia Watershed

The Anacostia watershed is geologically and geomorphically heterogeneous, which has influenced patterns of development and likely influences storm runoff processes. The NW branch of the river is predominantly in the Piedmont Province while the NE branch is in the Coastal Plain (Miller et al., 2007). Figure 4 shows the transition from the Piedmont to the Coastal Plain within the Anacostia Watershed.

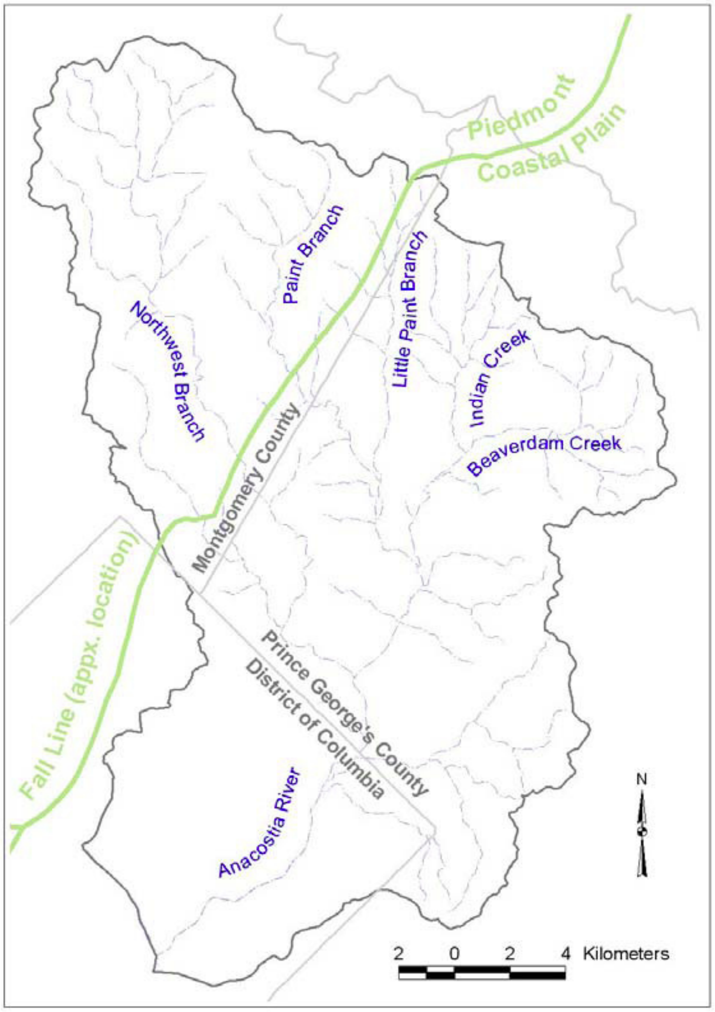


**Figure 4: Location of Piedmont and Coastal Plain Provinces within the Anacostia Watershed (Image taken from Teague et al., 2006)**

The NW Branch watershed resides mostly within the Piedmont Province, which is characterized by valleys, moderately hilly terrain and generally thin soils (Miller et al., 2007). The NW Branch is underlain by mostly the Lower Pelitic Schist member of the Wissahickon Formation with small pockets of Paleozoic Norbeck and Kensignton Quartz Diorites towards the headwaters (MGS, 1968).

The Coastal Plain Province, where the NE Branch watershed is located, is separated from the Piedmont Province by the Fall Zone, which is identified by an abrupt change in slope. The Coastal Plain Province is characterized by gentle topography which is less steep than the Piedmont Province. Major lithologies within the Coastal Plain include the Cretaceous Potomac Group and Quaternary Lowland Deposits (MGS, 1968). The alluvium in the Coastal Plain consists mainly of quartzitic and micaceous sands, gravels, silts and clays. Also included in the province are considerably thicker soil horizons than seen in the Piedmont Province (Miller et al., 2007).

## 2.3 Location of Stream Gauging Stations

The six gauged sites drain watershed areas with a range of impervious surfaces from eleven percent to twenty-six percent within the NE branch watershed (Devereux and Prestegaard, 2008; Council of Governments). Table I lists the name of the gauge, watershed size, total amount of impervious surfaces, and ownership of all gauges used in this study. Figure 5 is a watershed map provided to show the location of the watershed gauging sites as well as the rain gauge locations.

In order to critically evaluate the role of watershed scale in this study, it was critical that we choose watershed gauging locations with an order of magnitude difference in drainage areas. Both the NE and NW Branch watersheds have a tributary and watershed mouth stream gauging site. The tributary sites are Cherry Hill and Paint Branch for the NE and NW Branch sites respectively. The watershed mouth sites are the NE and NW Branch gauging locations. As most watershed studies focus on smaller watersheds (>10 km$^2$), the addition of the Green Castle gauge was added to the study to have a comparison catchment for other similar studies.

**Table I: Site information for Anacostia River Gauges used in this study. Information obtained from the USGS and Council of Governments, 2009.**

| Gauge Name* | Gauge Ownership | Drainage Area (km$^2$) | Impervious Cover (%) |
|---|---|---|---|
| Green Castle (🟩) | UMD | 9.6 | 11 |
| Cherry Hill (●) | UMD | 26.7 | 19 |
| Downstream Cherry Hill (●) | UMD | 26.9 | 19 |
| Paint Branch (▲) | USGS | 33.9 | 18 |
| NW Branch (♦) | USGS | 127.9 | 23 |
| NE Branch (■) | USGS | 188.6 | 26 |

***The symbols for each gauge can be found on the provided watershed map.**

### 2.3.1 USGS Gauged Sites:

The three USGS gauges are the NE, NW and Paint Branch stations. They automatically record gauge height, specific conductivity, temperature, pH, turbidity, and dissolved oxygen at 15 minute intervals. The NE branch of the Anacostia River gauge is located at lat 38°57'08.4"N, long 76°57'57.8"W and is identified as USGS gauge 01651000. The NW branch of the Anacostia River gauge is located at Lat 38°57'36.9"N, long 76°55'33.5"W and is identified as USGS gauge 01649500. These gauges represent the larger drainage areas investigated in this study. The NE and NW Branch gauges were chosen because they have the largest drainage area of established gauges in the watershed before you reach the tidally influenced portion of the Anacostia Watershed.

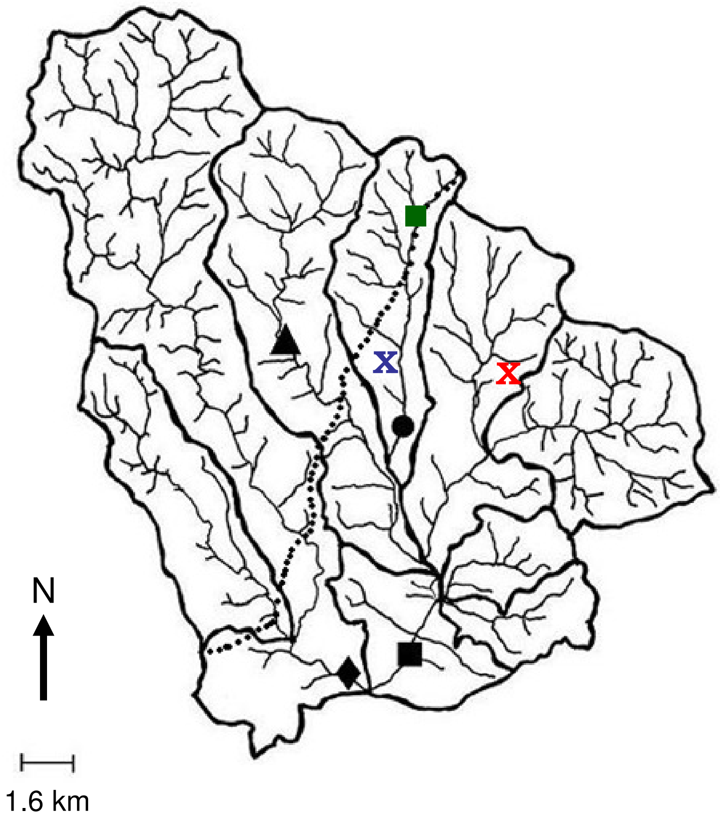


**Figure 5: Map of the non-tidal Anacostia Watershed. All gauging locations symbols identified in table I. The USDA and NADP precipitation gauges are noted with blue and red X marks, respectively. The transition from Piedmont to Coastal Plain provinces is shown as the dotted line.**

The Paint Branch gauge is located at lat 39°01’59.3”N, long 76°57’51.4” W and is identified as USGS gauge 01649190. This gauging station was chosen because even though the gauge is located within the Paint Branch portion of the

NE Branch watershed, it still resides in the Piedmont Province. This allows us to examine Piedmont tributary behavior without establishing a new gauging location in the NW Branch watershed. Data for the USGS gauging sites are available online for up to 60 days, after which it is archived and available from the USGS district office.

These USGS gauges have been in place for approximately 60 – 70 years, and the relationship between gauge height and stream discharge is well-defined by empirical rating curves. These rating curves are quite stable for channelized sections of river, such as the NE and NW branch. Data extracted from the USGS website for its gauged sites includes both gauge height and discharge.

### 2.3.2 UMD Gauged Sites:

The University of Maryland Watershed hydrology group, of which I am a part, maintains three watershed gauges. These gauges were designed to monitor an upstream area that has modern stormwater management (Green Castle) and two downstream gauges (Cherry Hill). These downstream UMD gauges are designed to provide information on storm responses from little Paint Branch Creek and to identify contributions of floodplain processes. The two Cherry Hill gauges were installed near each other, and the downstream location should provide information about floodplain processes on discharge and sediment transport between the two gauges. Both the Cherry Hill and Downstream Cherry Hill gauges are represented by the same symbol on Figure 5 because of their close proximity. The UMD sites are instrumented with Hydrolab MS5 (Hach, Loveland, CO) gauges that are set up to record data in 7.5 minute intervals. They record specific conductivity, temperature, turbidity and gauge height. These gauges have been monitored for only a few years, and therefore measurements of area and velocity must be conducted frequently to physically measure stream discharge and establish a reliable relationship between gauge height and discharge (Blanchet, 2009).

After three years of gauging, we have still not been able to create an accurate discharge rating curve at the Green Castle site because of extensive fine sediment deposition in the channel and rapid migration of riffle bars. As a consequence of not being able to relate gauge height, which is measured directly in the channel by the stream gauge, to discharge, we have not been able to assess the total runoff, or any other component of runoff. Not being able to accurately gauge this site has led us to question the effectiveness of storm water management practices from the emplacement of the Inter County Connector.

## 2.4 Location of Precipitation Gauges

As shown in Figure 6, two precipitation gauging stations were used in this study. The National Atmospheric Deposition Program (NADP), Beltsville, Maryland site is located at 39°1’40.7994 latitude and 76°49’1.5594 longitude. Data from the NADP gauging station was recorded as total daily precipitation and the precipitation’s electrical conductivity.

The USDA Beltsville Agricultural Research Center (BARC) located in Beltsville, Maryland is located at 39°1’52.993 latitude and 76°56’28.439

longitude. Precipitation totals are recorded at 15 minute intervals. Total precipitation data from the BARC station is used in this study because of its close proximity to the tributary (Cherry Hill and Paint Branch) stream gauging locations. Electrical conductivity data of precipitation was used from the NADP data sets as it was not available from the BARC gauging location.

Comparisons between NADP and BARC data reveal similar total precipitation for most storm events analyzed in this study. However, only BARC data was used with regard to total precipitation data due to its closer proximity to the study watersheds and the temporal resolution of the data available at BARC. .

# Chapter 3: Methods

## 3.1 Field Measurements

### 3.1.1 In Situ Field Probes

The three UMD gauging stations are outfitted with Hach Hydrolab MS5 in situ field probes which are able to track numerous water parameters (fig. 6). They are similar to the stream gauges used by the USGS at the NE, NW and Paint Branch watershed locations.

**Figure 6: Pictured is the Hach Hydrolab MS5 field probe used at the Green Castle, Cherry Hill and Downstream Cherry Hill site. The probe is secured inside a PVC pipe to protect the sensors during periods of high flow. The scale bar shows 1 ft.**

Data was downloaded from the sensor about every 10 days, which was based on battery life and required cleaning intervals. Data were downloaded onto a computer from the internal data logger. The sensors were then redeployed after specific conductivity, depth and turbidity calibrations were performed.

### 3.1.2 Discharge Rating Curves

The sensors monitor water depth with pressure transducers. This water depth is a gauge height that must be correlated to channel discharge at each gauge height. The relationship between gauge height and discharge must be established from field measurements of velocity and calculations of discharge. A stream discharge rating curve has been established for the Cherry Hill site (fig. 7). Rating curves are constructed by measurement of velocity within a cross section at various river stages (gauge heights). Once established, a well-defined rating curve can be used to determine the discharge of the stream from the gauge height data recorded by the sensors.

Discharge calculations require two main pieces of field data: cross sectional area and velocity measurements. The cross section of flow in the stream is measured by measuring local depth at 0.5 m intervals in a channel cross section (12-15 measurements are required as for most sites). Velocity in the channel increases logarithmically above the bed. Therefore average velocity is measured at each interval by measuring at 0.4 of the distance above the bed (Dunne and Leopold, 1987). A total of 12-15 velocity measurements are required to estimate channel discharge within 5% to 10% of the actual value (Dunne and Leopold, 1978). This type of analysis is consistent with the discharge calculations used by the USGS. Total discharge in the channel cross section is the sum of the local discharge (area*velocity) for each increment of channel width. For this project, an Ott meter is used to determine velocity, and velocity sampling intervals are 45-

60 seconds. The measured discharges are then compared with gauge height data measured from the in situ field probes, producing a discharge rating curve.

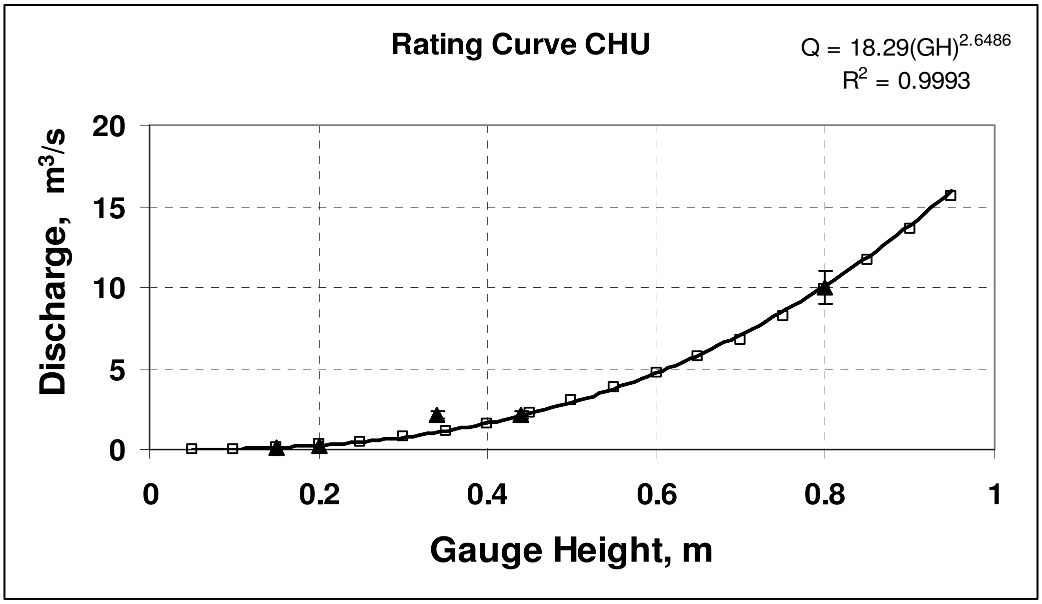


**Figure 7: Discharge rating curve (the empirical relationship between discharge in m$^3$/s and gauge height) for the Cherry Hill Gauge.**

A discharge rating curve was not established for the Green Castle gauge due to channel instability. Rapid sediment deposition and morphology changes site created an unstable cross sectional and thus a varying relationship between discharge and gauge height. The two gauges at the Cherry Hill location generated discharge values that were very similar to one another, therefore, only the Upstream Cherry Hill gauge is used in the hydrograph separation analyses.

### 3.1.3 Electrical Conductivity as a Tracer

Electrical conductivity is used as a tracer because it can be continuously monitored at each gauged location. For conductivity to be a useful tracer for hydrograph separation, stormflow discharge conductivity values must fall between stream baseflow (groundwater values) and precipitation values. An example of the change in stream conductivity over the course of a single storm event is shown in Figure 8.

It should be noted that electrical conductivity is being used in this study as a proxy for concentration. This relationship is valid if the relationship between electrical conductivity and concentration is linear, or in other words, the ionic composition of streamflow is not changing in terms of dominant ions present. Preliminary studies in the Anacostia and other neighboring watersheds conducted by O’Connell (1998) demonstrated that the dominant ions in solution are the same for precipitation and stream flow, indicating a linear relationship between concentration and electrical conductivity.

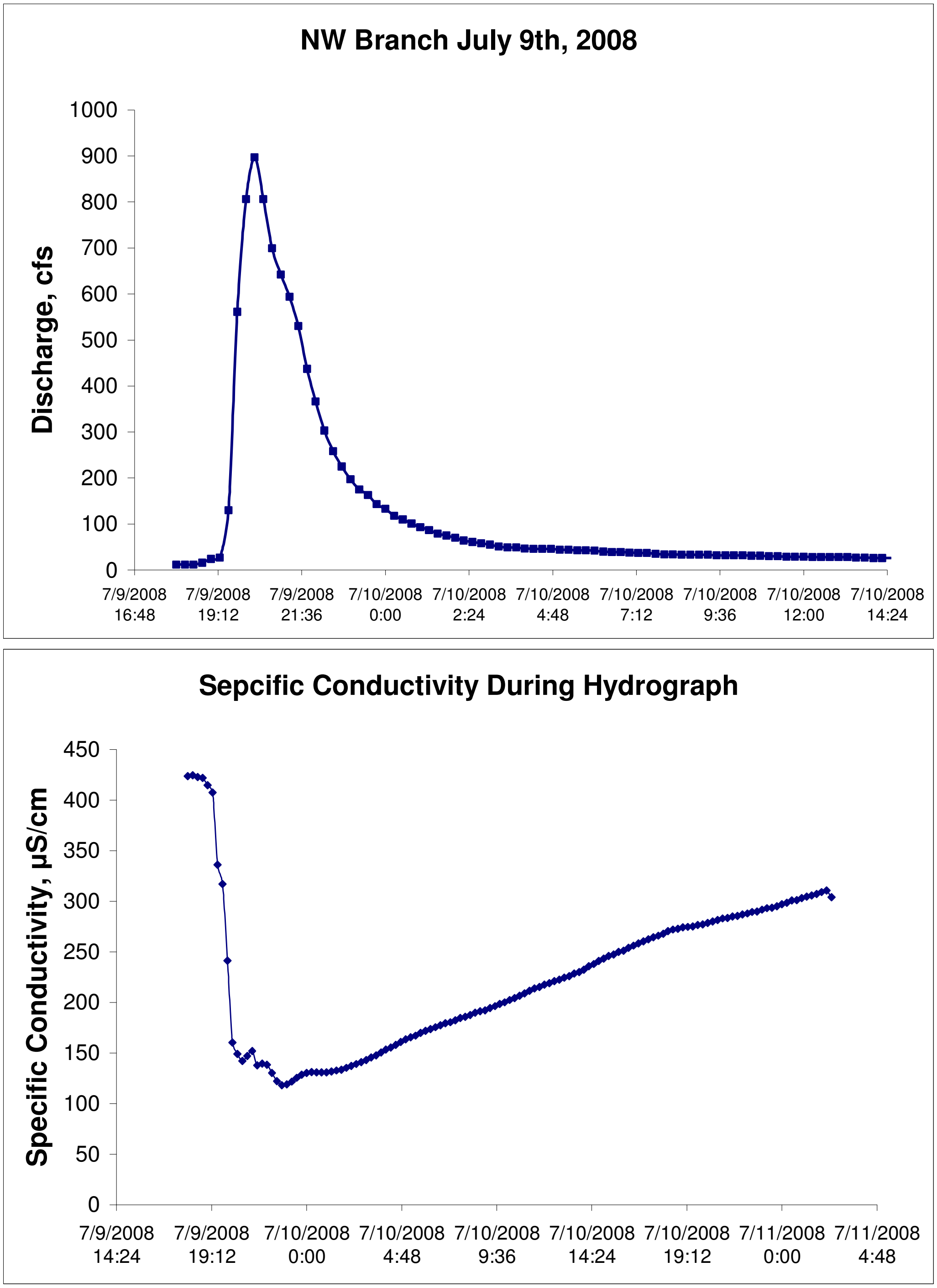


**Figure 8: Upper diagram: storm hydrograph discharge. Lower diagram: in stream conductivity over the course of the storm hydrograph. Data is from a July 9th, 2008 storm event at the NW Branch USGS gauge. Error in measurement conductivity is contained within the dot size.**

Conductivity values fall dramatically during the initial rise in the storm hydrograph and rise during the recession limb of the hydrograph. For this study, electrical conductivity values were obtained by direct field measurements and by continuous measurements with calibrated field probes. I also used data collected and compiled by NADP and USGS. Procedures for measurement and analysis of each type of data are reviewed below.

### 3.1.4 Comparison of Overland Flow Field Samples and Precipitation Conductivity

It is often assumed that the electrical conductivity of precipitation is similar to that of overland flow runoff (Gremillion, 2000). This assumption can be made because the precipitation does not have a long residence time and does not make much contact with mineral soils before entering the stream channel (Weiler et al., 1999).

Measurements were made to determine whether their conductivities were similar within the Anacostia Watershed. Overland flow and precipitation samples were collected and analyzed in order to test the hypothesis that overland flow and precipitation values were similar and thus represented the same end member in a two component mixing model of stream discharge sources. I collected samples of overland flow runoff and precipitation and measured their conductivity during two storm events at the Cherry Hill site. These measurements were made during the September 26th, 2008 and October 25th, 2008 storm events. Conductivity measurements of overland flow samples and precipitation samples were made with a Hach sensION156 Meter®. The meter has a sensor similar to that on Hach

MS5 and tests for conductivity by measurement of a current generated by the instrument sent across the instrument. Results from the September 26th storm event are presented in table II. The time column represents the amount of time since the onset of overland flow runoff from the storm sewer into the stream. Multiple conductivity measurements were taken of each sample five times in order to obtain standard deviation.

**Table II: Conductivity values of overland flow for September 26th, 2008.**

| Time (min) | Average conductivity of overland flow runoff in µS/cm | Standard deviation |
|---|---|---|
| 1 | 71.5 | 0.5 |
| 5 | 65.3 | 0.3 |
| 10 | 57.7 | 0.4 |
| 15 | 47.6 | 0.2 |
| 20 | 42.0 | 0.2 |

During the storm event, the electrical conductivity of the rainfall was also measured and yielded an average of 52.7 ± 0.3 µS/cm. The rainfall sample was tested a total of five times with the Hach SensION156 Meter®. The average overland flow runoff conductivity was 56.8 ± 12.2 µS/cm during the measurement period. This shows the similarity between the average overland flow conductivity value and the average rainfall conductivity value. Overland flow runoff was also sampled for the October 25th, 2008 storm event, just above a storm drain inlet that captures overland flow runoff. Each sample was tested a total of five times in order to obtain a standard deviation. These data also show similarities between overland flow runoff and precipitation conductivity values and are presented in table III.

**Table III: Conductivity values for 10/25/, 2008 overland flow samples**

| Time | Average conductivity of overland flow runoff in µS/cm | Standard deviation |
|---|---|---|
| 3:00 PM | 73.2 | 0.3 |
| 3:10 PM | 59.3 | 0.9 |
| 3:15 PM | 40.2 | 0.3 |
| 3:20 PM | 23.9 | 0.8 |

Rainfall samples for the October 25th storm were also collected and tested 5 times to find its conductivity value, with a standard deviation. The rainfall conductivity value was 41.6 ± 0.3 µS/cm. The average overland flow runoff conductivity was measured as 49.23 ± 21.5 µS/cm. This also shows a similarity between the average overland flow runoff conductivity value and rainfall conductivity. Because of this similarity and the fact that only one conductivity value can represent event water concentration, we have used rainfall conductivity data to represent event water conductivity to define our event, or new water end-member.

### 3.1.5 Measurement of Stream Specific Conductivity

The UMD MS5 gauges from Hydrolab® have sensors to monitor water parameters, such as temperature, gauge height, pH, dissolved oxygen, turbidity and specific conductance. The conductivity probes on the MS5 are similar to the Hach SensION156 Meter®. Stream gauge height and conductivity data are stored on a data logger within the gauge until the probes are taken from the field, cleaned and the data are retrieved and stored on multiple devices. The gauges are anchored into the streambed of the site locations. The anchor is composed of

PVC pipe filled with cement. Once the anchors were in place, the probes are placed in perforated PVC pipe to keep the probes from being damaged during high flow. The encased gauges were then secured to the anchor by thick metal wires. For all sites, the anchor was put directly in the channel adjacent to a stream bank.

The three other gauge sites used for this study are operated and maintained by the USGS and the data were downloaded from the USGS website or obtained from USGS personnel. Therefore, the gauge height and conductivity data for all six gauged locations are all measured in situ. This automated collection of data provides for continuous data on conductivity (specific or electrical) and discharge for each site.

### 3.2 Electrical Conductivity Determination of End-Member Samples

Hydrograph separation procedures are effective if the two sources contributing discharge have significantly different values of conductivity (Gremillion, 2000). Furthermore, I considered overland flow to be an end-member similar to precipitation for the purpose of hydrograph separation. Therefore, the baseflow, precipitation, and overland flow samples were characterized to test these assumptions.

#### 3.2.1 Baseflow (Groundwater) End-Member Characterization:

Following previous research (e.g. Pellerin, et al., 2008, Gremillion et al., 2000), the electrical conductivity of groundwater discharge, or pre-event water, is assumed to be the baseflow electrical conductivity prior to the elevated limb of the hydrograph caused by the storm event. Baseflow electrical conductivity and specific conductivity is measured in the channel prior to the storm events by the six gauges at their locations. The conductivity of the groundwater portion of discharge is represented by an average of baseflow conductivities over a twenty-four hour period prior to the storm event.

### 3.2.2 Precipitation (Surface Flow) End-Member Conductivity:

The precipitation conductivity data used for this project were measured and recorded at the NADP site in Beltsville, Maryland. The data are available online, and Dr. Jeff Stehr in the University of Maryland's department of Atmospheric and Oceanic Science has been helpful in obtaining values that are not yet posted on the website. The Beltsville site is located within the NE Branch of the Anacostia River, thus we will assume that the rainfall electrical conductivity is similar to the electrical conductivity of the rainfall on the NE branch watershed overall.

### 3.3 Hydrograph Separation Procedures:

For the purposes of this study, a storm hydrograph is defined as an increase in stream discharge due to a storm event. Storm hydrographs are characterized as having the same beginning and ending discharge. In other words, the time scale of the storm hydrograph is determined by directly by discharge, meaning that the end of the storm hydrograph is determined from the starting discharge. This type of storm hydrograph characterization is known as the "straight line" analysis.

End-member compositions of event water (overland flow) and pre-event water (baseflow) were identified. Therefore, hydrograph separation techniques for storm events could be conducted. Stormflow hydrographs are obtained from USGS 15-minute streamflow and UMD gauged site data. These hydrographs are then separated into overland flow and groundwater flow components using the stream conductivity samples and compositions of end member sources. To perform the hydrograph separations at each site, I have used the two endmember mass balance equations from Ladouche et al., 2001.

$$Q_t = Q_a + Q_b$$

$$Q_tC_t = Q_aC_a + Q_bC_b$$

The subscript a is considered the event water component and the subscript b is considered the pre-event water component. Event water can be considered "new water" because it is precipitation and overland flow runoff that composed of storm event precipitation that has not penetrated the ground or had any type of interaction with the groundwater table. Pre-event water can be considered "old water" because it is water that has been stored in the system prior to the storm event and had some sort of residence time in the sub-surface before being deposited to the stream.

The electrical conductivity values for each discharge source in the hydrograph separation equations are assumed to be homogeneous and to represent average concentrations of each discharge source. Therefore, the electrical conductivity of the event and pre-event waters are considered to be constant over the time of the hydrograph (Ladouche et al., 2001 and Gremillion et al., 2000).

### 3.4 Analysis of Error in Hydrograph Separation Analyses

Error in two-component mixing models comes from three sources: the variability of the two end-members (taken in this study to be the standard deviations of the two end members) and the analytical uncertainty in the measurement of stream values. These sources of error are incorporated into an error equation (Genereux, 1998).

$$W_{f_1} = \left\{ \left[ \frac{C_2 - C_S}{(C_2 - C_1)^2} W_{C_1} \right]^2 + \left[ \frac{C_S - C_1}{(C_2 - C_1)^2} W_{C_2} \right]^2 + \left[ \frac{-1}{(C_2 - C_1)} W_{C_S} \right]^2 \right\}^{1/2}$$

Where $W_{f1}$ is the error fraction for each measurement involved in the separation, $C_s$, $C_1$, $C_2$ are the conductivity of the stream, event water and pre-event water respectively, and $W_{C1}$, $W_{C2}$, and $W_{Cs}$ are the uncertainties of the event water, pre-event water and stream conductivities respectively. In most cases, the error in the measurement of stream values is much smaller than the variability in the end member compositions. In this case, the standard upper and lower standard deviations of each end member can be used to calculate an error envelope. The error envelope technique generates similar values of error as the Genereux error equation (Occhi, 2009).

### 3.5 Analysis of Error in Precipitation Measurements

For this study we are using precipitation data from a single USDA precipitation gauge located within a mile of the two tributary sites within the upper Anacostia watershed. Using a relationship between uncertainties in point precipitation and watershed area in square miles from Herschfield, (1961) will provide estimates of spatial variation of precipitation occurring at each gauged location. These estimates of precipitation uncertainty have been calibrated specifically for the Washington D. C. area and are thought to represent the Anacostia Watershed.

### 3.6 Limitations of Hydrograph Separation Procedures

As discussed in Chapter 1, there are assumptions that must accompany the hydrograph separation procedures. Discussing the assumptions and how they relate to the design of this study can help us critically evaluate the validity of our results from this analysis.

Part of the hydrograph separation analysis is choosing a tracer that will yield a significantly different value for each reservoir. Earlier in the chapter we have demonstrated that the surface and subsurface flow proxies are significantly different from one another (further discussed in Chapter 4). Also, since the analyses are being carried out in an urban watershed with up to 26% impervious surfaces, we can assume that a significant portion of the total runoff is derived from both reservoirs.

Using hydrograph separation techniques, we are assuming that the tracer concentrations chosen to represent surface and subsurface flow endmembers are homogeneous throughout the storm hydrograph. This assumption is most likely true within one standard deviation for surface flow, as there is no interaction that would likely modify the specific conductivity of surface flow to a great extent. Due to complex flow paths and behaviors this assumption is much more difficult to assess for subsurface flow. The assumption of homogeneity of subsurface flow will be addressed in Chapter 5.

The tracer concentrations chosen to represent each endmember must also be an average concentration value for each reservoir. This assumption is included most likely to address some natural variability within the endmember tracer concentration population. For both endmember populations, the tracer concentration chosen to represent each population is averaged over a time span; for the surface endmember the tracer is averaged over four years worth of precipitation data and the subsurface endmember is averaged over a 24 hour period of baseflow prior to the storm event.

The two component mixing model chosen for this study limits the study to separating total storm discharge into only two reservoirs, surface and subsurface flow. There are three component mixing models allowing one to isolate a third reservoir, however, a third reservoir which is significantly different in terms of conductivity is not thought to be present within this urban watershed. Also, to use the three component mixing model you must identify a second tracer that must also be homogeneous thought the storm hydrograph and fully represent each reservoir.

# Chapter 4: Hydrograph Separation Analyses

## 4.1 Introduction

The effects of urbanization on storm discharge are poorly understood for large (>10 km$^2$) watersheds (Gremillion et al., 2000). Urbanization increases impervious cover and localizes soil compaction, which leads to increased infiltration-excess overland flow within a catchment (Dunne and Leopold, 1978; Lee and Heaney, 2003; Brutsaert, 2005). Studies of the effects of scale on hydrological response suggest that runoff mechanisms control the hydrograph response of small (<10 km$^2$) watersheds, but flow in stream channel-floodplain systems determines the hydrograph characteristics in larger (>10 km$^2$) watersheds (e.g. Wood et al., 1990). Urbanization typically increases overland flow runoff in small catchments, but changes in drainage density, the organization of permeable and impermeable surfaces, and other changes in urban watersheds may also affect runoff behavior at larger watershed scales (Brutsaert, 2005).

Runoff processes (the surface and subsurface paths that water travels from precipitation to stream channels) affect the timing, amount, and chemical composition of streamflow (Horton, 1945; Dunne, 1978; Gremillion, et al., 1999; Bedan and Clausen, 2009). Understanding these flow pathways in large watershed is a first step in an understanding of the processes that influence changes in stream chemistry, sediment loads and contaminant fluxes as a response to urbanization (Blanchet, 2009; Gremillion et al., 2000).

Many of the pathways that water takes to streams are slow and are not likely to generate rapid responses in streamflow hydrographs. There are three main mechanisms that can generate rapid response in stream hydrographs. Rapid, macropore infiltration of rainwater to the capillary fringe can cause a rapid rise in the position of the water table. These changes in pressure head and total head can result in increase in groundwater discharge to streams (Beven and Germann, 1982; Abdul and Gillman, 1984; McDonnell, 1990). This primarily piezometric response is rapid and it pushes "old" groundwater to stream channels during storm events. Infiltrating water can create transient saturated conditions in the unsaturated zone, which can activate networks of macropores and "pipes" in the shallow subsurface which deliver water to stream channels (McDonnell et al., 1991; O'Connell, 1998). This process is slower, because it involves the transmission of water, not just pressure differences. Composition of shallow subsurface flow is variable and includes both "new" and "old" water sources.

Both the capillary fringe response and shallow subsurface stormflow can generate saturated areas in low-lying or convergent areas (Dunne and Black, 1970; Dunne, 1978). Saturated soil causes runoff due to a) direct precipitation onto saturated surfaces (new water) and b) exfiltrating shallow subsurface water. This return flow can contain variable mixtures of new and old water.

Precipitation in excess of infiltration rates can generate infiltration-excess overland flow, which can flow rapidly over land surfaces, delivering new water to stream channels. This process is common in urban areas due to impervious surfaces, compacted soils, and connections of impervious surfaces to storm sewers and directly to stream channels. Although physical studies of runoff processes have been studied in a variety of settings, geochemical methods provide an approach that is more suitable to large watersheds.

A variety of geochemical tracers have been used to separate storm water hydrographs into new water, and old water as an approach to identify runoff processes in watersheds at a variety of scales. New water is identified with a precipitation end-member composition and it is delivered to stream by overland flow and it is a component of shallow subsurface flow paths. Old water is identified through stream baseflow measurements prior to storm events and thus represents water stored in subsurface reservoirs (Sklash, 1990; Bohte et al., 2010; Ladouche et al., 2001). Other tracers, such as electrical conductivity, have been used to identify new and old water in both urban and non-urban watersheds (Pellerin et al., 2005, Matsubayashi et al., 1993; Velasquez et al., 1992). Most of these studies have also been on small catchments (<10 km$^2$) (e.g. Blume et al., 2010; Mastubayashi et al., 1993; Pellerin, 2005; Rice and Hornberger, 1998; Weiler et al., 1999).

Detailed studies of urban runoff production often find simple relationships between overland flow runoff volumes and impervious surface area (Carlson, 2004). Therefore, urban storm runoff is often estimated from empirical models that use basin area, rainfall intensity, and runoff coefficients (C) based on land use (e.g. Guo, 1999; Molgen and Beighley, 2002). These equations have the following form:

$$Q_d=\alpha C I_d A$$

where $Q_d$ is the peak runoff discharge, $\alpha$ is a unit conversion factor, C is a runoff coefficient, $I_d$ is the rainfall intensity in inches per hour, and A is the watershed area in acres (Guo, 1999). These equations were developed for small plots, but they are often used for larger watersheds. The runoff coefficient, C is often estimated from the amount of impervious cover (Schuler, 1994) and its connectivity (USDA, 1986). The rainfall intensity, $I_d$ of a storm usually decreases with storm duration. Therefore, if overland flow is the dominant mechanism, runoff response is likely highest with short duration, high intensity storms. The duration of the storms must be longer than the basin time of concentration. Overland flow response may be affected by other meteorological parameters such as antecedent moisture conditions, seasonality, and spatial distribution of rainfall (Molgen and Beighley, 2002).

The patchiness of urban development in large watersheds affects the connectivity of impervious surfaces to one another, to storm drains, and to stream channels (Lee and Heaney, 2003; Walsh et al., 2005). Recent research has highlighted the importance of impervious surface connectivity on the quantity of overland flow runoff (Lee and Heaney, 2003, Roy and Schuster, 2009, Konrad and Booth, 2005). In complex urban watersheds, such as the Anacostia Watershed, urban runoff can be routed directly to streams, to stormwater retention ponds, to ephemeral channels or intact riparian areas. These flow paths may influence the runoff response of watersheds.

## 4.2 Objectives and Hypotheses

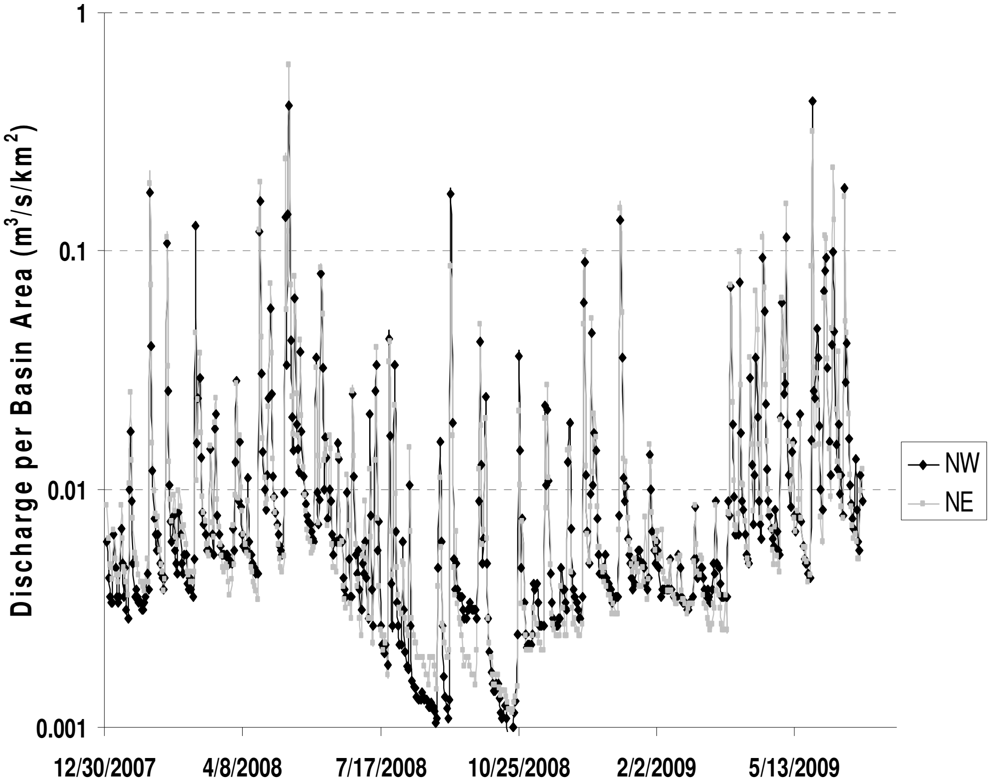
The purpose of this chapter is to use hydrograph separation procedures to quantify sources of storm water runoff in the urbanized Piedmont and Coastal Plain branches of the Anacostia watershed and two upstream tributaries (one Piedmont, and one Coastal Plain). Hydrograph separation results from a large, urban watershed will allow us to see how storm flow paths vary with spatial scale in large urban watersheds, while also assessing the role that impervious surfaces and other watershed characteristics play in surface flow runoff generation as experienced in the channel.

The following hypotheses will be tested in this chapter:

1. The percentage of “new” water in stream hydrographs is directly proportional to the percentage of impervious surface in large (>10 $km^2$) urban watersheds.
2. Due to less permeable bedrock, thin soils, and narrow floodplains, Piedmont watersheds will contribute proportionally larger amounts of overland flow runoff to streamflow than Coastal Plain watersheds.

## 4.3 Storm Selection for Hydrograph Separation Analyses

In this study, specific conductivity was chosen as a tracer to separate storm hydrographs into “new” water and “old” water components. All hydrograph separation procedures can be used only for events in which the end-members characteristics show small ranges compared to the differences between the compositions of the end members (Genereux, 1998). Electrical conductivity in an urban watershed can be affected by the use of road salts during winter months. During snowmelt, overland flow runoff may have higher conductivity than stream baseflow and thus it would not provide an end-member that is similar to precipitation. Therefore, time series of average daily discharge and average conductivity measured at the downstream gauge for the two branches (NW- Piedmont and NE - Coastal Plain) of the Anacostia River are shown in figure 9A. Peaks in the discharge time series represent storm events; data points between peaks represent periods of baseflow. For both the NE and NW branches, baseflow discharge is lower in the summer months due to evapotranspiration. Baseflow minima occur in late summer to early fall. Significant groundwater recharge occurs in the winter, leading to baseflow maxima in late winter and early spring (fig. 9A).


A
Discharge per Basin Area ($m^3/s/km^2$)
1
0.1
0.01
0.001
12/30/2007
4/8/2008
7/17/2008
10/25/2008
2/2/2009
5/13/2009
NW
NE

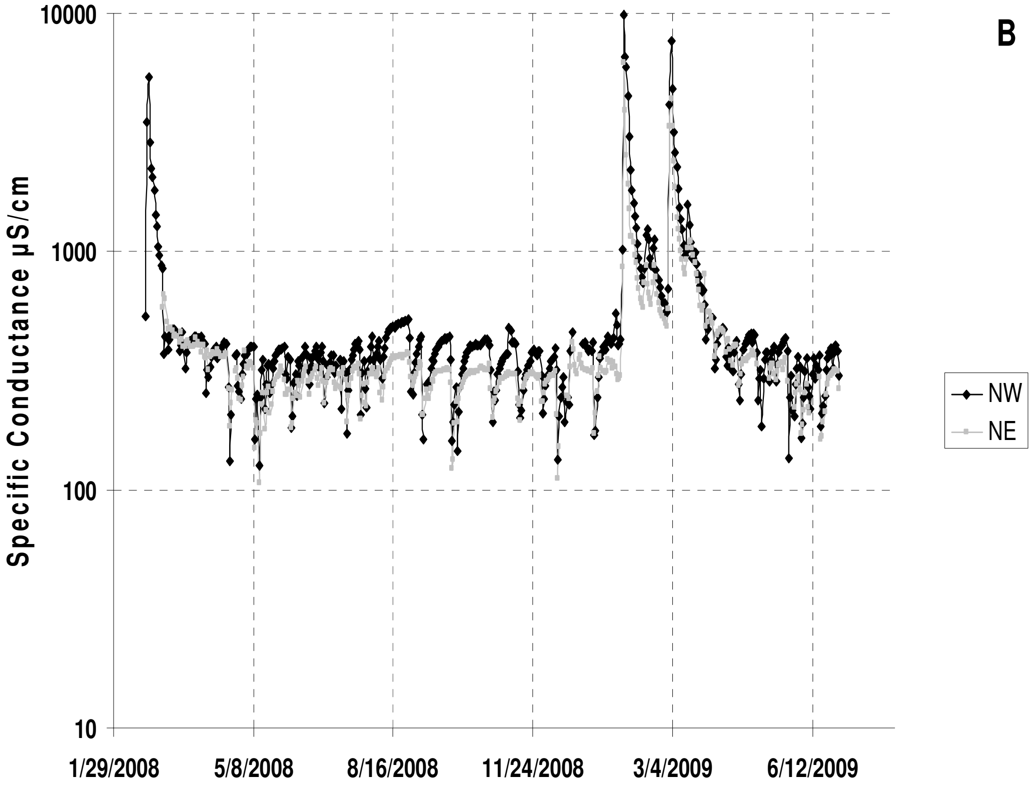

B
Specific Conductance µS/cm
10000
1000
100
10
1/29/2008
5/8/2008
8/16/2008
11/24/2008
3/4/2009
6/12/2009
NW
NE

**Figure 9: Time series diagrams of: (A) discharge per basin area, (B) specific conductivity for the two downstream gauges on NE and NW Branch of the Anacostia (USGS Data). The large peaks in conductivity in January, 2008 and January – March 2009 are conductivity spikes due to the application of road salts. Note return of conductivity to baseflow conditions May to December.**

The seasonal pattern of electrical conductivity is generally the inverse of the discharge pattern with several distinct spikes in conductivity in the winter and early spring due to roadway salt (fig. 9B). In this region of Maryland, winters are generally mild and roads are salted for relatively brief winter periods. A road salt peak is observed in February, 2008 at the NW branch gauge, along with two peaks observed in 2009. Road salt conductivity spikes show recession curves that take about 3 -5 weeks to return to normal conditions. Therefore, storm hydrographs were selected for time intervals when the conductivity data were not affected by salt runoff. Selected stormflow hydrographs were in the late spring to early winter months of each year of the study.

Low levels of baseflow discharge in the late summer and fall months correspond to high values of baseflow conductivity (figs. 9A and 9B). These high conductivity values generate larger differences between precipitation and baseflow values, thus generating smaller uncertainties in the hydrograph separations (Genereux, 1998). Therefore, summer and autumn storms are more favorable time periods for the use of conductivity for hydrograph separation.

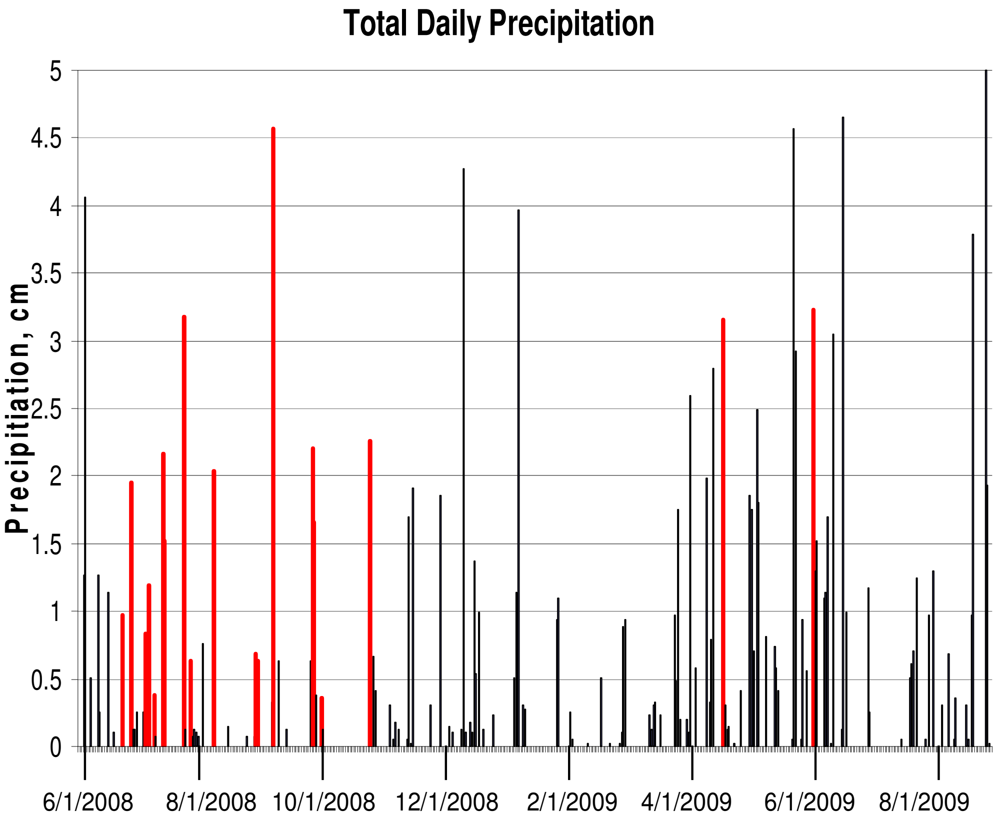


**Figure 10: Total daily precipitation data for Beltsville, MD (George Meyers, USDA, pers. Com). Precipitation data highlighted in red are the storm events used in this study. These events encompass the range of precipitation values but do not include data from the winter and early spring months.**

One of the objectives of this study is to evaluate the effects of storm characteristics on runoff behavior in large watersheds. Therefore, the 15 storm events chosen for analysis exhibit a range in storm durations, magnitudes and intensities (Table IV). The storms chosen for hydrograph separation analysis are indicated in figure 10 and their storm characteristics are summarized in Table IV.

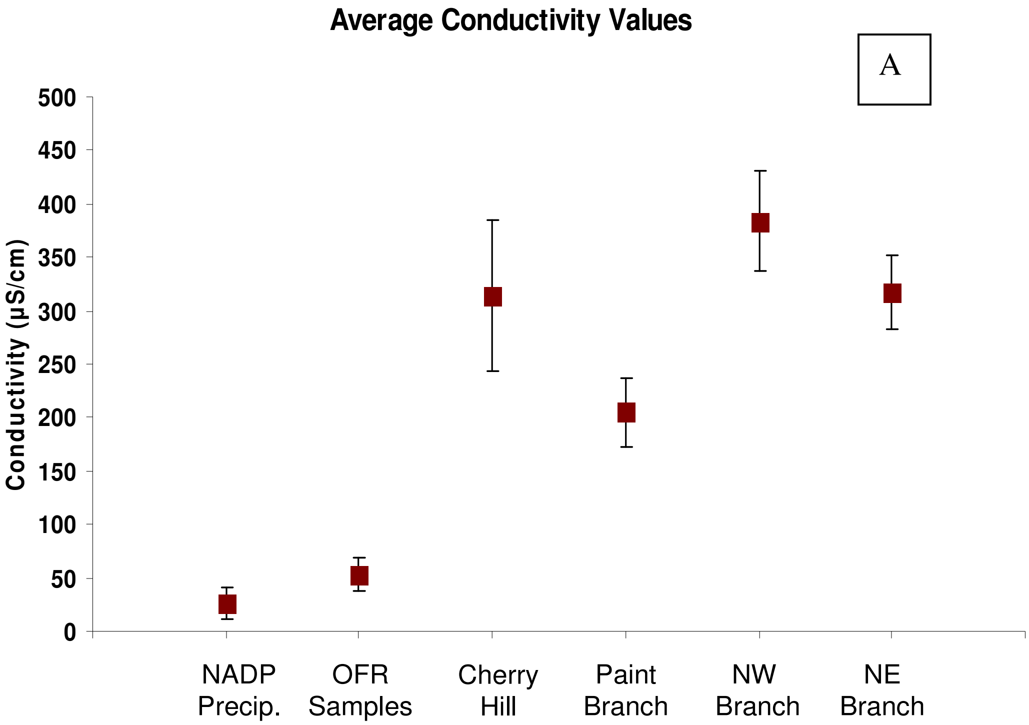
**Table IV: Storm characteristics for storm events chosen in this study.**

| Date of storm | Total Precipitation, cm | Total Duration, hours | Max Intensity (mm/hr) | Average Intensity (mm/hr) |
|---|---|---|---|---|
| 6/23/2008 | 0.69 | 5.25 | 15.2 | 5.5 |
| 6/27/2008 | 2.11 | 1.5 | 40.6 | 16.9 |
| 7/4/2008 | 0.99 | 4.5 | 10.2 | 3.8 |
| 7/9/2008 | 0.61 | 1.75 | 18.3 | 4.1 |
| 7/13/2008 | 2.51 | 11.75 | 16.3 | 3.2 |
| 7/23/2008 | 3.20 | 10.25 | 22.4 | 3.6 |
| 7/27/2008 | 2.03 | 1.25 | 37.6 | 21.7 |
| 8/7/2008 | 0.33 | 3.75 | 6.1 | 4.4 |
| 8/29/2008 | 1.73 | 14.25 | 6.1 | 2.0 |
| 9/6/2008 | 4.90 | 8 | 31.5 | 2.9 |
| 9/26/2008 | 3.86 | 4.5 | 14.2 | 2.9 |
| 10/1/2008 | 0.38 | 2.25 | 5.1 | 2.6 |
| 10/25/2008 | 2.21 | 16.75 | 29.5 | 4.0 |
| 4/20/2009 | 3.66 | 9 | 8.1 | 3.5 |
| 6/5/2009 | 1.57 | 21 | 2.9 | 1.3 |

It is apparent in table IV that there is a large variety in storm intensity, duration and magnitude. Choosing to analyze all storm events above will serve to assess the response of the watershed under varying storm characteristics.

### 4.4 Conductivity of End-Member Samples

Given the above sampling constraints, the conductivity of all of the end-member samples can be defined. The average conductivity of baseflow for the 24-hr period prior to the selected storm events were used to define old water end members for each of the gauge sites (NE Branch, NW Branch, Paint Branch and Cherry Hill; Fig. 11 A). The average conductivity of overland flow samples measured in the field and NADP measurements of precipitation conductivity (averaged over a four-year period) define the precipitation and overland flow end-members (Fig. 11 A). Baseflow conductivity at all of the gauge sites is significantly higher than the conductivity of precipitation and overland flow samples. Precipitation and overland flow runoff averages are similar; values fall within one standard deviation of the means.



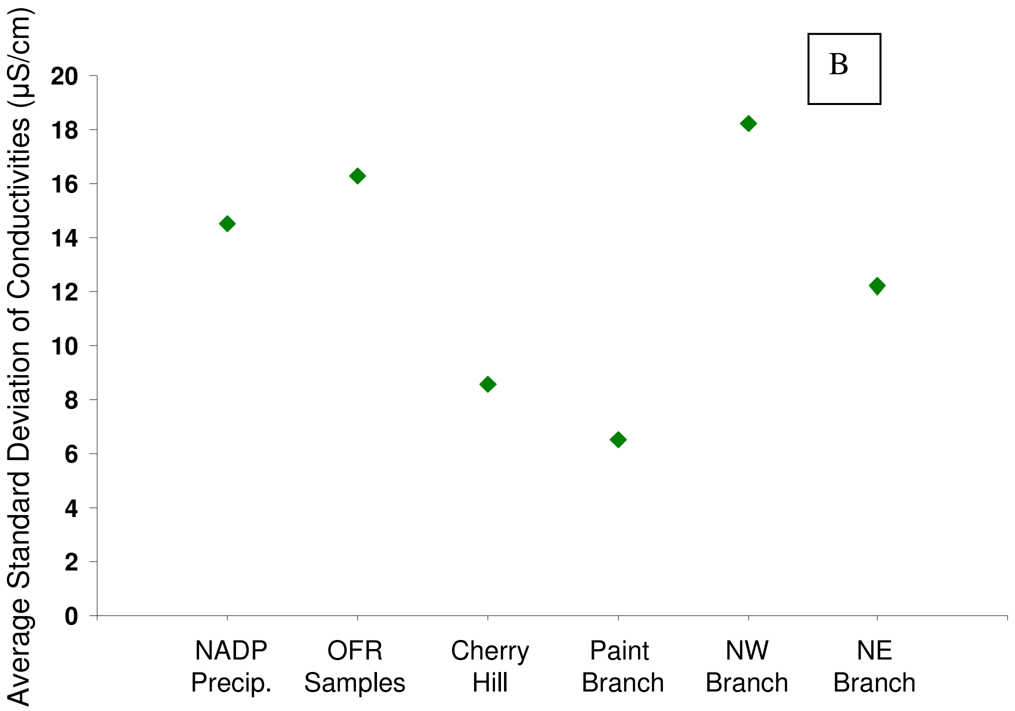


**Figure 11: (A) this shows the average baseflow conductivities prior to all analyzed storm events for the four gauged locations. The error bars show one standard deviation from the mean. The precipitation end-member is obtained from four years of precipitation conductivity data from the NADP. The conductivity of overland flow samples is also shown. (B) This shows the average standard deviation of all endmember conductivities for all four gauging locations along with NADP precipitation data and Overland flow runoff samples.**

The two Coastal Plain (Cherry Hill and NE Branch) sites have similar baseflow conductivities prior to selected storm events. The two Piedmont sites (Paint Branch and NW Branch) have significantly different baseflow conductivities of the storms chosen to be analyzed.

Its important to note that Figure 11 A is showing the average baseflow conductivity for the storm events chosen to analyze, and the error bars represent the variance among the baseflow measurements for a given number of storm events. Figure 11B is included to show that the average standard deviation of baseflow measurements prior to analyzed storm events is much less than the variations in baseflow conductivity occurring on a storm by storm basis. Therefore, the standard deviations of storm specific baseflow measurements from each site are used to determine uncertainty with Generaux's (1998) error equation discussed in Chapter 3.

Precipitation conductivity values do not vary much seasonally. Therefore, four years worth of conductivity data were used to compute the average and standard deviation for the precipitation end member. The averages in the baseflow conductivities are not representative of average annual baseflow conductivity because the measurements presented in figure 11 are limited to the storm events analyzed. With the conductivities of the endmembers identified for each storm event at each watershed location, we were able to successfully separate all storm hydrographs selected for each watershed location in this study.

### 4.5 Hydrograph Separation Results: Percent of New Water in Runoff

Hydrograph separation analyses were performed on fifteen selected storm runoff hydrographs using the procedures outlined in Chapter 3. The storm hydrographs analyzed covered a wide range of storm event behavior including varying intensity, duration and magnitude. It is clear from this analysis that variations in storm characteristics have a dramatic impact on the spatial response within each watershed. Spatial variations in hydrological response and watershed scale to the same storm event were observed between the Piedmont and Coastal Plain watersheds.

Stream hydrographs separated into total, old, and new water discharge for the 6/27/2008 storm event at all 4 gauges are shown in figure 12. Total precipitation for this high intensity, short duration storm event was 2.1 cm. Storm duration was 1.5 hours, maximum storm intensity was 41 mm/hr and average intensity was 17 mm/hr.

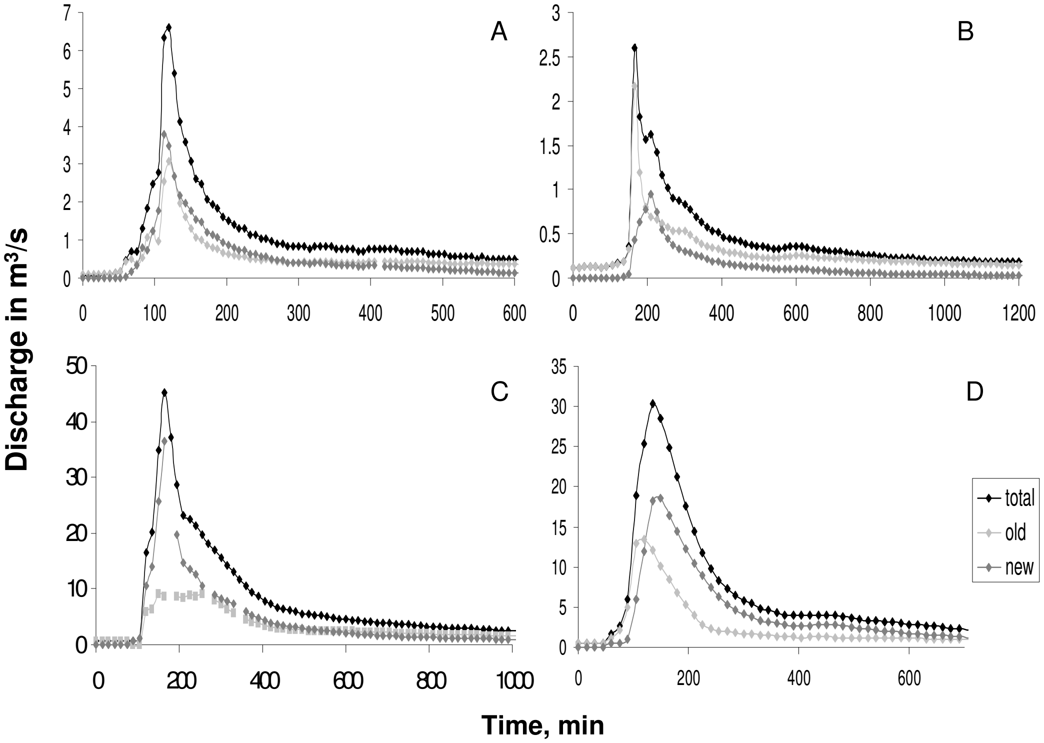


**Figure 12: Separated hydrographs for the 6-27-2008 storm event for all four gauged sites: the (A) Cherry Hill, (B) Paint Branch, (C) NE Branch, and (D) NW Branch. The x-axis is time in minutes since the onset of precipitation. The recession limbs of the hydrographs have been truncated to preserve detail near the main peak.**

This storm generated significantly different runoff responses at the 4 gauges. New water contributions to stream flow ranged from 26% to 56%. At both Coastal Plain locations (fig. 12 A &C), the new water discharge peak occurs earlier and at a higher value than the peak in old (subsurface) water. The Piedmont watersheds (figs. 12B and 12D) demonstrate significantly different runoff behavior than their Coastal Plain counterparts. In the Piedmont tributary (fig. 12 B), the old water discharge peak has a greater magnitude than the new water peak and it and occurs earlier. At the NW Branch site, the old water peak also occurs prior to the new water peak, but is of lower magnitude than the new water peak.

Hydrograph separation results for a long duration, low intensity storm event that occurred on 9/6/2008 are shown in figure 13. Total storm precipitation was 4.9 cm. The storm was 8 hours in duration and it had a maximum intensity of 32 mm/hr and an average intensity of 3 mm/hr.

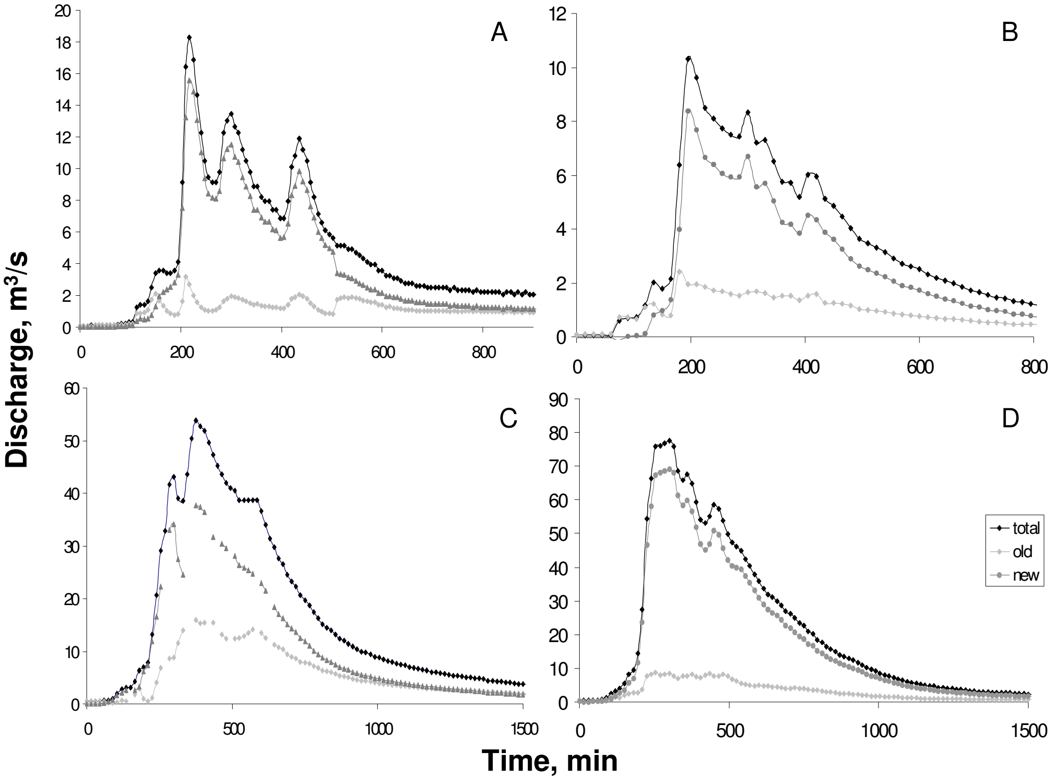


**Figure 13: Separated hydrographs for the 9-6-2008 storm event for all four gauged sites: the (A) Cherry Hill, (B) Paint Branch, (C) NE Branch, and (D) NW Branch. x-axis is time in minutes since the onset of precipitation. The recession limbs of the hydrographs have been truncated to preserve detail around the main peak.**

This long duration, low intensity storm event shown in figure 13 generated significantly different behavior from the previously discussed event at all watershed locations. The new water contributions to stream discharge are significantly higher than the old water contributions at all watershed locations (62-83%; Table V). The peak of new water discharge occurs prior to the old water discharge peak for all sites except for the Coastal Plain tributary site, which shows a small old water peak prior to any peaks in new water discharge. In general, overall runoff response to this larger duration storm event is more homogeneous than the hydrograph responses to the shorter duration storm (fig. 12).

The results of all of the hydrograph separation analyses are displayed in Table V, which summarizes the percent of new water in each hydrograph along with the associated error for each analysis (Genereux, 1998). The data are listed by gauge site, with the drainage area and location within physiographic province has been provided. The average and standard deviations of new water flow percentages at each gauge location are provided at the bottom of Table V.

**Table V: The percentage of new water in streamflow hydrographs. (CH: Cherry Hill, PB: Paint Branch, NW: North West Branch, NE: North East Branch).**

| **Date of Storm** | **CH** | **CP** | **NE** | **CP** | **PB** | **Pied** | **NW** | **Pied** |
|---|---|---|---|---|---|---|---|---|
| | **(26.7 km$^2$)** | CH error % | **(188.6 km$^2$)** | PB error % | **(33.9 km$^2$)** | NW error, % | **(127.9 km$^2$)** | NE error % |
| **6/23/2008** | **-** | **-** | **40.5** | 10.8 | **-** | - | **38.3** | 3.6 |
| **6/27/2008** | **29.7** | 3.5 | **39.8** | 4.0 | **21.1** | 4.0 | **54.5** | 3.7 |
| **7/4/2008** | **-** | | **27.2** | 6.1 | **23.7** | 4.3 | **25.7** | 2.8 |
| **7/9/2008** | **-** | | **48.3** | 3.4 | **4.9** | 2.6 | **58.9** | 3.1 |
| **7/13/2008** | **30.4** | 3.4 | **48.2** | 4.1 | **34.2** | 4.0 | **63.1** | 4.2 |
| **7/23/2008** | **73.6** | 3.8 | **61.8** | 3.3 | **-** | - | **75.2** | 3.2 |
| **7/27/2008** | **-** | - | **43.2** | 3.6 | **28.2** | 3.2 | **65.9** | 3.7 |
| **8/7/2008** | **-** | - | **50.0** | 3.5 | **-** | - | **51.0** | 2.9 |
| **8/29/2008** | **-** | - | **17.9** | 6.5 | **41.4** | 8.4 | **46.5** | 12.8 |
| **9/6/2008** | **63.0** | 3.2 | **62.1** | 5.8 | **67.4** | 6.0 | **83.2** | 3.3 |
| **9/26/2008** | **-** | - | **52.7** | 7.8 | **43.6** | 10.4 | **56.4** | 9.0 |
| **10/1/2008** | **49.2** | 3.7 | **-** | - | **-** | - | **-** | - |
| **10/25/2008** | **-** | - | **40.2** | 3.5 | **44.5** | 7.0 | **60.0** | 7.7 |
| **4/20/2009** | **50.2** | 4.9 | **-** | - | **-** | - | **-** | - |
| **6/5/2009** | **24.4** | 10.8 | **-** | - | **-** | - | **-** | **-** |
| **Average** | **45.6** | **8.6** | **44.3** | **5.2** | **34.3** | **5.5** | **56.3** | **5.0** |
| **Std. dev.** | **18.4** | **2.7** | **12.7** | **2.2** | **17.8** | **2.6** | **16.2** | **3.1** |

New water runoff is a significant portion of the total runoff at each site. Average new water contributions for all sites range from 34 to 63%, with individual storm new water contributions ranging from 4.9 to 83.2 %. At each watershed location there is a considerable variability in the percentage of new water; standard deviations ranged from 12.7 to 18.4%. These variations in new water contributions to various storm hydrographs are much greater than the error in the hydrograph separation analysis for individual storm events (Table V). The NW Branch site experiences the highest average new water component out of all four watershed locations. The Paint Branch site experiences the lowest average new water component. This suggests heterogeneity of responses for both Piedmont watershed locations. The Coastal Plain watersheds exhibit similar new water percentages for the upstream (Cherry Hill) and the downstream (NE branch) locations.

The percentage of overland flow in runoff is highly variable for different storm events and the standard deviation of new water averages are similar for all four sites. This suggests that variations in storm characteristics, e.g. total rainfall, duration, intensity, and antecedent moisture conditions may be responsible for these differences in runoff behavior. The relationship of rainfall to runoff components is investigated in the next section.

## 4.6 Error Calculations for Hydrograph Separation Analyses

The error for each hydrograph separation analysis (Table V) was determined from methods summarized in Chapter 3. Error in two-component mixing models comes from three sources: the error in of the each of the two end-members, and the analytical uncertainty in the measurement of stream values. If the analytical uncertainty in stream measurements is so low then the error, which is primarily the natural variability in the end member compositions dominates the error equation (Genereux, 1998). The standard deviations for each end member were used to define end-member error. This error can also be shown graphically by using the standard deviations to define an error envelope (fig. 14).

These error envelopes were calculated for each storm event analyzed by calculating three hydrograph separations for each analysis one using the average concentrations of each end-member and two more using the standard deviations above and below the mean for each end-member. The error envelope technique was compared with the error equation results calculated using Genereux's (1998) equation. The two methods of error calculation generated identical results for each of the 39 hydrograph separation analyses, due to the small amount of analytical uncertainty in the operation of the field sensors.

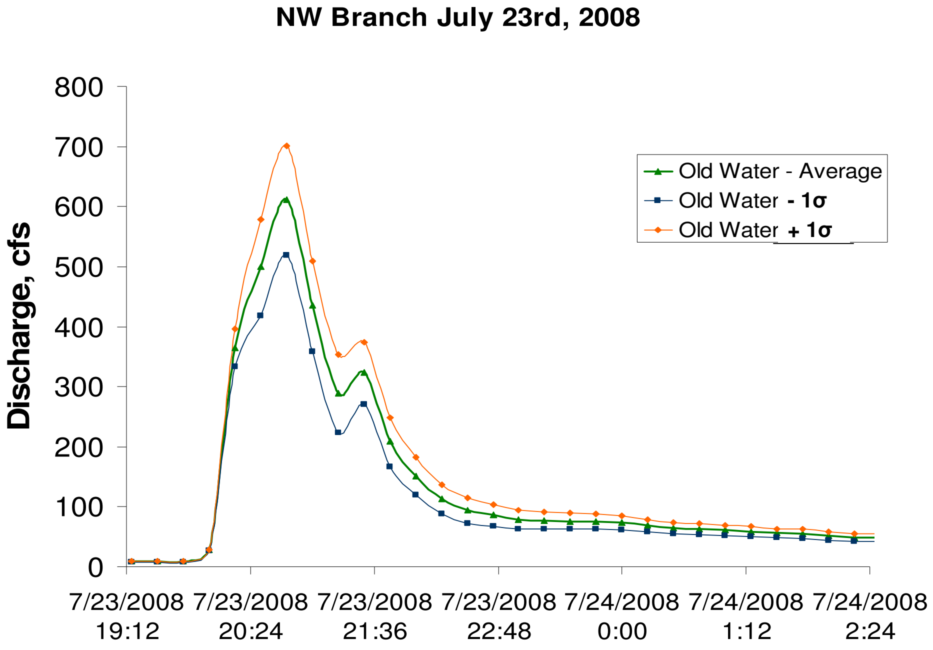


**Figure 14: This figure shows the error envelope using standard deviations from the average endmember concentrations.**

## 4.7 Rainfall Runoff Relationships

### 4.7.1 Total Rainfall Runoff Relationships

Rainfall-runoff relationships are used to determine the runoff response from watersheds and its relationship to rainfall. In order to isolate the total storm runoff, baseflow discharge was removed from each storm hydrograph analyzed in this study. Baseflow discharge is storm and site specific, and the average baseflow for the 24-hour period prior to the storm event was used for baseflow separation. After baseflow discharge was removed from each hydrograph, storm discharge was integrated over time to determine storm runoff volume. Total runoff volume is divided by contributing drainage area to determine runoff in cm that can be compared with rainfall, in cm for each watershed.

Total storm precipitation was obtained from the USDA Beltsville, MD site, located near the center of the watershed and close to both the upper Piedmont and Upper Coastal Plain tributaries. Precipitation data are collected in a tipping bucket rain gauge and reported in 15 minute intervals, which provides both hyetograph characteristics and total storm precipitation. Relationships between total precipitation and total storm runoff for each of the four gauged locations are shown in figure 15. All of the relationships are linear with intercepts near zero; therefore the slope of the line is the rainfall-runoff ratio, also known as the runoff coefficient (Table VII).

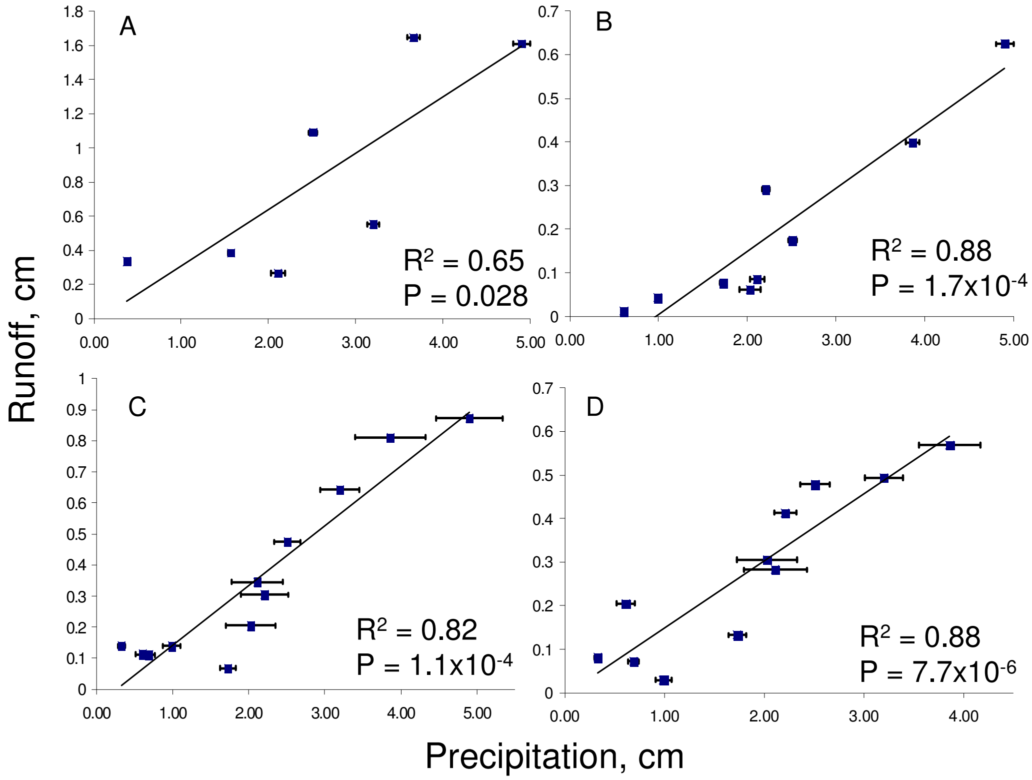


**Figure 15: Total rainfall runoff relationships are presented for the (A) Cherry Hill, (B) Paint Branch, (C) NE Branch and (D) NW Branch sites. One-way ANOVA indicates $p < 0.05$ for all 4 data sets.**

Rainfall-runoff equations were calculated from regression analyses of the relationship of runoff to rainfall at each watershed location (fig. 15). These equations and associated $R^2$ values are presented in Table VI. All sites, except for Cherry Hill , have runoff coefficients of 14-20%, which is less than the amount of impervious cover (19-26%). These values indicate that most (~80% )of the rainfall infiltrates into the watershed and contributes to other runoff processes, storage, and evapotranspirative losses. The Cherry Hill site receives channelized runoff from several roadways and has active construction near the center of the watershed. This watershed had the lowest $R^2$ value and highest value of total runoff (~33% of rainfall; table VI). Effective rainfall refers to the amount of precipitation required to trigger a runoff response at each watershed location. It is estimated as the x intercept of the regression line for rainfall-runoff relationship and included in table VI.

A one-way analysis of variance (ANOVA) was conducted on the rainfall runoff relationships. This analysis indicated that $p < 0.05$ for all of the regressions between total rainfall and runoff, thus indicating that the null hypothesis is rejected and that there is a statistically significant relationship between rainfall and runoff. Three sites (NE, NW and PB) have P-values less than 0.01.

**Table VI: Rainfall-Runoff Equations for the 4 gauged watersheds.**

| Watershed Location | Regression equation | $R^2$ | Effective Rainfall (cm) |
|---|---|---|---|
| Cherry Hill (A) | $y = 0.331 (x) - 0.03$ | 0.65 | 0.09 |
| Paint Branch (B) | $y = 0.145 (x) - 0.14$ | 0.88 | 0.97 |
| NE Branch (C) | $y = 0.193 (x) - 0.05$ | 0.88 | 0.26 |
| NW Branch (D) | $y = 0.154 (x) - 0.01$ | 0.82 | 0.06 |

The two coastal plain watersheds have higher runoff coefficients than the two Piedmont sites. The upstream tributaries for both the Piedmont and Coastal plain watersheds both have 18-19 % impervious surfaces and similar drainage areas (33.9 and 26.7 $km^2$, respectively). Despite these similarities, runoff is much lower for the Piedmont tributary (15%) than the Cherry Hill site (33%). The Cherry Hill site has significantly more road crossings and stream channelization near these roadways that might contribute to this high runoff coefficient. The difference in runoff coefficients between Piedmont and coastal Plain watersheds at the > 100 km$^2$ scale is less than that of the upstream tributaries, but runoff coefficients are also significantly larger for the NE Branch site (19.3%) than the NW Branch site (15.4%). At both downstream locations, runoff ratios are significantly less than the percentage of impervious cover (26 and 23% respectively; Table VII)

### 4.7.2 Relationship of New and Old Water Runoff to Rainfall

These differences between the amount of total runoff observed between Piedmont and Coastal Plain sites suggests differences in runoff response and processes, which can be evaluated by looking at the amount of runoff contributed by surface and subsurface flow (“new” and “old” water sources) at each of the sites. Separated hydrographs for new and old water were used to determine the total volume of surface and subsurface runoff for each storm analyzed at each gauge location. Figures 16A and 16B present the new and old water rainfall runoff diagrams for the Piedmont and Coastal Plain watersheds, respectively.

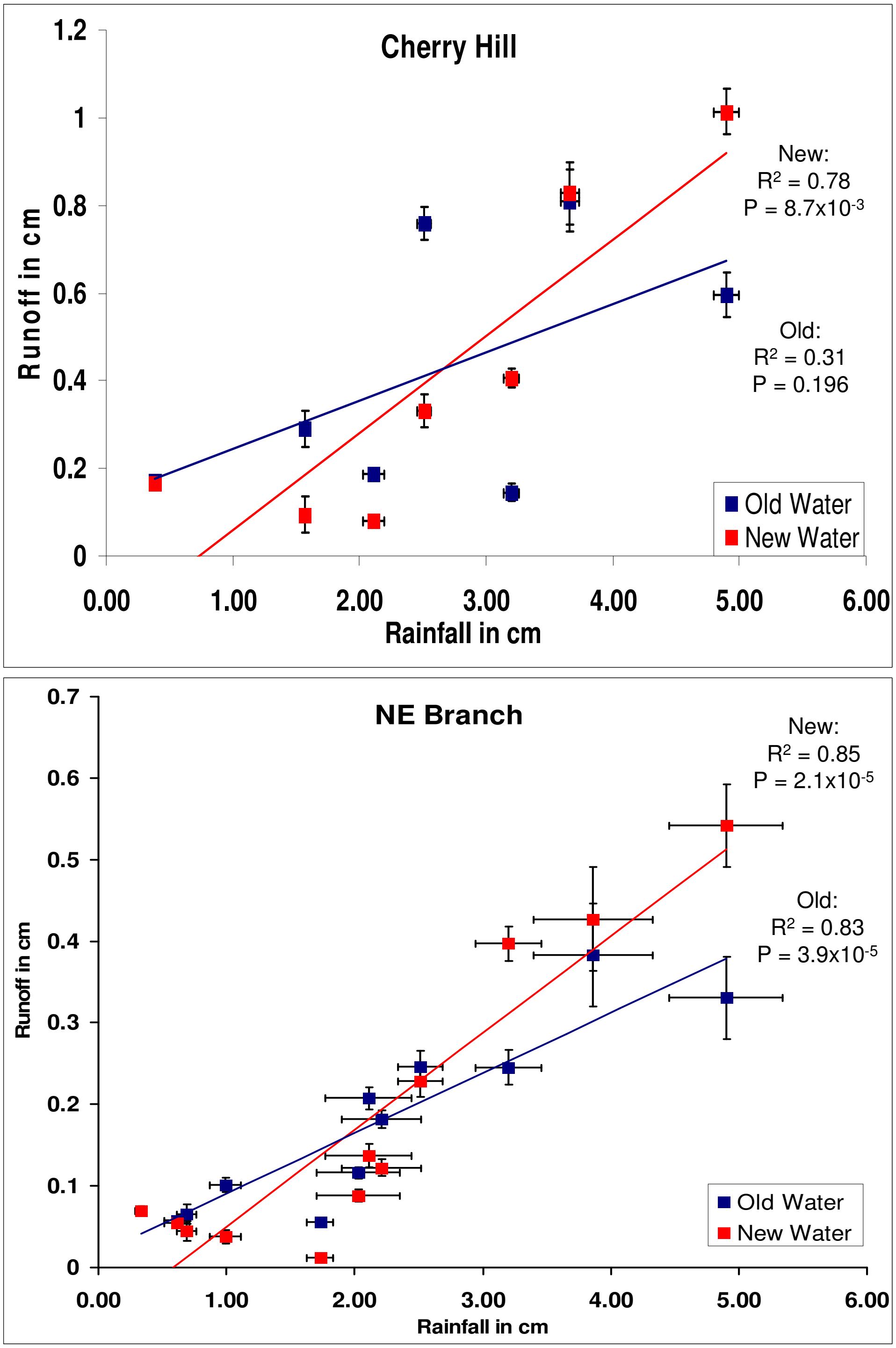


**Figure 16 A: Relationship of rainfall to Old and New water runoff for the Coastal Plain watersheds: Cherry Hill and NE Branch. P stands for P-value.**

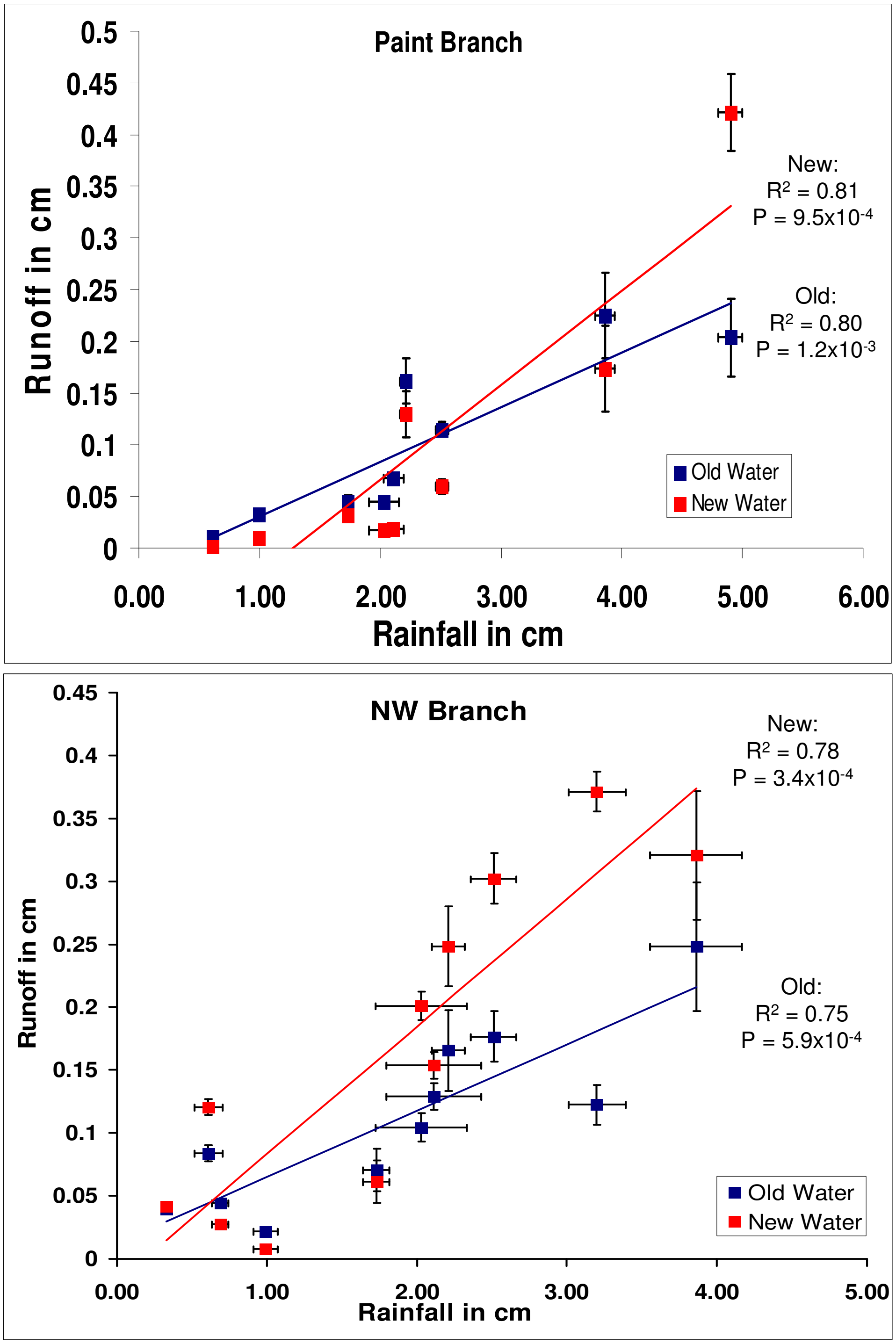


**Figure 16 B: Old and New water point runoff values for the Piedmont watersheds: Paint Branch and NW Branch watershed locations. P stands for P-value.**

The data shown in figures 16A and 16B is summarized in Table VII below. A one-way analysis of variance (ANOVA) was conducted on the rainfall runoff relationships. This analysis indicated that $p < 0.05$ for all of the regressions between rainfall and new runoff, thus indicating that the null hypothesis is rejected and that there is a statistically significant relationship between these parameters. An ANOVA analysis for old water, however, indicated $p > 0.05$ for the Coastal Plain tributary of Little Paint Branch Creek at Cherry Hill, indicating that the null hypothesis is not rejected. There was however, a statistically significant relationship ($p<0.05$) between rainfall and old water runoff amounts for the other three stations.

The two Coastal Plain sites linear relationships between rainfall and new water runoff, and the average new water runoff coefficients are higher than average old water runoff coefficients. The new water end-member (precipitation and overland flow) contributes more water than subsurface flow for the majority of storm events. The Piedmont watershed locations also have higher new water runoff coefficients than old water runoff. However, the differences between old and new water runoff coefficients are greater for the Piedmont locations.

**Table VII: Average runoff (Total, old, and new water) expressed as a percentage of total rainfall**

| Gauge Name | Drainage Area (km2) | Impervious Cover (%) | Total Runoff (%) rainfall | Old Water Runoff (%) rainfall | New Water Runoff (%) rainfall | Old to New Water Precipitation Threshold (cm) |
|---|---|---|---|---|---|---|
| Cherry Hill | 26.7 | 19 | 33.1 | 11.0 ± 0.9 | 22.1 ± 1.0 | 2.7 |
| Paint Branch | 33.9 | 18 | 14.5 | 5.3 ± 1.1 | 9.2 ± 1.1 | 2.5 |
| NW Branch | 127.9 | 23 | 15.4 | 5.3 ± 1.1 | 10. ± 1.1 | 0.6 |
| NE Branch | 188.6 | 26 | 19.3 | 7.4 ± 0.2 | 11.9 ± 3.1 | 1.9 |

All sites show a threshold precipitation value at which new water begins to dominate the storm hydrograph. This threshold occurs at a smaller precipitation value in the downstream watershed locations (0.6 and 1.9 cm for NW and NE Branch locations respectively where the percentage of impervious surfaces are higher and urban runoff is connected directly to channelized rivers). The upper watershed tributaries need a larger magnitude precipitation event to trigger a switch from old to new water runoff domination (2.5 and 2.7 cm for the Paint Branch and Cherry Hill sites respectively).

Another observable threshold is the amount of precipitation required to initiate new water runoff within the watersheds. The new rainfall- runoff trend lines intersect the x-axis at a similar value of precipitation for the two Coastal Plain sites: Cherry Hill site (0.7 cm) and the NE Branch site (0.6 cm). The Piedmont sites have more variation between the new water initiation thresholds

(0.3 and 1.4 cm for NW Branch and Paint Branch respectively). Note that these values are for spring through fall storm events, which are often higher in intensity than winter storms (Winston, 1994). While total runoff and therefore all components of total runoff are less than the amount of impervious cover for three out of four sites, the Cherry Hill site exhibits new water runoff nearly equal to the amount of impervious cover. This suggests either efficient transmission of runoff from impervious surfaces to the stream, fewer regions for stormwater runoff infiltration, or both. The Little Paint Branch Creek watershed is the only tributary with extensive channelization in the upstream reaches (which conveys runoff from HWY 95, the Beltway, and other major roads). This tributary, however, has the fewest number of separated storm events, seven in total, and the poorest fit for all four runoff values, which might be associated with changes in the watershed associated with construction of the ICC.

### 4.7.3 Error Analysis of Rainfall Runoff Coefficients

An enveloping technique similar to what was performed on the hydrograph separation results was used in calculating the uncertainty in the rainfall runoff coefficients (Taylor, 1982). This technique provided error estimates for the rainfall-runoff analyses of total, new and old water runoff at each gauging location. The results of this error analysis are found in Table VII.

### 4.8 Discussion

In this chapter, I evaluated the use of specific conductivity as a tracer to identify runoff sources in 4 complex, watersheds that are larger than 10 km$^2$. Differences in runoff behavior were observed as a function of storm characteristics, watershed size, pattern of urban development, and underlying geological differences. Most of the watersheds exhibited runoff coefficients (total runoff/rainfall) that are significantly smaller than the percent impervious cover in each watershed. The watersheds also showed significant differences in the amount of overland flow and the precipitation threshold for initiation of runoff and the dominance of overland flow. For all sites, overland flow runoff became the dominant runoff process as the magnitude of precipitation increased. The threshold of this change in dominant runoff process happened at a larger magnitude of precipitation in the smaller tributary watersheds. While this threshold is different for each gauged location, it could provide useful information for storm water and contaminant load mitigation purposes.

In the two Piedmont watersheds (33.9 and 127.9 km$^2$) there were many similarities between the runoff coefficients for total, new and old water runoff. This suggests the bedrock controlled morphology and the pattern of urban development may play an important role in storm water delivery. The total runoff within the Piedmont watershed locations was still much less than the amount of impervious surface and lower than the runoff ratios for the Coastal Plain watersheds. This is a surprising fact because both watershed locations have a significant amount of impervious surfaces within their drainage areas.

The pattern of urban development follows watershed morphology in the Northwest branch watershed. The Piedmont watershed (NW branch) has very steep, non-urbanized valleys with significant forest cover lining the NW Branch of the Anacostia. These forested valleys present in the Piedmont watershed likely act as infiltration areas for overland flow runoff derived from adjacent urban areas, as most of these older urban areas route overland flow runoff into small, ephemeral tributaries, not directly to the main channel. These gravel and sand bedded ephemeral channels may serve as infiltration sites for urban runoff. This process may be responsible for the low values of total storm runoff.

In the Coastal Plain watersheds, the floodplain fragments bordering the channel of the gauged sites are less continuous than the Piedmont watersheds and usually mostly smaller in area than in the Piedmont watersheds. This is likely the reason why the two Coastal Plain gauge locations along with the Piedmont tributary site show larger overland flow runoff coefficients than subsurface flow runoff coefficients for most of the storm events. It may also be responsible for the differences observed between the Piedmont and Coastal Plain watersheds.

### 4.9 Evaluation of Hypotheses

Two hypotheses presented earlier in this chapter were tested using the results of the hydrograph separation analyses and the construction of rainfall runoff diagrams for all four watershed locations. It was found that new water runoff ratios were not proportional to the amount of impervious surfaces for any of the watershed locations analyzed in this study. This finding refutes the first hypothesis addressed within this chapter.

Coastal Plain watersheds were found to contribute higher amounts of new water flow than their Piedmont counterparts, even though the Coastal Plain watersheds are characterized by having thicker soils and more permeable bedrock than the Piedmont watersheds. This directly refutes the second hypothesis addressed in this Chapter. These were both surprising results and led to further investigations into the unexpected behavior of the NE and NW Branch watersheds.

All of the watersheds showed an increase in the amount of new water runoff with longer duration storms. This suggests that soil saturation may affect runoff behavior in these urban watersheds and increase connectivity between urban areas and stream channels.

## 4.10 Conclusions

While most hydrograph separation procedures are focused on small watersheds, >10 km$^2$ (e.g., Pellerin, 2005), it can also provide excellent ways of identifying runoff sources in larger watersheds. For urban watersheds, specific conductivity allows for an inexpensive and continuous monitoring of streamflow sources, if conditions are appropriate for its use. For example, we were not able to analyze winter storm events due to road salts which lead to an increased stream conductivity. The differences in old and new water runoff between all four gauged location is significant and likely demonstrate how the geology and morphology of the area dictate the style, pattern and extent of urban development around rivers and their floodplain/riparian zones. While each watershed location has its own unique response, better storm water mitigation efforts can be taken by understanding the effects of scale and time on storm runoff processes within large watersheds, as simple runoff calculations using impervious (or land use in general) do not scale up to fit large, urban watersheds. Understanding more about the sources of storm flow and their relative proportions can allow for more effective and comprehensive storm water mitigation efforts, especially with regard surface and subsurface contaminant transport.

# Chapter 5: Investigation of Storm Flow Delivery Processes

## 5.1 Introduction

In the previous chapter, electrical conductivity was used to identify “new” and “old” contributions to storm hydrographs in the NE and NW Branch watersheds. Hortonian overland flow is assumed to be primarily new water due to the similarity of overland flow water and precipitation conductivity values. Similarly, old water contributions must come from subsurface processes, but the specific source is not defined. Subsurface flow contributions to a storm hydrograph can involve a variety of flow paths, including pathways that contain mixtures of new and old water. Both subsurface stormflow and saturated overland flow are derived from mixed old and new water sources (fig. 17).

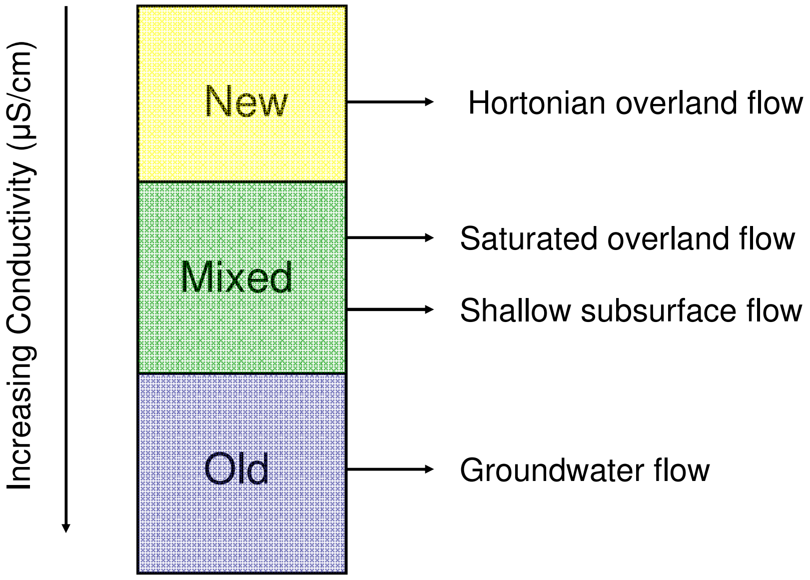


**Figure 17: Relationship between runoff processes and water sources.**

The hydrograph separation analyses (Ch. 4) indicate that old (subsurface) water contributes significantly to storm runoff at all gauge sites, including the largest evaluated watersheds (>100 km$^2$). For some storm events, the subsurface component is the largest contributor to the storm hydrograph. This was surprising because approximately 25% of the watershed areas of NE and NW Branch are impervious surfaces thus, overland flow runoff was expected to be the dominant runoff process..

The purpose of this chapter is to evaluate possible sources of old water contributions to storm hydrographs in Anacostia Watershed. Old water implies subsurface contributions to storm flow, which can be subdivided into two main categories: deep groundwater discharge and shallow subsurface flow. Groundwater flow contributes baseflow to channels between storms and it defines the old water end-member used in the hydrograph separation analysis. Darcian flow is a slow process and it responds to changes in hydraulic gradient, and/or hydraulic conductivity (Fetter, 1994; Brutsaert, 2005). In the past few decades, rapid transmission of groundwater to streams has been documented by hydrograph separation techniques and field measurements (e.g. Sklash et al., 1986; Abdul and Gillman, 1989;McDonnell et al., 1991, Angier et al., 2001). This rapid response has been attributed to several mechanisms including: a) pressure changes in the capillary fringe forming groundwater ridges and b) pressure changes leading to macropore exfiltration. The capillary fringe hypotheses was developed by Gillman and modified by subsequent workers (Abdul and Gillman, 1989; Berkowitz et al., 2004; McDonnell, 1991). Changes in water pressure from a tension-saturated to positively-saturated state can be caused by rapid macropore infiltration to shallow capillary fringes (Beven and

Germann, 1982) and results in a rapid rise in the position of the water table. In floodplain settings, capillary fringe responses can cause local groundwater mounds and increased seepage to channels (Abdul and Gillman, 1989; Matherne, 1991). This diffuse seepage doesn't transfer much water (Matherne, 1991). Several integrated field and tracer studies conducted in small, Maryland watersheds (O'Connell, 1993; Angier, 2001; Bohlke et al., 2007) indicate that piezometric responses to storm events can also cause macropore or focused discharge to streams. Both of these rapid groundwater response mechanisms force "old" groundwater to stream channels.

Other streamflow generation processes involve saturation or partial saturation of the unsaturated zone and transmission of shallow subsurface water to stream channels (shallow subsurface flow) or exfiltrated in low gradient or convergent areas near streams (saturated overland flow) Dunne, 1978. This water is composed of the original vadose (old) water, plus the recently infiltrated new water that activates the system. The capillary fringe mechanism described above may be involved in generating the zone of shallow subsurface flow (McDonnell et al., 1991). At one end of the spectrum, the subsurface flow is composed primarily of new water, which fills the larger pore spaces and pipes in the subsurface unsaturated zone (Noguchi et al, 1999). This transmission of water through conduit networks does not significantly interact with pre-existing pore water in the smaller pore spaces before being discharged to the channel (Pearce et al., 1986). Conduits for this flow through the former unsaturated zone are high hydraulic conductivity zones in shallow soils, inter-connected macropores, pipes, or other subsurface pathways (Pearce et al., 1986).

Considering the possible rapid subsurface pathways and residence times of throughflow, this population of subsurface flow will likely have a mixed water signature, or close to a new water signature when discharged to the stream channel (Weyman, 1970). Rapid throughflow is aided by steep topography and permeable soils (Dunne and Leopold, 1978). This subsurface flow process requires saturation and then transmission water through the soil, thus it is slower than the transmission of a pressure wave and slower than overland flow runoff (Dunne, 1978). Thus shallow, subsurface flow processes should be more dilute, and slower than pressure-transmitted deep groundwater responses (McGlynn et al., 2002)

Several studies indicate that several subsurface processes often occur in the same watersheds and can interact. For example, infiltrating new water can raise water tables in macroporous soils in steeplands or along incised streams, which generates a saturated zone that can cause significant movement of old water that was previously stored in the unsaturated zone (McDonnell et al., 1991; O'Connell, 1998).

Most of the previous work on subsurface flow processes has been conducted in forested or agricultural watersheds. Documentation of flow paths, however, may be even more important in urban watersheds. Contaminant transport in urban areas can be significantly influenced by subsurface flow processes. Shallow subsurface flow usually involves mixing of surface and subsurface components and these mixing processes might retain cations (e.g. Pb, Zn) introduced by rainwater (Scudlark et al, 2005), but transmit nitrate and other chemical species that occupy the oxic to suboxic shallow subsurface (Bohlke et al., 2007).

.

## 5.2 Hypotheses and Objectives

The purpose of this chapter is to use physical parameters of storm hydrographs, hydrograph separation results, and evaluations of field observations of flow processes to identify subsurface flow processes in the NW branch and NE branch Watersheds.

Hypotheses:

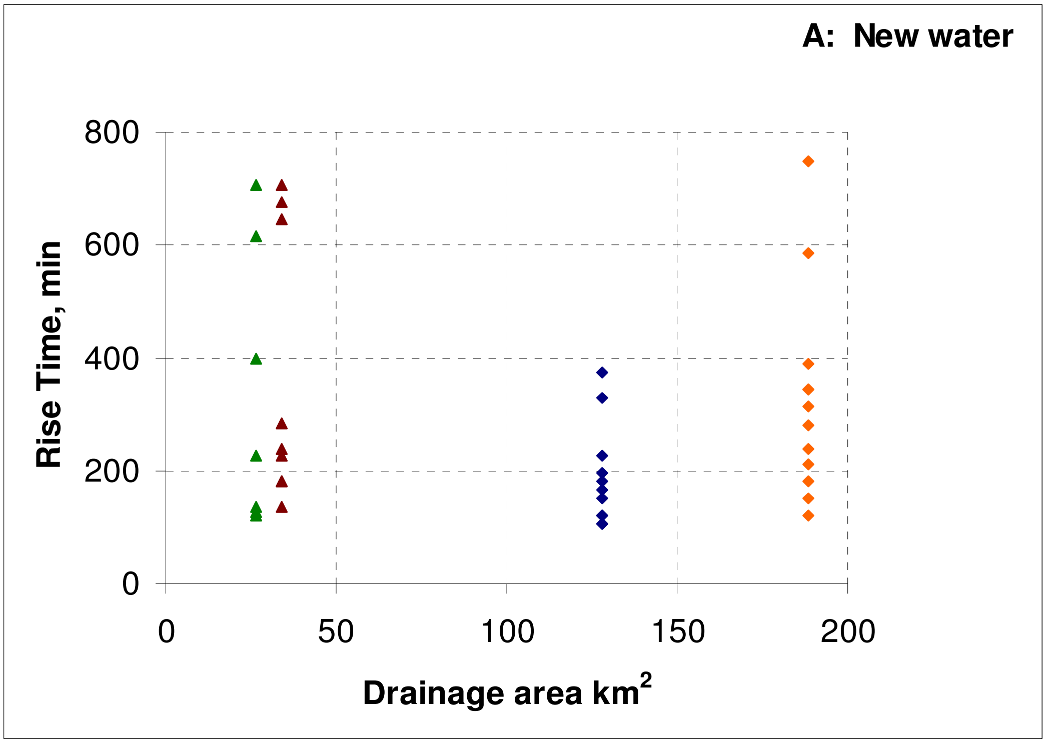
1. New water runoff occurs earlier in storm flow hydrograph than the groundwater runoff at all spatial scales.
2. Pressure changes in the groundwater system contribute “old” water rapidly to the stream. Therefore, “old” water components that arrive prior to or along with the flow runoff provide estimates of this end member.
3. Traditional methods of hydrograph separation analyses underestimate subsurface flow contributions to storm runoff due to mixing of “old” and new sources in shallow groundwater.

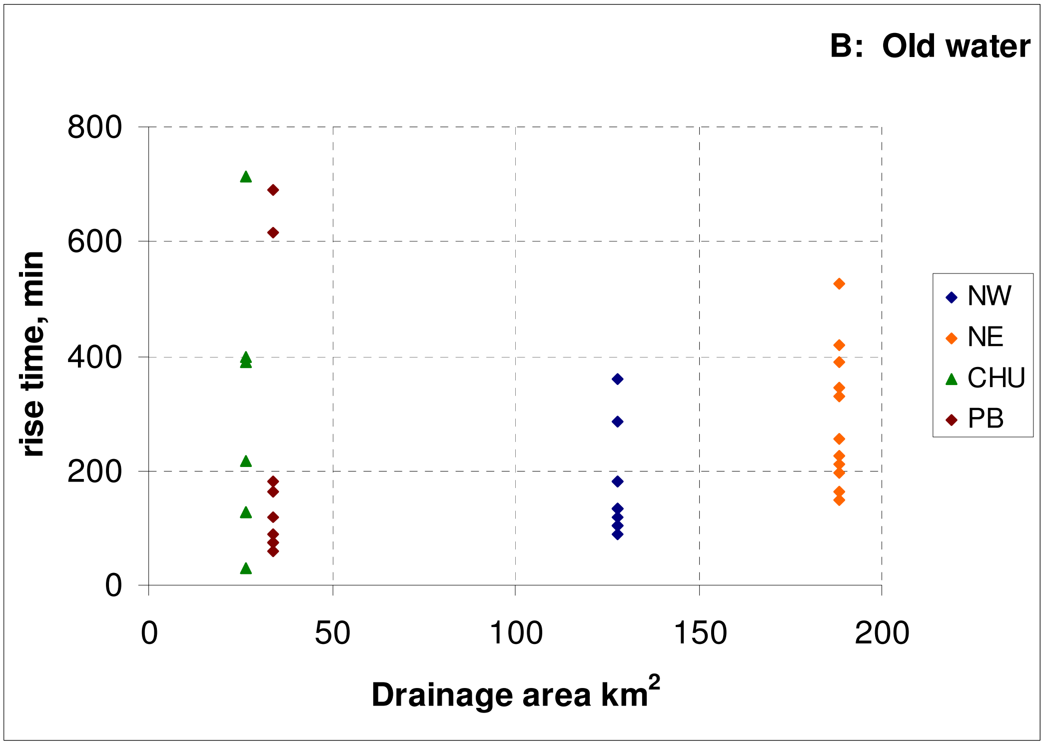
The approach to hypothesis testing is to evaluate: a) the timing of the subsurface response relative to the overland flow response in the watersheds; b) the dilution of the subsurface reservoirs by use of electrical conductivity data; and c) field evidence for infiltration and mixing of new and old waters.

## 5.3. Timing of Peak New and Old Water Contributions to Hydrographs

In the previous chapter, old and new water components of storm hydrographs were separated using electrical conductivity as a tracer. These separations were used to construct stormflow hydrographs for new and old water (Chapter 4). From the separated hydrographs peak discharge, rise time, duration, and other characteristics for “new” and “old” water hydrographs can be determined. The time to peak (rise time) is a characteristic response of hydrographs and rise time values for new and old water hydrographs were obtained for each storm event (figure 18A and B). Rise time is a hydrological response variable that consists of two components: a) the travel time of a runoff process (i.e. from hillslope to stream channels) and b) the time that it takes for water to move downstream to the gauge location (a stream routing component).

Measured rise times for large watersheds include both runoff time and streamflow time components. The difference between the rise times (new-old peak) removes the stream travel time component and compares the response time of the two water sources (figure 18C). If the old water component reaches the stream prior to or simultaneous with the new water component (difference times that are zero or positive), this indicates that either the old water components are only generated in downstream portions of the watershed or that the subsurface flow mechanism is more rapid than the overland flow components, which may indicate a pressure wave response rather than flow of shallow, subsurface water generated by partial saturation of the vadose zone.





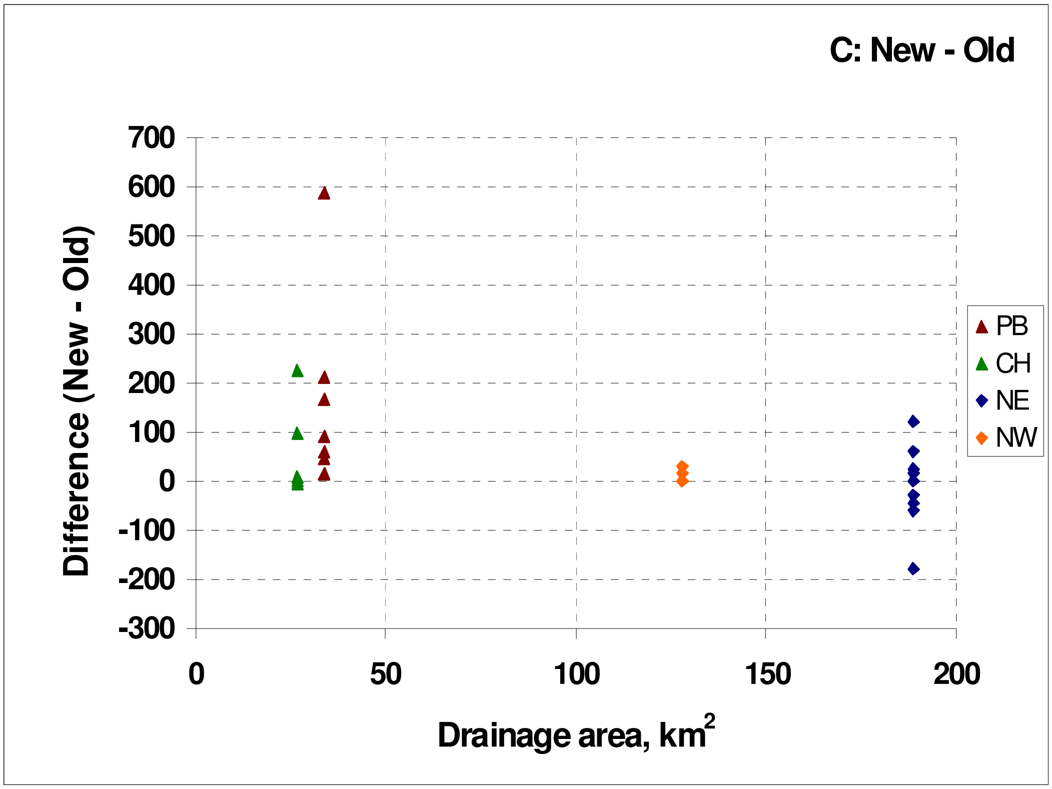


**Figure 18: (A) New water rise time for all storm events at four gauge sites. (B) Old water rise times. C) Difference between time of peak on new and old water.**

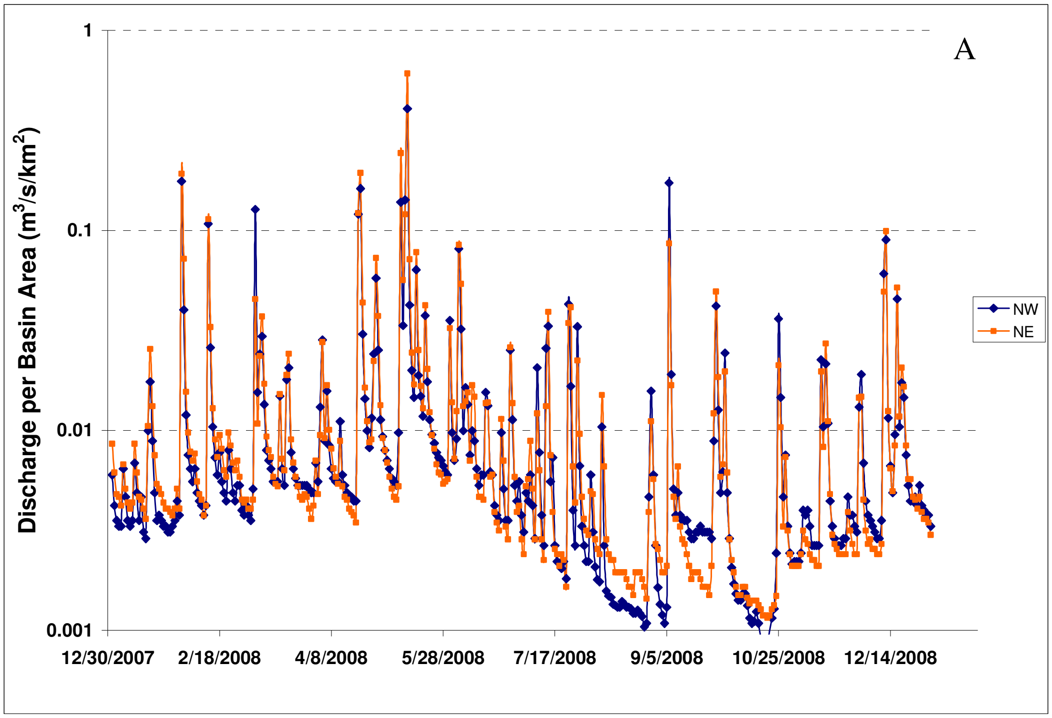
Figure 18C indicates the time differences between the new and old water hydrographs for the 4 gauged sites. These data indicate time differences near zero for the downstream NW branch gauge. The Downstream NE Branch gauge also shows time differences that average near zero, but includes both positive and negative values. The two tributary sites have positive values of new-old water rise time differences, indicating that the new water response had longer rise times than the old water response. The time differences for the tributary sites ranged from near zero to several hours, indicating either localized (lower basin) subsurface contributions, pressure responses that were more rapid than overland flow runoff, the effects of stormwater retention of overland flow or a combination of these processes.

The rise times for new and old water were evaluated over a range of storm characteristics for all sites analyzed in this study. Rise time was compared with storm characteristics to evaluate subsurface responses to storm characteristics. When the difference in rise times was compared with storm magnitude and maximum intensity, however, no simple correlations between storm characteristics and hydrologic behavior were observed.

### 5.4 Seasonal Variations in Baseflow Conductivity

Baseflow discharge in streams is derived from groundwater flow to the stream channel. If the groundwater source is similar throughout the year, the chemical and physical characteristics of the water from this end-member should remain constant. In Maryland, precipitation is not seasonal, therefore, variations in water table elevations are generated by evapotranspiration during summer months and recharge in winter months, which causes seasonal variation in baseflow discharge. Average annual evapotranspiration in the Anacostia Watershed is approximately 70% of precipitation (Prestegaard, pers. com). Daily average data from the USGS gauges on the NE and NW Branches were analyzed to examine seasonal variations in baseflow discharge and conductivity (figs. 19 A and B).

Both the NE and NW Branch watersheds show significant seasonal variations in baseflow. Baseflow discharge increases in the late fall as evapotranspiration decreases and it reaches a maximum in late spring (April-May) due to groundwater recharge. Baseflow minimum are observed in late August and early September for both sites as a result of cumulative summer evapotranspiration.



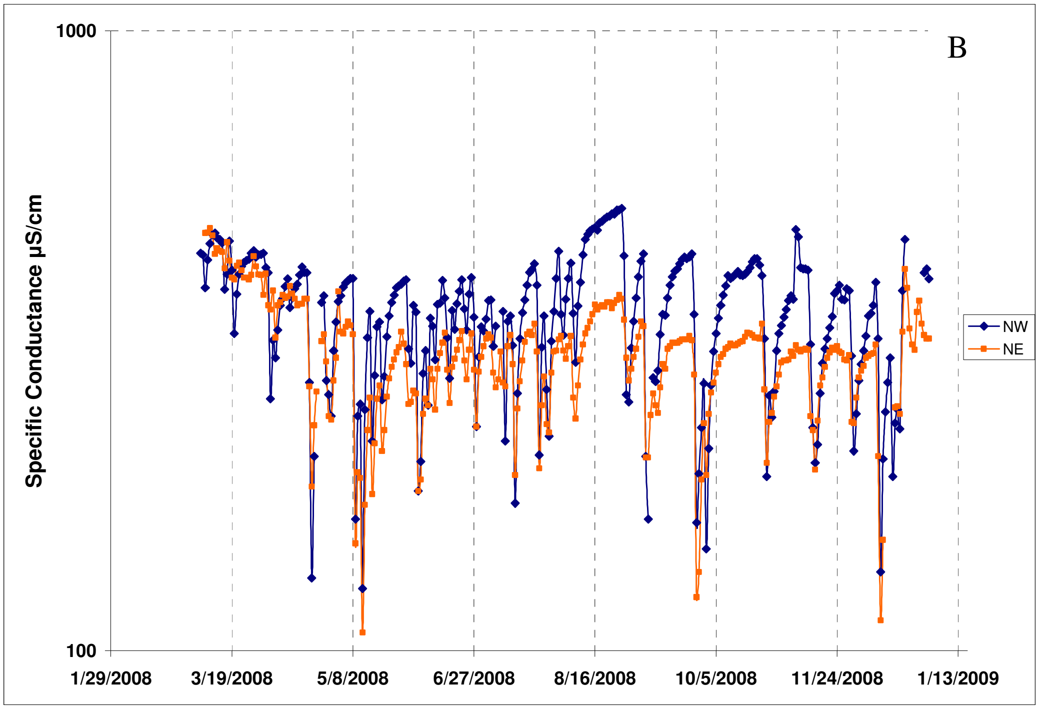


**Figure 19: (A) daily discharge per basin area for the NE and NW Branch USGS gauges for selected time interval (see chapter 4). (B) Daily specific conductance data for the NE and NW Branch USGS gauges.**

The conductivity of baseflow also changes seasonally, but these variations are more pronounced in the Piedmont watershed. During late summer months, only deeper, more conductive groundwater is discharged because water from summer storms is primarily used for evapotranspiration in late spring and summer months (fig. 19A). Conversely, during the winter and fall, groundwater is recharged by water with lower values of electrical conductivity resulting in lower conductivity of baseflow during winter months. In this urban watershed winter dilution is modified by road-salt runoff and winter salt spikes.

The baseflow dilution patterns are not the same for both large watersheds. The NW branch watershed shows more rapid declines in baseflow discharge over the summer period and a more rapid increase in the conductivity of the summer discharge. This suggests that the fractured bedrock that forms the groundwater reservoir in the NW branch might have less storage capacity than the more permeable sedimentary formations that underlie NE branch watershed (MGS, 1968). The smaller amount of available pore spaces in these bedrock aquifers results in more rapid depletion and drainage from deeper sources during summer months.

In order to enhance these differences and contrast the baseflow behaviors of the NE and NW Branch watersheds, daily conductivity data were normalized to daily unit discharge (cfs per basin area; Figs.20A and B). Seasonal variations in discharge and conductivity were observed at both sites, but the patterns are more pronounced in the NW Branch (Piedmont Province) than the NE Branch (Coastal Plain Province). Figures 20A and 20B indicate that conductivity values and patterns in NW branch are similar to the NE for late winter and early spring periods, but that during the summer, baseflow in NW branch becomes progressively more concentrated in dissolved solids and therefore more conductive.

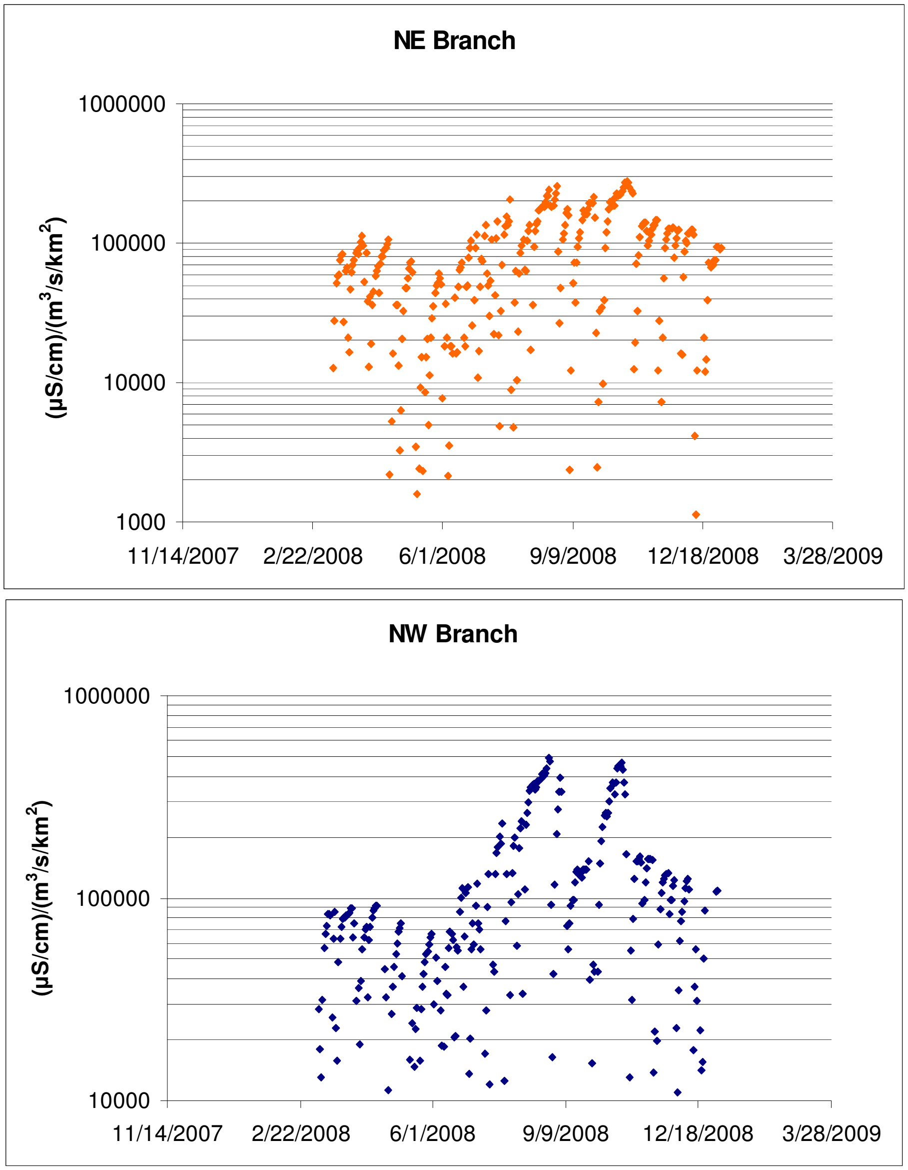


**Figure 20: (A) and (B) specific conductivity normalized by unit discharge ($m^3$/s per basin area) for the NE and NW branch watersheds, Note the significantly higher baseflow conductivity in NW branch watershed during the summer months.**

The response in conductivity to storm events is also significantly different between the two Anacostia branches. A large tropical storm in August, 2008 generated a significant dilution event in NW Branch, but this effect lasted only for several weeks before the baseflow conductivity began to rise and re-establish peak summer levels. This dilution during storms suggests that storm events initiate subsurface mixing processes in NW branch, which suggests interaction between precipitated water and the subsurface water reservoirs.

### 5.5 Baseflow Dilution by Storm Events.

The conductivity of baseflow did not return to its pre-storm value after most storms. In almost every hydrograph evaluated, the pre-storm baseflow conductivity was significantly higher than the post-storm baseflow conductivity. Figure 21 shows a sample hydrograph and plot of the specific conductivity over the course of the storm hydrograph from the NW Branch gauge. Prior to the storm, the baseflow had a conductivity of roughly 350 µS/cm. After the storm hydrograph ended, stream baseflow discharge was slightly higher but more dilute. The specific conductivity of the discharge is much less, (~250 µS/cm), which is almost 100 µS/cm lower than the pre-storm conductivity.

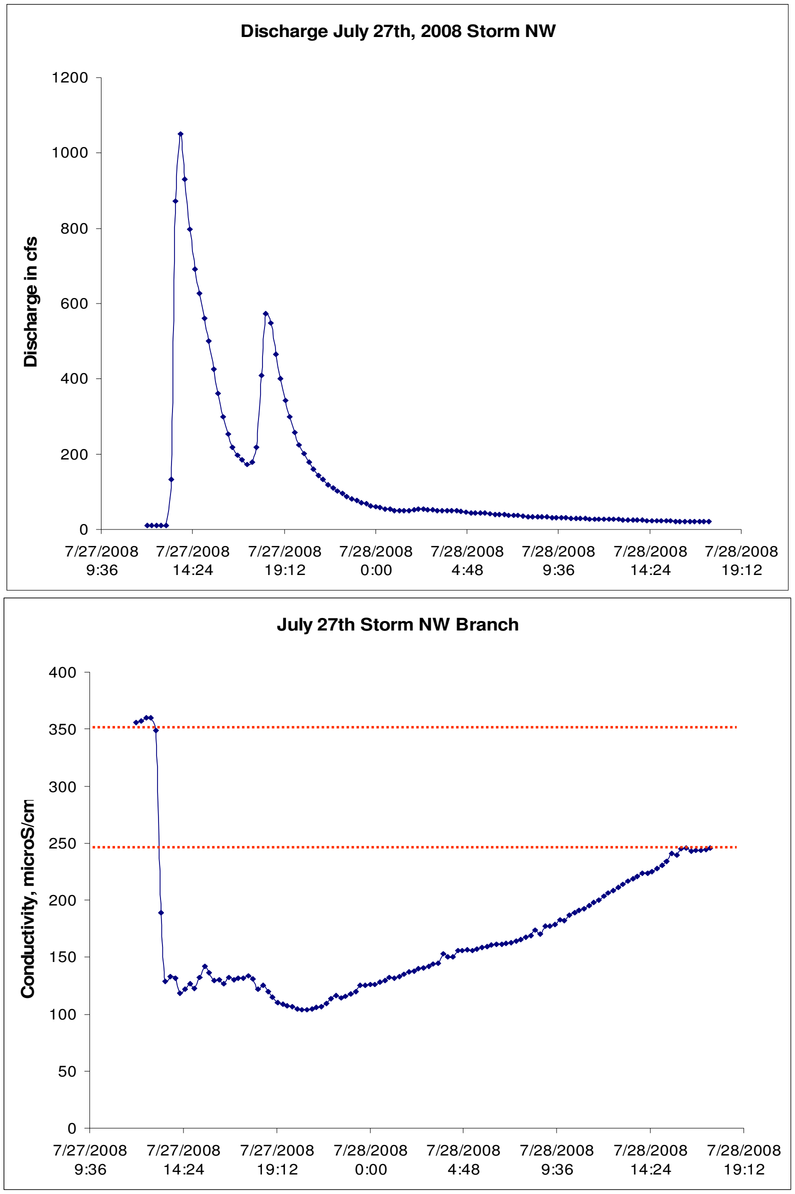


**Figure 21: (A) Storm hydrograph for the July 27th storm event. (B) Plot of specific conductivity over the course of the storm hydrograph. Red lines indicate the starting and ending conductivity of baseflow.**

This difference in pre and post baseflow conductivity suggests that infiltration into subsurface reservoirs takes place over the course of the storm and it results in a diluted post-storm baseflow discharge signature. Data on pre-storm and post storm conductivities were collected for all sites and all storms. These data are shown in figure 22.

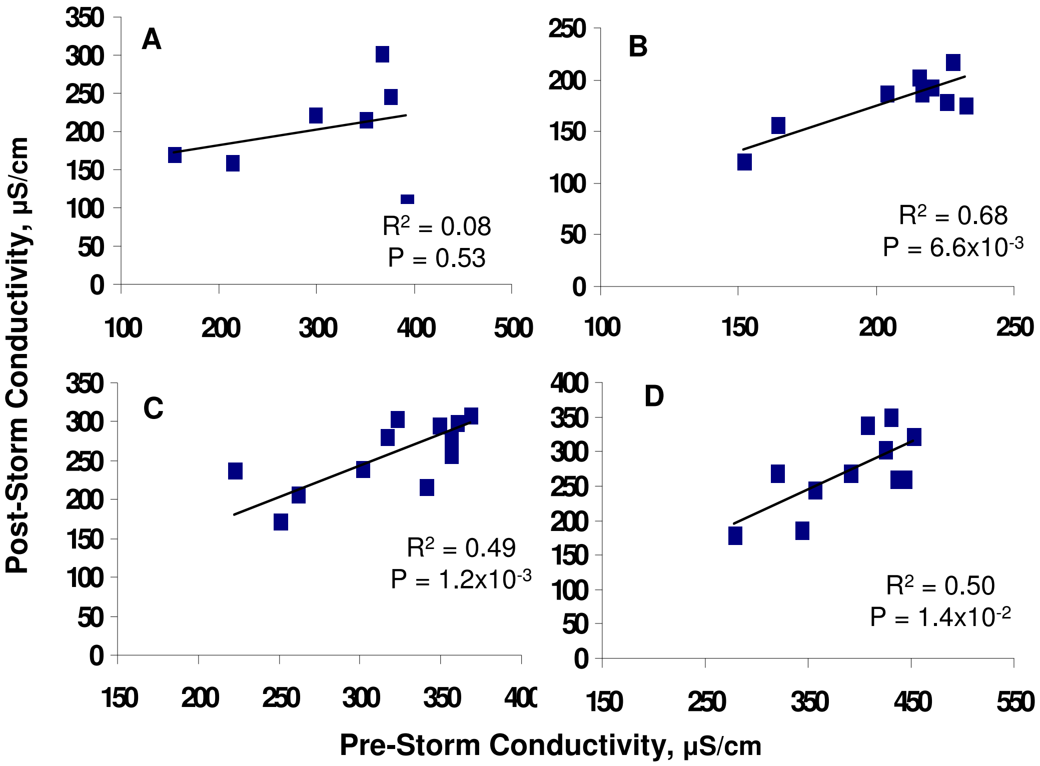


Figure 22: The relationship of pre-storm to post- storm conductivity for (A) Cherry Hill, (B) Paint Branch, (C) NE Branch and (D) NW Branch.

With the exception of the Cherry Hill site, most sites have a linear relationship between the pre and post storm specific conductivity. A one-way ANOVA indicates that the null hypothesis can not be rejected for the Cherry Hill site, but $p < 0.05$ for the other three sites, suggesting a simple linear relationship between pre-and post-storm baseflow conductivities. All of the data suggest that the post storm conductivity is 70 to 87% less conductive than the pre-storm data. These data suggest that mixing of new and old water results in an13-30% dilution of post-storm baseflow conductivities in the NE, NW and Paint Branch watersheds.

The Cherry Hill data show no relationship, which indicates a nearly constant value of post-storm conductivity.

Traditional hydrograph separation techniques use a constant value for end-member tracer composition. This assumption of a constant value for the old water end-member may not be valid if the goal is to define all subsurface contributions rather than to streamflow. The amount of change in the baseflow conductivity may reflect the amount of subsurface dilution (old and new water mixing) that takes place during a storm event. Therefore, evaluation of the changes in the baseflow end member composition might be used to quantify the amount of subsurface mixing that takes place.

### 5.6 Alternative Hydrograph Separation Analysis

To quantify the amount of storm runoff that has a mixed (old and new) signature, alternative hydrograph separations were performed on all storm events analyzed in Chapter 4. In the alternative method, new water conductivity is assumed to be constant, but the old water conductivity varies with time over the hydrograph. The pre and post-storm baseflow conductivity values are obtained from the storm data and groundwater conductivity is assumed to decrease linear with time during the storm (fig. 23). This evolving old water signature represents the new water dilution due to infiltration of precipitation. For more information about hydrograph separation methods, please refer to Chapter 3.

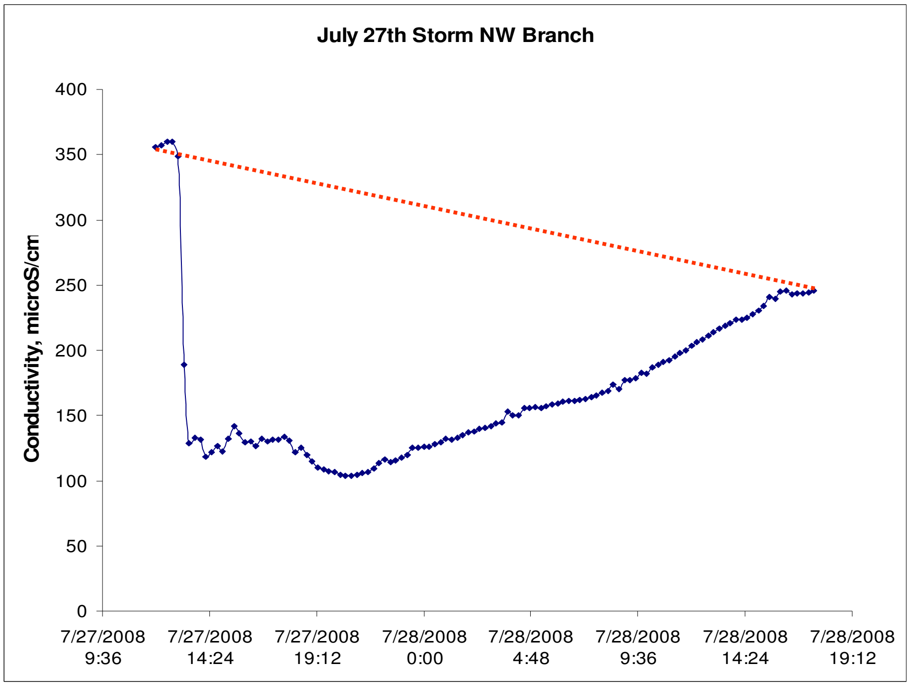


**Figure 23: The old water end member conductivity decrease with time (red line) and the streamflow conductivity (blue line) for the July 27$^{th}$, 2008, NW Branch at mouth. The conductivity decrease was 0.06 µS/cm per min.**

The behavior of the groundwater conductivity is likely much more complex than this simple linear decrease with time. This simple model, however, might provide an estimate of the dilute (shallow subsurface flow component) contributions to the old water end-member.

Alternative hydrograph separation analysis was conducted with the variable old water end-member composition for all storm events for the four watershed locations that were previously analyzed with traditional hydrograph separation techniques. These proportions of new and old water runoff generated from the alternative hydrograph separation analysis are organized in Table VIII.

**Table VIII: Percent of new water in total runoff (alternative separation method)**

| Date of Storm | CH (U) (26.7 km$^2$) | NE Branch (D) (188.6 km$^2$) | PB (U) (33.9 km$^2$) | NW Branch (D) (127.9 km$^2$) |
|---|---|---|---|---|
| 6/23/2008 | - | 30.1 ± 6.3 | - | 33.3 ± 3.9 |
| 6/27/2008 | 39.5 ± 4.0 | 34.9 ± 4.3 | 19.6 ± 4.0 | 49.1 ± 4.0 |
| 7/4/2008 | - | 20.6 ± 5.6 | 19.2 ± 4.3 | 19.7 ± 3.0 |
| 7/9/2008 | - | 46.7 ± 3.4 | 2.2 ± 2.2 | 54.7 ± 3.3 |
| 7/13/2008 | 30.5 ± 4.3 | 43.2 ± 4.4 | 31.4 ± 4.0 | 57.9 ± 4.7 |
| 7/23/2008 | 50.1 ± 4.6 | 58.0 ± 3.3 | - | 71.8 ± 3.5 |
| 7/27/2008 | - | 51.1 ± 3.4 | 26.3 ± 3.1 | 62.0 ± 4.2 |
| 8/7/2008 | - | 43.0 ± 3.8 | - | 39.5 ± 3.5 |
| 8/29/2008 | - | 13.5 ± 6.9 | 35.3 ± 9.3 | 43.4 ± 14.2 |
| 9/6/2008 | 63.7 ± 3.7 | 55.9 ± 7.0 | 65.1 ± 6.3 | - |
| 9/26/2008 | - | 47.2 ± 8.8 | 42.8 ± 10.5 | 49.1 ± 11.6 |
| 10/1/2008 | 49.2 ± 4.6 | - | - | - |
| 10/25/2008 | - | 29.8 ± 3.7 | 39.7 ± 6.8 | 51.3 ± 10.1 |
| 4/20/2009 | 45.3 ± 4.6 | - | - | - |
| 6/5/2009 | 28.8 ± 10.2 | - | - | - |

***U refers to upstream tributaries and D refers to downstream gauges located at the mouth.**

In this analysis, only the relative proportions of new and old water are modified from the traditional hydrograph separation analyses. The total runoff remains the same for both methods of analyses and rainfall-runoff ratios remain constant. Data from the alternative hydrograph separations were used to evaluate modified old and new water rainfall runoff ratios for each storm event (fig. 24A and 24B, Coastal Plain and Piedmont watershed locations, respectively). Table IX summarizes the old and new water runoff coefficients derived from the alternative hydrograph separation procedures.

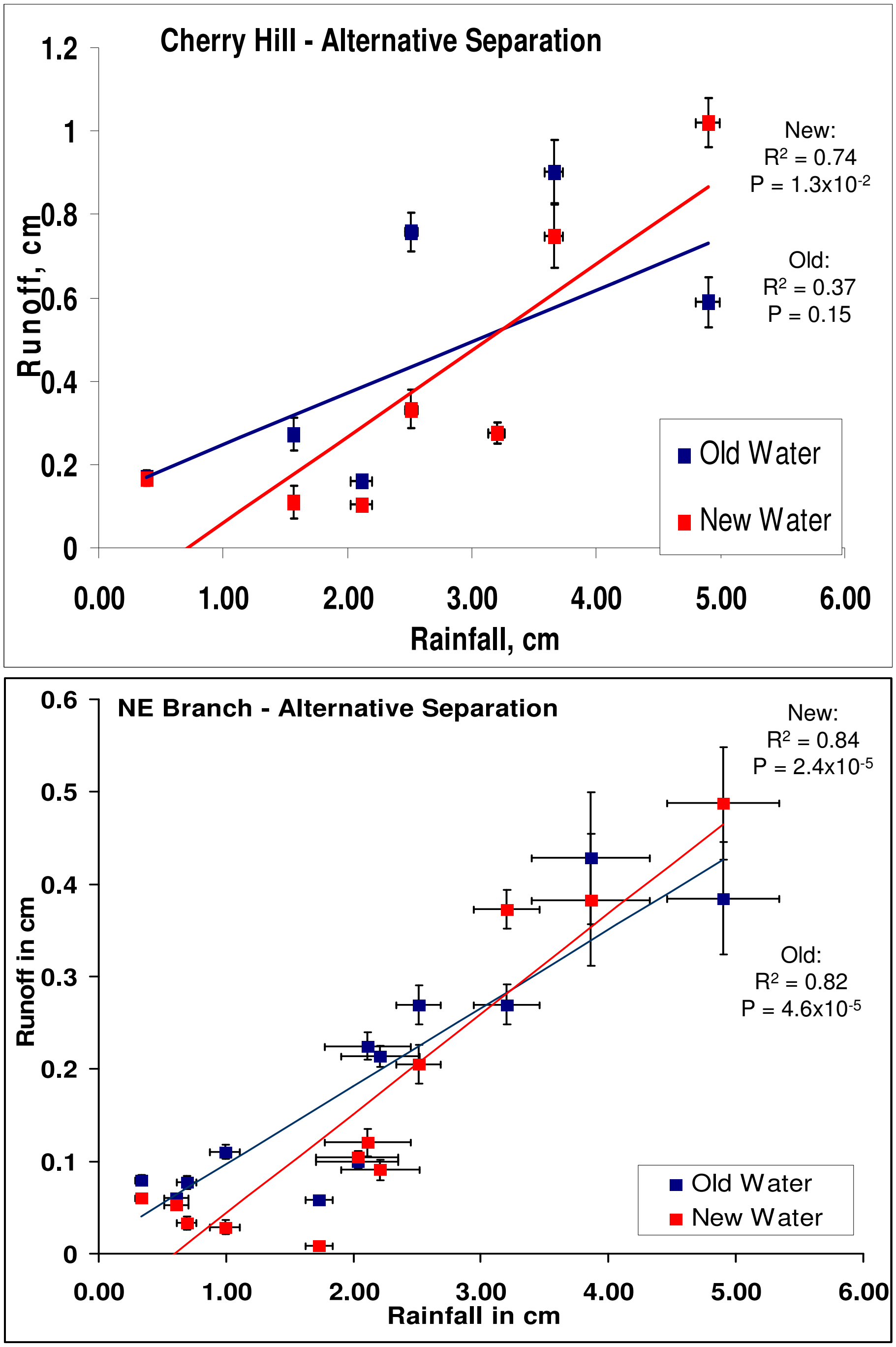


**Figure 24A: Coastal Plain watershed location rainfall runoff ratios using alternative hydrograph separation data. P stands for P-value.**

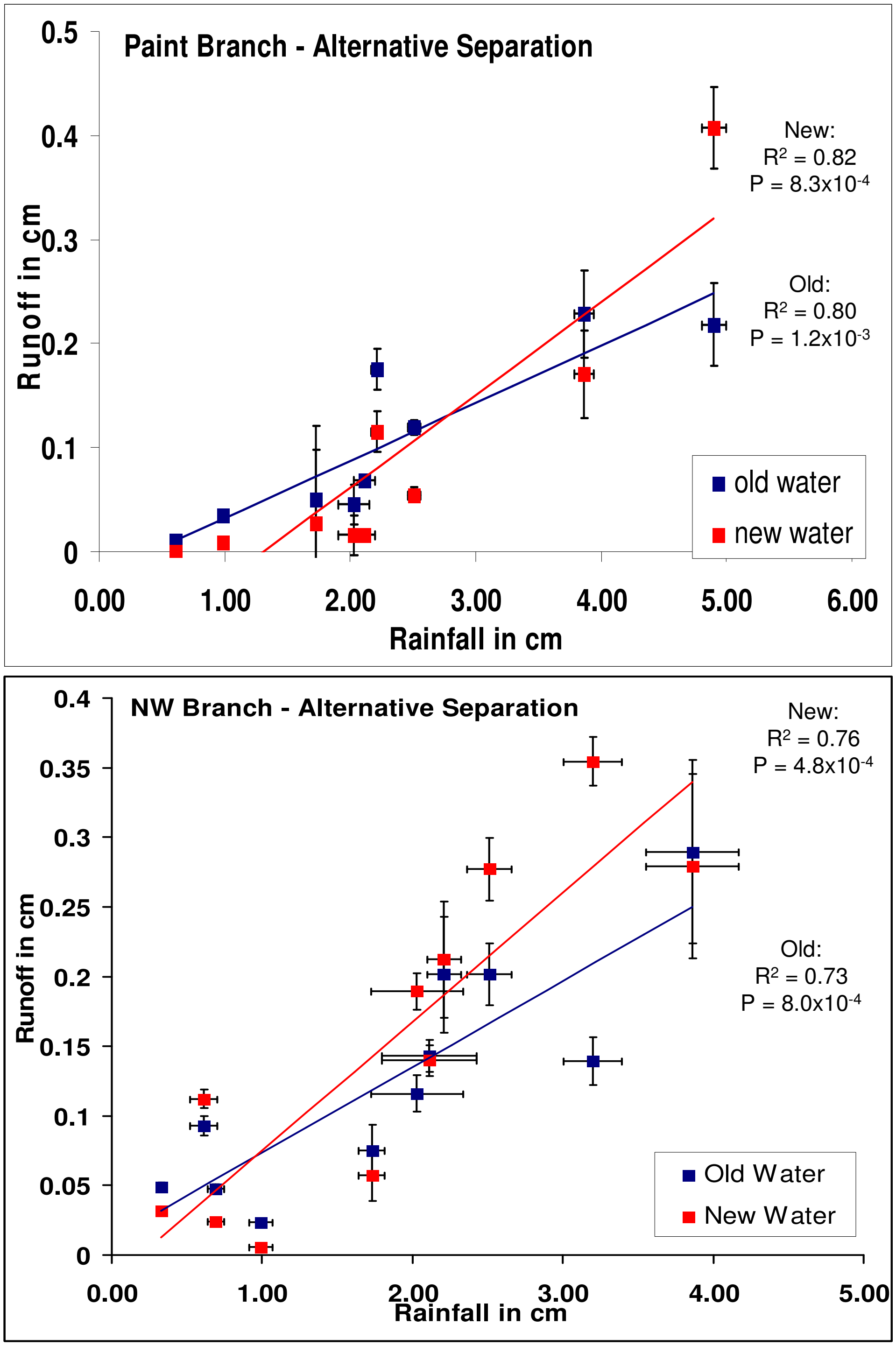


**Figure 24B: Piedmont watershed location rainfall runoff diagrams using alternative hydrograph separation data. P stands for P-value.**

For all watersheds, this alternative analysis modified the amount of old water contributions for each storm event and also modified the observable precipitation threshold at which new water dominates the storm hydrograph. The old water contributions for all watershed sites are greater with the alternative hydrograph separation analysis than the traditional. The increased levels of old water with this analysis are caused by the inclusion of the diluted old water as an end-member. Therefore, the "old" water runoff contributions are more likely to include both old groundwater contributions and a mixed subsurface flow contribution. The analysis could still underestimate the amount of overall subsurface flow if new water forms a major contribution to the flow.

**Table IX: Average runoff (Total, old, and new water) expressed as a percentage of total rainfall**

| Gauge Name | Drainage Area (km2) | Impervious Cover (%) | Total Runoff (%) rainfall | Old Water Runoff (%) rainfall | New Water Runoff (%) rainfall | Old to New Water Precipitation Threshold (cm) |
|---|---|---|---|---|---|---|
| Cherry Hill | 26.7 | 19 | 33.1 | 12.3 ± 0.9 | 20.8 ± 1.0 | 3.2 |
| Paint Branch | 33.9 | 18 | 14.5 | 5.6 ± 1.1 | 8.9 ± 1.1 | 2.7 |
| NW Branch | 127.9 | 23 | 15.4 | 6.2 ± 1.1 | 9.2 ± 1.1 | 0.9 |
| NE Branch | 188.6 | 26 | 19.3 | 8.4 ± 0.2 | 10.9 ± 3.1 | 3.3 |

The new water threshold for the Coastal Plain watershed increases with drainage area (3.2 cm for Cherry Hill and 3.3 cm for NE Branch). The threshold for new water dominance in the downstream Piedmont site (NW branch) is with a much lower than at the other sites (0.9 cm for NW Branch) although the upstream tributary has a higher threshold (2.7 cm for Paint Branch).   These threshold values are significantly higher than the thresholds defined using the traditional hydrograph separation methods (see Chapter 4).  The amount of precipitation required to initiate a new water runoff response was similar for both the traditional and alternative approach.

### 5.7 Comparison of Traditional and Alternative Hydrograph Separation Results – Mixed Water Component

Traditional methods of hydrograph separation, which assume constant end-member tracer concentrations,  likely underestimate the subsurface contribution to storm flow, as mixing in the subsurface is enhanced by infiltrating precipitation.  Alternative methods of hydrograph separation provide a more realistic approach of quantifying the subsurface water component.  But the traditional separation method might be the best technique to evaluate rapid old water contributions to stormflow.  Use of both separations might provide additional information on runoff processes.  The diluted old water component estimated with the alternative approach can be directly compared with the amount of old water determined by traditional hydrograph separation.  The difference in the old water components represents a lower bound on the amount of mixed subsurface flow delivered to stream channels.   These results are presented in tables according to increasing drainage area; (X) Cherry Hill, (XI) Paint Branch,

(XII) NW Branch, (XIII) NE Branch. Error analysis was conducted as previously discussed (Genereux, 1998).

The amount of mixed water presented in these tables was calculated as the difference between the alternative old water contribution and the traditional old water contribution to total runoff. It should be noted that shaded storm events in tables X through XIII denote events of either no apparent mixed-water source or where the calculated mixed water component is within the error calculated for the hydrograph separation analysis. .

**Table X: Cherry Hill old, new and mixed water proportions derived from alternative separations.**

| Date of storm | Old water* | New water* | Mixed water* |
|---|---|---|---|
| 6/27/2008 | 70.3 ± 4.0 | 29.7 ± 4.0 | 0 ± 4.0 |
| 7/13/2008 | 69.6 ± 4.3 | 30.4 ± 4.3 | 0 ± 4.3 |
| 7/23/2008 | 26.4 ± 4.6 | 73.6 ± 4.6 | 23.5 ± 4.6 |
| 9/6/2008 | 37.0 ± 3.7 | 63.0 ± 3.7 | 0 ± 3.7 |
| 10/1/2008 | 50.8 ± 4.6 | 49.2 ± 4.6 | 0 ± 4.6 |
| 4/20/2009 | 49.8 ± 4.9 | 50.2 ± 4.9 | 4.9 ± 4.9 |
| 6/5/2009 | 75.6 ± 10.8 | 24.4 ± 10.8 | 0 ± 10.8 |

**Table XI: Paint Branch old, new and mixed water proportions derived from alternative separations.**

| Date of storm | Old water * | New water * | Mixed water * |
|---|---|---|---|
| 6/27/2008 | 78.9 ± 4.0 | 19.6 ± 4.0 | 1.5 ± 4.0 |
| 7/4/2008 | 76.3 ± 4.3 | 19.2 ± 4.3 | 4.5 ± 4.3 |
| 7/9/2008 | 95.1 ± 2.6 | 2.2 ± 2.6 | 2.7 ± 2.6 |
| 7/13/2008 | 65.8 ± 4.0 | 31.4 ± 4.0 | 2.8 ± 4.0 |
| 7/27/2008 | 71.8 ± 3.2 | 26.3 ± 3.2 | 1.9 ± 3.2 |
| 8/29/2008 | 58.6 ± 9.3 | 35.3 ± 9.3 | 6.1 ± 9.3 |
| 9/6/2008 | 32.6 ± 6.3 | 65.1 ± 6.3 | 2.3 ± 6.3 |
| 9/26/2008 | 56.4 ± 10.5 | 42.8 ± 10.5 | 0.8 ± 10.5 |
| 10/25/2008 | 55.5 ± 6.8 | 39.7 ± 6.8 | 4.8 ± 6.8 |

**Table XII: NW Branch old, new and mixed water proportions derived from alternative separations.**

| Date of storm | Old water * | New water * | Mixed water * |
|---|---|---|---|
| 6/23/2008 | 61.2 ± 3.9 | 33.3 ± 3.9 | 5.5 ± 3.9 |
| 6/27/2008 | 45.5 ± 4.0 | 49.1 ± 4.0 | 5.4 ± 4.0 |
| 7/4/2008 | 74.3 ± 3.0 | 19.7 ± 3.0 | 6.0 ± 3.0 |
| 7/9/2008 | 41.1 ± 3.3 | 54.7 ± 3.3 | 4.2 ± 3.3 |
| 7/13/2008 | 36.9 ± 4.7 | 57.9 ± 4.7 | 5.2 ± 4.7 |
| 7/23/2008 | 24.8 ± 3.5 | 71.8 ± 3.5 | 3.4 ± 3.5 |
| 7/27/2008 | 34.1 ± 4.2 | 62.0 ± 4.2 | 3.9 ± 4.2 |
| 8/7/2008 | 49 ± 3.5 | 39.5 ± 3.5 | 11.5 ± 3.5 |
| 8/29/2008 | 53.5 ± 14.2 | 43.4 ± 14.2 | 3.1 ± 14.2 |
| 9/26/2008 | 43.6 ± 11.6 | 49.1 ± 11.6 | 7.3 ± 11.6 |
| 10/25/2008 | 39.4 ± 10.1 | 51.3 ± 10.1 | 9.3 ± 10.1 |

**Table XIII: NE Branch old, new and mixed water proportions derived from alternative separations.**

| Date of storm | Old water* | New water* | Mixed water* |
|---|---|---|---|
| 6/23/2008 | 59.5 ± 10.8 | 30.1 ± 10.8 | 10.4 ± 10.8 |
| 6/27/2008 | 60.2 ± 4.3 | 34.9 ± 4.3 | 4.9 ± 4.3 |
| 7/4/2008 | 72.8 ± 6.1 | 20.6 ± 6.1 | 6.6 ± 6.1 |
| 7/9/2008 | 51.7 ± 3.4 | 46.7 ± 3.4 | 1.6 ± 3.4 |
| 7/13/2008 | 51.8 ± 4.4 | 43.2 ± 4.4 | 5.0 ± 4.4 |
| 7/23/2008 | 38.2 ± 3.3 | 58 ± 3.3 | 3.8 ± 3.3 |
| 7/27/2008 | 56.8 ± 3.6 | 43.2 ± 3.6 | 0 ± 3.6 |
| 8/7/2008 | 50.0 ± 3.8 | 43.0 ± 3.8 | 7.0 ± 3.8 |
| 8/29/2008 | 82.1 ± 6.9 | 13.5 ± 6.9 | 4.4 ± 6.9 |
| 9/6/2008 | 37.9 ± 7.0 | 55.9 ± 7.0 | 6.2 ± 7.0 |
| 9/26/2008 | 47.3 ± 8.8 | 47.2 ± 8.8 | 5.5 ± 8.8 |
| 10/25/2008 | 59.8 ± 3.7 | 29.8 ± 3.7 | 10.4 ± 3.7 |

The results of the alternate hydrograph separation analysis suggest that mixed subsurface contributions are minor components for the two tributary streams measured at Cherry Hill and Paint Branch site, within the presented uncertainty. Data from the larger watersheds (NE and NW Branches), indicate that ~ 50% of storm events generated small components of mixed subsurface sources (generally less than 10% of the streamflow hydrograph). These data are consistent with the results of the timing analyses: both of the tributaries exhibited old water responses that were up to several hours faster than the new water response, suggesting possible rapid groundwater responses involving primarily old water. Floodplain fragments located along NE Branch watershed likely contribute shallow dilute groundwater to NE Branch during storms. While mixed subsurface contributions are not observed for each storm event, it does not seem to correlate to storm intensity, duration or magnitude. It should be noted that this analysis (comparing old water contributions for both types of hydrograph separation) are likely underestimating the amount of subsurface mixing and the hydrograph separation analysis could not be used during mid-winter conditions.

## 5.8 Conceptual Model of Runoff for NW and NE Branch Watersheds – Synthesis of Field Observations and Data Analysis

The major differences between the NW and NE branch watersheds include pronounced differences in topography, geology, and associated land-use development. The NW Branch watershed is in the Piedmont Province. Alluvial valley fills are thin to absent and the bedrock is he Lower Pelitic Schist member of the Wissahickon formation (MGS, 1968). Hillslope soils are relatively thin < 2 m, with visible bedrock outcrops. NW branch stream is incised to bedrock along the lower 2/3 of its length. Therefore, baseflow contributions during summer months are likely from the fractured bedrock aquifer.

### 5.8.1 The NW Branch Model

The steep valley along NW Branch has significantly influenced the patterns of suburban development (fig. 25). Houses and streets are built along the hilltops, but the steep valley sides have been left largely undeveloped and are forested. This pattern of development has left an intact riparian corridor along the length of the stream. Field examination indicates that storm sewer outfalls for the older suburban areas are usually at the upslope end of this forested riparian corridor (fig. 25). Therefore, total runoff response from the urban areas includes both overland flow production in the suburban hilltops and the mitigation of this runoff due to infiltration in the forested riparian valley.

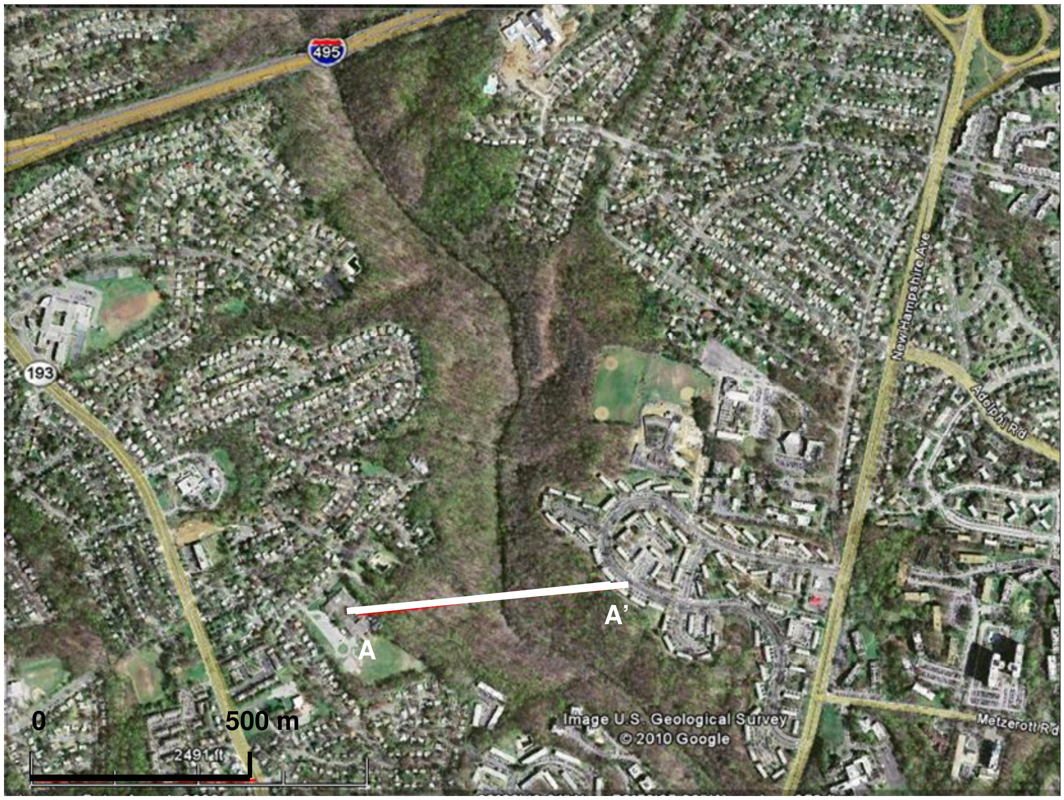


**Figure 25: Air photo of the NW Branch. Note the extensive suburban development along the tops of hills and forested valley side. (2006 Image, USGS). Note cross section of A-A'.**

This steep, forested valley, with sandy and gravelly soils provides significant sites for infiltration of overland flow runoff delivered to the riparian zones by storm sewer networks. Assessment of this infiltration for summer, 2010 storms was conducted from field measurements of flow cross sectional area, as assessment of roughness (grain size distribution) and gradient to calculate velocity

$$(u/(gdS)^{0.5} = 2.8 + 5.75 \log d/D_{84}$$

where u is average velocity, g is gravitational acceleration, S is gradient, and $D_{84}$ is the particle size one standard deviation above the mean (Dunne and Leopold, 1978). These measurements were made in 3 ephemeral channels along the NW Branch (fig. 25). Measurements were made at two locations in each ephemeral channel: near the storm sewer outfall (within 5 m) and just upslope of the junction between the ephemeral channel and NW Branch channel (~5 m up channel). The field measurements for site A were conducted on June 6th, 2008, three days after a storm event. High flow field indicators such as erosional scouring, clumps of leaves, etc. were used to determine peak flow. Roughness values, n, calculated from the Manning equation (Henderson, 1966) were 0.055 for the upstream and 0.04 for the downstream site, as there were larger particles present at the upstream site. Peak discharge estimates were determined from cross sectional area multiplied by velocity (Table XIV).

**Table XIV: Estimated peak discharge June 3rd, 2008 storm.**

| Site Location | Area, $m^2$ | Gradient | Velocity, m/s | Discharge $m^3/s$ |
|---|---|---|---|---|
| Near sewer outflow | 1.11 | 0.0638 | 2.18 | 2.42 |
| Entering channel | 0.62 | 0.0318 | 1.56 | 0.967 |

For this storm event, the peak discharge produced by overland flow runoff and delivered to the ephemeral channel was 60% higher than the peak discharge transmitted from the ephemeral channel to NW Branch. This loss of 60% of the peak discharge suggests significant infiltration into the unsaturated zone underlying this ephemeral channel. Field investigation indicates these urban runoff-ephemeral channel systems throughout the length of NW branch stream. In some cases, the ephemeral channels do not extend to the stream channel, suggesting 100% infiltration of runoff for most storm events.

This extensive forested valley along NW branch stream extends most of the length of the watershed (fig. 25). This figure presents forested valley widths measured from air photos for both the right and left riparian zones at 100m intervals. The average riparian zone width is 460 m. In figure 26, both the right and left bank riparian widths are plotted as a function of distance upstream from the USGS NW Branch gauge (ID 01651000). Ephemeral channels cross these riparian zones throughout the length of NW branch, suggesting that this infiltration process may be a significant factor in the basin response to storms.

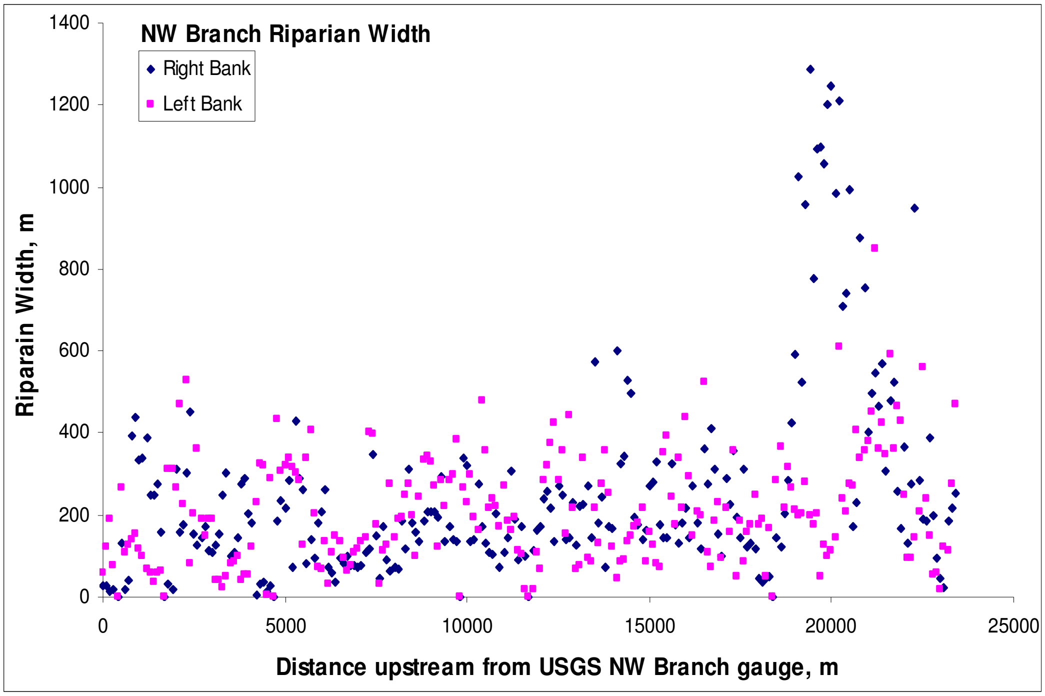


**Figure 26: Forested valley width measured at 100 m intervals upstream of the USGS NW Branch gauge.**

Data from the hydrograph separation analyses along with the topographic and geological characteristics of the watershed were used to develop a conceptual model of streamflow generation in NW Branch Watershed. Figure 27 is a schematic cross section (A – A') for the site indicated on figure 25. This cross section presents a wide riparian valley underlain by fractured bedrock. Soils are thin to absent along the stream, but thicker along the upper hillslopes. Dark blue arrows indicate overland flow runoff and light blue arrows indicate infiltration into the riparian valley, which may influence groundwater responses. Summer and winter water table positions are also shown.

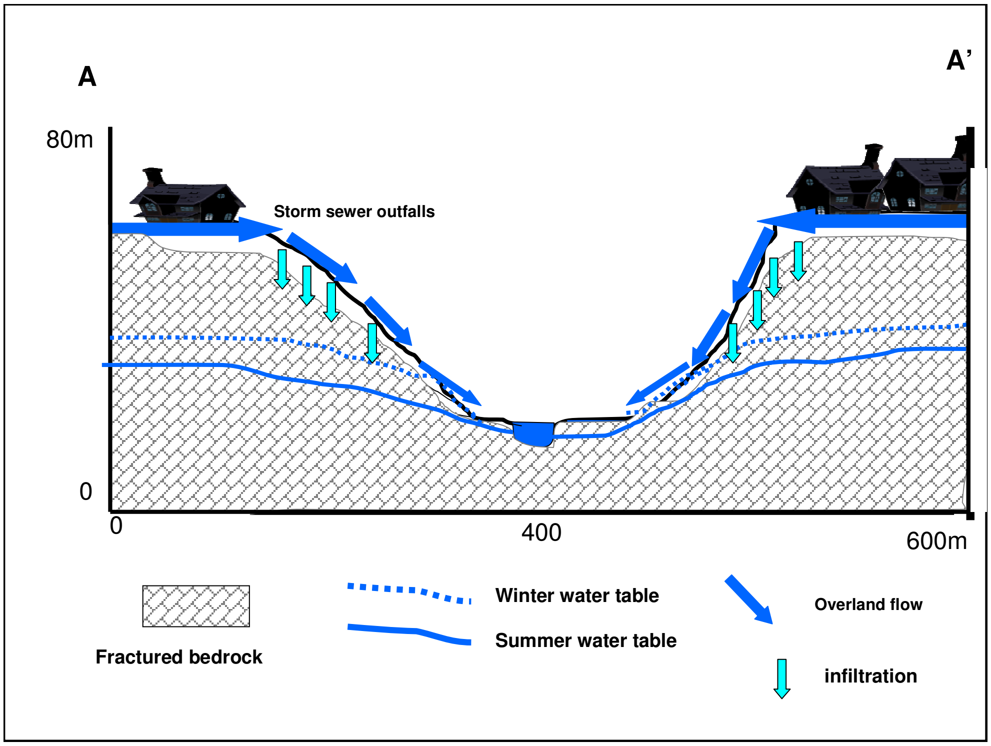


**Figure 27: A-A’ Schematic cross section of NW Branch valley. The grey area represents fractured metasedimentary bedrock units overlain by moderately thin soils (white). Storm sewer outfalls are near the tops of hillslopes and infiltration occurs along the riparian hillslope.**

Due to the high relief in the valley, groundwater always flows from the hillslopes towards the channels. The summer water table minimum is contained within the bedrock. Winter water tables are higher, and may include saturated soils. The steep topography with shallow soils drains quickly between storm events. Thus, the region between the storm sewer outflows are the stream remains unsaturated most of year. This provides a significant region for infiltration of stormwater runoff that can affect the groundwater piezometric response. Therefore, the “old” water component from NW does not show a significant mixed component. Piezometric responses alone do not generate significant runoff, therefore, overland flow runoff is the dominant runoff component in NW branch watershed, but the total overland flow runoff is significantly less than impervious cover due to infiltration in the riparian zone.

### 5.8.2 The NE Branch Model

Unlike NW Branch Watershed, the NE Branch Watershed is in the Coastal Plain, which is characterized by permeable bedrock, low relief, and wide valleys on which urban and suburban development has taken place. Land use patterns have lead to significant spatial differences in floodplain characteristics. The land-use, valley, and topographic characteristics near the two NE branch gauges are shown on the air photos in figure 28 A & B. The NE branch watershed is a much more heterogeneous than NW branch in topography, land use patterns and riparian integrity. Extensive segments of both tributary streams and the main stream channels are channelized (fig. 28B). The pre-urbanized NE Branch had flat floodplains the occupied wide expanses of land adjacent to the channel in the downstream portion of each tributary and along the main stream. Channelization has modified these floodplains, but floodplain remnants exist throughout the lower tributaries and upper main stem. These floodplain remnants contain sedimentary units that are more permeable than the fractured bedrock in NW Branch Watershed.

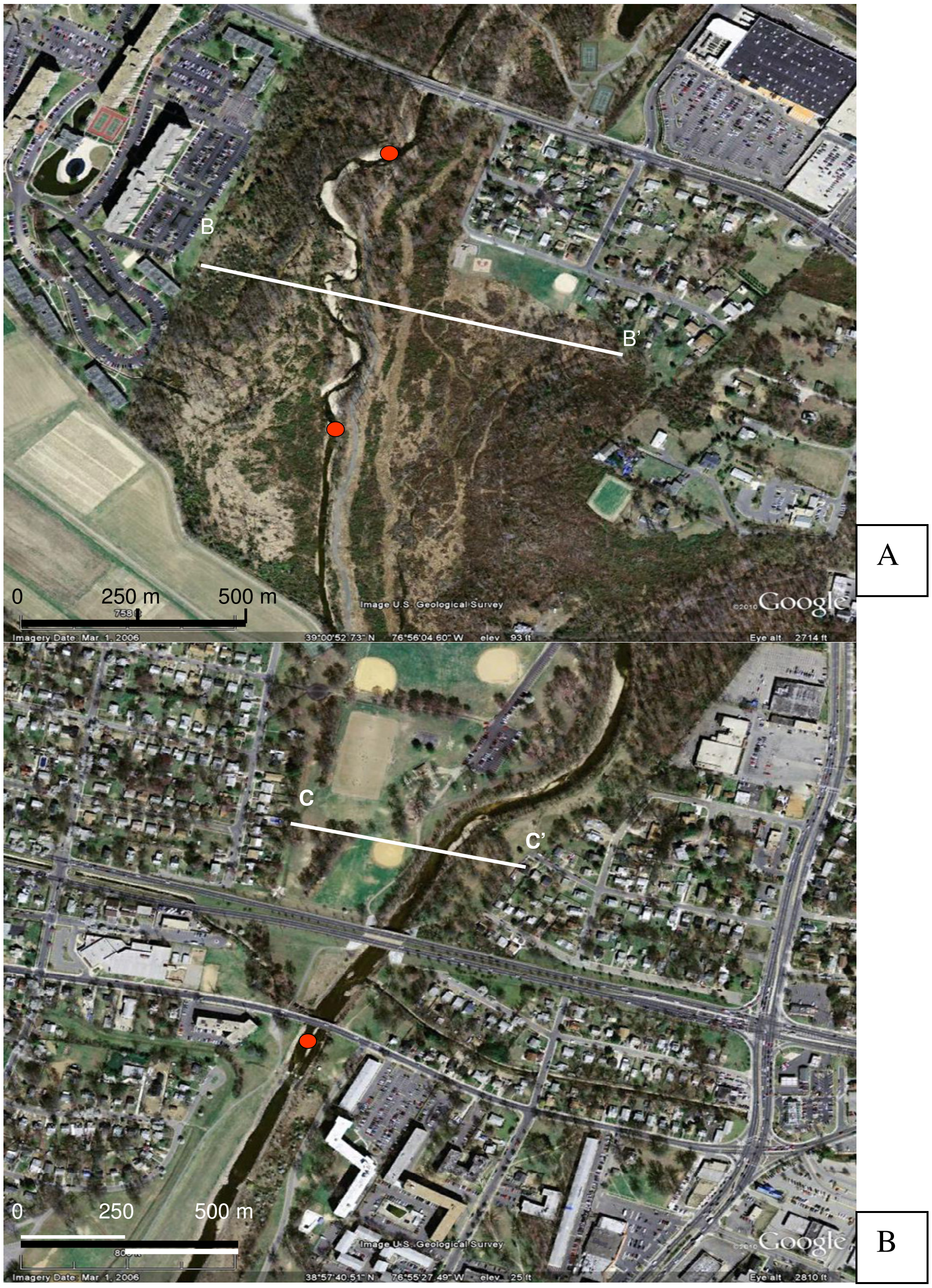


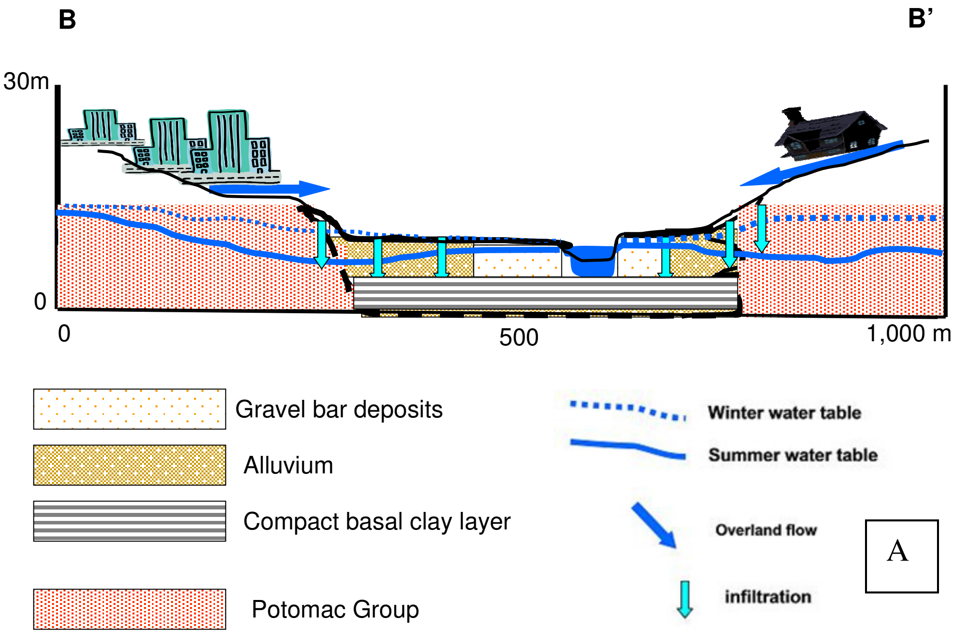
**Figure 28: (A) Cherry Hill upstream and downstream site (marked with red circles). Note the extensive floodplain remnant left intact. (B) Lower NE Branch watershed (USGS NE Branch gauge marked with red circle). Note the channelization in B where storm sewer systems are routed directly to the channel.**

The NE Branch tributary of Little Paint Branch Creek (fig. 28A) expands into a wide (500 m) floodplain just above the gauge location. The river has constructed a corridor of sediment bars of sand and gravel and the surrounding floodplain has silty soils, underlain by compacted clay (Blanchet, 2009). These floodplain remnants are rare within the NE Branch and are not as extensive as the riparian buffers within the NW Branch.

The Floodplain near the USGS NE Branch gauge is shown in figure 28B. This diagram shows the flood controlled channelized river, a narrowed floodplain (C to C'), and channelized tributary streams. In this portion of the watershed, storm runoff derived from urban areas is brought directly to the stream channel concrete channels. In such sites, little infiltration takes place in the floodplain.

Schematic cross sections for these two NE Branch watershed locations are presented in figure 29. In figure 29A, recent alluvial sediments and the underlying Potomac Group comprises the stratigraphy shown in the cross section. The gentle stream valley is underlain with a compacted clay layer with alluvial sediments along the sides of the channel. Extensive recent gravel bar complexes border the active channel. This floodplain remnant provides stormwater storage for the adjacent urban areas and only a small amount of the local overland flow runoff makes it to the channel. Extensive channelized portions of the stream above Cherry Hill, however, convey runoff directly into the channel.

In the lower portions of NE Branch Watershed, the floodplain is extensively developed and flood discharge is channeled from impervious surfaces to channelized tributaries, to the channelized main branch. There is little hydrologic communication between the channel and the floodplain in this portion of the watershed, therefore, the underlying geology has less affect on runoff response.



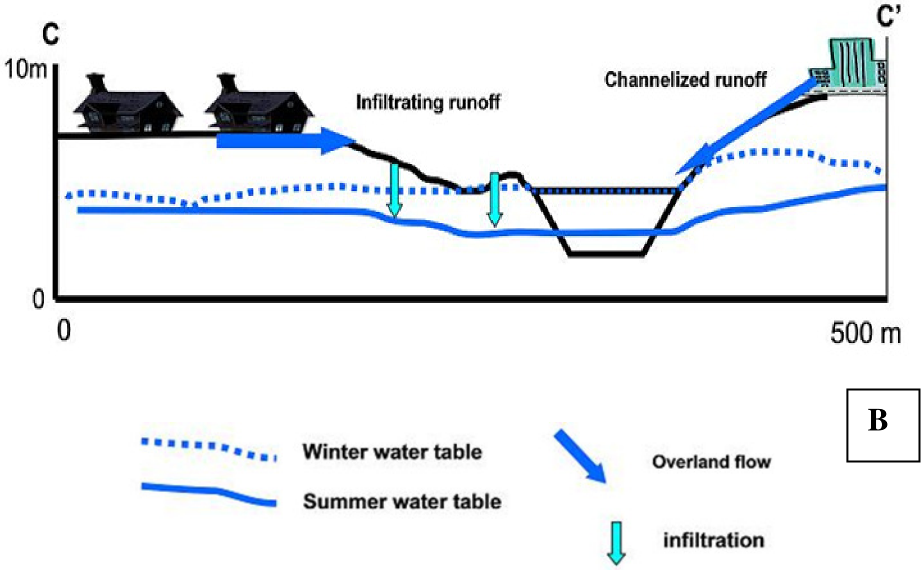


**Figure 29: (A) Schematic cross section of the Cherry Hill watershed location (B –B’). (B) Schematic cross section of the NE Branch gauging location (C - C’).**

Due to the low relief of the floodplains along NE Branch, the floodplains provide limited storage of stormwater. As indicated on the schematic cross sections in figure 29A, groundwater flows from the floodplain into the channels in winter, but reverses to flow from the channel into the floodplain during summer months when water tables are lower in the floodplains (Lundgren pers. Com). Floodplains also provide groundwater discharge to streams during large storm event. The limited storage for infiltrating precipitation in the floodplains creates similar floodplain groundwater compositions for summer storms and high winter baseflow. This may explain why post storm conductivity values are relatively constant for a wide variety of storm events.

## 5.9 Discussion and Evaluation of Hypotheses

### 5.9.1 Rise Time Analysis

The timing of old water contributions to storm hydrographs varied among the 4 gauged sites. In the NW Branch watershed, the old water contributions to storm hydrographs are rapid and arrive with the new water contributions. This suggests the two runoff processes are connected. The rapid old water response may be induced by infiltration of new water and piezometric response of the groundwater. The Piedmont tributary also showed a rapid groundwater response, including events where the old water response was several hours faster than the overland flow response. The NE Branch watershed showed a variety of behaviors, old water peaks arrived both faster and slower than the old water component.

Both of the upstream tributaries have shorter old water rise times. This indicates rapid groundwater outflow mechanisms that have been measured in upstream tributaries of NE Branch (Angier et al., 2001). The rise time analysis was used to provide a preliminary assessment of the old water delivery mechanism within the subsurface. This analysis does not provide any information about how storm characteristics affect these processes, which likely indicates that the subsurface discharge mechanism is related to watershed characteristics and modified by storm characteristics.

New water peaks arrived with or after the old water peaks for all storm hydrographs at all sites with the exception of lower NE Branch. This directly refutes the first hypothesis posed in this chapter. This was a surprising result considering the amount of impervious surfaces that contribute overland flow at each watershed location. It suggests that original, pre-urban runoff mechanisms still operate in the post-urban condition.

### 5.9.2 Baseflow dilution and Alternative Hydrograph Separation Analyses

Analysis of seasonal and storm-induced changes in baseflow conductivity suggests mixing of old and new water in subsurface reservoirs during storm events. The relative size of this mixed reservoir was examined using an alternative mixing model using time-dependent old water end-member compositions. The alternative hydrograph separation data indicated even higher contributions of subsurface flow to the channels and shifted the threshold for new water runoff dominance on the rainfall-runoff diagrams to higher precipitation values. This result is consistent with the third hypothesis listed within this chapter.

## 5.10 Conclusions

The results of this research indicate that hydrographic separation analyses can be combined with analysis of hydrograph characteristics and field examination to provide conceptual models of runoff generation in large urban watersheds. Results of this investigation indicate that subsurface contributions may come from several processes, including mechanisms that continue to operate in the watershed after urbanization. Although examination of streamflow generation mechanisms has not been evaluated for large urban watershed, understanding subsurface and subsurface storm water delivery mechanisms is an important first step in understanding contaminant transfer pathways.

# Chapter 6: Conclusions

## 6.1 Summary

Electrical conductivity was used as a tracer to separate multiple storm hydrographs at four watershed locations within the urban/suburban Anacostia watershed. The storm hydrographs used in this study were chosen to represent a range of storm magnitude, intensity and antecedent moisture conditions. Under certain conditions, specific conductivity is demonstrated to be an inexpensive, continuous tracer that can inform on streamflow generation processes within large, urban watersheds.

Overland flow runoff and total storm runoff did not show simple relationships to impervious cover in the watershed as is predicted from simple runoff models for small urban watersheds (e.g. Rational Method, SCS Curve Number). The main conclusion from the rainfall-runoff analysis is that these large urban watersheds behave differently than previously examined small watersheds in terms of total, new and old water runoff generation during storm events. For all sites analyzed the amount of overland flow runoff was significantly less than the amount of impervious surfaces and runoff increased with total storm precipitation, not precipitation intensity. These results suggest that infiltration of overland flow runoff likely occurs. Field examination of floodplain and riparian areas identified significant infiltration of surface runoff derived from urban developments, thus effectively decreasing the amount of total runoff. These infiltration zones are prominent along the length of NW Branch stream and are likely the cause for the total runoff coefficients for NW Branch. Floodplain and riparian zones can be viewed as “free” stormwater mitigation, particularly in regions where depth to the water table and soil storage capacities are significant.

The zone of riparian infiltration that lines the length of the NW Branch of the Anacostia may affect the transport of surface runoff contaminants (e.g. atmospherically-derived trace metals) to the stream.

The separated storm hydrograph results and other hydrograph data (rainfall-runoff relationships, old and new water rise time, and baseflow dilution) were used to evaluate old and mixed water runoff during a variety of storm events at four watershed locations throughout the NE and NW Branch Watersheds. At all the sites, old water was a portion of total runoff. This was a surprising result considering the amount of urbanization throughout the watershed. An alternative hydrograph separation analysis was conducted to evaluate minimum contributions of mixed water as subsurface flow. Further research is required to identify the mixed subsurface component of streamflow.

The results of this study and the physical characteristics of the watershed were used to develop conceptual models for the NE and NW Branches that were consistent with the rainfall-runoff ratios and hydrograph separation results for all four sites.

This study also serves to highlight the importance of intact riparian/floodplain fragments throughout urban watersheds. They are sites of overland flow infiltration and act as free storm water mitigation.

## 6.2 Implications

Watershed morphology can influence patterns of urban and suburban development. The organization of urban areas can affect hydrological processes and thus sediment transport and stream water quality. Riparian corridors and floodplains can serve as infiltration zones if they are located between urban runoff production areas and stream channels. Urban development on floodplains and riparian corridors, however, can convert these areas from sites of storm runoff infiltration to overland flow generation. Overland flow runoff generated on the floodplains is generally routed directly to streams by pipes or channels. The role of riparian and floodplain infiltration has implications for redevelopment projects in mature suburban or urban areas that have these natural infiltration features.

Much of the previous work on rainfall-runoff relationships in urban areas has been conducted on small watersheds (e.g., Rice, 1998). Small watersheds are predominantly on the upper fringes of larger watersheds and therefore are largely in groundwater recharge areas. These findings are then applied to watersheds of various sizes for water management purposes, some much larger than the watersheds that produced the experimental results. Effective impervious surfaces should be examined within large urban watersheds before any new development takes place, especially if developers are using simple runoff models to estimate the peak runoff.

Compared with hydrographs from non-urban watersheds of similar size, geology, and climate, watersheds with significant contributions from overland flow runoff sources produce a larger peak flow earlier in the storm hydrograph

(Gremillion et al., 2000). These changes in the storm hydrograph increase the frequency and magnitude of floods, which is particularly dangerous in densely populated urban areas (Lazaro, 1990).

Overland flow runoff transports contaminants from atmospheric sources to stream channels. Subsurface flow pathways, such as groundwater and shallow sub-surface flow discharge through soil macropores and matrices provide sites with organic carbon and oxyhydroxides of Fe, Mn, and Al that can sorb trace metals and organic contaminants from infiltrated water and retain it on soil surfaces (Scudlark et al., 2005). Overland flow runoff, by definition, does not infiltrate into the soils and thus does not interact with soil surfaces before entering the stream network. Therefore it transports more contaminants than subsurface discharge pathways. Understanding proportions of surface and subsurface flow paths contributions to the storm hydrograph can be a significant tool in understanding and mitigating water quality problems.

Large watersheds are not large versions of small watersheds. This study indicates that significant proportions of stormflow is generated by subsurface flow processes in 4 watersheds with basin areas > 10 $km^2$. With this in mind, predictive modeling needs to account for more complex flow paths, especially within the subsurface.

## References

Abdul, A. S., Gillman, R. W., (1984). Laboratory Studies of the Effects of the Capillary Fringe on Streamflow Generation: Water Resources Research, Vol. 20, No. 6, pp. 691-698.

Anamala, J., Zhang, B., Govindaraju, R. S., (2000). Comparison of ANNs and Empirical Approaches for Predicting Watershed Runoff: Journal of Water Resources Planning and Management, Vol. 126, No. 3, pp. 156-166.

Angier, J. T., (2001). Hydrologic Controls on Nitrate-N Removal in a Riparian System: PhD Dissertation, University of Maryland, College Park.

Bahaduri, B., Minner, M., Tatalovich, S., Harbor, J., (2001). Long-Term Hydrologic Impact of Urbanization: A Tale of Two Models: Journal of Water Resources Planning and Management, Vol. 127, No. 1, pp. 13-19.

Bedan, E. S. and Clausen, J. C., (2009). Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds: Journal of the American Water Resources Association, Vol. 45, No. 4, pp. 998-1008.

Berkowitz, B., Silliman, S. E., Dunn, A. M., (2004). Impact of the Capillary Fringe on Local Flow, Chemical Migration, and Microbiology: Vadose Zone Journal, Vol. 3, pp. 534-548.

Beven, K., Germann, P., (1982). Macropores and Water Flow in Soils: Water Resources Research, Vol. 18, pp. 1311-1325.

Beven, K. J., Kirkby, M. J., (1979). A Physically Based, Variable Contributing Area Model of Basin Hydrology: Hydrological Sciences Bulletin, Vol. 24, No. 1, pp. 43-69.

Blanchet, Z. (2009). Effects of Bar Formation on Channel Stability and Sediment Loads in an Urban Watershed: M.S. Thesis Dissertation, University of Maryland, Department of Geology.

Blume, T., Zehe, E., Bronstert, A., (2007). Rainfall-runoff Response, Event-based Runoff Coefficients and Hydrograph Separation: Hydrological Sciences Journal, Vol. 52, pp. 843-862.

Bohte, R., Mul, M. L., Bogaard, T. A., Savenije, H. H. G., Uhlenbrook, S., Kessler, T. C., (2010). Hydrograph Separation and Scale Dependency of Natural Tracers in a Semi-arid Catchment: Hydrology and Earth System Sciences Discussions, Vol. 7, pp. 1343-1372.

Booth, D.B., (1991). Urbanization and the Natural Drainage System– Impacts, Solutions and Prognoses: The Northwest Environmental Journal, Vol. 7, pp. 93-118.

Brun, S. E., Band, L. E., (2000). Simulating Runoff Behavior in an Urbanizing Watershed: Computers, Environment and Urban Systems, Vol. 24, pp. 5-22.

Buchanan, T. J., Somers, W. P., (2005). U.S. Geological survey, Techniques of Water-Resources Investigations: Book 3, Chapter A8.

Carlson, T. N., (2004). Analysis and Prediction of Surface Runoff in an Urbanizing Watershed Using Satellite Imagery: Journal of the American Water Resources Association, Vol. 40, No. 4, pp. 1087-1098.

Chow, V. T., (1964). Handbook of Applied Hydrology: A Compendium of Water-Resources Technology: McGraw-Hill Book Co., New York.

Dietz, M. E., Clausen, J. C., (2006). Saturation to Improve Pollutant Retention in a Rain Garden: Environmental Science Technology, Vol. 40, pp. 1335-1340.

Dingman, S. L., (1994). Physical Hydrology: Macmillan Publishing Company, New York, New York.

Dunne, T., (1978). Field Studies of Hillslope Flow Processes: Hillslope Hydrology, John Wiley and Sons, New York, New York, pp. 227-293.

Dunne, T. and Black, R.D., (1970). An Experimental Investigation of Runoff production in Permeable Soils: Water Resources Research., No. 6, pp. 478-90.

Dunne, T., Leopold, A., (1978) Water in Environmental Planning: W.H. Freeman, San Francisco, CA.

Fetter, C.W., 1994. Applied Hydrogeology Third Addition: McMillian, New York.

Genereux, D., (1998). Quantifying Uncertainty in Tracer-Based Hydrograph Separations: Water Resources Research, No.4, pp. 915-919.

Gremillion, P., Gonyeau, A., Wanielista, M., (2000). Application of Alternative Hydrograph Separation Models to Detect Changes in Flow Paths in a Watershed Undergoing Urban Development: Hydrologic Processes, Vol. 14, pp. 1485-1501.

Guo, J. C. Y., (1999). Detention Storage Volume for Small Urban Catchments: Journal of Water Resources Planning and Management, Vol. 125, No. 6, pp. 380-382.

Henderson, F. M., (1966). Open Channel Flow: Macmillan Publishing Company, New York, New York.

Heppel, C.M., Chapman, A.S., (2006). Analysis of a Two-Component Hydrograph Separation Model to Predict Herbicide Runoff in Drained Soils: Agriculture Water Management, Vol. 79, issue 2, pp. 177-207.

Herschfield, D. M., (1961). Rainfall Frequency Atlas of the United States for Durations From 30 Minutes to 25 Hours and Return Periods from 1 to 100 Years: Washington D. C., US Weather Bureau Technical Paper 40.

Hewlett, J. D., Hibbert, A. R., (1967). Factors Affecting The Response of Small Watersheds to Precipitation in Humid Areas: In: Proc. Int. Symposium on Forest Hydrogeology, pp. 275-290, Pergamon Press, New York.

Hoeg, S., Uhlenbrook, S., Leibundgut, C., (2000). Hydrograph Separation in a Mountainous Catchment-Combining Hydrochemical and Isotopic Tracers: Hydrologic Processes, Vol. 14, No. 7, pp. 1199-1216.

Horton, R. E., (1933). The Role of Infiltration in the Hydrologic Cycle: Transactions American Geophysical Union, Vol. 14, pp. 446-460.

Horton, R. E., (1945). Erosional Development of Streams and Their Drainage Basins: Geological Society of America, Special Bulletin, Vol. 56, pp. 275-370.

Huth, A. K., Leydecker, A., Sickman, J. O., Bales, R. C., (2004). A Two-Component Hydrograph Separation for Three High-Elevation Catchments in the Sierra Nevada, California: Hydrological Processes, Vol. 18, No. 9, pp. 1721-1733.

Joerin, C., Beven, K. J., Iorgulescu, I., Musy, A., (2002). Uncertainty in Hydrograph Separations Based on Geochemical Mixing Models: Journal of Hydrology, Vol. 255, pp. 90-106.

Konrad, C.P. and D.B. Booth, (2005). Hydrologic Changes in Urban Streams and Their Ecological Significance. In: Effects of Urbanization on Stream Ecosystems, American Fisheries Society, Symposium 47, Bethesda, Maryland, pp. 157-177.

Ladouche, B., Probst, A., Viville, D., Idir, S., Baque, D., Loubet, M., Probst, J. L., Bariac, T., (2001). Hydrograph Separation Using Isotopic, Chemical and Hydrological Approaches: Journal of Hydrology, Vol. 242, pp. 255-274.

Lazaro, T. M. (1990). Urban Hydrology: A multidisciplinary Perspective, Revised Edition: Technomic Publishing Company, Lancaster, PA.

Lee, J. G., and Heaney, J. P., (2003). Estimation of Urban Imperviousness and Its Impacts on Storm Water Systems: Journal of Water Resources Planning and Management, Vol. 129, No. 5, pp. 419-426.

Loague, K. M., Freeze, R. A., (1985). A Comparison of Rainfall-Runoff Modeling Techniques on Small Upland Catchments: Water Resources Research, Vol. 21, No. 2, pp. 229-248.

Matherne, A. M., (1991). Scale Changes in the Hydrologic Response of Watersheds: PhD Dissertation, University of Maryland, College Park.

Matsubayashi, U., Velasquez, G. T., Takagi, F., (1993). Hydrograph Separation and Flow Analysis by Specific Electrical Conductance of Water: Journal of Hydrology, Vol. 152, pp. 179-199.

McDonnell, J. J., (1990). A Rationale for Old Water Discharge through Macropores in a Steep, Humid Catchment: Water Resources Research, Vol. 26, pp. 2821-2832.

McDonnell, J. J., Owens, I. F., Stewart, M. K., (1991). A Case Study of Shallow Flow Paths in a Steep Zero-Order Basin: Water Resources Bulletin, Vol. 27, pp. 679-685.

McGlynn, B. L., McDonnell, J. J., Brammer, D. D., (2002). A Review of the Evolving Perceptual Model of Hillslope Flowpaths at the Maimai Catchments, New Zealand: Journal of Hydrology, Vol. 257, pp. 1-26.

MDNR, (2005). Characterization of the Anacostia River Watershed in Prince George's County, Maryland: Maryland Department of Natural Resources, DNR-14-1209-0021.

MGS, (1968). Geologic Map of Maryland: Maryland Geological Survey.

Miller, C. V., Gutierrez-Magness, A. L., Fiet Majedi, B. L., Foster, G. D., (2007). Water Quality in the Upper Anacostia River, Maryland: Continuous and Discrete Monitoring with Simulations to Estimate Concentrations and Yields 2003-05: United States Geological Survey, Scientific Investigations Report 2007 – 5142.

Mishra, S. K., Singh, V. P., (1999). Another Look at SCS-CN Method: Journal of Hydrologic Engineering, Vol. 4, No. 3, pp. 257-264

Molgen, G. E., Beighley, R. E., (2002). Spatially Explicit Hydrologic Modeling of Land Use Change: Journal of the American Water Resources Association, Vol. 38, No. 1, pp. 241-253.

Noguchi, S., Tsuboyama, Y., Sidle, R. C., Hosoda, I. (1999). Morphological Characteristics of Macropores and the Distribution of Preferential Flow Pathways in a Forested Slope Segment: Soil Science of America Journal, Vol. 63, pp. 1413-1423.

Occhi, M., (2009). Sources of Stream Discharge in the North East and North West Branches of the Anacostia Watershed: Unpublished manuscript.

O'Connell, M.E., (1998). Process Affecting the Discharge of Nitrate from a Small Agricultural Watershed over a Range of Flow Conditions, Maryland Coastal Plain: UMI number 9920983. pp. 204-224.

Pappas, E. A., Smith, D. R., Huang, C., Shuster, W. D., Bonta, J. V., (2008). Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation: Catena, Vol. 72, pp. 146-152.

Pearce, A. J., Stewart, M. K., Sklash, M. G., (1986). Storm Runoff Generation in Humid Headwater Catchments – Where Does the Water Come From?: Water Resources Research, Vol. 22, No. 8, pp 1263-1272.

Pellerin, B. A., Wollheim, W. M., Feng, X., Vorosmarty, C. J., (2008). The Application of Electrical Conductivity as a Tracer for Hydrograph Separation in Urban Catchments: Hydrological Processes, Vol. 22, pp. 1810-1818.

Pilgrim, D. H., Huff, D. D., Steele, T. D., (1979). Use of Specific Electrical conductance and Contact Time Relations for Separating Flow Components in Storm Runoff: Water Resources Research, Vol. 15, No. 5, pp. 329-339.

Rantz, S. E., et al., (1982). Measurement and Computation of Streamflow: Volume 2. Computation of Discharge: US Geological Survey Water-Supply Paper 2175, pp. 347.

Rice, K.C., Hornberger, G. M., 1998. Comparison of Hydrochemical Tracers to Estimate Source Contributions to Peak Flow in a Small, Forested, Headwater Catchment: Water Resources Research, Vol. 34, No. 7, pp. 1755-1766.

Roy, A. H. and Shuster, W. D., (2009). Assessing Impervious Surface Connectivity and Applications for Watershed Management: Journal of the American Water Resources Association, Vol. 45, No. 1, pp. 198-209.

Schiff, R., and Benoit, G., (2007). Effects of Impervious Cover at Multiple Spatial Scales on Coastal Watershed Streams: Journal of the American Water Resources Association, Vol. 43, No. 3, pp. 712-730.

Schueler, T., (1994). The importance of imperviousness: Watershed Protection Techniques, Vol. 1, No. 3, pp. 100-111.

Scudlark, J. R., Rice, K. C., Conko, K. M., Bricker, O. P., Church, T. M., (2005). Transmission of Atmospherically Derived Trace Elements Through an Undeveloped, Forested Maryland Watershed: Water, Air, and Soil Pollution, Vol. 163, pp. 53-79.

Sklash, (1990). Environmental Isotope Studies of Storm and Snowmelt Runoff Generation: M.G. Anderson and T. P. Burt, editors: Process Studies in Hillslope Hydrology, John Wiley and Sons.

Sklash, M. G., Farvolden, R. N., (1982). The use of environmental isotopes in the study of high runoff episodes in streams: Isotope Studies of Hydrologic Processes, DeKalb, IL, Northern Illinois University Press.

Sloan, P. G., Moore, I. D., (1984). Modeling Subsurface Stormflow on Steeply Sloping Forested Watersheds: Water Resources Research, Vol. 20, No. 12, pp. 1815-1822.

Taylor, J. R., (1982). An Introduction to Error Analysis: University Science Books, Mill Valley, CA.

Teague, J., Sneddon, J., Simmons, R., Parrish, J., Tice, M., Strong, M., (2006). Upper Anacostia Watershed Plant Communities of Conservation Significance. NatureServe, Arlington, Virginia.

Thurston, H. W., Goddard, H. C., Szlag, D., Lemberg, B., (2003). Controlling Storm-Water Runoff with Tradable Allowances for Impervious Surfaces: Journal of Water Resources Planning and Management, Vol. 129, No. 5, pp. 409-418.

USDA (1986). Urban Hydrology for Small Watersheds: Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55.

Velasquez, G. T., Matsubayashi, U., Takagi, F., (1992). An experimental Study on the Properties of Specific Electrical Conductance for use in Tracing the Components of Flow: Proceedings of Hydraulic Engineering, JSCE, Vol. 28, pp. 587-592.

Walsh, C. J., Fletcher, T. D., Ladson, A. R., (2005). Stream Restoration in Urban Catchments Through Redesigning Stormwater Systems: Looking to the Catchment to Save the Stream: Journal of the North American Benthological Society, Vol. 24, No. 3, pp. 690-750.

Weiler, M., Scherrer, S., Naef, F., Burlando, P., (1999). Hydrograph Separation of Runoff Components Based on Measuring Hydraulic Sate Variables, Tracer Experiments, and Weighting Methods: International Association of Hydrologic Sciences Publications, No. 258, pp. 245-255.

Weyman, D. R., (1970). Throughflow on Hillslopes and its Relation to the Stream Hydrograph: Bulletin of the International Association of Scientific Hydrology.

Winston, (1994). Ph.D. Thesis Dissertation, University of Maryland, Department of Geology.

Wood, E. F., Sivapalan, M., Beven, K., (1990). Similarity and Scale in Catchment Storm Response: Reviews of Geophysics, Vol. 28, pp. 1-18.

Wood, E. F., (1994). Scaling, Soil Moisture and Evapotranspiration in Runoff Models: Advances in Water Resources, Vol. 17, pp. 25-34.

Xiao, Q., McPherson, E. G., Simpson, J. R., Ustin, S. L., (1998). Rainfall Interception By Sacramento's Urban Forest: Journal of Arboriculture, Vol. 24, No. 4.