ABSTRACT

DREPS, CHRISTOPHER LEE. Water Storage Dynamics and Water Balances of Two Piedmont North Carolina Headwater Catchments. (Under the direction of Dr. April James).

In order to meet the great need for watershed restoration in the highly urbanized Piedmont Region of the USA, a stronger understanding of the basic functioning of headwater streams is required. The water balance is one of the most basic hydrologic models that can serve as a reference to guide headwater watershed, or catchment-level, restoration efforts. Although other water balances have been created within the Piedmont Region, none have been at the size and temporal scales appropriate for headwater watershed management and restoration.

This Master's Thesis compares the water balances of two forested headwater catchments of the same size (29 ha), under nearly identical climate and precipitation conditions, and both within the Carolina Slate Belt Ecoregion. One catchment, in Hill Forest (HF), has relatively steep topography and well-drained, clay subsoils, while the other catchment in Umstead Farms (UF) has relatively low-gradient slopes and low-conductivity, expansive clay soils. One year of continuous monitoring and analysis of the precipitation, weather, stream flow, shallow groundwater, and soil moisture revealed significant seasonal differences in the unsaturated and saturated-zone storage between the two catchments. Soil moisture and streamflow data reveal that the UF catchment stored more water in the shallow subsurface during the non-growing season (November-March). Topographical and typological (soil) differences were the major drivers influencing soil moisture storage dynamics. The UF

catchment's ability to store water was limited by a confining clay subsurface soil horizon, while the HF catchment stored a greater amount of water at depth.

The differences in storage dynamics caused significant differences in the daily cumulative, monthly, and seasonal water balances of the two catchments. The UF catchment displayed higher ratios of stream flow to precipitation (333 ± 17mm, or 52 ± 3%) than did HF (224 ± 11mm, or 33 ± 2%) during the non-growing season. During this same period, the HF catchment exhibited greater deep groundwater flux (261 ± 54mm, or 38 ± 8%) than UF (-24 ±67mm, or -4 ± 10%). During the late growing season 2009, UF produced almost no streamflow (6 mm, or 2%), while HF had higher streamflow (29 ± 1mm, or 14%), including continuous baseflow. Two separate approaches to estimating annual changes in soil moisture storage showed 64 ± 16mm (5 ± 1%) or 91 ± 23mm (7 ± 2%) storage change in HF and -51 ± 13mm (-4 ± 1%) or 50 ± 12mm (4 ± 1%) in UF. The monthly and seasonal water balances revealed significant differences in HF and UF water balances, with more storage appearing to occur in both catchments during the non-growing season. The daily cumulative water balance best revealed the dynamics of water balance changes.

Hydrologic differences in these catchments are not fully explained by geology or the Ecoregion concept. The "hydrologic landscape" concept provides a useful framework for describing possible drivers behind the hydrologic differences in the HF and UF catchments.

Hydrologic landscapes have been mapped at a national level, but local mapping could provide useful insight to improve our understanding of reference hydrology in the region.

Water Storage Dynamics and Water Balances of Two Piedmont North Carolina Headwater Catchments

by
Christopher Lee Dreps

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

Forestry

Raleigh, North Carolina

January 11, 2011

APPROVED BY:

_____	_____
April L. James, Ph.D. Committee Chair	Ge Sun, Ph.D.
_____	
David Genereux, Ph.D.	

DEDICATION

To Sophia, Thomas, and Eva Brooke.

BIOGRAPHY

Chris Dreps lives and works in Durham, North Carolina. His professional experience includes directing the Upper Neuse River Basin Association, working as an environmental consultant, serving as a Peace Corps Volunteer in Africa and Central America, and managing an outreach program to migrant and seasonal farm workers in eastern North Carolina. Chris holds a BA in Latin American Studies from UNC-Chapel Hill and a MS in Planning from the University of Arizona. His favorite activities are gardening, hanging around with his kids, and being social.

ACKNOWLEDGMENTS

While creating this Master's thesis, my family endured my many distractions in front of a computer, on the phone, or away in the woods. Thank you to my wife, Sylvia, and our children, Sophia, Thomas, and Eva for your patience and support. Sylvia, you have been my greatest supporter during this project. To my kids, I hope you learn that science is important, fun, and a potential career for serving others and bettering the world.

Thank you so much to April James for your advice, patience, and generosity of time and resources. You did a great job keeping me focused on producing good research despite my natural inclinations to wander.

Thanks also to Ge Sun and Johnny Boggs at the US Forest Service for your great collaboration and patience. You both are so refreshing to work with, and your genuine interest in science is contagious.

Thank you to Dave Genereux for your patience and guidance as I tried to figure out what in the heck happens to water below a depth of one meter.

Thanks to so many others who have gone out of your way to help me with my myriad questions and musings. Thank you to Aziz Amoozigar and Joseph Kleiss for your sage guidance as I explored the world of soils and water. Your conversations, listening skills, and equipment loans often set me on the correct path. Thanks to Mike Vepraskas and Chris

Niewoehner for your time, advice, and even the a-a' Dipiridyl dye that proved critical in my soils analyses. Thank you to Josh Heitman and Adam Howard for the generous use of your soils lab, answers to my questions about how soils work, and equipment loans. Thanks to Erika Cohen at US Forest Service for helping me navigate MODIS data and GIS. Thanks also to Jerry Stimpson for your willingness to help us understand the soils under our feet at Umstead Farms.

TABLE OF CONTENTS

LIST OF TABLES viii
LIST OF FIGURES ix
CHAPTER 1: INTRODUCTION 1
1.1 Quantifying Reference Hydrology Conditions for Watershed Management 1
1.2 The Need for Headwater Catchment Research 3
1.3 Water Balance Applications in the Southeast United States 5
1.4 General Research Objectives and Organization of the Thesis 9
1.5 Study Catchment Descriptions 11
1.5.1 Catchment Locations 11
1.5.2 Climate 12
1.5.3 Topography 13
1.5.4 Land Use 13
1.5.5 Soils 14
CHAPTER 2: WATER STORAGE DYNAMICS IN THE HILL FOREST AND UMSTEAD FARMS CATCHMENTS 17
2.1 Introduction and Literature Review 17
2.2 Objectives 23
2.3 Methods 23
2.3.1 Soil Characterization 23
2.3.2 Estimation of Change in Shallow Storage 26
2.3.2.1 Saturated-zone Change in Storage 27
2.3.2.2 Unsaturated-zone Change in Storage 30
2.3.3 Estimation of Catchment-scale Change in Storage 33
2.3.3.1 “One-dimensional (1-D)” Scenario 33
2.3.3.2 “Three-dimensional (3-D)” Scenario 34
2.4 Results 39
2.4.1 Soil Characterization 39
2.4.1.1 Soil Type and Textural Analysis 39
2.4.1.2 Saturated Hydraulic Conductivity 42
2.4.2 Change in Shallow Storage 44
2.4.2.1 Riparian Groundwater Storage 44
2.4.2.2 Unsaturated-zone Storage 47
2.4.3 Estimating Catchment-scale Storage 49
2.4.3.1 1-D Scenario 49
2.4.3.2 3-D Scenario 50
2.5 Discussion 55
2.6 Conclusions 59
CHAPTER 3: WATER BALANCES FOR THE HILL FOREST AND UMSTEAD FARMS CATCHMENTS 61
3.1 Introduction and Literature Review 61
3.2 Objectives 66

3.3 Methodology: Water Balances....66
3.3.1 Precipitation....68
3.3.2 Evapotranspiration....69
3.3.3 Catchment Stream Discharge....71
3.3.4 Change in Unsaturated and Saturated-zone Storage....71
3.3.5 Groundwater Flux....72
3.3.6 Uncertainty in Water Balance Components....73
3.4 Results....75
3.4.1 Precipitation....75
3.4.2 Evapotranspiration....75
3.4.3 Catchment Stream Discharge....77
3.4.4 Change in Storage....78
3.4.5 Groundwater Flux....80
3.4.6 Daily Cumulative Water Balance....81
3.4.7 Monthly, Seasonal, and Annual Water Balances....82
3.5 Discussion....85
CHAPTER 4: CONCLUSION....89
REFERENCES....92
FIGURES AND TABLES....109
APPENDICES....152
APPENDIX 1: Soil Profile Descriptions and Well Drawings....153
APPENDIX 2: Well Calibration Results....173
APPENDIX 3: HF and UF Bi-monthly Soil Moisture Profiles....176

LIST OF TABLES

Table 1. Terrain and Soil Characterization of the HF and UF Catchments 113
Table 2. Calibration for the HF and UF Riparian Groundwater Wells 118
Table 3. Criteria for Defining HF Upland, Hillslope, and Riparian Units 119
Table 4. Criteria for Defining UF Upland and Hillslope Units 119
Table 5. HF Soil Physical and Hydrologic Properties 122
Table 6. UF Soil Physical and Hydrologic Properties 123
Table 7. HF and UF Seasonal Profile Average and Depth-specific Volumetric Soil Moisture Contents at UF T2 and HF T1 136
Table 8. Monthly, Seasonal, and Annual Water Balances of the HF Catchment 148
Table 9. Monthly, Seasonal, and Annual Water Balances of the UF Catchment 149

LIST OF FIGURES

Figure 1: Location of Study Catchments in Falls Lake Watershed 110
Figure 2: Hill Forest Catchment with USFS Streamflow Gauging Locations..... 111
Figure 3: Umstead Farms Catchment with USFS Streamflow Gauging Locations..... 112
Figure 4: Hill Forest Catchment Soils 114
Figure 5: Umstead Farms Catchment Soils 115
Figure 6: HF Catchment Topography and Monitoring Sites 116
Figure 7: UF Catchment Topography and Monitoring Sites 117
Figure 8: Calibrated Water Table Levels for HF Well 2 118
Figure 9: Hill Forest Upland, Hillslope, and Riparian Landscape Units 120
Figure 10: Umstead Farms Upland and Hillslope Landscape Units..... 121
Figure 11: HF Catchment Soil Textural Analysis by Landscape Unit Type 124
Figure 12: UF Catchment Soil Textural Analysis by Landscape Unit Type 125
Figure 13: HF Hillslope Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities 126
Figure 14: HF Upland Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities 127
Figure 15: UF Hillslope Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities 128
Figure 16: UF Upland Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities 129
Figure 17: Daily Precipitation and Groundwater Levels for the HF Catchment for July 2009 to July 2010..... 130
Figure 18: Daily Precipitation and Groundwater Levels for the UF Catchment for July 2009 to July 2010..... 131
Figure 19: Average Daily Groundwater Levels Used to Represent Changing Saturated-zone Storage in HF and UF 132
Figure 20: UF Catchment Perched Water Table Levels below Ground Surface..... 133
Figure 21: Daily Precipitation and Mean Daily Volumetric Soil Moisture Content of Four Depths at the HF T1 Continuous Site 134
Figure 22: Daily Precipitation and Mean Daily Volumetric Soil Moisture Content of Four Depths at the UF T2 Continuous Site 135
Figure 23: Daily Profile Average Soil Moisture at HF T1 and UF T2 Sites for July 2009 to July 2010..... 136
Figure 24: Bi-monthly Soil Moisture Profiles (access tubes) at the HF T1(a) and UF T6 (b) Sites..... 137
Figure 25: HF and UF Soil Moisture Profile Averages Using 3-D Approach..... 138
Figure 26: HF Hillslope, Upland, and Riparian Soil Moisture Profile Averages Based on the 3-D Analysis 139
Figure 27: UF Hillslope and Upland Soil Moisture Profile Averages Based on the 3-D Analysis..... 140
Figure 28: T3 Template Characterizing the HF and UF Catchments (Buttle 2006)..... 141

Figure 29: HF Daily Precipitation, ETo, and Streamflow 142
Figure 30: UF Daily Precipitation, ETo, and Streamflow 143
Figure 31: FAO Grass-reference PET..... 144
Figure 32: Comparison of Daily FAO Grass-reference PET Values Derived from NC Climate Office and Hill Forest Climate Data 145
Figure 33: Cumulative Daily Water Balance for the Hill Forest Catchment..... 146
Figure 34: Cumulative Daily Water Balance for the Umstead Farms Catchment..... 147
Figure 35: Conceptual, Non-growing Season Water Balance Models of the HF and UF Catchments..... 150
Figure 36: UF Catchment-Type Hydrologic Landscapes in the Falls Lake Basin 151

INTRODUCTION

1.1 Quantifying Reference Hydrology Conditions for Watershed Management

Surface water is the primary source of water supply in the United States, and its increasing scarcity and degradation are among the greatest natural resource management challenges facing people all over the world (Kenny et al. 2009). Here in the Piedmont region of North Carolina, droughts and drought-related water quality degradation exist despite a generous average annual rainfall of over 45 inches (1,140 mm) (NC Climate Office 2010, NC Drought Management Advisory Council 2010). That is to say, the water scarcity problem is, in large part, one of water management.

For example, many communities face low reservoir levels and water restrictions each summer, while at the same time our stormwater management regulations require that we "manage" rain water by releasing it directly into streams through storm drainage systems. Two ironic results of this management are that 1) we miss the opportunity to store and use massive volumes of water and 2) released excess storm water is the root cause of stream and river degradation (US EPA 2002, NC DENR 2009). Harvesting, using, and infiltrating rainwater closer to where it falls could alleviate these problems (US EPA 2000, Dietz 2007). Many innovative site and watershed management approaches (e.g. "Stormwater Low-Impact Development" or watershed management plans) attempt to maintain or restore "pre-development hydrologic conditions" in disturbed areas (US EPA 2000, Dietz 2007).

However, what does "pre-development hydrologic conditions" mean in the Piedmont region of North Carolina?

Water resource managers are currently interested in land management approaches that more effectively mimic natural, forested hydrologic conditions (Dietz 2007, Roy et al. 2008). However, such practices as stormwater Low-Impact Development are almost always limited to site-level analysis, and there is a dearth of practical information about the natural, or "reference" hydrology at the small watershed scale (see Roy et al. 2008; Dietz and Claussen 2005 for example). The question still remains, ***"What is the natural, reference hydrology of a Piedmont headwater watershed?"*** With the goal of answering this question, this master's thesis provides 1) detailed comparisons of watershed storage processes and 2) detailed water balances for two headwater catchments in the Piedmont region of North Carolina. Since both of the study catchments overly Slate Belt geology but differ significantly in soil type and topography, current conceptual models are used to describe their hydrologic differences, or hydrologic landscapes (Winter 2001, Buttle 2006) and the potential drivers of these differences.

It is clear to historians and naturalists that the Piedmont was heavily farmed and forested during the nineteenth and twentieth centuries and that up to half of Piedmont landscapes are in secondary succession, with pines giving way to hardwoods (Godfrey 1997). This is true for both the study catchments. Trees in the Hill Forest are generally about 30 years old (Hazel et al. 1989, Boggs et al. 2010), while those in the Umstead Farms are up to 70 years

old (Boggs et al. 2010). Thus, for this study, "reference conditions" should be understood to mean typical forested conditions in the Piedmont region of today and not a "pristine" condition that might have occurred prior to the mass deforestation brought by European settlers.

1.2 The Need for Headwater Catchment Research

Studies at the catchment scale are needed because small, first or second-order "headwater" streams comprise over 70% of total stream length in US river systems (Leopold et al. 1964), so the great majority of our land is drained by headwater streams. Research shows that headwater streams respond strongly to the land around them, and land use changes strongly affect headwater stream hydrology (Burns et al. 2005, Freeman et al. 2007), ecology (Wipfli et al. 2007) and water quality (Alexander et al. 2007). The result is that land use changes over large areas and many headwater streams can impact regional water resources (Freeman et al. 2007).

Since small stream hydrology is strongly influenced by watershed land use, an understanding of the natural, or "reference" hydrology of small watersheds is useful for watershed management. In this project, small watersheds of less than one square mile area are referred to as "catchments." The catchment is the scale at which urban development, agriculture, and much forestry in the U.S. Southeastern Piedmont region is undertaken. Therefore, the catchment scale is appropriate and necessary for developing an understanding of reference

hydrology for practical use in watershed planning and management (Center for Watershed Protection 1998).

Despite the emerging understanding of the ecological and water quality-related importance of headwater streams and their watersheds (Meyer et al. 2007), regulations and practice are not based on a full understanding of the functions of headwater watersheds. Bishop et al. (2008) used the phrase "aqua incognita" to describe the problem of the lack of mapping and understanding of the characteristics of headwater streams. The authors encourage researchers to generalize our detailed studies of a few headwater streams into "systematic inventories and classification systems needed to make an assessment of headwaters and how they are altered by human influence."

During the last decade, several approaches for classifying hydrologic systems have been developed for practical application in the water resources and watershed management fields. Recent conceptual hydrology literature defines the "hydrologic landscape" on the basis of land-surface form, geology, and climate (Winter 2001, Wolock et al. 2004, Devito et al. 2005, and Buttle 2006). Winter (2001) defined the hydrologic landscape as "a complete hydrologic system consisting of surface runoff, ground-water flow, and interaction with atmospheric water" and envisioned it as a conceptual framework that would be the "foundation for design of studies and data networks, syntheses of information on local to national scales, and *comparison of process research across small study units in a variety of*

settings." In other words, the hydrologic landscape should be the basis for watershed research, and by extension, management.

Wolock et al. (2004) delineated hydrologic-landscape regions for the United States, and Santhi et al. (2008) used the model to make regional estimations of baseflow. Other authors have attempted to update the classification of hydrologic landscape units for regional-scale use (Devito et al. 2005) and refine the concept for the local scale (Buttle 2006). Devito et al. (2005) argued that climate, bedrock geology, surficial geology, and soil type and depth should be considered prior to topography for regional scale hydrologic modeling.

Buttle (2006) extended the classification approach to the small-watershed scale with the T3 Template, a conceptual model useful for comparing the relative controls exerted on catchment hydrology by topography, typology (controls on lateral flow), and topology (connectedness of the surface drainage network). The T3 Template compares catchments within the same climatological zones, allowing the user to focus more directly on physical characteristics of the catchments. In this study T3 is used to compare the drivers of catchment hydrology in the two catchments. The T3 template is discussed in more detail in section 2.5.

1.3 Water Balance Applications in the Southeast United States

One of the most basic tools of the hydrologist, the water balance is a budget of water in a given area for any given period of time. Water balances vary from annual, large-scale

balances that provide general guidance about management of a resource (Moreau and Challa 1985) to daily or monthly, small-scale water balances that investigate water movement (Sun et al.. 2002, Guan et al. 2010). Water balances are used for various purposes such as estimating potential water supplies, forecasting river flow (Alley 1984), analyzing the effect of rainfall on hydrologic behavior (Tomasella et al. 2008), modeling water quality (Moreau and Challa 1985), modeling soil water availability (Moroizumi et al. 2008) and water project design (Xu and Vandewiele 1995).

The general water balance approach used in watersheds is a mass-balance equation that assumes all inputs of water (precipitation or groundwater, for example) equal the outputs (such as evaporation, plant transpiration, or streamflow). The basic equation looks like the following:

$$P = ET + Q + G + \Delta S \quad (1)$$

P = precipitation

ET = evaporation + plant transpiration (evapotranspiration)

Q = streamflow

G = groundwater flux from watershed

ΔS = changes in the amount of water stored within the catchment

Many variations on this basic water balance equation exist, and they vary based on the study objective, the physical system, or the type or amount of data available. For example, evaporation and transpiration can be measured separately using very expensive, time-consuming processes, or they can be estimated using basic weather data.

Despite the importance of the water balance as a practical management tool, there is a dearth of catchment-scale, fine temporal resolution (daily or monthly) water balance studies in the Piedmont region of the Southeastern USA. The great majority of existing water balances have been large-scale or based on a few parameters. For example, Mohamoud (2004) created monthly and daily water balances for four Piedmont watersheds ranging in size from 23 to 585 km^2 (in Maryland and Virginia) based on long-term stream flow and regional data/assumptions of precipitation, weather, and soil moisture. A local example of a large-scale water balance is the 1985 Moreau and Challa model calculating monthly balances for Jordan Lake, which has a watershed of over 2,000 square miles. This study used stream flow to the lake as the major input and focused on flow between sectors of the water supply reservoir. Although regional models such as these are very informative for reservoir and water resource managers, their basin-wide scale limit their use as references for watershed managers, who are often tasked with solving watershed-scale (a few square-miles or less) problems and thus need a basic understanding of the pre-development catchment-scale processes that can serve as a benchmark for targeting management strategies.

Chapter 3 describes the handful of small-scale North Carolina water balances relevant to the current study. Some small-scale, annual water balances exist and can provide useful insights for the current research. Schäfer et al. (2002) calculated three annual hydrologic balances for small (30-m. diameter) land plots in the nearby Duke Forest in Durham, N.C. This study was not at the catchment scale, there was no streamflow data, and the researchers estimated drainage and overland flow using a model based on physical parameters and directly measured precipitation, through-fall, shallow (30 cm) soil moisture, and climatic parameters. Kovnee (1957) and Lieberman and Fletcher (1947) calculated annual water balances for small (30-acre, or 12-hectare) mountain catchments in the Coweeta Hydrologic Observatory. These water balances assumed no annual changes occurred in unsaturated storage.

Non-Piedmont monthly and seasonal water balances have been calculated in North Carolina. Sun et al. (2002) compared long-term and annual water balances of coastal and mountain watersheds but did not consider changes in soil moisture storage. Harder et al. (2007) quantified annual and seasonal coastal plain water balances in the US Forest Service Santee Experimental Forest in South Carolina. The Harder et al. (2007) study directly measured shallow soil moisture storage and compared various models for estimating ET and thus provides useful insights for the current research. These water balances are described in more detail in Chapter 3.

Finally, a recent Master's thesis by Keyworth (2008) created a water balance for a small, suburban watershed within the Falls Lake Basin in nearby Wake County. The thesis focused on both natural and human induced inputs and outputs as part of the balance. Although conceptually and practically useful for water managers, the Keyworth study did not include watershed streamflow or storage data. Water balance calculations created by the present study can provide baseline hydrologic quantifications to inform future efforts similar to the Keyworth (2008) study.

1.4 General Research Objectives and Organization of the Thesis

This research hypothesizes that the components of the water balance will vary greatly between small watersheds on very different soils and geologic parent materials, with other factors such as climate, watershed size, and vegetation being equal. Both catchments lie within the Carolina Slate Belt geologic region, which consists mainly of up to 600 million year-old crystalline rocks of volcanic or metamorphosed volcanic or sedimentary origin (Daniels et al. 1999, NCGS 1964). Although the catchments have similar geologic origins, experience the same climate, and have similar vegetation, they have distinct topography and soils. The remainder of Chapter 1 provides an introduction to the study catchments, generally describing site soils, topography, geography, and climate. In addition, basic soil characteristics such as texture and bulk density are described to provide background information for analyses described in Chapter 2.

Chapter 2 compares shallow (1 m.) soil moisture dynamics occurring in each catchment over the period of thirteen months, from July 1, 2009 until July 31, 2010. Soil moisture storage in both the unsaturated and saturated zones are quantified using one continuous soil moisture monitoring location, five to six dispersed, periodically-measured soil profile monitoring locations, and 3 continuous riparian water table wells in each catchment. The resulting data are used to generate estimates of changing storage within the top 1 m. of the soil profile across the catchment. Changes in unsaturated soil moisture are estimated using a representative soil profile (1-D) and a spatially-integrated (3-D) approach. The specific objectives and methods are described in Chapter 2. The resulting soil moisture calculations are compared using Buttle's conceptual T3 template, a conceptual model of the major drivers affecting soil moisture storage in each catchment.

Chapter 3 develops monthly and cumulative daily water balances for the HF and UF catchments. A basic research question that has not been answered but is important in the water resources management of the urbanizing Piedmont region is: What are the basic differences between the water balances of headwater catchments in differing hydrologic landscapes? If hydrologic differences exist, can they be explained by parameters in the water balances? Can any differences in individual water balance components be attributed to any differences in typology, topology, and topography as defined by the T3 template (Buttle 2006)? The products of Chapter 3 are daily cumulative water balances, monthly water balances, and quantified conceptual water balance models for the HF and UF catchments.

1.5 Study Catchment Descriptions

The Piedmont Region is home to millions of people, covering portions of Alabama, Georgia, South Carolina, North Carolina, Virginia, D.C., Maryland, Pennsylvania, New Jersey, and New York and the major metropolitan areas of Atlanta, Charlotte, Raleigh, Richmond, D.C., Philadelphia, and New York City (Commission on Environmental Cooperation 2006). This research focuses on two small, Piedmont headwater catchments that are part of a US Forest Service (USFS) watershed study on the effectiveness of current Forestry Best Management practices in the Falls Lake Watershed of North Carolina. The Falls Lake Watershed in the upper Neuse River Basin (Hydrologic Unit Code 03020201) covers a six-county area in the Piedmont region of North Carolina in the eastern USA (Figure 1).

1.5.1 Catchment Locations

This master's thesis focuses on two 73-acre (29.5-hectare) catchments shown in Figure 2 and as HFW1 and in Figure 3 as UF2. The HFW1 catchment lies within NC State University's 2,540-acre (1,028-hectare) Hill Demonstration Forest in the upper NC Piedmont. This catchment lies in the Carolina Slate Belt over intrusive metamorphosed granitic rock (Daniels et al. 1999, NC Geological Survey 1964, Griffith et al. 2002). At HFW1, a historical weir was re-established for the USFS buffer study, and the USFS established two flumes gauging the nested control (HF2) and treatment (HF1) catchments. For the purpose of this Master's Thesis, HFW1 is the gauging station used to delineate the study catchment, and HFW1 is heretofore described as the Hill Forest (HF) catchment.

The USFS is also studying two catchments at Umstead Farms (UF), located 5 miles east of the HF catchment and overlying the same geology (NC Geological Survey 1964, Griffith et al. 2002). The USFS study catchments at UF include a 73-acre (29.5-hectare) control (UF2) catchment and a 30-acre (12-hectare) treatment (UF1) catchment (see Figure 3). Each catchment is outfitted with a flume and rain gages, described in more detail in later sections. This research focuses on only the UF2 catchment, heretofore referred to as the UF catchment.

There is disagreement about the location of the HF and UF catchments on maps of ecological regions. The US Environmental Protection Agency's (EPA) map of North and South Carolina (Griffith et al. 2002) shows both HF and UF in the Carolina Slate Belt. However, the US Forest Service's map of ecological subunits (ECOMAP 2007) describes HF as being in the Carolina Slate Belt and UF in the "Southern Triassic Uplands." The USGS Ecoregions map aligns the Carolina Slate Belt and Triassic Basin Ecoregions strictly along geological divides, placing both catchments in the Carolina Slate Belt. Although for this study the exact definition of an ecological region is a moot point, this disagreement illustrates the need for a more hydrologically-based set of parameters for describing watersheds (Winter 2001). This research further underscores that need.

1.5.2 Climate

The Upper Piedmont has a warm, humid climate, with mean annual temperatures of 58° F (14° C.) and ranging from 56° F (13° C.) to 61° F (16° C.) (NC Climate Office website, http://www.nc-climate.ncsu.edu). Since the beginning of available temperature records for

the region (1895), mean monthly temperatures have ranged from 39.8° F (4.3° C.) in January to 76.1° F (24.5° C.) in July. Precipitation falls primarily in the form of rain, with occasional winter (Dec.-Mar.) snows. Average annual precipitation is 44.4 inches (1130 mm) and ranges from 26 to 61 inches (660 to 1550 mm). Mean monthly precipitation for the period of record ranges from 2.8 inches (71 mm) in November to 4.8 inches (122 mm) in July.

1.5.3 Topography

Table 1 characterizes the terrain and soils of the HF and UF catchments. The topography of the HF catchment is rolling, with slopes ranging from zero to 25% (NRCS 1971) and elevation between 540 and 700 ft. above sea level. Average slope is 13%, and total relief is 160 feet. The average slope in the UF catchment is 7%, and total catchment relief is 94 feet.

1.5.4 Land Use

Both HF and UF are predominately forested catchments with historic farming and logging evident from the age of tree stands and landforms left by old farm roads (Boggs et al. 2010) The HF catchment was forested with loblolly pine (*Pinus taeda* L.) in 1982 (Hazel et al. 1989). Tree core samples indicate that the age of the largest riparian trees in HF are 30-35 years. Currently, land use in the HF catchment is completely forested. The major species of the lower hillslopes and valley bottoms are loblolly pine (*Pinus taeda*.), white oak (*Quercus alba*), mockernut hickory (*Carya tomentosa*), American beech (*Fagus grandifolia*), and sourwood (*Oxydendrum arboreum*). In the drier, upland areas, Virginia pine (*Pinus virginiana*) and chestnut oak (*Quercus montana*) with an understory of blueberries

(*Vaccinium* spp.) dominate. In areas of more recent disturbance, little thinning has occurred, and large dense patches of common blackberry (*rubus argutus*) have taken hold.

The UF catchment is primarily a mixed forest with some stands up to 65-70 years old (Boggs et al. 2010). The catchment is 92% forested, and 8% along the western uplands are under agriculture. The primary forest species in the UF catchment are loblolly pine (*Pinus taeda*.), white oak (*Quercus alba*), tulip poplar (*Liriodendron tulipifera*), and sourwood (*Oxydendrum arboreum*), with large areas of common blackberry (*rubus argutus*) in the understory. It is potentially important to note that rush (*Juncus* spp.), a wetland indicator, is common in the riparian and non-riparian understory throughout the UF catchment. During the period of this study, the agricultural areas of the UF catchment were fallow, with a mix of grasses.

1.5.5 Soils

Soil Systems of North Carolina (Daniels et al. 1999) recognizes that soils of the Carolina Slate Belt Soil System vary greatly with slope and elevation. Flat uplands tend to have deep, residually-formed soils, while flat valley lands tend to be deep and formed by alluvium and colluvium from the more eroded steep slopes, on which soils are shallow (Daniels et al. 1999). For both the HF and UF catchments, soils surveys from the US Natural Resources Conservation Service provided background information on soil type (USDA 1971, 1997, 2010). Interviews and site visits with professional soil scientists verified the mapping information in the soils surveys (personal communication, Jerry Stimpson, retired NRCS soil scientist).

Table 1 provides a general characterization of the soils of the HF and UF catchments. Figures 4 and 5 are soil maps of the HF and UF catchments, respectively. In HF, Tatum is the dominant soil series, covering 55% of the catchment, primarily on hillslopes around stream areas. The Tatum series (fine, mixed, semiactive, thermic Typic Hapludults) formed over residuum from sericite schist, phyllite, or other fine-grained metamorphic rocks (USDA 2010). The Tatum E series has 15% to 25% slopes (USDA 1971, 2010), and many locations in the hillslopes around the HF valley are greater than 40%. The Georgeville, Cecil, and Appling series, which are hydrologically very similar upland soils, cover the remaining 45% of the HF catchment. Both the Appling and Cecil soil series are fine, kaolinitic, thermic Typic Kanhapludults formed in residuum weathered from felsic igneous and high-grade metamorphic rock (USDA 2010). The Georgeville series are also fine, kaolinitic, thermic Typic Kanhapludults, but are formed in residuum weathered from fine-grained metavolcanic rocks (USDA 2010). All of the upland Typic Kanhapludults are deep, with depth to bedrock greater than 5 feet (USDA 1971). All the hillslope and upland soils in HF are classified as well-drained, indicating that depth to typical water table is estimated as greater than 6 ft. (USDA 2010). The Tatum series, because it has mixed mineralogy, has semiactive clays that are described as having moderate shrink-swell potential. The Appling and Georgeville series of the HF catchment have clay layers in the subsurface, but these are kaolinitic clays with low shrink-swell potential (USDA 1971).

The existing soil series map of HF represents riparian areas in catchment as Tatum; however, initial field studies of the soil prove that the riparian soils are morphologically distinct from the surrounding Tatum soils, with much sandier surface and subsurface horizons. The omission of these riparian soils is common in soil surveys because the scale of the soil mapping (1:20,000) does not recognize small inclusions of other soil series. Analysis described later in this study addresses HF riparian soils as distinct units (see Section 2.3.3.2). For the purpose of this general soils analysis, the HF riparian soils are generally described as belonging to the less developed Entisols.

Both USDA soil surveys (USDA 1997, 2010) and field visits confirm that the Helena series is the dominant series in the UF catchment (personal communication, Jerry Stimpson), covering 55% of the catchment, and almost all near-stream, riparian areas. Helena is a fine, mixed, semiactive, thermic Aquic Hapludult that forms a seasonal perched water table during the wet winter periods (USDA 1997, 2010), thus its description as "Aquic." Helena's mixed mineralogy means that the soils formed over mafic parent material, likely a product of the post-metamorphic diabase dikes of probable Triassic age that are found in the UF catchment (McConnell and Glover 1982). These mafic parent materials lead to the development of highly expansive, plastic and sticky soils (USDA 2010). The resulting shallow expansive clay layer (USDA 2010) typically causes the development of a perched water table during the November-March non-growing season (USDA 1997, 2010). No such seasonal perched water tables are reported for any of the HF soils (USDA 1971, 2010). In the UF catchment's upland areas, Vance soils dominate the landscape. The Vance series (Fine, mixed,

semiactive, thermic Typic Hapludults) covers 41% of the catchment. Vance subsurface layers can have moderate shrink-swell potentials, but perched water tables typically do not occur (USDA 2010).

2. WATER STORAGE DYNAMICS IN THE HILL FOREST AND UMSTEAD FARMS CATCHMENTS

2.1 Introduction and Literature Review

The water balance studies referenced in Chapter 1 of this thesis all emphasize the importance of direct observation of soil moisture storage in understanding the relationships between the more frequently observed components, precipitation (P) and streamflow (Q), and evapotranspiration (ET) in small catchments. Early studies such as Kovnee's (1957) NC Mountain water balance did not include direct, continuous measurement of storage, usually measuring only changes in groundwater storage and assuming annual changes in unsaturated-zone storage to be approximately zero.

Only during the last 30 years has time-domain reflectometer (TDR) technology allowed for less labor-intensive measurement of soil moisture (Topp et al, 2003). Despite these advances, there still remain no detailed, monthly water balances in the Piedmont region. The most cited water balance in the region is the Schäfer et al. (2002) study of 30 m.-diameter plots in Duke Forest, NC, which calculated three years of annual water balances. The Duke Forest ET ranged from 64% to 79% of total annual precipitation, annual changes in shallow soil moisture storage (upper 30 cm) ranged from 0.5% to 3%, and water drainage to depth (below 30 cm) ranged from 17%-30% (Schäfer et al. 2002). The current research fills the gaps in knowledge regarding monthly and seasonal variations in the water balance for the Piedmont region of North Carolina.

The Harder et al. (2007) Coastal Plain water balance measured rainfall, streamflow, shallow soil moisture storage, and climate components for evapotranspiration models, comparing the Thornthwaite, Hamon, and Penman-Monteith methods for ET estimation. This Coastal Plain study demonstrated the important role soil moisture changes (ΔS) have on ET rates; which rose with increasing soil moisture. However, because the Harder et al. (2007) study did not examine soil moisture, ET, and Q on a daily basis, estimating ΔS and calculating daily cumulative and monthly water balances were not possible. The Sun et al. (2002) comparative study of mountain and coastal catchments also leaves questions regarding the role of soil moisture storage in the water balance. The study observed that climate was a more influential factor than topography in affecting the water balances between coastal and mountainous watersheds (Sun et al. 2002). However, the current study examines the potentially significant role played by more local factors such as topography and soil, comparing two catchments with the same climate and precipitation.

The volume of water that a subsurface can store is generally a function of the type and condition of the soil and its underlying parent geologic material. Clay or Clay-loam soils with small particle sizes and high surface areas hold more water through adsorption than do sandy or sandy-loam soils with large particle sizes and low surface areas (Hillel 2004). Additionally, for any given soil type, undisturbed soils with low bulk density and high porosity values can store relatively more water than compacted soils with higher bulk density and lower porosity values (Hillel 2004). In the forested HF and UF catchments, shallow,

unconfined groundwater can cycle rapidly through the watershed, whereas water in bedrock material can take decades or centuries to emerge (Heath 1984). Heath (1984) conceptually describes the more active water in the soils and underlying regolith from water in the underlying bedrock by showing that the storage in Piedmont bedrock material is a small fraction of that in regolith and soils.

Observations by Endale et al. (2006) of a small Georgia Piedmont catchment under pasture demonstrated that the depth of clay (Bt) horizons can greatly influence soil moisture in a Piedmont catchment. The sites where the Bt horizon was close to the surface were wetter than those where the Bt was deeper, even when the shallow Bt horizons were higher in the landscape and the lower Bt horizons were in the lower part of the landscape. Endale et al. (2006) observed shallow (0-15 cm) average volumetric soil moisture contents of 22-30% during winter and 8-12% during summer. The authors conclude that, "The depth to the Bt horizon may serve as an indicator of the portions of the watershed most likely to be primary sources of runoff in association with the depth of the overlying coarse-textured soil." As shown in Section 1.5.5, the Appling, Cecil, and Georgeville soils in the HF catchment are in the same soil family (fine, kaolinitic, thermic Typic Kanhapludults) as the Cecil and Pacolet soils studied by Endale et al. (2006) and may thus be hydrologically similar. In the UF catchment, the shallow, expansive Bt horizons in dominant Helena soils with reported seasonally-perched water tables (USDA 1997, 2010) are more likely to limit the vertical flow of water. The analysis of soil textures, bulk densities, and hydraulic conductivities provided

in this chapter provide a more detailed understanding of the influence of these soils on storage and the water balance.

The observations of Tromp-van Meerveld and McDonnell (2006b) in the Panola Mountain Research Watershed (Southern Piedmont Province of Georgia, USA) show that soil moisture storage in Piedmont hillslope soils is limited by soil depth (1-2m.) and thus limits other components of the water balance, in particular transpiration. The shallow soil depths of upper slopes were water-limiting enough to influence vegetation species type (Tromp-van Meerveld and McDonnell, 2006b). Because the Piedmont NC climate, topography, vegetation, and soils are similar to those at Panola Mountain, we might expect similar soil moisture storage processes and subsequent effects on ET within the shallow (<2m.) Tatum soils on hillslopes of the HF catchment. The UF catchment differs from HF primarily in topography and soils (see section 1.5 Study Catchment Descriptions), with soils that are expected to provide a stronger limit on the vertical flow of water through the Bt horizon (USDA 1997, 2010); therefore, the Tromp-van Meerveld and McDonnell (2006b) observations that soil depth limits soil moisture storage also may be valid in this catchment where the clay Bt horizon limits vertical flow, especially during the winter when the clay is saturated and expanded and ET rates are low.

Monitoring of soil moisture dynamics is critical to quantifying soil moisture storage and, thus, calculating storage change for use in water balances. Fine-temporal scale quantification of soil moisture storage provides independent measures of unsaturated-zone storage changes

to support monthly or seasonal water balances. Various studies from around the world have demonstrated the great influence of shallow soil moisture storage on overall catchment hydrology. In particular, a study of the Yellowknife, Northwest Territory area of Canada by Spence and Woo (2006) found that headwater catchments generated runoff only after the saturation threshold was exceeded and soil moisture conditions increased lateral flows. Grayson et al. (1997) observed that small catchments in temperate regions in Australia switched between wet and dry states within shallow soil horizons. The summer dry state of soil moisture was dominated by vertical water fluxes (P and ET) with small differences in vertical conductivity values, while during the winter wet state, P values were greater than ET, leading to increased soil moisture storage and lateral fluxes increased. Tromp van Meerveld and McDonnell (2006a) observed wet and dry states in Panola Mountain, Georgia, USA, although they were examining transient water table development at the soil-bedrock interface during storm events. James and Roulet (2007) also observed the wet-to-dry shifts in soil moisture in Mt. Saint Hilaire, Quebec, Canada, but did not observe any changes in soil moisture patterns as conditions moved from dry to wet conditions. However, James and Roulet (2007) observed a nonlinear change in storm runoff generation over a small change in moisture conditions. In this study, wet and dry states are defined by distinct changes in seasonal riparian groundwater levels and corresponding integrated-profile soil moisture storage. Wet and dry also correspond to definitions of non-growing and growing seasons, respectively.

Shallow Bt horizons and shallow depths to regolith (Cr or R) horizons may play a significant role in soil moisture storage in Piedmont, North Carolina headwater catchments. Changes in shallow (<2 m.) soil moisture storage may, in turn, play a strong role in the streamflow dynamics and the overall water balance, particularly during wet season when Bt horizons can become saturated. This may be particularly true in the Umstead Farms (UF) catchment, where soils form seasonal water tables during the wet, non-growing season (USDA 1971, 1997, 2010). Based on the site review for the HF and UF catchments (presented in Section 1.5), it is possible that the catchments will differ in their internal storage amounts and water balances. The storage calculations in this study focus on shallow storage in the unsaturated and saturated portions of the catchment soils.

Buttle's T3 Template (2006), which was introduced in Section 1.2, provides a framework for hydrologic comparisons across these two catchments. The T3 template is a conceptual model useful for comparing the relative controls exerted on catchment hydrology by topography, typology (controls on lateral flow), and topology (connectedness of the surface drainage network). The T3 template compares catchments within the same climatological zones, assuming climate influences such as potential evapotranspiration are the same across the catchments under comparison (Buttle 2006). Guan et al. (2010) used the T3 template to compare relative controls on the hydrology of small (< 4 ha.) peat land, valley, and wetland sites in the Northwest Territories of Canada. They observed differences in these relative controls, with the valley site being more topographically controlled and topology exerting greater controls on soil moisture and ground thaw interactions at the wetland site. The

authors observed that no single control dominated within a given site; rather, controls did not act independently of each other. The current research uses the T3 template to compare the drivers of catchment hydrology in the two catchments. The T3 template is discussed in more detail in section 2.5.

2.2 Objectives

Chapter 2 describes the water storage dynamics occurring in the HF and UF catchments and uses daily data to calculate changes in water storage in each catchment. The resulting storage analyses are used in the water balance of the HF and UF catchments in Chapter 3. The research objectives are to:

1) Analyze soil properties such as texture and saturated hydraulic conductivity that affect moisture storage in the HF and UF catchments;
2) Compare internal soil moisture dynamics between catchments in order to infer storage processes occurring in each catchment;
3) Quantify the daily, monthly, and seasonal unsaturated soil moisture and shallow groundwater storage occurring in the HF and UF catchments; and
4) Use the T3 conceptual framework (Buttle 2006) to compare the relative drivers affecting shallow storage, and thus catchment hydrology, in these two catchments.

2.3 Methods

2.3.1 Soil Characterization

Soil profile descriptions and textural and bulk density analyses were performed for the surface (A), clay (Bt), and BC horizons for six soil moisture monitoring locations in each catchment (see Figures 6 and 7, and see Appendix 1 for soil profile field descriptions). At these locations, a drop-hammer 100 cc core sampler was used to collect samples in A, Bt, and BC horizons (through the soil profile, to refusal where possible). To collect samples from these horizons, sampling depths ranged from the surface down to as deep as 1.5 m. The litter layer was removed, and mineral soil was collected. Textual analysis and bulk density were performed on samples from the A, Bt, and BC horizons by the NC State University Soil Physical Properties lab.

The samples were compared for texture and, where possible, bulk density. Because saturated hydraulic conductivity (K_{sat}) was needed for estimates in changes in saturated zone water storage, both direct measurement and pedotransfer function (PTF)-based estimates were used to determine K_{sat}. Direct measurements were taken at one site in each catchment using a Guelph constant-head permeameter. At each direct measurement site, 3-4 depths were read through a 1-meter-deep profile. Permeameter readings were converted to K_{sat} values using the Richards' solution (Reynolds et al. 1985). Because of difficulties creating dependable measurement holes in the rocky HF hillslope soils and K_{sat} values below the range of the Guelph Permeameter in the UF's expansive clay Bt horizon, direct measurement of K_{sat} was of limited value in this analysis, and it was necessary to use other approaches to estimate K_{sat}.

The texture and bulk density analysis provided inputs into pedotransfer functions (PTF) for estimating saturated hydraulic conductivity, saturation, and drainable porosity values for the soils. PTF's allow for the estimation of various soil hydrologic properties using more easily measurable properties such as percent sand, silt, and clay, percent organic matter, and bulk density (Wösten et al. 2001). Two PTF functions were used to estimate saturated hydraulic conductivity (K_{sat}). Saxton et al. (1986) uses sand and clay content of the soil to estimate K_{sat}. Kluitenberg (2008) found the Saxton et al. (1986) methodology to be among the simplest, most accurate K_{sat} PTF methods. Equation 2 shows the PTF developed by Saxton et al. (1986) as

$$K = 2.778 \times 10^{-6} \{\exp [12.012 - 0.0755(\%\ \text{sand}) + [-3.8950 + 0.03671\ (\%\ \text{sand}) - 0.1103\ (\%\ \text{clay}) + 8.7546 \times 10^{-4}\ (\%\ \text{clay})^2]\ (1/\theta)]\} \quad (2)$$

where K is unsaturated hydraulic conductivity, (m/s), θ is volumetric soil moisture content (m^3/m^3), % sand is the percentage of the sample that is classified as USDA NRCS sand texture, and % clay is the percentage of the sample that is classified as USDA NRCS clay texture.

The second PTF used was the USDA Natural Resource Conservation Service (NRCS) Soil Handbook and Manual (NRCS 2010). The NRCS Handbook method builds a PTF that estimates K_{sat} based on sand and clay content and bulk density of the soil. The user locates

the sand and clay percentages and the bulk density on a textural triangle showing a range of possible K_{sat} values for the given texture and bulk density. NRCS (2010) does not provide the PTF equation. However, this methodology is useful for conceptual modeling because it provides a range of values for K_{sat} based on thousands of observations in a national NRCS dataset (personal communication, Walter Rawls, retired NRCS). All five direct measurements of K_{sat} taken for this study fell within the NRCS ranges. Samples were collected and analyzed at each of the five soil moisture sites in HF and at the six soil moisture sites in UF.

2.3.2 Estimation of Change in Shallow Storage

At each of the HF and UF catchments, changes in shallow (<2m.) water storage were estimated using a method that combined unsaturated-zone soil moisture monitoring with saturated-zone shallow well monitoring. The general approach to calculate daily change in shallow storage, ΔS, for each catchment followed a methodology described by Spence and Woo (2003) and used by Guan et al. (2010), and shown in Equation 3:

$$\Delta S = \Delta S_U + \Delta S_S$$
$$\Delta S_U = \theta[z_w(t) - z_w(t-1)]$$
$$\Delta S_S = S_y\,[(z - z_w(t)) - (z - z_w(t-1))] \quad (3)$$

where ΔS_u is change in unsaturated storage; ΔS_s is change in saturated zone storage, also referred to as "net" recharge (Healy and Cook 2002); θ is observed volumetric soil moisture

content in the unsaturated zone; S_y is the specific yield of soil; z is the total soil thickness; and z_w is the depth of the water table from the soil surface at any given point in time, with t and t-1 being the present and previous time periods, respectively. The calculation of the above parameters is described in the following sections.

2.3.2.1 Saturated-zone Change in Storage

Changes in saturated storage were calculated using the network of shallow (1.5-2.5 m.) riparian water table wells in HF and UF. All wells are 2-inch (5-cm) PVC tubes installed by hand using NC Division of Water Quality guidelines (NC Administrative Code 15A NCAC 02c). All wells except the deep wells at UF2 (W1 and W3; Figure 7) are screened to just below ground surface and capped with Bentonite clay. A special approach to measuring water tables at UF2 W1 and W3 was needed due to the expansive clay Bt horizon in the Helena soil at these locations. The approach is described below.

Figure 6 shows the Hill Forest catchment network consisting of three wells located along a stream valley transect. The wells are shown with red and white circles. The wells (W2, W3, and W4) were installed in June of 2009. Wells W2-W4 were equipped with Odyssey capacitance water level loggers housed in 2-inch perforated PVC pipe collecting water table levels at 15-minute intervals. No hillslope or upland wells were installed in HF because of the difficulty of manually installing these PVC-type wells to the necessary depths in these rocky locations.

In UF (Figure 7) three riparian wells (W1, W2, and W3) were installed in June of 2009. The two most downstream well sites (W1a + b and W3a + b) comprise a riparian-to-hillslope well transect. Based on the reported shallow expansive clay (Bt) horizon and perched water table known to occur in Helena soils (see section 1.5.4 for more detailed soil descriptions), the W1 and W3 sites each utilized two wells, one above and one below the shallow confining clay layer. The deeper wells were screened within and below the clay layer (W1b screened from 80-180 cm and W3b from 5 to 128 cm) to monitor groundwater dynamics at depth and the connection (or disconnection) between the subsurface at depth and the surface horizons above the expansive clay layer. These deeper wells were equipped with Odyssey capacitance well-level loggers collecting water table data at 15-minute intervals. The shallow wells were screened above the clay layer (W1a above 46 cm and W3a above 37 cm). Water table levels in the shallow wells were measured manually three to four times monthly. The most upstream well in the Umstead Farms catchment (W2) was located in the riparian area approximately 120 meters (400 feet) upstream of the downstream wells. At W2, the observed soil did not correspond with the Soil Survey map unit of Helena displayed for this location (USDA 1997). At this location, a fully-screened 185 cm deep well was installed and outfitted with an Odyssey capacitance well level logger collecting data at 15-minute intervals. Data from the capacitance loggers were compared to manual measurements taken within these wells three to four times monthly throughout the project (50 total manual measurements). Based on these comparisons, accuracy of the manual method was estimated to be within 1 cm. Figure 8 shows an example of the calibration results for HF Well 2.

Table 2 shows the statistical comparison of the 50 calibrated Odyssey and manual water level measurements.

At each well location, the change in saturated-zone storage was calculated using the saturated storage component of Equation 3 (Guan et al., 2010; Spence and Woo, 2006), which is the equation for "net" recharge described by Healy and Cook (2002). Daily water table depths were calculated using the mean of the 15-minute interval well logger data for each day during the study period (July 1, 2009 to June 30, 2010). The use of mean daily water table depths minimizes diurnal effects on the water table depth (Coes et al., 2007). S_y is defined as the ratio of the volume of water a soil will yield by gravity drainage to the volume of the soil (cm^3/cm^3) (Fetter 2001). S_y can be estimated as the difference between saturated conditions and field capacity, which is the maximum amount of water that the unsaturated zone of a soil can hold against the pull of gravity (Fetter 2001). This field approach to estimating S_y can be mathematically expressed as:

$$S_y = \theta_S - \theta_{FC} \quad (4)$$

where θ_S is the saturated volumetric soil moisture content and θ_{FC} is the volumetric soil moisture content at field capacity, both in cm^3/cm^3. S_y was estimated at the shallow soil moisture monitoring sites (described in the next section) co-located with wells (T1 in HF and T2 in UF). T1 in HF is on a well drained hillslope. The estimation of S_y was done using the difference in the maximum soil moisture value observed during the period of record

(assumed to be θ_S) minus the field capacity soil moisture value. Field capacity was estimated using soil moisture data at the end of the Dec. 26-Jan. 15 period with minimal (<8 mm) precipitation. At the end of this interstorm winter period, soil drainage had occurred, and the effects of ET were minimized during this winter period.

The above methodology is used for calculating changes in daily saturated storage at the three riparian wells placed along the stream channel, extending from just above the flumes to ephemeral (or intermittent) stream locations. The resulting daily ΔSs values for HF and UF were assumed to represent the saturated storage changes across each catchment.

2.3.2.2 Unsaturated-zone Change in Storage

In each catchment, a dual approach to measuring unsaturated-zone volumetric soil moisture content was used. The first approach provided continuous, high-temporal resolution data through the soil profile at one catchment location, while the second provided spatial data across topographic positions but at a coarser temporal resolution. In the high-temporal resolution approach, volumetric soil moisture content (VSMC) was measured hourly at depths of 12.5, 25, 50, and 90 cm in the Tatum soil of the HF Catchment (Figure 6, location T1) and at depths of 12.5, 25, 45, and 80 cm in the Helena soil of the UF Catchment (Figure 7, location T2) using a cluster of four Time Domain Transmissivity (TDT) volumetric soil moisture probes connected to a data logger (Environmental Systems Incorporated, ESI). A second, spatially-dispersed, low-temporal resolution approach was used to provide a more spatially-representative estimate of catchment-wide VSMC. In each catchment, two transects

of access tubes were installed perpendicular to the stream channel and spanning topographic position (upland, hillslope, and riparian). VSMC was measured 3-4 times monthly at each access tube with a portable IMKO TRIME Gro-Point Time Domain Reflectometry (TDR) volumetric soil moisture probe. The access tubes were 2-inch PVC tubes augured to refusal and installed vertically to various depths (0.5 to 1.5 meters). The TRIME TDR probe was used to collect data at 0.1-meter intervals (0.2 m, 0.3 m, 0.4 m, etc.) at these sites. The HF soil moisture access tube network originally consisted of six locations; however, T3 was abandoned due to poor data caused by air pockets between the access tube and soil. The remaining five HF access tubes extended to refusal (0.5 to 1.5 meters). In UF, the six access tubes extended to refusal (0.55 to 1.15 meters).

For both the continuous TDT profiles and access tube sites, the daily or periodic soil moisture change was calculated using the unsaturated component of Equation 3. The method for calculating the profile average soil moisture in the unsaturated zone was the same for both TDT profile and access tube sites, using an adaptation of a depth-integration method used by Tromp-van Meerveld and McDonnell (2006b) and Moroizumi et al. (2008). A separate calculation was done at each location. Equation 5 calculates the volumetric soil moisture content of the 1-meter deep T1 continuous TDT profile site in the Hill Forest watershed:

$$\theta_{HFT1} = ((\theta_{0.2} \times 0.2m) + (\theta_{0.3} \times 0.1\ m) + (\theta_{0.4} \times 0.1m) + (\theta_{0.5} \times 0.1m) + (\theta_{0.6} \times 0.1m) + (\theta_{0.7} \times 0.1m) + (\theta_{0.8} \times 0.1m) + (\theta_{0.9} \times 0.2m)) / 1\ m. \quad (5)$$

where θ_{HFT} (meters) is the profile average soil moisture content per 1-meter depth, and $\theta_{0.2}$, $\theta_{0.3}$, $\theta_{0.4}$, etc. are the 20, 30, 40 cm, etc. soil depths. This methodology is based on the assumption that the soil water content at depth 0.2 represents the soil water content between 0 and 0.2 meters, the content at depth 0.3 represents the 0.2-0.3 depth, and so on. Because depths vary at each monitoring site, Equation 5 differs in number of measurements, multiplier values, and total depth (the denominator) for each of the 14 soil moisture locations. Daily volumetric soil moisture content (VSMC) values were calculated at the continuous (TDT) probe using the mean of hourly values. Changes at the bi-weekly monitored access tubes (TDR) were calculated on a monthly basis using the monthly mean of VSMC values.

2.3.3 Estimation of Catchment-scale Change in Storage

Once profile averages of unsaturated-zone change in storage were completed for each continuous TDT profile and access tube site, unsaturated and saturated-zone storage estimates were combined to estimate total catchment-scale storage (Equation 3) using two different scenarios, described below.

2.3.3.1 "One-dimensional (1-D)" Scenario

In the 1-D scenario, the daily mean unsaturated-zone change in storage generated from the continuous TDT profile sites were used to represent the mean daily change in unsaturated-zone storage of each catchment. Inherent in this approach are the assumptions i) that changes in the top 1-2 m. of the soil profile accounts for most of the change in unsaturated-zone

storage and ii) vertical integration of changes in storage from one point in space can be used to estimate catchment-scale change in storage. The total thickness of the unsaturated zone was assumed to be the distance between ground surface and the mean daily water table depth measured by the well co-located with each soil moisture logger site.

2.3.3.2 "Three-dimensional (3-D)" Scenario

In order to scale soil moisture values to the catchment scale in the 3-D scenario, each catchment area was categorized into riparian, hillslope, or upland units using a combination of factors such as slope, soil type and texture, depth to water table, reported existence of perched water table by soil survey, and saturated hydraulic conductivity of confining layer. Unlike the 1-D scenario, the 3-D scenario uses the spatially generated data from the access tube sites, along with the riparian well-generated mean water table depth, to estimate a spatially integrated value for catchment-wide unsaturated-zone change in storage. This is similar to the approach used by Peters et al. (2003) to define riparian, hillslope, and bedrock outcrops in the Panola Mountain Research Watershed. Earlier work done by England and Holtan (1969) used slopes and depth to Bt horizon to define riparian, hillslope, and upland units in a 185-hectare USDA experimental watershed near Hastings, Nebraska, USA.

Tables 3 and 4 describe the criteria for defining landscape units for the HF and UF catchments. Landscape units were mapped (Figures 9 and 10) using an overlay analysis of soil type (which includes depth to water table, depth to Bt horizon, depth to regolith, and slope range) with riparian soils. Upland and hillslope units correspond with upland and

hillslope soils types on soils maps, while soils maps do not include riparian areas, which are too small to be mapped at the soil survey scale (1:20,000). In the HF catchment (Figure 9), units of upland, hillslope, and riparian were defined similarly to previously studied Piedmont landscapes described by Peters (2003) and England and Holtan (1969). Definition of the HF riparian unit was based on field observations of sandy loam soils in the flat (<12% slope) stream valley bottom. The riparian unit in HF was hand-delineated in ArcMAP by selecting low-slope (<12%) areas within a 50-foot buffer of the delineated stream channels. HF hillslope units correspond with the Tatum soil series and are on relatively steep (12-50%) slopes with eroded soils that have a shallow depth to bedrock or refusal and shallow-to-deep water tables. HF upland units are relatively flat slopes on thick soils and correspond to Cecil, Appling, and Georgeville soil series. Upland depth to bedrock or impeding layer is deep, and depth to water table can be deep (USDA 1971). In UF (Figure 10), the hillslope units are on the steepest slopes (up to 37%) with eroded soils that have a shallow depth to impeding layer (expansive Bt horizon). UF hillslope units correspond to the Helena soil series. Upland units are relatively flat slopes on thick soils, with greater depths to a water-impeding layer. Upland units correspond with the Vance soil series. No riparian units were mapped in UF because soils with Helena-series properties are adjacent to non-flooding, highly incised streambeds throughout most of the catchment.

Similar to the Peters et al. (2003) and England and Holton (1969) methodologies, the hillslope, riparian, and upland units were used for scaling up unsaturated-zone profile average moisture content from the access tube sites to the catchment. To accomplish this

using the access tubes that were located in transects of varying elevations within each unit type, a distance-weighted profile average soil moisture depth (Moroizumi et al., 2008) was calculated for each unit in the HF and UF catchment. Because access tubes were located at varying elevations within hillslope and upland units, the distance-weighted approach removes potential variations within individual units. For example, Equation 6 below calculates the distance-weighted profile average soil moisture depth for the UF hillslope unit, where 3 access tube sites were located.

$$\theta_{UFHilslope} = \frac{\left[\frac{\theta_{T2} + \theta_{T4}}{2}\right] * L_{T4-T2} + \left[\frac{\theta_{T4} + \theta_{T6}}{2}\right] * L_{T6-T4}}{L_{T4-T2} + L_{T6-T4}} \quad (6)$$

where θ_T is the profile average soil moisture content for a periodic monitoring location for a given measurement time, and $L_{T2\text{-}T1}$ is the distance (meters) between two access tube locations (T1 and T2 in Figure 7). The result is the distance-weighted profile average soil moisture content for the UF catchment hillslope unit ($\theta_{UFHillslope}$). Distance-integrated profile averages were completed for the hillslope and upland units within each catchment. In HF, the T5 access tube was the only riparian monitoring location; therefore, an integrated profile was not possible, and the HF riparian unit profile average was based on data from this site alone.

As described in equation 3, unit-representative soil moisture content was then multiplied by depth to get total unsaturated-zone storage. Based on information from the soil surveys

(USDA 1971, USDA 1997) and from the official USDA soil descriptions available on the USDA NRCS Official Soil Descriptions website (http://ortho.ftw.nrcs.usda.gov/cgi-bin/osd/osdname.cgi), it was assumed that the unsaturated zones of the upland and hillslope units extended through the full soil thickness in each unit. As a simple verification of this assumption, average unsaturated zone soil depths were verified against soil profile descriptive data collected upon installation of soil moisture and well sites. Layers of apparent nitrogen reduction (chroma values of 2 or less and becoming red upon application of a-a' Dipiridyl dye) that were saturated for at least 15 days annually during the growing season (March 15 – Nov. 1) were assumed to be the upper depth of the water table, and oxidized layers (chroma values greater than 2) were assumed to be part of the unsaturated zone (USDA 2006). In HF upland soil samples (230 cm depth), no saturation was observed. In UF upland samples (136 cm), saturation was not reached, although grey colors with chroma values near 2 were observed. Generally, it was difficult to reach depths of 180 cm in both HF and UF hillslopes, where refusal occurred before saturation could be reached. However, UF wells 1 and 2 did show chroma values of <2 at depths of 160-175 cm. Tables 3 and 4 show representative unsaturated-zone depths for the HF and UF catchments, respectively.

To integrate periodic soil moisture contents across the catchment, the resulting hydrologic unit-specific profile averages were combined in Equation 7 below:

$$\theta_{UF} = \frac{(\theta_{UFHillslope} * A_{UFHillslope}) + (\theta_{UFUpland} * A_{UFUpland}) + (\theta_{UFRiparian} * A_{UFRiparian})}{A_{UF}} \quad (7)$$

where $A_{UFHillslope}$ is the areal extent of the hillslope area in UF, $A_{UFUpland}$ is the areal extent of the upland area, $A_{UFRiparian}$ is the areal extent of the riparian area, and A_{UF} is the total area of the UF catchment. The result was a single, integrated catchment-scale value for θ for the given day.

Once 1-D and 3-D unsaturated θ values were calculated for each catchment, Equation 3 was used to calculate daily change in storage. The 1-D version of catchment-scale change in storage provides a daily change in storage value based on the representative, continuous soil moisture site for HF (T1) and UF (T2). The 3-D version provides spatially-integrated, but more temporally-coarse change in storage values. The resulting daily 1-D and periodic 3-D values were then applied to the water balance.

2.4 Results

2.4.1 Soil Characterization

2.4.1.1 Soil Type and Textural Analysis

Soil depths range from 1 to >3 m. in the HF catchment and from 0.5 to >3 m in the UF catchment. These findings are consistent with representative profile data presented in soil surveys (USDA 1971, USDA 1997, USDA 2010). In the HF uplands, on Cecil, Appling, and Georgeville soils (Figure 4), refusal was not reached within 3 meters (the length of the auger), which is consistent with depths reported in USDA (2010) soil descriptions. In HF hillslope soils, the relatively shallower depths to refusal meant that access tubes were limited to depths of $\leq$0.9 m. The observed HF hillslope soil depths are generally consistent with a depth of 1.1 m. reported in USDA (2010) for Tatum hillslope soils. All HF hillslope and upland soils exhibited oxidized coloration (chroma values above 2) throughout the sampled horizons, indicating no evidence of prolonged water perching (USDA 2006). Although USDA soil surveys do not identify a separate soil series in the riparian zone, soils samples from these locations were sandy loams to depths of >1 m., clearly not the Tatum soils mapped in the Durham Soil Survey (USDA 1971), but more likely Entisols formed by continuous alluvial deposition and inundation by the stream (Buol et al.. 2003). All HF riparian soils exhibited iron reduction (chroma values $\leq$2) at shallow depths, suggesting continuous, long-term (<14 days) saturation and anoxic conditions during the growing season (USDA 2006). Appendix 1 includes detailed field profiles of all monitoring sites.

In UF, there was no observable difference in depth to refusal of upland (Vance series), hillslope (Helena), and riparian soils (Figure 5). Depths to refusal in TDR access tube locations ranged from 0.7 to 1.6 m., while depths to refusal in riparian wells were slightly deeper, ranging from 1.3 to 1.85 m. Soil textural analysis and site visits (personal communication, Jerry Stimpson, retired NRCS soil scientist) confirm the classification of the dominant soil in the catchment as the Helena series. As reported in the Granville County Soil Survey (USDA 1997) and the official series description for Helena soils (USDA 2010b), a very sticky, very plastic clay (Bt) horizon was observed starting at 0.2-0.5 m. deep at all hillslope and riparian sites. UF Helena soils exhibited light grey and tan coloration (chroma values $\leq$2) in and above the Bt horizons, indicating iron reduction associated with continuous saturation and anoxic conditions during the growing season (USDA 2006). Vance soils occupy the upland portions of the catchment. These soils have subsurface horizons of clay increase (Bt), but these layers fall into the loam classification. In addition to their lower clay contents, these Bt horizons lacked the stickiness and plasticity of those in the Helena soils. Appendix 1 includes detailed field profiles of all monitoring sites.

Tables 5 and 6 present physical and hydrological properties, and Figures 11 and 12 present the textural analyses of the HF and UF catchments on the USDA Textural Triangle. Textural analysis of the HF soils showed sand contents ranging from 4% to 69%, silt contents ranging from 22% to 45%, and clay contents ranging from 8% to 68%. There was a clear delineation between the subsoils of riparian, hillslope, and upland soils. The upland Appling (ApC) and hillslope Tatum (TaE) soil sites had the greatest clay content in Bt horizons (54-68%), while

riparian soils had sandy loam Bt horizons. Hillslope soils had sandy loams in surface (A & E) horizons, and clay (Bt) horizons began at shallow depths of 20-30 cm. Upland soils also had shallow surface (A & E) horizons. Hillslope Bt horizons varied greatly in their clay contents (from 17-68%). Hillslope soils nearer to the uplands had higher clay contents in the Bt horizons, while those nearer to the riparian area had low clay contents in the Bt horizons. Deep upland clay horizons in HF had very high clay contents (54-63%). Riparian soils were deep, sandy loams with high sand content (41-69%) and low clay content (8-16%). These clays were slightly sticky and slightly plastic.

Textural analyses from the UF catchment (Table 6, Figure 12) showed sand contents ranging from 2% to 75%, silt contents ranging from 10% to 48%, and clay contents ranging from 5% to 67%. The greatest clay contents in the UF catchment were in the hillslope Helena (HeB) series Bt horizons (45-67%), while the Bt horizons of the upland Vance (VaB) series were clay loams and loams with 26-36% clay content in Bt horizons. A and E horizons in the UF catchment fell within the sandy loam and loam textural classes.

Absolute comparisons between the HF and UF catchment soils are difficult to make solely based on texture. The absolute values of clay content show the HF and UF hillslope soils to be very similar; however, the upland soils in HF have much higher clay content than do those of the UF catchments. The mixed mineralogy of the dominant hillslope Helena soil series in UF (McConnell and Glover 1982) leads to highly expansive, plastic and sticky clays classified as smectite/montmorrillonite 2:1 clay (USDA 2010). These clays are expected to

adsorb relatively more water and have lower wet-weather vertical hydraulic conductivity values than do the kaolinitic 1:1 clay subsoils of the HF catchment (Hillel 2004). In order to make direct hydrologic comparisons of the catchment soils, more information such as saturated hydraulic conductivity values are needed.

Dry bulk density is a ratio of the mass of solids in a soil to total soil volume, usually measured in g/cm^3. Bulk density can be highly variable depending upon the structure of the soil as well as swelling and shrinking characteristics (Hillel 2004). Bulk density values in the HF catchment (Table 5) ranged from 0.93 to 1.77 in the surface (A, E) horizons, and from 1.38 to 2.03 in the B horizons. Bulk densities of sandy loam soils A horizons in HF varied greatly, and the soils with highest percentages of large (>2mm) particles had the greatest densities. In the UF catchment (Table 6), bulk density values ranged from 1.39 to 1.58 in the A horizons and 1.54 to 1.88 in the B horizons. UF bulk densities were highest in the subsurface Bt horizons of both Vance and Helena soils.

2.4.1.2 Saturated Hydraulic Conductivity

Tables 5 and 6 also show the HF and UF K_{sat} estimates, respectively derived from direct measurement and pedotransfer function calculations. HF catchment K_{sat} values were highest in riparian areas, ranging from 0.36 to 36 cm/hr in surface (A) horizons, and ranging from 0.036 to 3.6 cm/hr in the subsurface (Table 5). In hillslope and upland locations, K_{sat} values decreased with depth. These values are consistent with values commonly listed in general literature (Hillel 2004).

Figure 13 visually presents this trend for two HF hillslope soil sites, T1 and T4. Site T1 is represented with diamonds, and site T4 is represented with circles. The solid diamonds represent direct measurements taken with the Guelph permeameter, and all other values are estimates from the Saxton and NRCS PTF calculations. There is a general trend of decreasing K_{sat} values with depth throughout the profile, especially in the Bt horizon. Permeameter measurements of the T1 location soil (diamonds) fell within the low end of the USDA NRCS range. The Saxton PTF estimated slightly lower K_{sat} values in the surface and slightly higher values with increasing depth at T1 with respect to the NRCS range. This may be an underestimation of extreme values consistent with critiques of PTF calculations (Pachepsky et al. 2006), but there are not enough field measurements to make direct measurement-to-PTF comparisons. The lone HF upland site, T6, is shown in Figure 14. Estimates of K_{sat} at this location show a slight decrease from surface horizons to the deepest (90 cm) measurement. In this case, NRCS estimates are one to two orders of magnitude less than those of Saxton.

In the UF catchment, K_{sat} values in the upland locations (Figure 15) on Vance series soils decreased with depth, with lowest values (0.004-0.04 cm/hr) at the greatest depths (120-140 cm). This is similar to the decreases in K_{sat} values with increasing depth in the HF catchment upland and hillslope soils. However, the UF hillslope sites, which lie on the dominant Helena soil series, show a different pattern than do any of the other sites observed. As can be seen in Figure 16, directly measured K_{sat} values in UF hillslope soils drop three orders of

magnitude between the surface horizon and Bt horizon. Figure 16 shows this clearly in the direct measurement and NRCS estimates at T6 and in the estimates from T2. However, the T6 Saxton estimate does not show the difference in K_{sat} values between the surface and Bt horizons. This is possibly due to an underestimation of the surface horizon K_{sat} value common with this type of PTF (Pachepsky et al. 2006). The findings from this saturated hydraulic conductivity analysis are consistent with the idea that an expansive clay layer exists only on Helena soils within the UF catchment.

2.4.2 Change in Shallow Storage

2.4.2.1 Riparian Groundwater Storage

Figure 17 shows the average daily water table depths with respect to ground surface at HF wells 2, 3, and 4 (Figure 6) during the period from July 1, 2009 until July 31, 2010. Daily averaged groundwater levels for the most downstream well, W2, ranged between -25 cm (e.g. July 12, 2009) and 3 cm (above ground surface in January 2010). W3, 100 meters upstream of W2, demonstrated a similar pattern of water levels. W4 was the most upstream riparian well, located adjacent to an intermittently flowing stream reach upstream of the perennial portion of the stream. This 105 cm-deep well was dry for most of the period of July until early November, when seasonal shift in water table could be observed in all wells. This seasonal shift in moisture is evidence of the wet and dry states of soil moisture observed by others doing hydrologic research in the Piedmont (Tromp-van Meerveld et al. 2006) and around the world (Grayson et al. 1997). The distance-weighted water table average also showed the seasonal shift, although this average likely underestimates the extent of the shift

due to the fact that W4 recorded depths to the bottom of the well, which was too shallow to record growing-season water table levels. During the late growing season of 2009, the distance-weighted average depth remained below -40 cm for the entire period (July-Oct. 2009) with the exception of one large rainfall event (7/20/2009). During the non-growing season (Nov. 1, 2009 – Mar.15, 2010), the average water table depth was never below -20 cm depth, and for many weeks was closer to -10 cm depth.

Well levels in the UF catchment (Figure 18) also demonstrate the wet and dry states. Water table levels in UF W1 were below -80 cm depth until the November dry-to-wet shift, at which point the water level rose to the surface for the period of early November, 2009 until April 2010. After April, 2010 the levels began to fall back down to the dry state. In May and early June, 2010 there was a series of large rainstorms (total of 233 mm) which brought water table levels above -40 cm for most of that period, and then the water table levels fell again to below -120 cm. The most upstream well (W2) had a similar, although less variable, pattern, maintaining levels of -125 cm to -140 cm between Jul. 2009 and early Nov. 2009 and rising to maintain constant levels of -80 to -100 cm during the Nov. 2009 to Apr. 2010 period before falling to around -130 cm in Jul. 2010. The lone hillslope well in UF, W3, exhibited a pattern similar to those of the riparian wells. UF W3 was dry (-133 cm) for much of the Jul.-Nov. 2009 period, fluctuating between levels of -121 to -130 cm in responses to rain events. After the dry-to-wet shift, W3 rose to above -40 cm below the surface until Apr. 2010.

Figure 19 shows the mean daily distance-averaged water table levels, in cm below ground surface, for both the HF and UF catchments. The dry-to-wet shift is clear in both catchments for the period between early Nov. 2009 and mid-Apr. 2010. The return to the dry state was briefly interrupted by a series of storms during May 15-29 (213 mm in HF, and 188 mm in UF), and then the catchments reached the dry state in June. The seasonal shift was much more subtle in HF than in UF. In HF, the average water table levels rose from approximately -50 cm to above -20 cm, a rise of 30 cm, over a 6-week period. In UF, the shift was greater and more immediate, rising from -130 cm to above -60 cm during a two-week period in early November. The greater magnitude and more responsive well level changes in UF were also evident during the return to the dry state, when UF average well levels fell (and rose during the May storms) relatively faster than those of HF. The distance-averaged water table levels thus demonstrate that the UF catchment becomes wet and dries down to a greater degree response to precipitation than does the HF catchment. These distance-averaged water table time series were used to calculate changes in saturated-zone storage.

Data from UF well W1 screened above the Bt horizon (W1a) provides evidence of the development of a perched water table. Figure 20 shows the results of the 54 manual measurements taken at W1a during the study period. Well W1a developed intermittent perched water in response to rainfall during the late growing season (Jul.-Oct.) 2009. Note, manual measurements were collected during no-rain periods, so perched conditions were typically present for some length of time after storm events. During this period, the deep well (W1b) water table was continuously below the expansive clay Bt horizon until Nov. 2,

when it rose above the well's screening. This indicates that temporary, shallow perched water tables developed independently of deeper groundwater. During the non-growing season (Nov. 2009 – Mar. 2010), the shallow well showed continuous water tables within 20 cm of the soil surface. At this time, the W1b exhibited similar water tables to those in W1a. After May, W1b fell while W1a continued to show intermittent development of a perched table in June. The upland shallow well (W3a) demonstrated similar patterns, temporarily perching in late growing season 2009, staying wet from Nov. to April and then remaining dry with one wetting event in mid-May.

2.4.2.2 Unsaturated-zone Storage

Figures 21 and 22 show the continuous soil moisture data from HF (T1) and UF (T2) TDT profiles, respectively. In both catchments, the deepest probes clearly demonstrate the dry-to-wet shift in Nov. 2009, consistent with water table levels. Both catchments shifted within one week in early Nov. 2009 and maintained moisture levels above those of the growing (or dry) season. The deepest probes also showed the least response to individual rain events, with little rise in response to individual events; however, the HF 90 cm depth lost moisture relatively more quickly than did the similar depth at UF T2 during extended periods of little rainfall (e.g. Dec. 26, 2009 - Jan. 15, 2010). During this period of low rainfall, the HF T1 90-cm depth drained 10%, while the UF 80-cm soil drained 1%. The 50 cm depth at HF also drained 5%, while the similar depth at UF T2 actually gained moisture through this brief dry period, possibly from the perched water table above. The higher clay content and expansive clay type may explain the UF deep soil's more consistently saturated moisture state. The

textural analyses (Tables 5 and 6, and Figures 11 and 12) show that the 90 cm-deep soil at the HF logger (T1) is a sandy loam and that the 80 cm-deep soil at the UF logger (T2) is a sandy clay loam. Alternatively, the saprolite below the hillslope soils and/or steeper slopes in HF may allow for greater vertical seepage.

In UF, the 80 cm-deep probe also showed a more dampened response to individual precipitation events and a more sudden dry-to-wet shift in Nov. 2009 compared with the HF site. The 25 and 45-cm both exhibited a similar dry-to-wet shift and maintenance of the saturated state (27-30%) during the entirety of the wet season. The 25 depth exhibited a pattern more similar to the surface (12.5-cm) horizon during the dry season, with rapid response to storms and decreases in response to short dry periods. The 12.5-cm surface horizon exhibited the largest range of any HF or UF probe (22-39%) and the highest VSMC values of all probes (39%). During the wet season, the 12.5-cm depth soil, a sandy loam, stayed wetter than did the 25 cm soil, a loam, and the 45 cm soil, a clay loam. These results suggest that both catchments exhibit states of soil moisture that may influence the directional flux of water, similar to the findings of Grayson and others (1997) and Tromp-van Meerveld and others (1997). Particularly in the UF catchment, observations of soil moisture dynamics suggest the expansive clay subsoils (25, 45, and 80 cm depths) became expanded with moisture during the non-growing (wet) season, greatly reducing vertical fluxes. After this switch, soil moisture values above 25 cm rose and fell in response to storm events, consistent with a perched water table.

Figure 23 and Table 7 show the mean daily profile average soil moisture for the 1-D scenario in both HF and UF catchments. HF and UF profile averages for the period Jul-Oct. 2009 are 19% and 20% VSMC, respectively. The dry-to-wet shift is clear in early November, and HF and UF profile averages shift to 27% and 31% VSMC, respectively, during the wet period from November 1, 2009 to March 15, 2010. In late March 2010, a shift back to the dry state began, and VSMC of both catchments briefly fell below 20% before rising with the May storms and then returning to the dry state in June 2010. During the wet season, UF soil moisture values were always higher those that of HF. UF soil moisture varied less than 3% during the wet season (Nov. 1, 2009 to Mar. 15, 2010), while HF soil moisture fell during periods of low rainfall and rose in response to rainfall events, varying almost 9% during this period. These patterns demonstrate that during the wet, non-growing season, UF catchment soils became wetter and retained more water than did those of the HF catchment. These differences are consistent with a UF catchment of shallow, highly-expansive clays that adsorb and retain moisture and form a perched water table, and a HF catchment with shallow clays that become wet yet more rapidly lose moisture to drainage.

2.4.3 Estimating Catchment-scale Storage

2.4.3.1. 1-D Scenario

In the 1-D scenario, the change in daily mean storage generated from the TDT profiles representing unsaturated zone storage and average riparian groundwater levels representing saturated storage were used to represent the change in mean daily unsaturated-zone storage of each catchment. During the late growing season of 2009 (Jul 1-Oct 31), the HF

unsaturated zone change in storage was 47 mm, a gain of 22%, while the UF change in storage was -23 mm, a loss of 9%. During the non-growing season, (Nov. 1- Mar. 15) the UF catchment gained much more storage than did HF. UF non-growing season change in storage was 154 mm, a gain of 24%, while HF non-growing season storage change was 28 mm, a gain of 4%. Both catchments lost storage during the early growing season of 2010 (Mar. 16 – Jul. 31). HF change in storage was -11 mm (-2%), while UF change in storage was -176 mm (-47%).

The annual changes in total storage are calculated by subtracting the storage value at the beginning of the period (Aug. 1, 2009) from the storage value at the end of the period (July 31, 2010). The annual 1-D change in storage in HF was 64 mm (5%), while that of UF was -51 mm (-4%). So, over the Aug-Jul period of 2009-2010 the HF catchment showed a small gain in total storage, while the UF catchment showed a small loss.

2.4.3.2. 3-D Scenario

Results from the access tube sites provide additional insights into the seasonal storage dynamics and storage change occurring at sites within the HF and UF catchments. Figure 24 shows soil moisture profiles at UF T6 and HF T1 hillslope sites to illustrate the differences in soil moisture dynamics between catchments. Each line in Figure 24 represents the profile of measurements at a point in time. The UF access tube allowed measurements to a 100-cm depth, while the HF depth was 80 cm. The red lines represent growing-season measurements (Jun. – Nov. 2009 and Jun.-Aug. 2010), the blue lines non-growing season measurements

(Nov.1 –Mar. 15), and the dotted black lines represent a transition period (Mar. 15- May 30). The transition period observed in these data is arbitrary but consistent with the transitions already cited and observed by other authors (Grayson et al. 1997; Tromp-van Meerveld and McDonnell 2006b).

In HF (Figure 24a), volumetric soil moisture content (VSMC) values were lowest at the surface and greatest at depth throughout the period. The greatest variations in soil moisture between dry and wet seasons (about 20%) were observed at the 80-cm depth. The range in surface (20 cm) horizons was lower (10%) than the surface (12.5 and 25 cm) measurements observed within the co-located continuous TDT profile. The access tube profile measurements at HF T1 indicate saturation development at the bottom of the profile, but not at the top. All profiles exhibit the same shape, drier at the top and wetter at the bottom, throughout the period, suggesting that vertical water movement is occurring at all times. The relative dryness of the upper layers potentially results from the increased clay contents with depth at this (as well as other HF) locations as well as the vertical movement of water. It should be noted that since access tube observations were generally made during inter-storm periods, saturation of the surface soils during these times was not often observed but may have occurred. Spikes in surface VSMC were observed within the co-located TDT profile (Figure 21) during storms.

The pattern of increasing soil moisture with depth observed in HF T1 occurred at all HF access tubes, including the upland site (T6), but not at the riparian site (T5). HF hillslope and

upland sites exhibited a shift from the wet to dry state in early Nov. 2009. The HF riparian site became wet to the surface at many times throughout the wet winter period, exhibiting the highest VSMC values of all sites. Appendix 3 shows results for all soil moisture access tube sites in HF and UF.

The UF hillslope (Figure 24b) access tube (T6) is a typical hillslope site within the UF catchment, with moderate slopes and Helena soil series with an expansive clay Bt horizon starting at 30 cm depth. This typical UF hillslope site demonstrates a much different pattern than those of HF hillslopes. Just as in HF, the increase in soil moisture between dry (red lines) and wet (blue lines) season occurs throughout the unsaturated zone profile. However, the VSMC values in UF were higher through the non-growing season, and no values fell below dry-season values until the transitional period beginning in April 2010. The range at the 30-cm depth is also much greater (25%) than were the lower depths. This demonstrates that the UF soil moisture was more variable above the Bt horizon than within it.

During the non-growing season, there were profiles for which the VSMC steadily increased between the ~-50-60 cm and -20 cm depths below ground surface. This increase from the Bt to the A horizon corresponds with saturation observed in shallow wells and only occurred during the non-growing season. There were also examples when VSMC increased between the ~-50-60 cm and- 30 cm depths (Bt horizon) and then decreased at the shallowest depths. During the growing season and transition period, the latter case was dominant, with soil moisture highest around the 30 cm depth and decreasing at both the shallowest and deepest

depths. This pattern of saturation above the Bt horizon occurred at other UF hillslope synoptic sites, although not as markedly as at UF synoptic site T6. At the UF upland synoptic sites (T3 and T7), no such pattern occurred; VSMC increased with depth at these upland sites. This is consistent with the lack of an expansive, flow-impeding clay layer in the upland Vance soils.

Figure 25 shows the HF and UF mean catchment-wide integrated profile averages based on data from the access tube sites (described in Section 2.3.3.2). In HF (red line), 3-D catchment-wide mean VSMC was between 23 and 25% during late growing season 2009. The moisture shift is observable after October, when catchment-wide mean VSMC rose above 25% and stayed at that level until May, 2010. In the UF catchment, the dry-to-wet shift was more pronounced, with UF catchment-wide mean VSMC ranging from 18-25% during late growing season 2009, and then staying above 35% during the non-growing season. Both catchments returned to the dry state after May 2010.

Figures 26 and 27 provide more detailed results of the 3-D synoptic analysis for HF and UF catchments, respectively. The HF hillslope mean VSMC (blue diamonds) ranged from 15-35%, and the HF upland (squares) ranged from 24-43%. The HF riparian area (circles) clearly demonstrated a strong shift from dry (20%-25%) to wet (40%-50%) conditions. The riparian area was by far the wettest during the winter, staying above 40% VSMC until May 2010.

The UF hillslope mean VSMC (Figure 27, blue diamonds) ranged from 23-37%, while UF upland (squares) ranged from 13-43%. During the dry growing season of 2009, the UF uplands were the driest, ranging from 13-22%, while the UF hillslopes were wetter and ranged from 23-30%. The dry-to-wet shift was evident in both hillslope and upland locations, but the UF uplands were wetter, ranging between 30% and 43% until May.

Comparing HF and UF hillslope areas, HF hillslopes were generally drier throughout the study period, with a few exceptions. HF and UF hillslopes demonstrated an increase in VSMC that is defined here as a shift to a wet state, although the shift is clearer in the UF catchment. Comparing the upland sites, the HF catchment uplands did not show a strong seasonal trend of wet and dry states. The wettest values (44%) and driest values (23%) in the HF uplands both occurred in the winter. The UF upland values, however, demonstrated the greatest seasonal differences, ranging from the lowest consistent values (12-20%) in the dry period to the highest consistent values (37-45%) during the wet period. The UF uplands also show the clearest shifts in dry to wet and then from wet to dry. The clay soils on relatively flat surfaces in the UF uplands may have held water in place during the wet winter, minimizing lateral flows more prevalent in the UF hillslopes. The fact that UF Uplands stayed wetter to a greater depth than in the UF hillslopes suggests greater vertical movement of water to depth in the upland area (see Appendix 3).

2.5 Discussion

The analysis of soil properties such as texture and saturated hydraulic conductivity provide valuable insight into hydrologic dynamics in both the HF and UF catchments. Although both catchments overlay Slate Belt geology (Griffith et al. 2002), they have very different soils. Upland and hillslope soils in both catchments have loamy or sandy loam surface horizons and similar clay contents (up to >60%) in their subsurface horizons; however, the subsoils in the UF catchment's Helena hillslope soil series are moderately to highly expansive (USDA 1997), leading to seasonally perched water tables that do not occur in UF uplands or in the HF catchment. Soil analysis showing iron reduction uniquely in Helena soils, and evidence of perched water tables in these soils (Fig. 20) support this concept.

A comparison of the internal soil moisture dynamics between catchments infers some similarities in storage processes occurring in each catchment. Shallow riparian water table levels in each catchment demonstrated a clear dry-to-wet shift between growing and non-growing seasons. The seasonal water table increases in the UF catchment were greater and more immediate than those of the HF catchment. Shallow wells in the UF catchment demonstrated the formation of a perched water table at depths of <30 cm in UF hillslope soils during the late growing season and through the non-growing season (Fig. 20). Soil analyses and field observations confirm that the long term (i.e. seasonal) perched water tables did not occur at the UF upland sites or at any HF site. Saturation to the surface occurred at the HF riparian access tube site (HF T5); however, saturation at this site appeared to occur from

below due to a rising water table, with deeper VSMC values equal to, or above the surface VSMC values.

TDT profiles (HF T1 and UF T2), and transects of soil moisture access tubes in each catchment (Figs. 6 and 7) provide more explanation of the soil moisture dynamics in each catchment. The TDT profile at UF T2 and the access tube sites at T1, T2, T4, and T6, all indicated >20% increases in soil moisture in the clay (Bt) horizon starting at ±30 cm depth beginning in early November (Figs. 22 and 24b). Similar increases occurred at the deepest HF TDT probe, but not in the upper horizons (Fig. 21). VSMC increased slightly throughout the non-growing season in the UF clay horizons (Fig. 22, 25 cm, 45 cm, and 80 cm depths), while all horizons in HF (Fig. 21) lost VSMC due to drainage during periods of low rainfall (e.g. Dec. 26, 2009-Jan. 15, 2010).

Typical hillslope profiles from access tubes show that the HF hillslope and upland soils became wetter with increasing depth, with highest VSMC at depths of 1 m (±20%) (Fig. 24a and Appendix 3). UF upland sites also became wetter at depths approaching 1 m (Appendix 3). The UF hillslopes, by contrast, were wetter in and above the Bt horizon and exhibited less change below the clay layers (Figs. 22 and 24b), possibly due to non-growing season impedance of vertical flow (anisotropy) by the clay horizons. This process was described well by Grayson et al. (1997).

The T3 template of Buttle (2006) is used here to categorize the HF and UF catchments based on the drivers that are most critical in controlling the partitioning of water within the catchment. The 3 T's in the template are described below.

1. Typology—the relative role of hydrologic partitioning between vertical and horizontal pathways in controlling hydrologic response, or the ability of the different landscape elements to generate runoff (lateral flow of water, both by surface and subsurface pathways).

2. Topography—the relative role of hydraulic gradients (as controlled by catchment topography) in controlling streamflow response.

3. Topology—the capacity of the drainage network to carry runoff to the basin outlet, or the relative role of connectivity to control streamflow response.

Based on the terrain and soil characterization (Table 1) and the storage analyses presented, Figure 28 maps the HF and UF catchments on the T3 Template, conceptually showing the relative influences of typology, topography, and topology on the hydrology of each catchment. The HF catchment is likely controlled by topography (14% mean slope and 160 ft. relief) and typology (shallow hillslope soils) related to the underlying parent material, while UF is a more variably-controlled catchment, with relative influences of topography (8% slopes) controlling during the growing season and typology (expansion of clay layers and perched water) controlling during the non-growing season. Measurements and estimations of K_{sat} values, perched water table data, and continuous and access tube soil moisture profiles all support the conceptual model of the UF catchment as a typologically

and topographically controlled system and the HF catchment as a more topographically controlled system.

Analysis of seasonal rainfall-to-runoff ratios (Q/P) in both catchments further illustrates the T3 conceptual model presented here. During the late growing season (Jul.1-Oct. 31) of 2009, precipitation in HF and UF were 365 and 398 mm, respectively. In HF, area-averaged streamflow (40 mm) was 11% of total precipitation. In UF, area-averaged streamflow (10 mm) was 2% of precipitation. In the early growing season of 2010, streamflow values were higher in HF and UF, with streamflow at 26% of precipitation in HF and 16% of precipitation in UF. During the non-growing season (Nov. 1-Mar. 15), the total precipitation in HF and UF were 629 mm and 614 mm, respectively. Streamflow was 200 mm (32% of P and) 320 mm (52% of P) for HF and UF catchments, respectively. The more pronounced increase in Q/P in the UF catchment is likely due to shallow subsurface flow in the surface horizons, overland flow, or both, although storm-based examination would be required as further support. In HF, the increases in the Q/P ratio are more subtle than in UF. Typology may be a driver, but if this is the case, the impeding layers are likely deeper, at the interface between the soils and underlying regolith (Heath 1994). This is consistent with findings from other Piedmont studies, such as Tromp-van Meerveld and McDonnell's (2006a) "fill and spill" hypothesis.

Further analysis of the drainage densities (density of streams per area) in each catchment would shed additional light on the relative influences of topology. Table 1 shows that the

drainage densities of HF and UF are very similar based on 1:24,000 scale maps; however, the field observations of intermittently-flowing channels during the winter and early spring of 2009-2010 reveal a different reality. In HF, observations revealed an extension of total catchment stream length, as previously dry channels began to flow with the rising water table. In UF, the increase in total length of flowing streams was dramatic, with many small channels flowing for the entire winter period. Channels that appeared ephemeral based on field observations using NC Division of Water Quality methods for identifying stream origins (NC DWQ 2005) ran constantly for the entire winter period. This phenomenon is likely caused by the shallow water tables of the wet hillslope soils, which rose above the bottom of the very shallow channels and appeared to create an extensive system of shallow, ephemeral-sized channels that flowed throughout the wet winter period, hydrologically functioning as intermittent streams despite the fact that these channels appeared to lack intermittent stream morphology or biology (NC DWQ 2005). The functioning of the topology of this system merits further study, including detailed mapping of the small, ephemeral-sized channels in the UF catchment, the dry and wet-season drainage densities of both catchments, and the effects of these changes on streamflow.

2.6 Conclusions

HF and UF experience the same climate, very similar precipitation conditions, and both lie within the Carolina Slate Belt Ecoregion (Figure 1). However, the catchments have significantly distinct topography and soils and can be described as having unique hydrologic

landscapes (Winter 2001). As detailed field and laboratory analyses of the soils in both catchments show, the major soils of the HF and UF catchments differ significantly. Both catchments have subsurface Bt horizons classified as clay in texture, but UF has an expansive clay subsurface horizon in hillslope locations and HF does not. This difference results in greater differences in K_{sat} in the Bt horizons of the HF and UF hillslopes, which in turn causes great seasonal differences in hydrology. One year (Aug. 2009 – Jul. 2010) of rainfall, streamflow, water table, and soil moisture monitoring confirm that the UF hillslopes (Helena soils) form seasonal perched water tables during the non-growing season. Based on seasonal runoff ratio (Q/P) values, we can infer that the UF perched water system moves laterally either in the shallow subsurface or as overland flow across the flatter slopes of the UF catchment, causing rapid lateral flow into the stream during this wetter time of year. With identical climate, the catchments are best described using Buttle's (2006) T3 conceptual model. This model describes the UF catchment as exhibiting strong non-growing season typologic controls (causing lateral flows) on hydrology, while typology is less controlling and topography more controlling role in the HF catchment.

3 WATER BALANCES FOR THE HILL FOREST AND UMSTEAD FARMS CATCHMENTS

3.1 Introduction and Literature Review

Chapter 2 of this study analyzed changes in unsaturated and saturated-zone storage (ΔS_U and ΔS_S) to describe soil moisture dynamics in two 29.5-hectare (73-acre) catchments located 5 miles apart in the Carolina Slate Belt Ecoregion within the Piedmont Region of North Carolina (see Figure 1). The US Forest Service has monitored weather, precipitation, shallow groundwater, and streamflows in both catchments since December 2007 as part of a paired watershed study comparing the hydrologic and water quality response of forested streams to those logged under Neuse River Basin-wide forestry best management practices. Chapter 2 reveals seasonal variations in shallow unsaturated-zone and saturated-zone storage in each watershed. Significant seasonal differences in these parameters and in the runoff-to-rainfall ratios (Q/P) point to the need for detailed water balance equations to further analyze differences and infer their potential driving factors. This chapter combines USFS data with detailed soil moisture and shallow groundwater data collected during the period of July 2009 through July 2010 and calculates and compares daily cumulative, monthly, seasonal, and annual water balances for both catchments.

The cumulative water balance graphically presents the cumulative amount of each component of the water balance (P, ET, Q, ΔS_U, or ΔS_S) on a daily basis. This method reveals seasonal processes such as changes in storage and seasonally-variable flows that are

not detected in annual water balances, which may not reveal inter-catchment differences in these variables. Change in water storage becomes especially clear in the cumulative water balance because rising and falling storage values during wet and dry seasons clarify the process of storage increases and decreases relative to day one of the period. In addition, comparison of cumulative water balances across catchments can provide insight into how these processes differ across the hydrologic landscape. Guan et al. (2010) used the cumulative water balance to analyze the relative influence of water balance components through spring and summer seasons in subarctic Canadian peat land, valley, and wetland sites. These differences can also be detected, although not in such temporal detail, using monthly and seasonal water balances. Detailed water balances such as these help to reveal the factors driving hydrology, and specifically streamflow, which is useful for watershed management. Such detailed comparisons are lacking for the Piedmont region of the USA.

Only one small-scale, detailed water balance study is available for comparisons within the Piedmont Region of the USA. Schäfer et al. (2002) used 3.5 years of interception, evaporation, transpiration, and shallow soil moisture measurements to calculate three annual hydrologic balances for small (30 m.-diameter) plots in the nearby Duke Forest. The Duke Forest study's objective was to determine whether elevated atmospheric CO2 concentration causes changes in forest water use. The researchers estimated drainage and overland flow using a model based on physical parameters and directly measured precipitation, throughfall, shallow (30 cm) soil moisture, and climatic parameters. Under ambient CO_2 conditions at the Duke Forest plots, annual evapotranspiration ranged from 64%-79%, annual changes in

shallow soil moisture storage ranged from 0.5%-3%, and annual vertical drainage to depth (modeled for the upper 30 cm) ranged from 17%-30% (Schäfer et al. 2002). Although the Duke Forest study was at a small 30-m. plot scale, we can compare our estimates of evapotranspiration and storage change with those generated by Schäfer et al. (2002). However, because the Duke Forest study was not at a catchment scale, it lacks surface water and water table data, leaving gaps in knowledge about monthly and seasonal variations in the water balance or in specific components of the water balance. The current study provides new streamflow, storage change, and shallow groundwater data across two different landscapes within the Piedmont Region.

Catchment-scale studies from other physiographic provinces in the southeastern USA are available for comparison with this water balance. Sun et al. (2002) compared the long-term monthly and annual water balances of small, coastal and mountain watersheds in North Carolina, using long-term precipitation and runoff data and calculating actual evapotranspiration (AET) as the difference between precipitation and runoff. The authors also calculated PET using the Hamon's method (Hamon 1963). The NC coastal plain catchment, which is similar in size and climate to the HF and UF catchments, received an average of 1524 mm rainfall, produced an average of 470 mm runoff (30% of precipitation), and lost an estimated average of 1054 mm AET (70% of precipitation). The Sun et al. (2002) study did not discuss seasonal variability in the water balance components or changes in storage. The current study of the HF and UF catchments directly or indirectly (in the case of ET) measures all components of the water balance except deep groundwater fluxes (G). It

also generates monthly and cumulative daily comparisons between HF and UF catchments and, therefore reveals additional information about the processes driving the water balances across two hydrologic landscapes that are defined using Buttle's (2006) T3 template (discussed in more detail in Chapter 2).

Water balances from other North Carolina provinces also provide useful comparisons with this study. A Coastal Plain water balance by Harder et al. (2007) quantified the annual and seasonal water balances of a 160-hectare forested catchment in the USFS Santee Experimental Forest northeast of Charleston, South Carolina. The authors measured rainfall, outflow, shallow soil moisture storage, and climate components for evapotranspiration models, comparing the Thornthwaite, Hamon, and Penman-Monteith methods for ET. The study created a water balance for each year and "growing" and "dormant" seasons during the study period. The results showed a high annual variability of water budget components, apparently due to the great differences in precipitation between 2003 and 2004 (Harder et al. 2007). During the 2003 calendar year, when precipitation was high (1671 mm), runoff was also high (784 mm, or 47%). In contrast, P was low in 2004 (962 mm), Q and Q/P were also low (73 mm and 8%, respectively). The two-year average of Q/P was 33%, similar to that of the Sun et al. (2002) and HF and UF catchments (see Discussion, Section 2.5). The Harder et al. (2007) study also showed great seasonal variations in Q and Q/P, although the results do not show strong patterns between dormant and growing seasons, likely because of great differences in precipitation between the two years of the study. These seasonal variations underscore the need for daily cumulative, monthly, and seasonal water balances. The Harder

et al. (2007) study also found that the Thornthwaite monthly water budget model using Penman-Monteith PET was the closest to actual ET (70% and 66% of P, respectively). This study did not provide daily cumulative and monthly water balances.

Finally, comparisons can be made with studies from the North Carolina mountains. Kovnee (1957) calculated annual water balances for 30-acre Watershed 18 in the Coweeta Hydrologic Laboratory over an 18-year period. Kovnee (1957) used direct measurements of precipitation and streamflow, estimated groundwater storage based on a groundwater depletion curve (unsaturated-zone storage was assumed to equal zero between hydrologic years, May 1-Apr. 30), and calculated evapotranspiration as a residual of precipitation minus runoff and changes in the estimated storage. The annual water balance components were P (69 inches, or 1750 mm), ET (1020 mm, or 58%), and Q (690 mm, or 39%). The Lieberman and Fletcher (1947) study of Coweeta Hydrologic Laboratory Watershed 2, also a 30-acre catchment, used a similar approach, continuously measuring P and Q, assuming changes in soil moisture in the unsaturated zone equaled zero between hydrologic years (beginning Apr. 1), measuring changes in saturated-zone storage once yearly, and assuming deep seepage equaled zero. The authors concluded with the recommendation that more detailed soil moisture data are needed to better understand the connections between precipitation, moisture storage, and streamflow.

3.2 Objectives

The research objectives of Chapter 3 are to quantify and compare daily cumulative, monthly, seasonal, and annual water balances for the HF and UF catchments. In addition to using existing precipitation, streamflow, and weather data provided by the US Forest Service Southern Research Station (USFS) the objectives were:

1) Calculate daily and monthly evapotranspiration;
2) Use the daily and monthly unsaturated and saturated zone storage change values calculated in Chapter 2;
3) Develop monthly, seasonal, and annual water balances from these components; and
4) Use the water balance residual values as estimates of groundwater fluxes from the catchments;
5) Compare water balances and individual components from UF and HF sites;
6) Integrate water balances and characterizations from Chapter 2 into an understanding of Piedmont specific hydrologic landscapes and their differences, as represented by UF and HF catchments.

The catchment-level hydrologic differences calculated as part of the water balances are described in the context of the Buttle (2006) T3 Template, and a quantified conceptual model of the seasonal water balance is presented for each catchment-type.

3.3 Methodology: Water Balances

Both the HF and UF catchments were monitored for weather and precipitation, streamflow, shallow, unsaturated-zone soil moisture, and riparian groundwater levels for the time period

of August 1, 2009 to July 31, 2010, as described in Chapter 2. The USFS has continuously collected precipitation, weather, and stream flow data in both the HF and UF catchments since December 2007 and provided daily data for the study period. In addition, daily changes in shallow subsurface storage were calculated. ET was not presented in Chapter 2. The daily values were used as the basic units used to compile the cumulative, monthly, seasonal, and annual water balances were calculated for each catchment. Comparisons of components of precipitation, evapotranspiration, runoff, and changes in storage are made, allowing for comparisons of the water balances.

The basic water balance equation shown in Equation 1, and the change in storage described in Equation 3 can be combined and rearranged into the water balance shown in Equation 10

$$G = P - ET - Q - (\Delta S_U + \Delta S_S) \qquad (10)$$

P = precipitation

ET = evapotranspiration

Q = streamflow

G = groundwater flux from watershed

ΔS_U = changes in the amount of water stored in the unsaturated zone

ΔS_S = changes in the amount of water stored in the saturated zone, or net recharge

The data collection and analysis behind the net recharge and unsaturated zone storage is explained in previous methodology sections. Data collection, analysis, and assumptions for calculating P, ET, Q, ΔS, and G calculations are explained herein.

The cumulative daily water balance presents each component of the water balance as a sum of the values of all previous days relative to day one of the study period (e.g. Guan et al. 2010). The monthly water balance calculation follows Equation 10, using an adaptation of grass-reference ET_O to actual ET and summed to monthly ET for local forested conditions, as well as monthly sums of P and Q, monthly estimates of G, and monthly mean ΔS and G. Monthly P, ET, Q, ΔS and G were summed to seasonal totals for August 1–October 31, 2009 (late growing season 2009), November 1–March 15, 2010 (wet, non-growing season), and March 15–July July 31, 2010 (early growing season 2010) for seasonal intra- and cross-catchment comparisons. Annual totals were also compared.

3.3.1 Precipitation

Each catchment was outfitted with one manual rain gauge and one Hobo tipping-bucket (Onset Corporation) that records each 0.2 mm of rainfall. Manual rain gages were emptied after each rain event. In UF, the rain gauge was located approximately 100 meters downstream of the outlet of the catchment (see Figure 7). In HF, the rain gauge was located approximately 500 meters west of the watershed boundary (see Figure 6). At each location, total rainfall from the two types of gages was compared for consistency. Where losses of tipping bucket data occurred, manual rain gage data were substituted. Since precipitation

collected in the rain gauges is assumed to represent the average precipitation over the entire watershed, the depth of precipitation measured is used directly in the water balance equation.

3.3.2. Evapotranspiration

To collect data necessary for ET calculation, the USFS meteorological station at the HF site (Onset Corporation) continuously recorded a 1-hour mean of solar radiation, wind speed and direction, air temperature, and relative humidity. Daily evapotranspiration (ET) for use in the daily cumulative water balance was estimated using a commonly used grass-reference evapotranspiration formula from the United Nations Food and Agriculture Organization method (Allen et al. 1994) adapted from the Penman-Monteith method (Monteith 1965). The result is an estimation of actual daily ET of a hypothetical well-watered grass (ET_o) that has a 0.12 m canopy height, a leaf area of 4.8, a bulk surface resistance of 70 s/m, and an albedo of 0.23 as follows:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(\frac{C}{T+273})\mu_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,\mu_2)} \quad (11)$$

ET_O = grass reference evapotranspiration (mm)

Δ = slope of the saturation water vapor pressure at air temperature T (kPa °C^{-1})

R_n = net radiation (MJ m^{-2})

G = soil heat flux (MJ m^{-2})

γ = the psychrometric constant, (KPa °C^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

μ_2 = mean wind speed (m s^{-1})

C = unit conversion factor with a value of 900

A shortcoming of Equation 11 for use in forested catchments is that it estimates ET for a hypothetical grassed location under the local weather conditions. This study therefore uses an empirical adaptation of Equation 11 for forested conditions developed by Sun et al. (2010). This approach provides an estimation of actual monthly ET using Equation 12, which adapts ET_O calculated in Eq. 11 with daily precipitation data and mean monthly actual leaf area indices (LAI) calculated using 10-day incremental data from US NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) available online (http://daac.ornl.gov/cgi-bin/MODIS/GLBVIZ_1_Glb/modis_subset_order_global_col5.pl). The equation, developed for worldwide use and calibrated with sites from North Carolina, improves upon the grass-reference ET_O, which can underestimate ET of forested areas (Sun et al. 2010). Monthly ET is calculated as,

$$ET = 11.94 + 4.76\ LAI + ET_O\ (0.032\ LAI + 0.0026\ P + 0.15) \quad (12)$$

The calculated monthly ET was compared with findings from the literature, especially nearby studies in Duke Forest (Schäfer et al. 2002) and estimates of Flat River, N.C. ET in a review of water balance-derived ET in the southeastern U.S. by Lu et al. (2005).

3.3.3. Catchment stream discharge

Continual stream discharge (Q) was measured in the UF catchment using a H flume with a stilling well and SIGMA 900 MAX (Hach) portable automated water sampler recording stage on a 10-minute interval. In HF, the USFS used a 90° V-notch weir installed prior to 1981 (Barker 1983) with a stilling well and SIGMA 900 MAX (Hach) portable automated water sampler recording stage on a 10-minute interval. Figures 6 and 7 show the continual stream discharge measurement stations as triangles. USFS staff calculated the area-averaged daily stream flow by summing the continuous (10-minute) flow data into a total daily discharge volume and normalized the daily discharge over the area of each catchment (29.5 hectares, or 73 acres for each catchment). The result is the daily average depth of stream flow. The daily average stream flow depth was used in the cumulative daily water balance and then summed into monthly, seasonal, and annual average streamflow depths (mm).

3.3.4. Change in Unsaturated and Saturated-zone Storage

All storage change estimations for use in the water balances were calculated using Equation 3 (Chapter 2), as the sum of change in unsaturated storage (ΔS_u) plus change in saturated zone storage (ΔS_s). The 1-D storage change scenario is used to calculate the daily cumulative water balance. For the monthly water balance, both the 1-D and 3-D scenario storage

changes described in Chapter 2 were calculated and compared. For the 1-D scenario, the daily change in saturated and unsaturated storage was used to calculate a monthly change in storage by subtracting the storage estimate on the last day from that on the first day of each month. For the 3-D approach, because soil moisture at the access tube sites were not measured daily, but rather bi-monthly, a mean monthly unsaturated-zone storage was calculated and then multiplied by the change in unsaturated-zone thickness occurring from the first to the last day of each month.. This monthly change in unsaturated zone storage was then summed with the change in saturated storage, calculated as the difference between storage values on the first and last day of the month.

3.3.5. Groundwater Flux

Groundwater flux from the catchments was estimated for monthly, seasonal, and annual water balances using Equation 10. This approach assumes that the residual of the components of the water balance is water lost or gained to the catchment through deep seepage or flux below the streamflow measurement devices. It is understood that the residual of Equation 10 includes cumulative error of the balance and all individual components; however, the information is relevant for the purposes of comparing the HF and UF catchment G values because methodologies in each catchment were identical and, therefore, the degree of error should not vary significantly between the catchments. Daily calculations are not presented as G because of the inability to separate out individual rain events and calculate flux associated with these events. On a monthly basis, this problem is avoided with the

exception of precipitation events spanning the end of one month to the beginning of the new month. The resulting estimates of residual G were compared across catchments.

3.3.6. Uncertainty in Water Balance Components

Based on guidance from Winter (1981) for catchments of areas less than 0.1 m^2 (0.26 km^2), the uncertainty in annual, seasonal, and monthly precipitation in HF and UF was estimated to be 4%. The uncertainty in annual stream discharge for flumes and weirs with high temporal-resolution recording capacitance devices is 5% (Winter 1981, Lesack 1993, Genereux 2005). Monthly reference Penman-Monteith ET estimates were shown by Allen et al. (1989) to have standard errors of 0.36 mm/day. Allen et al. (1989) found that daily error estimates were greater, on the order of 0.77 mm/day.

Factors contributing to uncertainty in catchment-wide storage changes include 1) soil moisture content measurement by the TDR and TDT probes, 2) water table measurement, and 3) uncertainty associated with the regionalization of point data to represent catchment-wide changes in storage. Reported uncertainty of the TDT continuous probes is 1% (ESI 2010). Uncertainty of the TRIME TDR probe used with access tubes is higher because these point measurements could not account for daily fluctuations. A conservative estimate of uncertainty in the access tubes is to assume uncertainty can be no greater than the daily fluctuations of VSMC, an uncertainty of about 5%. Uncertainty in absolute well-level measurements has been shown to be less than 1%. Although the range in VSMC across catchments was large (16-42% in HF, 13-43% in UF), research on temporal stability of soil

moisture (Vachaud et al. 1985) has shown that within a soil series, a given location on the landscape tends to maintain its relative rank in soil moisture across time. Stated another way, on a given soil (e.g. Appling) series, the wettest location on Jan. 1 will be the wettest location on Aug. 1. In this analysis of ΔS based on landscape (and soil) type, temporal stability of soils means that changes in soil moisture content should not vary significantly across individual landscapes. For this reason, ΔS uncertainty should be low. A conservative estimate of uncertainty associated with regionalization was estimated to be 20%. Combining measurement and scaling uncertainties, the total uncertainty of changes in catchment-wide storage is estimated to be 25%.

Uncertainty of the groundwater flux estimate (G), which is the residual of Equation 10, was estimated based on the standard techniques for propagation of uncertainty through calculations (Lesack 1993, Genereux 2005). The "root square sum" estimation of uncertainty was used to estimate uncertainty in G,

$$W_G = \sqrt{(W_P)^2 + (W_Q)^2 + (W_{\Delta S})^2 + (W_{ET})^2}\,, \qquad (11)$$

where W_X is the uncertainty (in mm of water) of component X of the water balance (Equation 10).

3.4 Results

3.4.1. Precipitation

Figures 29 and 30 show the daily precipitation, streamflow, and FAO grass-reference ET_O for the HF and UF catchments (all in units of mm). HF annual precipitation was 1,368 mm ± 55 mm and UF annual precipitation was 1,293 mm ± 52 mm. Precipitation in HF was 12% above, and P in UF was 6% above, the 111-year annual average of 1,219 mm reported for Durham County by the NC Climate Office (NCCO 2010). Tables 8 and 9 show the monthly distribution of P. In both catchments, rainfall ranged from below 30 mm in April 2010 to highs around 220 mm in November 2009. The highest rainfall totals were in Nov.-Dec. 2009 and May 2010. These three months were well above averages reported by the NC Climate Office. HF and UF November rainfall totals were around 220 mm, almost twice the November average of 114 mm reported by the NC Climate Office.

3.4.2. Evapotranspiration

Figure 31 shows the FAO Grass-reference ET (ET_O) over the study period. The HF weather station data lacked daily net radiation data from August 8 through November 12, 2009, so these data were filled with net radiation from the NC Climate Office North Durham Water Reclamation Facility (WRF), approximately 12 miles (19 kilometers) south of the catchments. The resulting daily ET_O values rise and fall with temperature values. Temperature and ET_O values appear closely aligned during the growing-season, but ET_O values do not rise with temperature values during warm periods in the winter. Figure 32 compares ET_O values using NC Climate Office data from the North Durham station with

values from the Hill Forest weather station. The two sites compared favorably, with R^2 = 0.94. Thus, substitution of the NC Climate data values appears to be acceptable when Hill Forest data were missing.

Annual total ET values adjusted for local forested conditions using Sun et al. (2010) were 812 mm ± 118 mm in the HF catchment and 836 mm ± 118 mm in the UF catchment (Tables 8 and 9). The HF ET value was 13% lower than the ET_O value. The UF ET value (836 mm) was 11% lower than the ET_O. Because the actual ET adjusted by the Sun et al. (2010) equation accounts for local catchment-specific leaf-area index (LAI) and precipitation (P), this calculation is preferred over ET_O, which has the same value for both catchments, for use in monthly water balances.

For comparative purposes, the calculated ET of a pine-dominated stand in nearby Duke Forest for the years 1998-2000 ranged from 844 mm to 895 mm (or 64% to 79% of P). Lu et al. (2005) calculated ET in the 386-km^2 Flat River watershed, in which the HF catchment is nested, using the residual value of 30-year average precipitation minus streamflow at a USGS gauging station. The Flat River watershed's mean annual ET was 791 mm, or 72% of the average annual precipitation (1,122 mm). Considering uncertainty, the ET values in the current study overlap the range from the Duke Forest and Flat River studies (Schäfer et al. 2002).

Monthly ET values in Tables 8 and 9 show the varying seasonal shift in ET in both catchments. For the two catchments, growing season ET ranged from 41-143 mm, while non-growing season ET ranged from 27-49 mm. ET values were 12% higher in UF than in HF during the period of August, 2009 until April, 2010. During that period, LAI values were 31% higher in UF than in HF. In May 2010, ET in both catchments almost doubled compare to the previous month, and ET in the HF catchment rose above that of the UF for the remainder of the study period. During this period, the LAI values were similar, but the HF rainfall values were 29% higher in HF than in UF, and total ET as a percentage of P remained higher in the UF catchment (118%) than in HF (97%).

3.4.3 Stream discharge

Tables 8 and 9 show the monthly stream discharge values for the HF and UF catchments, respectively. In HF, annual streamflow was 354 mm ± 18 mm (26% of P), while in UF annual streamflow was 386 mm ± 19 mm (30% of P). The HF catchment monthly streamflows ranged from a low of 8 mm (Aug.) to a high of 57 mm (Dec.). The UF range was much greater, from 1 mm (Aug. and Jul.) to 109 mm (Dec.). Although the patterns of increasing Q during the non-growing season exist in both catchments, the UF catchment showed more extreme flow conditions, with lower discharge in all growing season months (March – October) and significantly higher discharge during all wet, non-growing season months.

Figures 29 and 30 show daily stream discharge values for the HF and UF catchments, respectively. The seasonal differences in discharge are clear in the daily data, which make visible the extremely low growing-season daily flows and high daily discharge values in response to wet, non-growing season rainfalls in the UF catchment. Growing season daily baseflow (defined using daily data with no rainfall and >48 hrs after rain events over 5mm) in UF consistently approached 0.01 mm, while that of HF consistently ranged between 0.2 and 0.5 mm. In HF, there were no days without flow during the entire study period. Once the seasonal shift from dry to wet conditions occurred, flows increased in early November, when PET values fell from high growing-season values (4-6 mm/day) to low, wet winter values (0-2 mm/day). From this time forward, UF baseflow increased to levels similar to those of HF, and storm-related discharge levels were much higher in UF than in HF.

As shown in Tables 8 and 9, the total growing season streamflow was higher in HF (14% in late 2009 and 21% in early 2010) than in UF (2% and 12%). However, this was reversed during the non-growing season, when streamflow in UF was 52% of precipitation (Table 9), while it was only 33% of precipitation in the HF catchment (Table 8).

3.4.4. Change in Storage

Tables 8 and 9, compare monthly 1-D and 3-D results for the HF and UF catchments respectively. In general, 3-D analyses estimates of change in storage tended to be higher than those of the 1-D analyses. In HF, magnitudes of 3-D storage change (91 mm ± 23 mm) were slightly higher than was the 1-D analysis (64 mm ± 16); however, considering

uncertainty, the estimates overlap. In UF, 3-D storage change was 50 mm ±12 mm, while 1-D was -51 mm ± 13 mm. Here uncertainties cannot account for differences between these two numbers. There are several possible explanations for the difference between the two estimates. One possibility is that the 3-D analysis, which is based on soil profile data from multiple soil moisture monitoring locations spanning upland, hillslope and riparian positions, may be more representative of catchment-wide changes in storage. Another possibility is that the 3-D analysis, which is based on bi-monthly measurements of storage, is relatively more susceptible to the influence of individual extreme values than is the 1-D analysis, which is based on a single hillslope integrated profile but with hourly moisture data.

In HF, the 1-D and 3-D changes in S follow similar patterns of monthly increases and decreases throughout the study period, though their absolute values vary significantly. Monthly 1-D and 3-D totals in UF also followed similar patterns, although the June-July 2010 patterns diverged significantly. The infrequence of monitoring at the access tube sites used in the 3-D analysis may lead to over-representing extreme events. For example, the access tube sites were monitored only twice in July 2010, so the 46 mm rain event that occurred just before the second monitoring created a high VSMC and water table, raising the July 3-D ΔS average (see Tables 8 and 9). The 1-D ΔS average was not as greatly affected by this event because the 1-D VSMC data were averaged for the entire month of July, 2010. Because of these factors, differences in 1-D and 3-D storage change analysis were sometimes significant. The seasonal changes in storage differed by 37-80 mm in UF (Table 9) and 3-68 mm in HF (Table 8).

3.4.5. Groundwater Flux

Tables 8 and 9 show groundwater flux (G) values calculated using the residual approach of Equation 10. The annual estimation of G in HF was 136 mm ± 132 mm (10% ± 10% of P) and in UF was 123 ± 131 mm (9% ± 10% of P). The uncertainties in annual G are equal to the estimates, making assessment of annual groundwater flux unreliable. However, seasonal values provide some useful information to contrast catchment behavior. Considering only the 1-D analysis (1-D and 3-D were similar in HF), in HF, G was calculated to be 261 ± 54 mm (38% ± 8%) during the wet, non-growing season and only -48 ± 33mm to -77 ± 47mm during the non-growing seasons. This pattern of recharge during the wet, low-ET season is consistent with general models of Piedmont hydrology (Heath 1994). During the wet non-growing season months of Nov.-Feb. when ET was low (16-33% of P), G ranged from 17-62% of P. During these months, 1-D storage changes in HF were not high (-12-17%), indicating that excess rainfall moved vertically through the relatively well-drained unsaturated zone and into Q (17-62% of P) or G.

At UF, monthly data show less G (-26% to 17%) and high Q (37-76%) during the non-growing season. In addition, a very large change in storage during Nov. (71% and 100% for 1-D and 3-D analyses, respectively) followed by little to no increases in storage during Dec.-Feb. is consistent with a perched, saturated water table that moves laterally into Q. The higher G totals in September (73 ± 14mm, or 64 ± 12%), April (67 ± 32 mm., or 246 ± 123%), and July (91 ± 28mm, or 77 ± 24%) suggest fluxes occurred either when perched

water existed but no rainfalls occurred causing differences in head sufficient to produce lateral flows (e.g. April), or during drier periods when large amounts of rain occurred and the expansive clay horizons were not saturated and allowed vertical flow (September and July).

3.4.6. Daily Cumulative Water Balance

Figure 33 shows the daily cumulative water balance for the HF catchment. The solid blue line shows cumulative P, the green, dashed line shows ET_O, the black dot-and-dashed line shows cumulative Q, and the red, dotted line shows 1-D ΔS. During the late growing season of 2009 (left 1/3 of graph), ET_O was higher than P, resulting in negative or near-zero ΔS and low Q values. When P increased in November 2009, this accompanied the leaf loss and reductions in ET_O (flattening of the cumulative ET_O curve) resulting in increases in ΔS and Q. The ΔS values remained positive throughout the non-growing season, only trending back toward zero starting in April when ET_O values increased with the start of a new growing season. From April 2010, ET values rose with a similar slope to that of P, and this, along with continuing discharge, reduced ΔS to near zero.

Figure 34 shows similar processes occurring in UF, with late growing season 2009 P and ET_O tracking together. During this period, ΔS were typically zero, only increasing in response to the very largest storms. Even the large storms and positive ΔS conditions did not produce significant stream discharge, and Q for the late growing season period only reached 6 mm. The early Nov. 2009 increases in P and decreases in ET_O brought about significant

changes, first in storage, which increased in response to the early rains, and then in Q, when discharge increased significantly about 10 days after the increases in storage. During the entire non-growing season, cumulative Q increased to 52% of the seasonal P. Relatively high Q values began to plateau with the beginning of the growing season accompanying increases in ET_O rates. Large storms in May 2010 delayed this return to the dry state as ΔS levels jumped back to levels of the non-growing season, but this was short-lived. By June, ΔS values returned to zero and went negative as ET_O rates matched Q. From the point when ΔS reached zero in June, cumulative Q did not increase as the streamflow dried to no flow. From this point forward, even large storm events that increased storage changes (in July) did not produce streamflow after the dry state had been reached. This is distinct from the HF catchment, where Q continued to rise throughout the growing season 2010.

3.4.7. Monthly, Seasonal, and Annual Water Balances

The monthly, seasonal, and annual water balances for HF are shown in Table 8. The HF catchment's annual ET value was 812 ± 118mm (59 ± 9%) of P (1368 ± 55mm). Discharge (Q) was 354 ± 18mm, 26 ± 5% of P, and change in shallow storage (ΔS) was 64 ± 16mm (5 ± 1%) based on the 1-D analysis and 91 ± 23mm (7 ± 2%) based on the 3-D analysis. The residual of this annual water balance, assumed to be water lost to deep groundwater seepage and flux (G) was 136 ± 132mm (10 ±10%). The annual water balances for UF are shown in Table 9. Total P was 1293 ± 52mm, ET was 836 mm ± 118mm (65 ± 9%), Q was 386 mm ± 19mm (30 ± 1%), and ΔS was -51 ±13 mm (-4 ± 1%) based on the 1-D analysis and 50 ±

12mm (4 ± 1%) based on the 3-D analysis. Based on the water balance using the 1-D ΔS, G was estimated to be 123 ± 131mm (9 ± 10%). The annual water balances for HF and UF are similar, showing only slight variations in the percentages of Q (difference of 4%), ΔS (difference of 3-9%), ET (difference of 6%), and G (difference of 1%) comprising the water balances.

The monthly water balance illustrates the seasonal changes that occurred in the catchments. In UF, 219 ± 9mm of rainfall in Nov. 2009 caused strong monthly changes in storage of 154 ± 39mm (70 ± 18%) and 219 ± 55mm (100 ± 25%), for 1-D and 3-D estimates, respectively. This implies that the majority of the Nov. 2009 rainfall went into storage in and above the expansive clay horizon. During that same month, mean Q values in UF increased from 3 mm/month in October to 81 ± 4mm/month and then to 109 ±5mm/month in December. In HF, virtually the same amount of precipitation occurred in Nov. 2009 (227 ± 9mm), but ΔS values only increased slightly in November (between 9 ± 2mm and 19 ± 5 mm, or 4-8%), and December (between 31 ± 8 mm and 34 ± 9 mm, or 17-19%). Total Q in the HF catchment increased from 12 ± 1 mm/month in October to 39 ± 2 mm/month in November and 57 ± 3 mm/month in December, much less of a streamflow increase (375% increase from Oct.-Dec.) than in UF (3530% increase).

A seasonal summary (Tables 8 and 9) further illustrates differences in the HF and UF catchments. In HF, streamflow was 14% of P during the late growing season of 2009. ET

during this period was 87 ± 14% of P. During the non-growing season that followed, ET reduced to 24 ± 7%, while Q increased to 33 ± 2% of total P. Slight increases in storage (4 ± 1% -14 ±4%) occurred, and 38 ±8% of the water was lost from the balance, assumed lost to deep seepage and flux (G). After March, in the early growing season of 2010, Q fell to 21 ± 1% and ET rose to 97 ± 9% of P, while losses in storage (-3 ± 1%) occurred. Based on this balance, G values were actually negative during the growing season periods. This may suggest a net gain from deep groundwater below the shallow subsurface storage zone assessed by observations, contributing to make up the water balance (possibly as part of ET or Q). The negative residual G values during these periods may also suggest some error in the water balances.

Seasonal patterns in water balance components differed in UF. During late growing season 2009, total Q was 2% of P, while ET was 77 ± 11% of P. During that time, storage changes ranged from -9 ± 2% to 21 ± 6%, and G was estimated to be 0-30%. When ET fell to 28 ± 7% during the non-growing season, UF Q rose to 52 ± 3% of P, and ΔS rose to between 24 ± 6% and 35 ± 9%, leaving G ranging between -24 ±67 mm and -96 ±85 mm. These very low G values are fundamentally different from the patterns of G in the HF catchment. Once ET rose again (to 118 ± 11% of P) during early growing season 2010, Q fell to 12 ± 1% of P, shallow storage showed losses (ΔS was -47 ± 11% to -56 ± 14%), while there is no evidence for G.

3.6. Discussion

Over the 1-year study period, patterns in ΔS differed greatly for HF and UF. The seasonal water balance suggests that greater increases in shallow storage occurred in UF during the non-growing season, and the monthly data show that these increases occurred mainly in November 2009. This is consistent with the formation of the perched water system and subsequent increases in storage in and above the expansive clay horizon. The UF catchment stayed consistently wetter through the winter (ΔS varied only slightly from Dec. 2009 to March 2010) and then lost almost all the storage gains made during the non-growing season during April 2010. This loss in storage is consistent with the loss of most of the perched water system. Similar patterns in ΔS occurred in HF, where the ΔS also rose and experienced a plateau until losses occurred in April. However, the November rise and April fall in ΔS were not nearly as steep, and the plateau not nearly as high, as those in UF. In November, UF storage S rose to between 154 ± 39 and 219 ± 55 mm/month, while HF storage rose to between 67 ± 17 and 96 ± 24 mm/month. In April, UF ΔS fell to between -124 ± 31 and -171 ± 43 mm/month, while HF ΔS fell to between -47 ± 12 and -77 ± 19 mm/month. The greater values for storage change in UF likely reflect that the shallow (<2 m. depths of probes) monitoring methodology better captured the soil moisture storage occurring in UF, where much of the storage was trapped in the shallow surface of the Helena hillslope soils, than in HF, where storage moved vertically through upland and hillslope soils. Observation of the differences between 1-D and residual ΔS values in Figure 33 and 34 also illustrates this point. In the UF catchment, 1-D and residual ΔS tracked closely throughout the study period,

diverging slightly (>40 mm) when residual values were higher than 1-D values during the non-growing season. However, the differences in HF 1-D and residual ΔS tell a different story, as residual values differed by around 200 mm during most of the period from December to April. This suggests that there is a significant difference between water infiltrating into the ground in HF (not becoming ET or Q) in HF and the amount of storage detected by this analysis, which assumes the top 1 m represents the unsaturated-zone. This water is likely lost to depth, as represented by G.

The values in G also differed greatly between catchments. The UF values for G were zero or negative during the non-growing season, while the HF value for G was 29-39% of total P. This suggests that in HF, loss to depth (subsurface flux and deep seepage) occurred during Nov. 2009 – Mar. 2010, while in UF it did not. The water balance also suggests that almost all of the precipitation in UF during this period resulted in Q, ET, and ΔS. The general values for G in the HF and UF catchments are consistent with values for recharge posited by Heath (1994). Heath (1994) also provides a good description of the effects of soils on groundwater recharge that is consistent with the explanation that expansive, very low-Ksat clay (Bt) horizons in UF reduce vertical flow and increase Q during non-growing seasons.

The differences illustrated by cumulative daily water balance are consistent with the Chapter 2 description of factors driving catchment hydrology in HF and UF. The T3 Template (Buttle 2006) describes the UF catchment as being strongly controlled by typology, or controls on vertical flow by the shallow, expansive clay layer during the wet, non-growing

season. During this season, UF discharge values increased dramatically (52% of P) beyond those of the HF catchment (33% of P). Before and after the growing season, the HF catchment displayed greater discharge values (14-21%) than did the UF catchment (2-12%). These data, and the soil moisture and shallow well analyses presented in Chapter 2, suggest that the expansive clays in UF impede vertical flow when saturated, causing perched water tables and lateral surface and subsurface flow and, thus, increases in Q and accompanying decreases in vertical groundwater fluxes. The cumulative daily water balance further illustrates this model by showing that changes in soil moisture state in UF preceded accompanying changes in discharge. In HF (Figure 34, 11/14/09), changes in storage also accompanied changes in streamflow, but the changes were not as sudden or dramatic.

Figure 35 illustrates the significant differences in non-growing season hydrology following the dry-to-wet moisture state shift and accompanying changes in storage in both catchments. Increases in Q, associated with perched water tables over the shallow, expansive clay layer lead to less recharge of deep storage. Precipitation in HF (680 ± 27 mm) and UF (644 ± 26 mm) was very similar during the period, and ET was very similar in HF (24 ± 7%) and UF (28 ± 7%). Much of the winter storage in HF appears to flux below the monitored portion of the catchment, while most of the storage in UF occurs in the unsaturated zone and in the perched water table above the unsaturated zone. Non-growing season increases in storage and reductions in ET appear to cause significant increases in streamflow in both catchments, which is consistent with other studies describing dry and wet state changes in catchment hydrology (Grayson et al. 1997, Tromp-van Meerveld and McDonnell 2006a). Changes

from vertical to lateral flows are magnified in UF, where low slopes allow perched water to occur and shallow, expansive clay horizons force lateral flows during storms.

4. CONCLUSION

This study examined precipitation, evapotranspiration, stream discharge, and changes in soil moisture storage during a one-year period (August 1, 2009-July 31, 2010) in two 73 acre (29.5 hectare) headwater catchments on Carolina Slate Belt geology in the Piedmont region of North Carolina. Although the climate and geological settings of the catchments are very similar, the soils and topography differ greatly and can be described as having unique hydrologic landscapes (Winter 2001).

Detailed field and laboratory analyses of the soils in both catchments show that the major soils of the HF and UF catchments differ significantly. We can infer that the UF perched water system moves only slowly laterally on the relatively flat slopes of the UF catchment, causing rapid lateral flow into the stream during rain events (Kuntukova 2010). Because the HF and UF climates are identical, the catchments are best described using Buttle's (2006) T3 conceptual framework of relative drivers of hydrology across landscape types. Using this framework, the behavior of UF catchment suggests strong seasonal typologic controls on hydrology, while typology is less controlling and topography more controlling role in the HF catchment.

These differences in hydrology are not clear in annual water balances. The HF and UF annual water balances showed little differences in overall stream discharge, evapotranspiration, and changes in storage. However, daily cumulative, monthly, and seasonal water balances demonstrate the seasonal differences in HF and UF. In UF, flows

disappeared during the growing season but were as much as 75% of total monthly precipitation during the non-growing season. HF stream discharges also increased during the non-growing season, but not as dramatically (from 14% to 33% of total precipitation). Based on the residual of the water balance, losses to deep groundwater seepage and flux may be much greater in HF (38 ± 8% of P) than in UF (-4 ± 10% of P) during the non-growing season. If this is the case, the major limiting factor to groundwater recharge in UF may be the expansive clay layer.

Using the hydrologic landscape concept (Winter 2001) to map lands in the region with soils similar to those of the UF catchment may prove useful to hydrologists and water resources managers working within this seasonably variable type of landscape. For example, a hydrologic landscape unit map at a local scale could provide stormwater and watershed managers guidance by which to gage the effectiveness of site-specific management practices in meeting catchment-wide hydrologic and water quality performance standards such as Low Impact Development. A Hydrologic Landscape map of the USA by Wipfli et al (2004) exists, but the scale does not show significant differences across this area of the Piedmont region of NC and is not useful at a catchment scale.

Figure 36 is a map of Falls Lake watershed showing lands with low-gradient soils forming seasonal perched water tables above expansive clay layers. It is clear that these systems are very prevalent in the region. The findings from this thesis suggest that these areas may form a unique hydrologic landscape that warrants special consideration in models and

management decisions. Where streamflow and precipitation data are available, further study of UF-type hydrologic landscapes and hydrologic response could validate the conceptual models in this thesis.

REFERENCES

Alexander, R. B., E.W. Boyer, R.A. Smith, G.E. Schwarz, and R.B. Moore, 2007. The Role of Headwater Streams in Downstream Water Quality. Journal of the American Water Resources Association (JAWRA), 43: 41–59.

Allen, R.G., M.E. Jensen, J.L. Wright, R.D. Burman, 1989. Operational Estimates of Reference Evapotranspiration. Agronomy Journal 81: 650-662.

Allen R.G., Smith M., Perrier A., Pereira L.S. 1994. An Update for the Definition of Reference Evapotranspiration. ICID Bulletin 43: 1–34.

Alley, W., 1984. On the Treatment of Evapotranspiration, Soil Moisture Accounting, and Aquifer Recharge in Monthly Water Balance Models. Water Resources Research 20 (8): 1137-1149.

Barker, S.E., 1983. The Development, Current Use, and Effectiveness of Streamside Buffer Zones in Precluding Sediment Delivery to Forest Streams. Master's Thesis, NC State University Department of Forestry.

Beven, K.J., M.J. Kirkby., N. Schofield, and A.F. Tagg, 1984. Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. Journal of Hydrology 69:

119-143.

Bishop, K., I. Buffam, M. Erlandsson, J. Fölster, H. Laudon, J. Seibert, and J. Temnerud, 2008. Aqua Incognita: the unknown headwaters. Hydrological Processes 22: 1239-1242.

Boggs, J.L., G. Sun, S.G. McNulty, D. Jones, and W. Swartley, 2010. Final Grant Report: Effectiveness of streamside management zones and stream crossing BMPs on water quality protection in the piedmont of NC forested watersheds. US-EPA Non-Point Source Pollution Control Grant through Section 319h of the Clean Water Act. NC Department of Environment and Natural Resources Division of Water Quality.

Bouwer, H. and R.C. Rice, 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research 12 (3): 423-428.

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel, 2003. Soil Genesis and Classification, Fifth Edition. Iowa State Press, Ames.

Burns, D., T. Vitvar, J. McDonnell, J. Hassett, J. Duncan, and C. Kendall, 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. Journal of Hydrology 311: 266-281.

Buttle, J.. 2006. Mapping first-order controls on streamflow from drainage basins: the T^3 template. Hydrological Processes 20: 3415—3422.

Center for Watershed Protection, 1998. Rapid Watershed Planning Handbook: A Comprehensive Guide for Managing Urbanizing Watersheds. Center for Watershed Protection, Ellicott City.

Chang, M., 2003. Forest Hydrology: An Introduction to Water and Forests. CRC Press LLC, Boca Raton. Page 166.

Chapman, M.J., R.E. Bolich, and B.A. Huffman, 2005. Hydrogeologic setting, ground-water flow, and ground-water quality at the Lake Wheeler Road Research Station, 2001-2003. NC Piedmont and Mountains Resource Evaluation Program: US Geological Survey Investigation Report 2005-5166.

Coes, A.L., T.B. Spruill, and M.J. Thomasson, 2007. Multiple-method estimation of recharge rates at diverse locations in the North Carolina Coastal Plain, USA. Hydrogeology Journal 15: 773-788.

Commission on Environmental Cooperation, 2006. Ecoregions of North America, Level III. Map of Ecoregions created by the CEC, a regional cooperation of the governments of the

USA, Canada, and Mexico. Map available at:
http://www.epa.gov/wed/pages/ecoregions.htm

Daniels, R.B., S.W. Buol, H.J. Kleiss, and C.A. Ditzler, 1999. Soil Systems in North Carolina. North Carolina State University Soil Science Department. January.

Fetter, C.W., 2001. Applied Hydrogeology. Prentice Hall, Upper Saddle River.

Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Silins and B. Smerdon, 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? Hydrological Processes 19: 1705–1714.

Dietz, M. E., 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water, Air, and Soil Pollution 186: 351–363.

Dietz, M. E., & Clausen, J. C., 2005. A field evaluation of rain garden flow and pollutant treatment. Water, Air and Soil Pollution 167(1–4): 123–138.

Endale, D.M., D.S. Fisher, and H.H. Schomberg, 2006. Soil Water Regime in Space and Time in a Small Georgia Piedmont Catchment under Pasture. Soil Science Society of America Journal 70:1-13.

England, C.B. and H.N. Holtan, 1969. Geomorphic Grouping of Soils in Watershed Engineering. Journal of Hydrology 7:217-225.

Fetter, C.W., 2001. Applied Hydrogeology. Prentice Hall, Upper Saddle River, N.J.

Freeman, M.C., C.M. Pringle, and C. R. Jackson, 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association (JARWA) 43(1):5-14.

Genereux, D.P., M.T. Jordan, and D. Carbonell, 2005. A paired-watershed budget study to quantify interbasin groundwater flow in a lowland rain forest, Costa Rica. Water Resources Research 41, W04011.

Godfrey, M.A., 1997. Field Guide to the Piedmont: The Natural Habitats of America's Most Lived-in Region, from New York City to Montgomery, Alabama. University of North Carolina Press.

Grayson, R.B., A.W. Western, F.H.S. Chiew, and G. Blöschl, 1997. Preferred states in spatial soil moisture patterns: Local and nonlocal controls. Water Resources Research 33 (12): 2897-2908.

Griffith, G.E., J.M. Omernik, J.A. Comstock, M.P. Schafale, W.H. McNab, D.R. Lenat, T.F. MacPherson, J.B. Glover, and V.B. Shelburne, 2002. Ecoregions of North Carolina and South Carolina (color poster with map, descriptive text, summary tables, and photographs). Reston, Virginia, U.S. Geological Survey (map scale 1:1,500,000).

Guan, X.J., C.J. Westbrook, and C. Spence, 2010. Shallow soil moisture: ground thaw interactions and controls—Part 1: Spatiotemporal patterns and correlations over a subarctic landscape. Hydrology and Earth Systems Science 7:33-65.

Hamon, W.R., 1963. Computation of Direct Runoff Amounts from Storm Rainfall. Int. Assoc. Sci. Hydrol. Pub 63:52-62.

Harder, S.V., D.M. Amatya, T.J. Callahan, C.C. Trettin, and J. Hakkila, 2007. Hydrology and Water Budget for a Forested Atlantic Coastal Plain Watershed, South Carolina. Journal of the American Water Resources Association 43 (3):563-575.

Hazel, D.W., M.D. Smith, and C. Franklin, 1989. Direct-Seeding of Loblolly Pine in the North Carolina Piedmont: Four-Year Results. Southern Journal of Applied Forestry 13 (2): 91-93.

Healy, R.W. and P.G. Cook, 2002. Using groundwater levels to estimate recharge. Hydrogeology Journal 10: 91-109.

Heath, R.C., 1984. Ground-Water Regions of the United States. US Geological Survey Water-Supply Paper 2242.

Heath, R.C., 1994. Ground-Water Recharge in North Carolina. Prepared for NC Department of Environment and Natural Resources. March.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Elsevier Science, San Diego.

Hoffman, C.W. and P.E. Gallagher, 1989. Geology of the Southeast Durham and Southwest Durham 7.5-Minute Quadrangles, North Carolina. Bulletin 92 of the NC Geological Survey, Division of Land Resources, Raleigh.

James, A.L. and N.T. Roulet, 2007. Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed. Hydrological Processes 21 (25): 3391-3408.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009. Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

Keyworth, A.J., 2008. A Quantitative Assessment of Water Inputs and Outputs to a Small Watershed in Northwestern Wake County: Evaluating the Effects of Human Water Use on Groundwater Resources. Master's Thesis, NC State University College of Natural Resources.

Kluitenberg, G.J., 2008. Pedotransfer Functions for Estimating Saturated Hydraulic Conductivity: Opportunities for Minimizing Uncertainty. Presentation to NRCS North Central Regional Work Planning Conference, Manhattan, KS. June 23.

Kovnee, J.L., 1957. Evapotranspiration in Forest Stands of the Southern Appalachian Mountains. Southeastern Forest Experiment Station, Forest Service, USDA.

Kuntukova, Y., 2010. Storm-event Rainfall-runoff Response in Carolina Slate Belt and Triassic Basin Catchments. Master's Thesis, NC State University College of Natural Resources.

Lesack, L.F.W., 1993. Water Balance and Hydrologic Characteristics of a Rain Forest Catchment in the Central Amazon Basin. Water Resources Research 29 (3): 759-773.

Leopold, L.B., M.G. Wolman, and J.P. Miller, 1964. Fluvial processes in Geomorphology. W.H. Freeman and Company, San Francisco.

Lieberman, J.A. and P.W. Fletcher, 1947. Further Studies of the Balanced Water Cycle on Experimental Watersheds. Transactions, American Geophysical Union. 28 (3): 421-424.

Lu, J., G. Sun, S.G. McNulty, and D.M. Amatya, 2005. A Comparison of Six Potential Evapotranspiration Methods for Regional Use in the Southeastern United States. Journal of the American Water Resources Association (JAWRA) 41(3):621-633.

McConnell, K.I. and L. Glover III, 1982. Age and emplacement of the Flat River complex, and Eocambrian sub-volcanic pluton near Durham, North Carolina. Geological Society of America Special Paper 191.

Meyer, J.L., D.L. Strayer, J.B. Wallace, S.L. Eggert, G.S. Helfman, and N.E. Leonard, 2007. The Contribution of Headwater Streams to Biodiversity in River Networks. Journal of the American Water Resources Association 43(1):86-103.

Mohamoud, Y., 2004. Comparison of Hydrologic Responses at Different Watershed Scales. Ecosystems Research Division, U.S. Environmental Protection Agency. Athens, GA. EPA/600/R-04/103, September.

Moreau, D.H. and R.Challa, 1985. An Analysis of the Water Balance of B. Everett Jordan Lake Including Estimates of Flows Between Segments. Water Resources Research Institute of the University of North Carolina. Raleigh. April.

Moroizumi, T., H. Hamada, S. Sukchan, M. Ikemoto, 2008. Soil Water Content and Water Balance in Rainfed Fields in Northeast Thailand. Agricultural Water Management 96:160-166.

NC Climate Office, 2010. State Climate Office of North Carolina website, http://www.nc-climate.ncsu.edu/climate/ncclimate.html.

NC DENR, 2009. Final Neuse River Basinwide Water Quality Plan. Chapter 17, Stressors and Sources. Document compiled by North Carolina Department of Environment and Natural Resources, Division of Water Quality. July. (Available at http://portal.ncdenr.org/web/wq/ps/bpu)

NC DWQ, 2005. Identification Methods for the Origins of Intermittent and Perennial streams, Version 3.1. North Carolina Department of Environment and Natural Resources, Division of Water Quality. Raleigh, NC.

NC Drought Management Advisory Council, 2010. Website, http://www.ncdrought.org/

NC Geological Survey, 1964. Composite Geologic Map of the Slate Belt in North Carolina, west of the Cape Fear Triassic Basin. A map created by NCGS and available at http://www.carolinageologicalsociety.org/cgscdguide.htm

Pachepsky, Y.A., W.J. Rawls, and H.S. Lin, 2006. Hydropedology and pedotransfer functions. Geoderma 131: 308-316.

Peters, N.E., J. Freer, B.T. Aulenbach, and L.E. Jones, 2003. Streamflow Generation and Ground-Water Recharge of the Surficial Aquifer at the Panola Mountain Research Watershed, in Methods Used to Assess the Occurrence and Availability of Ground Water in Fractured-Crystalline Bedrock: An Excursion into Areas of Lithonia Gneiss in Eastern Metropolitan Atlanta, Georgia: Guidebook 23. Compiled by Lester J. Williams, U.S. Geological Survey. Atlanta, Georgia. October.

Reynolds, W.D., D.E. Elrick, and B.E. Clothier, 1985. The constant head well permeameter: Effect of unsaturated flow. Soil Science 144(3): 172-180.

Richardson, J.L. and M.J. Vepraskas, 2000. Wetland Soils: Genesis, Hydrology, Landscapes and Classification. Lewis Publishers, Boca Raton, Fl. (ISBN: 1566704847).

Roy, A.H., S.J. Wegner, T.D. Fletcher, C.J. Walsh, A.R. Ladson, W.D. Shuster, H.W. Thurston, R.R. Brown, 2008. Impediments and Solutions to Sustainable, Watershed-scale Urban Stormwater Management: Lessons from Australia and the United States. Environmental Management 42: 344-359.

Rutledge, A.T., 1992, Methods of using streamflow records for estimating total and effective recharge in the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic province.

Santhi, C., P.M. Allen, R.S. Muttiah, J.G. Arnold, and P. Tuppad, 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. Journal of Hydrology 351: 139-153.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick, 1986. Estimating Generalized Soil-water Characteristics from Texture. Soil Science Society of America Journal 50: 1031-1036.

Scanlon, B.R., R.W. Healy, and P.G. Cook, 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal 10:18–39.

Schäfer, K.V.R., R. Oren, C.T. Lai & G.G. Katul, 2002. Hydrologic balance in an intact temperate forest ecosystem under ambient and elevated atmospheric CO2 concentration. Global Change Biology 8: 895-911.

Spence, C. and M. Woo, 2003. Hydrology of subarctic Canadian shield: soil-filled valleys. Journal of Hydrology 279: 151-166.

Spence, C. and M.Woo, 2006. Hydrology of subarctic Canadian shield: heterogeneous headwater basins. Journal of Hydrology 317: 138-154.

Sun, G., S.G. McNulty, D.M. Amatya, R.W. Skaggs, L.W. Swift Jr., J.P. Shepard, and H. Riekerk, 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. Journal of Hydrology 263: 92-104.

Sun, G., K. Alstad, J. Chen, S. Chen, C.R. Ford, G. Lin, C. Liu, N. Lu, S.G. McNulty, H. Miao, A. Noormets, J.M. Vose, B. Wilske, M. Zeppel, Y. Zhang, and Z. Zhang, 2010 (In Progress). A General Predictive Model for Estimating Monthly Ecosystem Evapotranspiration. Ecohydrology. Manuscript ID ECO-10-0018.R1.

Tomasella, J., M.G. Hodnett, L.A. Cuartas, A.D. Nobre, M.J. Waterloo, and S.M. Oliveira, 2008. The water balance of an Amazonian micro-catchment: the effect of interannual variability of rainfall on hydrological behavior. Hydrological Processes 22: 2133-2147.

Topp, G. Clarke, J.L Davis, and A.P Annan, 2003. The Early Development of TDR for Soil Measurements. Vadose Zone Journal 2: 492-499.

Toth J, 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research 68: 4785-4812.

Tromp-van Meerveld, H.J. and J.J. McDonnell, 2006a. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. Water Resources Research 42: W02411.

Tromp-van Meerveld, H.J. and J.J. McDonnell, 2006b. On the Interrelations between Topography, Soil Depth, Soil Moisture, Transpiration Rates and Species Distribution at the Hillslope Scale. Advances in Water Resources 29: 293-310.

Tromp-van Meerveld, H.J., N.E. Peters, and J.J. McDonnell, 2006. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA. Hydrological Processes: in press.

USDA, Natural Resources Conservation Service, 1971. Soil Survey of Durham County, North Carolina. (An interactive soils map from the NRCS showing this data can also be found at http://websoilsurvey.nrcs.usda.gov)

USDA, Natural Resources Conservation Service, 1997. Soil Survey of Granville County, North Carolina. (An interactive soils map from the NRCS showing this data can also be found at http://websoilsurvey.nrcs.usda.gov)

USDA, Natural Resources Conservation Service, 2006. Field Indicators of Hydric Soils in the United States, Version 6.0. G.W. Hurt and L.M. Vasilas (eds.). USDA, NRCS, in cooperation with the National Technical Committee for Hydric Soils.

USDA, Natural Resources Conservation Service, 2010. National Soil Survey Handbook, title 430-VI. Available online at: http://soils.usda.gov/technical/handbook/ accessed 3/3/2010

USDA, Natural Resources Conservation Service, 2010b. NRCS website description of Helena soils. On the internet at http://ortho.ftw.nrcs.usda.gov/osd/dat/H/HELENA.html

US EPA, 2000. Low impact development (LID), a literature review. United States Environmental Protection Agency, EPA-841-B-00-005.

US EPA, 2002. National water quality inventory, 2000 report. United States Environmental Protection Agency, EPA- 841-R-02-001.

Vachaud, G., A.P. De Silans, P. Balabanis, and M. Vauclin, 1985. Temporal Stability of Spatially Measured Soil Water Probability Density Function. Soil Science Society of America Journal 49: 822-828.

Verry, E.S., 2003. Estimating Ground Water Yield in Small Research Basins. Ground Water 41 (7): 1001-1004.

Winter, T.C., 1981. Uncertainty in Estimating the Water Balance of Lakes. Water Resources Bulletin (AWRA) 17 (1): 82-115.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley, 1998. Ground Water and Surface Water: A Single Resource. U.S. Geological Survey Circular 1139.

Winter, T.C., 2001. The Concept of Hydrologic Landscapes. Journal of the American Water Resources Association (JAWRA) 37(2): 335-349.

Winter, T.C., 2007. The Role of Ground Water in Generating Streamflow in Headwater Areas and in Maintaining Base Flow. Journal of the American Water Resources Association (JAWRA) 43(1):15-25.

Wipfli, M.S., J.S. Richardson, and R.J. Naiman, 2007. Ecological linkages between headwaters and downstream ecosystems: transport of organic matter, invertebrates, and wood down headwater channels. Journal of the American Water Resources Association (JARWA) 43(1):72-85.

Wolock, D.M., T.C. Winter,, and G. McMahon, 2004. Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. Environmental Management 34 (1): 71-88.

Wösten, J.H., M. Ya. A. Pachepsky, and W.J. Rawls, 2001. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydrologic characteristics. Journal of Hydrology 251: 123-150.

Xu, C.Y. and V.P. Singh, 1998. A Review on Monthly Water Balance Models for Water Resources Investigations. Water Resources Management 12:31-50.

Xu, C.-Y. and G.L. Vandewiele, 1995. Parsimonious monthly rainfall-runoff models for humid basins with different input requirements. Advances in Water Resources 18:39-48.

Yeh, H., C.H. Lee, J.F. Chen, and W.P. Chen, 2007. Estimation of Groundwater Recharge Using Water Balance Model. Water Resources 34 (2): 153-162.

FIGURES AND TABLES

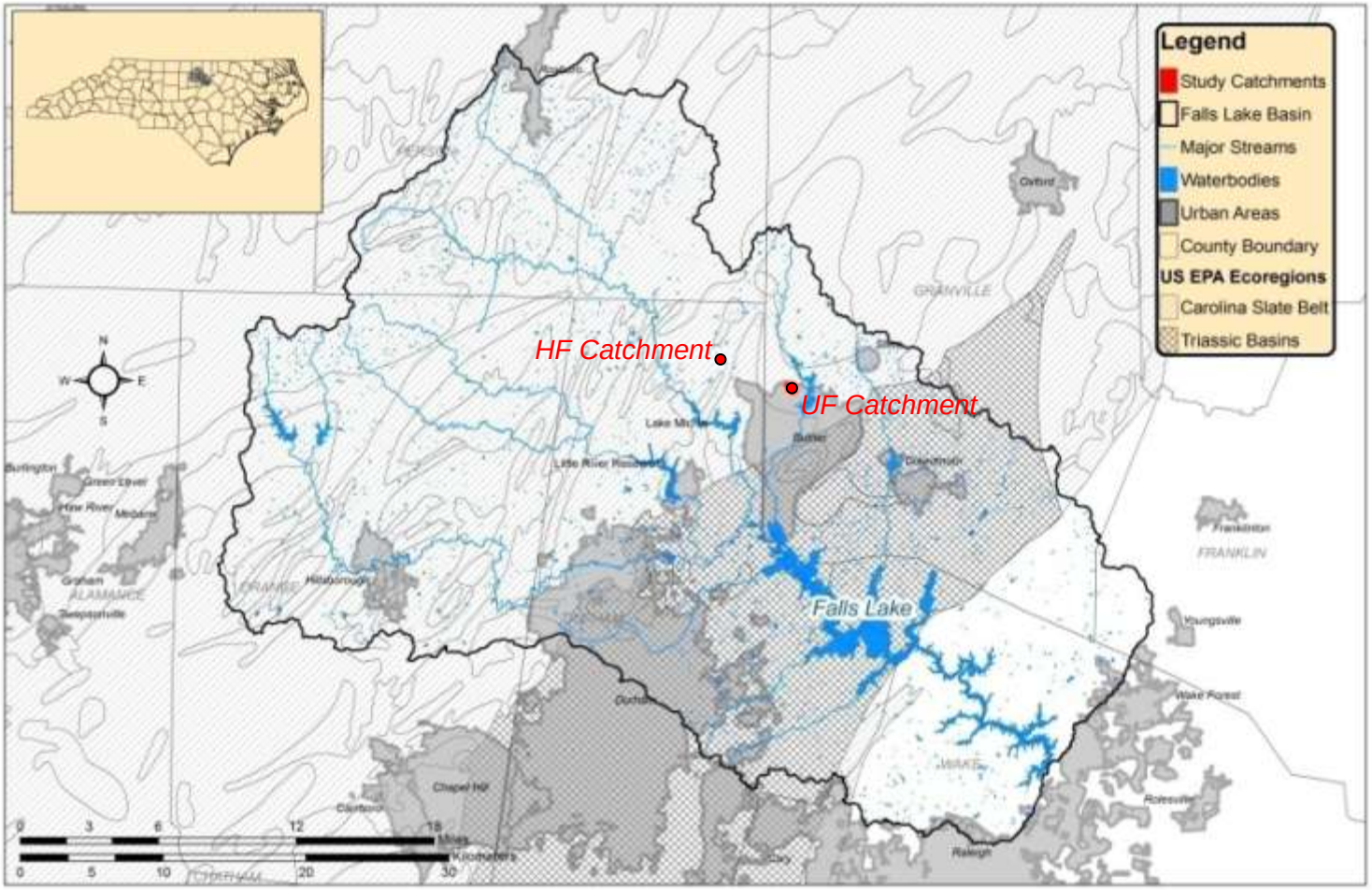


Figure 1: Location of Study Catchments in Falls Lake Watershed and US EPA Ecoregions (Griffith et al. 2002).

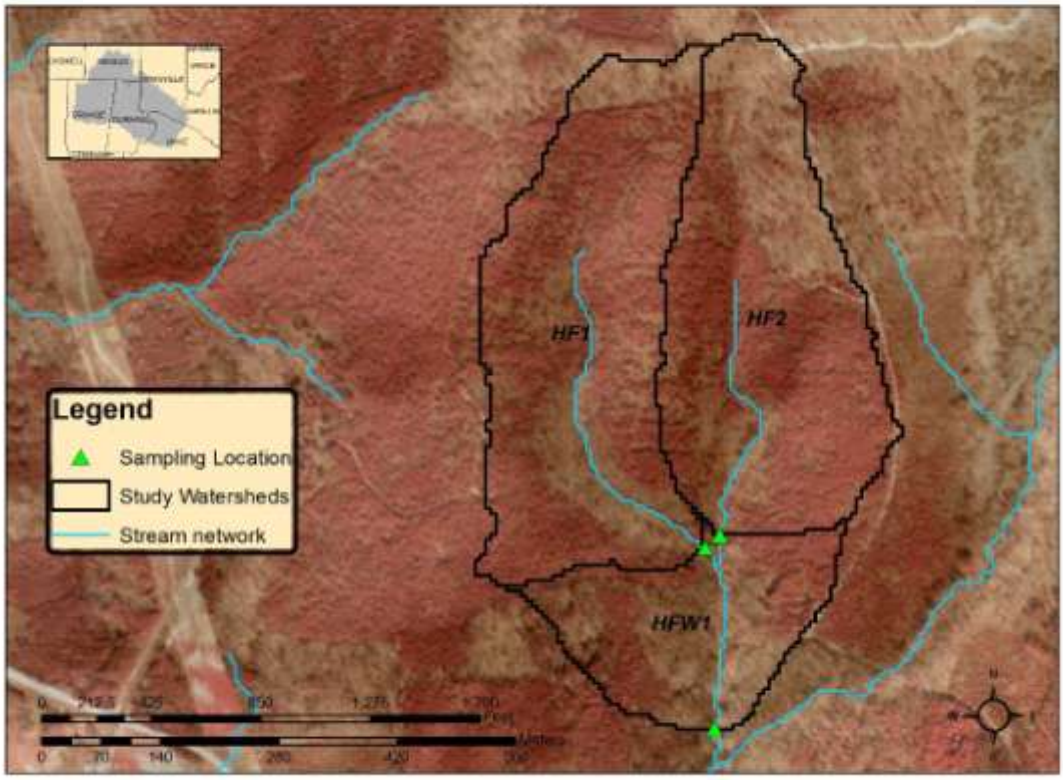


Figure 2. Hill Forest Catchment with USFS Streamflow Gauging Locations

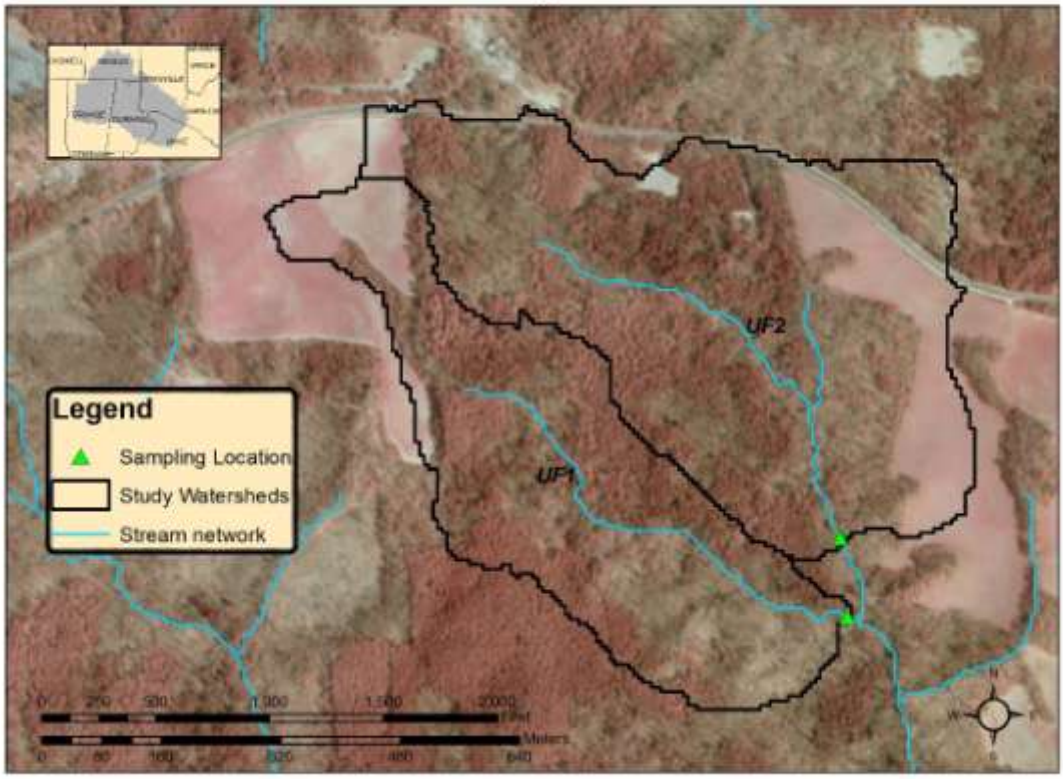


Figure 3: Umstead Farms Catchment and USFS Streamflow Gauging Locations

Table 1. Terrain and Soil Characterization of the HF and UF Catchments

Catchment	Area (acres)	Total Catchment Relief	Average Slope	Drainage Density**	Expansive clays	Shallow impeding clay layer?	Shallow perched water?
Hill Forest catchment	73	160 ft.	13.1%	0.00094	No	No	No
Umstead Farms catchment	73	94 ft.	7.6%	0.00092	Yes	Yes	Yes

**Drainage density (m/m^2) is the ratio of the sum of the length of stream in the catchment to the total area of the catchment (Brooks et al 1997).

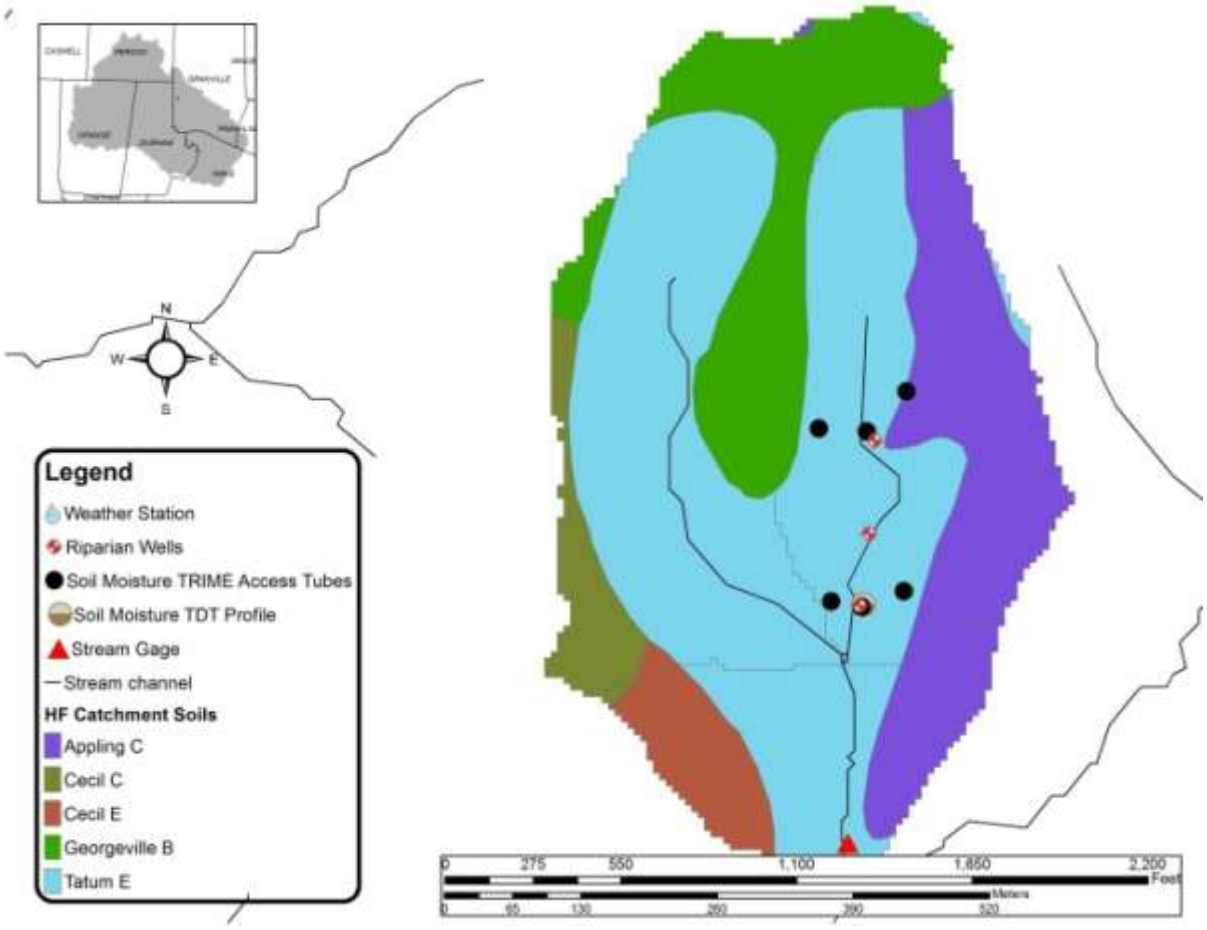


Figure 4. Hill Forest Catchment Soils

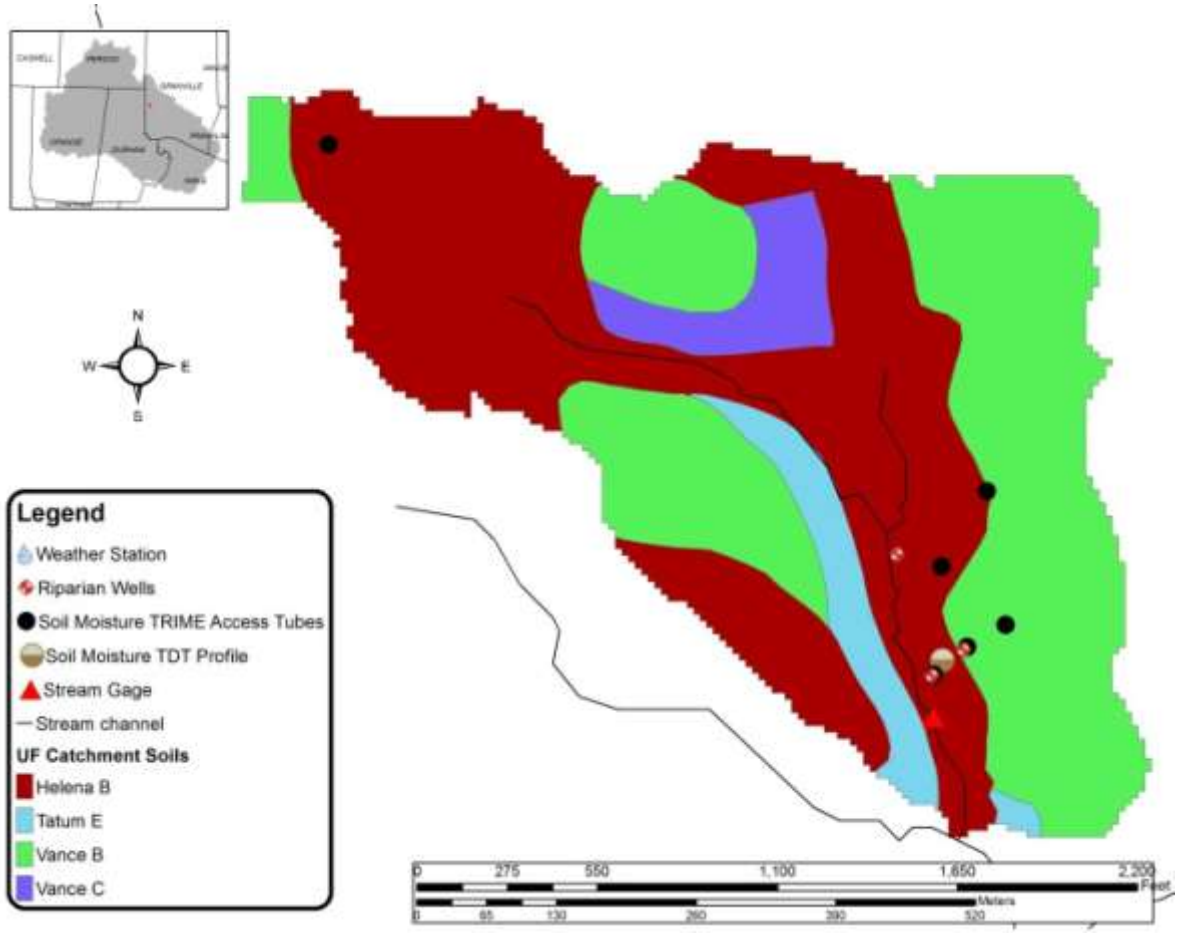


Figure 5. Umstead Farms Catchment Soils

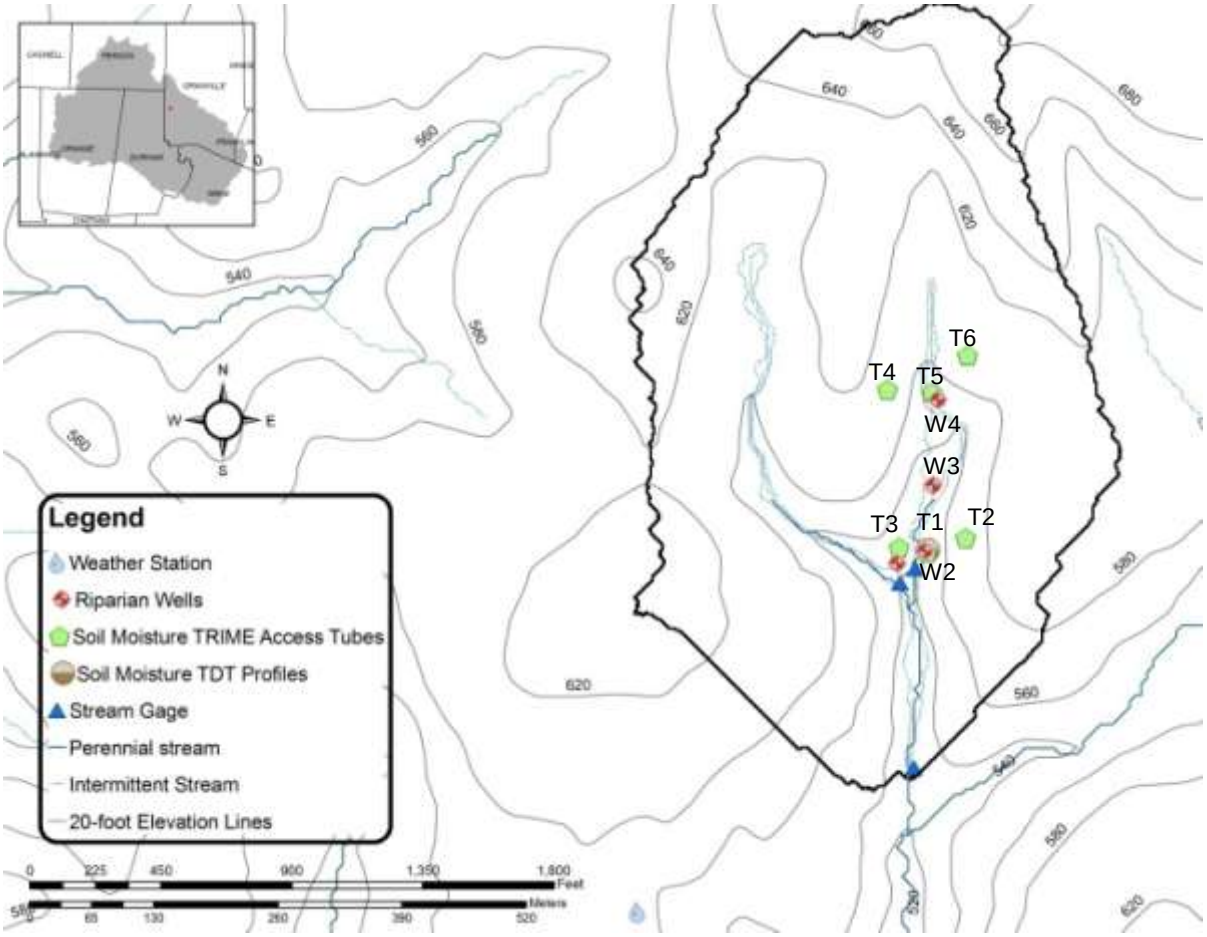


Figure 6. HF Catchment Topography and Monitoring Sites. T1-6 indicates locations of permanently installed access tubes for monitoring of soil moisture content. T1 site includes collocation of access tube and continuous TDT profile of soil moisture probes.

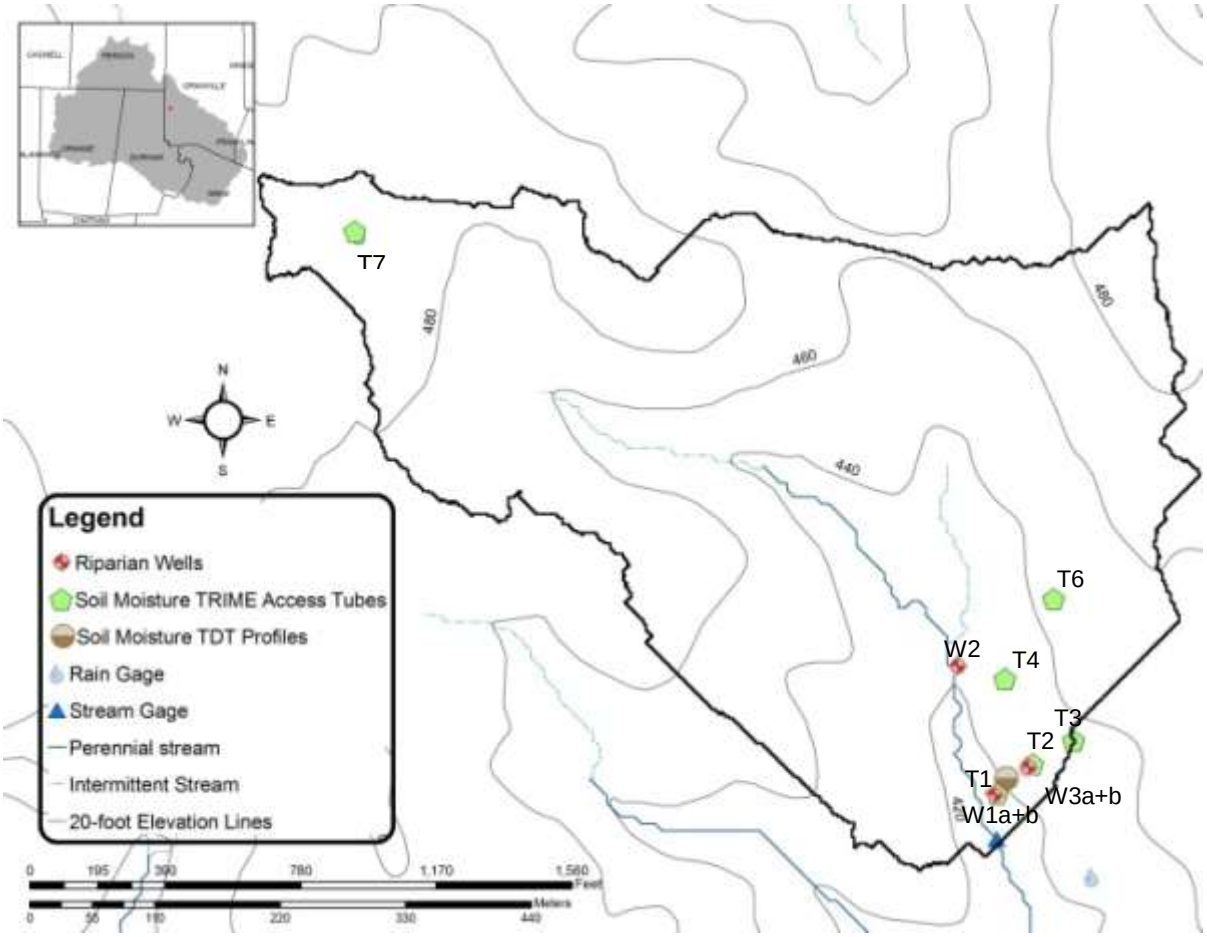


Figure 7. UF Catchment Topography and Monitoring Sites. T1-4 and T6-7 indicate locations of permanently installed access tubes for monitoring of soil moisture content. T2 site includes collocation of access tube and continuous TDT profile of soil moisture probes.

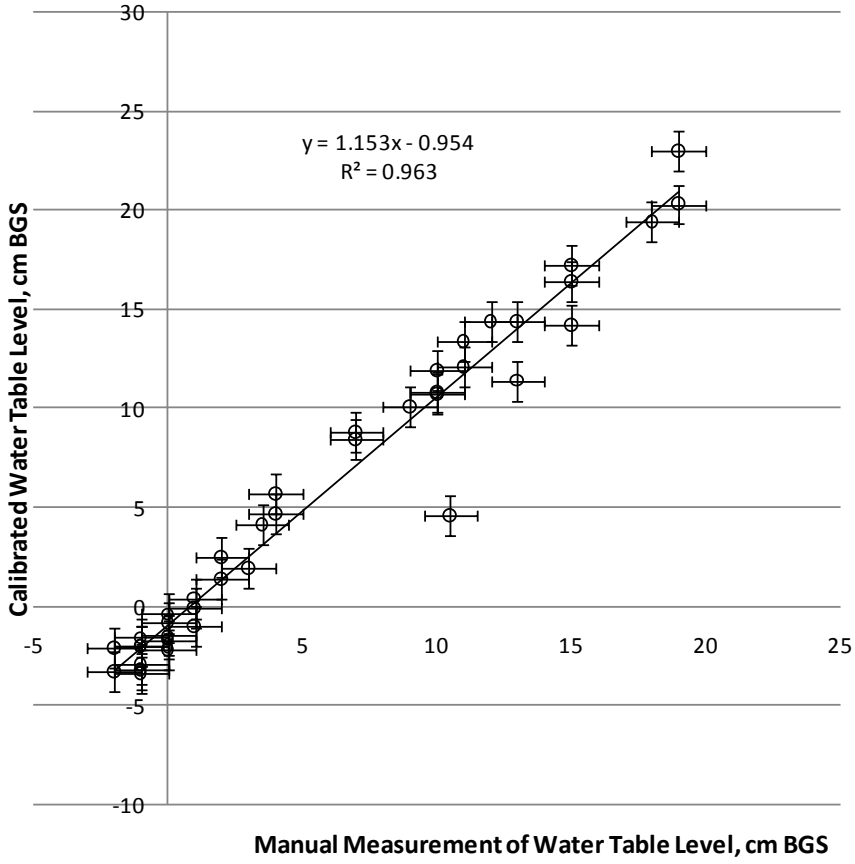


Figure 8. Calibrated Water Table Levels for HF Well 2 (BGS indicates below ground surface). Error bars indicate ±1 cm.

Table 2. Calibration for the HF and UF Riparian Groundwater Wells

Well Name	Linear best fit equation of calibrated Odyssey to manual measurements	R^2 Value
UF2 Well 1	y = 1.061x - 14.73	0.993
UF2 Well 2	y = 0.987x + 2.344	0.985
UF2 Well 3	y = 0.945x + 9.298	0.995
HF2 Well 2	y = 1.153x - 0.954	0.963
HF2 Well 3	y = 0.979x + 1.470	0.986
HF2 Well 4	y = 0.759x + 27.35	0.985

Table 3. Criteria for Defining HF Upland, Hillslope, and Riparian Units

Area Type	Access Tube Location	Slope*	Soil Type	Unsaturated Zone Depth (cm)	Depth to Expansive Bt Horizon (cm)	Presence of Perched Water Table	Depth to Bedrock (cm)*
Upland	T4, T6	0-16%	Cecil, Appling, Georgeville	180*	N/A	No	>197
Hillslope	T1, T2	12%-50%	Tatum	180*	N/A	No	135
Riparian	T5	0-12%	Tatum**	30***	N/A	No	>135

*from USDA 2010

**Riparian soils not mapped at scale of USDA NRCS Soils Survey Maps (1:20,000)

***Riparian unsaturated zone depth calculated as mean water table depth of study period (7/1/09 - 7/31/10)

Table 4. Criteria for Defining UF Upland and Hillslope Units

Area Type	Access Tube Location	Slope*	Soil Type	Unsaturated Zone Depth (cm)	Depth to Expansive Bt Horizon (cm)	Presence of Perched Water Table	Depth to Bedrock (cm)*
Upland	**T7, T3**	0-12%	Vance	180*	N/A	No	>263
Hillslope	**T1, T2, T4, T6**	0%-37%	Helena, Tatum	45-90*	45	Yes	>263

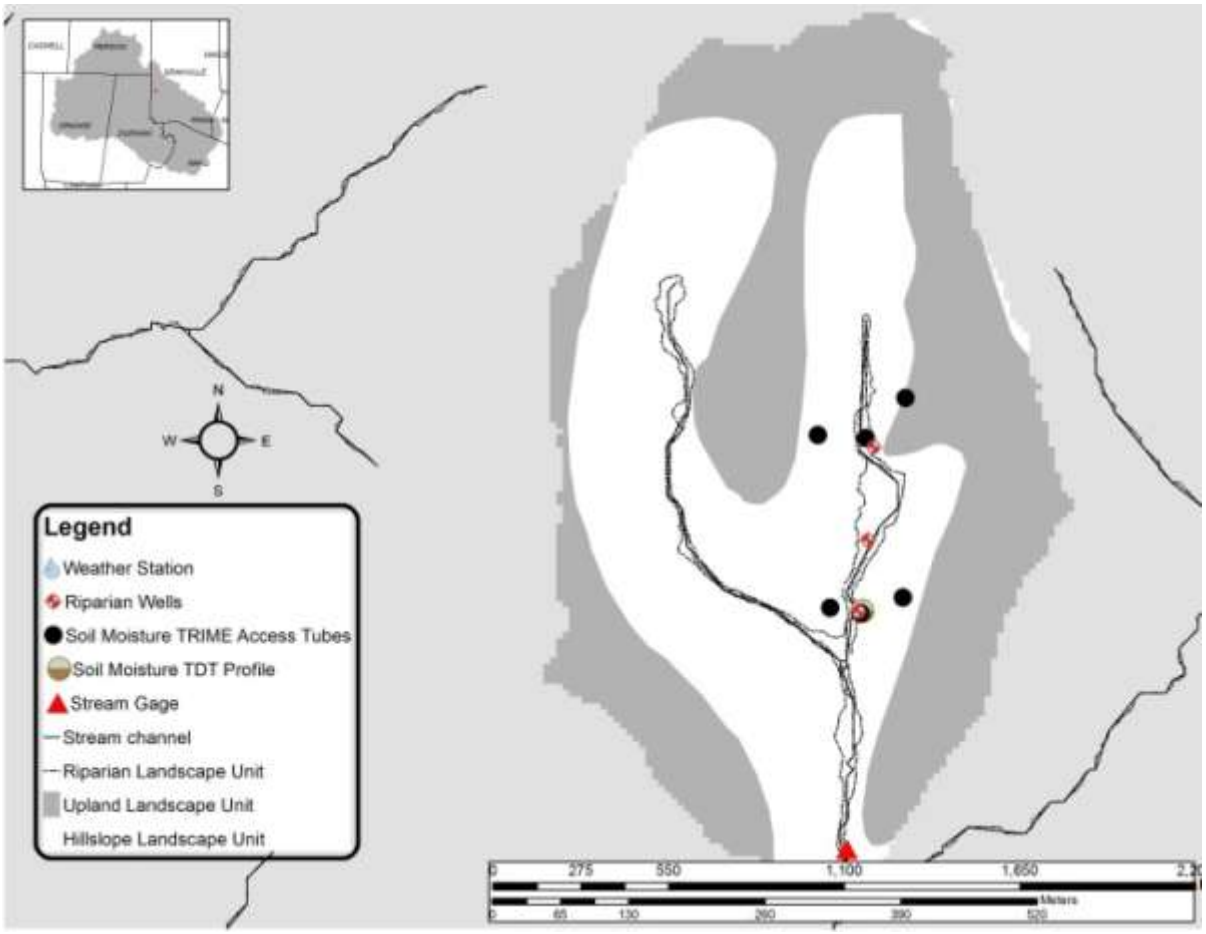


Figure 9. Hill Forest Upland, Hillslope, and Riparian Landscape Units

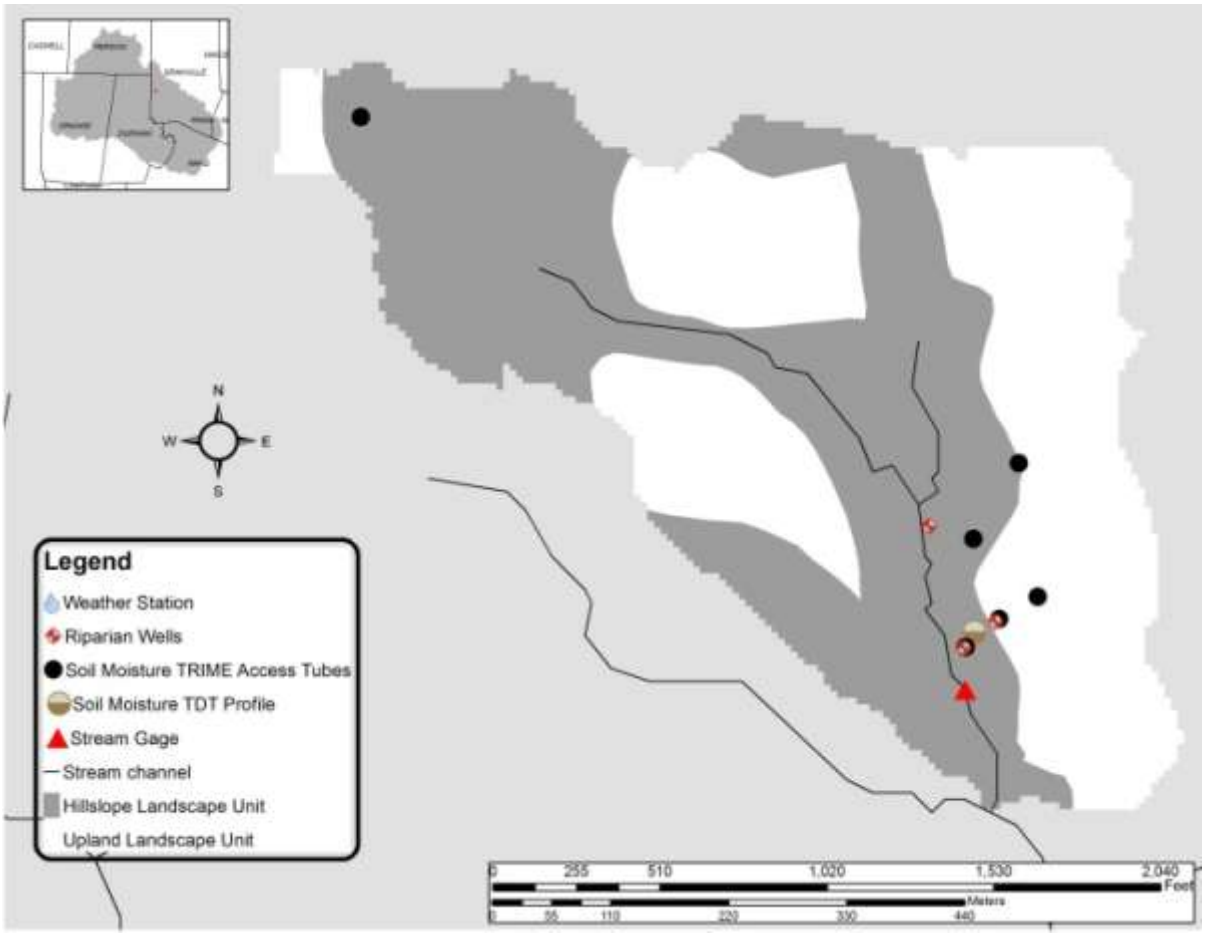


Figure 10. Umstead Farms Upland and Hillslope Landscape Units

Table 5. HF Soil Physical and Hydrologic Properties

Hill Forest Catchment

										Estimates		
										NRCS (2010)		Saxton et al (1986)
Sample Location	Soil Horizon	Sample Depth (cm)	Avg. Depth (cm)	Sand %	Silt %	Clay %	USDA Class.	>2mm %	ρ_b (measured)	K_{sat} (measured) (cm/hr)	K_{sat} (NRCS est. high value)[#] (cm/hr)	K_{sat} (NRCS est. low value)[#] (cm/hr)	K_{sat} (Saxton est. value)[##] (cm/hr)
T1/ESI (Hillslope)	A	9 -- 15	12	53.5	35.9	10.6	sandy loam	27.5	0.93	6.29	36.00	3.63	2.44
T1/ESI (Hillslope)	Bt	25 -- 31	28	54.3	29.5	16.2	sandy loam	26.3	1.40		3.63	0.38	1.19
T1/ESI (Hillslope)	Bt	45 -- 51	48	51.7	29.5	18.8	loam	30.4	1.90	0.04	0.38	0.04	0.89
T1/ESI (Hillslope)	Bt	45--51	48	54.5	31.5	14.0	sandy loam	8.5	1.86		3.60	0.36	1.57
T1/ESI (Hillslope)	Bt	62--68	65	55.6	27.9	16.6	sandy loam	16.6	2.01		3.60	0.36	1.12
T1/ESI (Hillslope)	Bt	74--80	77	55.3	27.3	17.4	sandy loam	16.3	2.03		3.60	0.36	1.02
T1/ESI (Hillslope)	Bt	89--95	92	58.1	24.5	17.4	sandy loam	34.2	1.62		3.60	0.36	1
T4 (Hillslope)	A	5--11	8	55.4	36.2	8.5	sandy loam	42.3	1.32		3.60	0.36	3.2
T4 (Hillslope)	E	20--26	23	60.1	32.0	7.9	sandy loam	73.8	1.77		3.60	0.36	3.51
T4 (Hillslope)	Bt	5--11	8	38.4	40.7	20.9	loam	27.5	1.49		3.6	0.36	0.81
T4 (Hillslope)	Bt	24--30	27	17.4	36.4	46.2	clay	3.3	1.63		0.36	0.036	0.22
T4 (Hillslope)	Bt	53--59	56	12.0	31.4	56.6	clay	6.4	1.38		0.36	0.036	0.22
T4 (Hillslope)	Bt	69--75	72	4.2	27.4	68.4	clay	0.0	1.40		0.36	0.036	n/a
T5 (Riparian)	A	5--11	8	41.3	45.7	13.0	loam	1.8	1.18		3.6	0.36	1.9
HF1 Sample 1 (Riparian)	A	0--10	5	69.3	22.4	8.3	sandy loam	5.5	**		36	3.6	3.49
HF1 Sample 2 (Riparian)	Bt	75--82	79	61.1	22.7	16.3	sandy loam	4.0	**		36	3.6	1.13
HF1 Sample 3 (Riparian)	Bt	100--110	105	58.8	27.1	14.1	sandy loam	7.7	**		3.6	0.36	1.53
T6 (Upland site)	A	5--15	18	37.3	33.7	29.0	clay loam	*****	**		0.36	0.036	0.39
T6 (Upland site)	Bt	40--45	43	7.5	30.0	62.5	clay	*****	**		0.036	0.0036	n/a
T6 (Upland site)	Bt	75--85	80	12.7	33.1	54.2	clay	*****	**		0.036	0.0036	0.22
T6 (Upland site)	Bt	87 -- 93	90	8.8	28.5	62.7	clay	*****	**		0.036	0.0036	n/a

***** = No lab analysis performed because no significant particles in >2mm. range observed

** = Bulk density analysis not performed

Table 6. UF Soil Physical and Hydrologic Properties

Umstead Farms Catchment										Estimates NRCS (2010)		Saxton et al (1986)
Sample Location	Soil Horizon	Sample Depth (cm)	Avg. Depth (cm)	Sand %	Silt %	Clay %	USDA Class.	>2mm %	ρ_b (measured)	K_{sat} (measured) (cm/hr)	K_{sat} (NRCS est. high value)# (cm/hr)	K_{sat} (NRCS est. low value)# (cm/hr)	K_{sat} (Saxton 1986 est. value)## (cm/hr)
T1 (Hillslope)	A	5--11	8	46.8	48.2	4.9	sandy loam	8.6	1.39		3.60	0.360	4.44
T1 (Hillslope)	Bt	27--33	30	34.7	34.8	30.5	clay loam	16.8	1.70		0.04	0.004	0.34
T1 (Hillslope)	Bt	42--48	45	16.9	27.8	55.3	clay	0.0	1.54		0.04	0.004	0.02
T2 /ESI (Hillslope)	A	10 -- 16	13	56.2	36.1	7.7	sandy loam	7.7	1.40		3.60	0.360	3.55
T2 /ESI (Hillslope)	E	25 -- 31	28	53.6	33.0	13.5	sandy loam	43.0	1.73		3.60	0.360	1.68
T2 /ESI (Hillslope)	Bt	33 -- 39	36	27.3	27.7	45.0	clay	*****	1.60		0.04	0.004	0.19
T2 /ESI (Hillslope)	Bt	49 -- 55	52	39.4	28.2	32.4	clay loam	*****	1.62		0.36	0.036	0.29
T2 /ESI (Hillslope)	Bt	67 -- 73	70	56.9	21.8	21.3	sandy clay loam	*****	1.70		0.36	0.04	0.64
T3 (Upland)	A	5--11	8	61.2	32.2	6.7	sandy loam	18.7	1.56		3.6	0.36	4.13
T3 (Upland)	E	21--27	24	65.8	27.2	7.0	sandy loam	20.1	1.63		3.6	0.36	4.1
T3 (Upland)	Bt	37--43	40	55.9	30.4	13.6	sandy loam	11.9	1.75		3.6	0.36	1.64
T3 (Upland)	Bt	55--61	58	59.8	13.8	26.4	sandy clay loam	2.0	1.86		0.36	0.036	0.36
T3 (Upland)	Bt	69--75	72	75.3	9.7	15.0	sandy loam	17.4	1.88		0.36	0.036	1.31
UF2 near T2&4 (Hillslope)	Bt	30	30	2.2	31.1	66.7	clay	*****	**		0.36	0.036	n/a
UF2 near T4 (Hillslope)	Bt	60	60	6.3	29.0	64.7	clay	*****	**		0.36	0.036	n/a
T6 (Hillslope)	A	5--11	8	57.1	35.7	7.1	sandy loam	12.5	1.58	14.8	3.60	0.36	0.2
T6 (Hillslope)	E	20--26	23	53.6	35.4	11.0	sandy loam	20.7	**	0.02	0.36	0.04	0.2
T6 (Hillslope)	Bt	36--42	39	20.4	29.4	50.2	clay	0.0	1.60	0.02	0.04	0.004	0.5
T7 (Upland)	A	8 -- 14	11	49.7	42.0	8.3	loam	*****	**		0.36	0.04	3.25
T7 (Upland)	E	20 -- 26	23	42.6	46.6	10.8	loam	*****	1.71		3.60	0.36	2.45
T7 (Upland)	Bt	30 -- 36	33	43.2	41.3	15.5	loam	*****	1.82		0.36	0.04	1.4
T7 (Upland)	Bt	47 -- 53	50	42.6	37.7	19.6	loam	44.9	1.76		0.36	0.04	0.88
T7 (Upland)	Bt	65 -- 71	68	33.9	36.7	29.4	clay loam	*****	1.62		0.36	0.04	0.39
T7 (Upland)	Bt	120 -- 140	130	20.9	42.8	36.3	clay loam	*****	**		0.04	0.004	0.32

***** = No lab analysis performed because no significant particles in >2mm. range observed

** = Bulk density analysis not performed

Hillslope locations (TaE)

- A&E horizons (0-25 cm)
- Bt horizons (25-95 cm)

Upland locations (ApC)

- A&E horizons (0-20 cm)
- Bt horizons (below 20 cm

Riparian locations

- A&E horizons (0-70 cm)
- Bt horizons (below 70 cm)

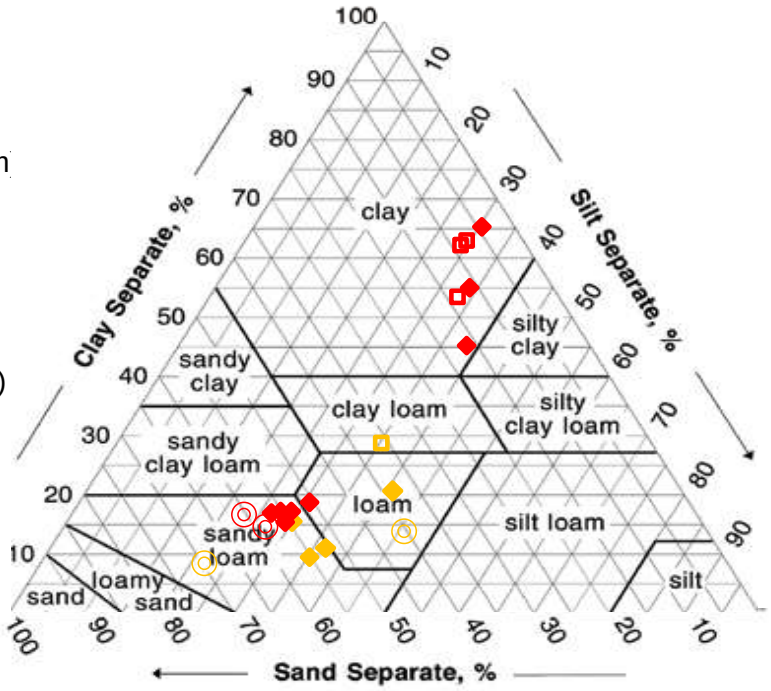


Figure 11. HF Catchment Soil Textural Analysis by Landscape Unit Type and Horizon

Hillslope locations (HeB)

- A&E horizons (0-30 cm)
- Bt horizons (30-70 cm)
- BC horizons (below 70cm)

Upland locations (VaB)

- A&E horizons (0-40 cm)
- Bt horizons (50-130 cm)
- BC horizons (below 130 cm)

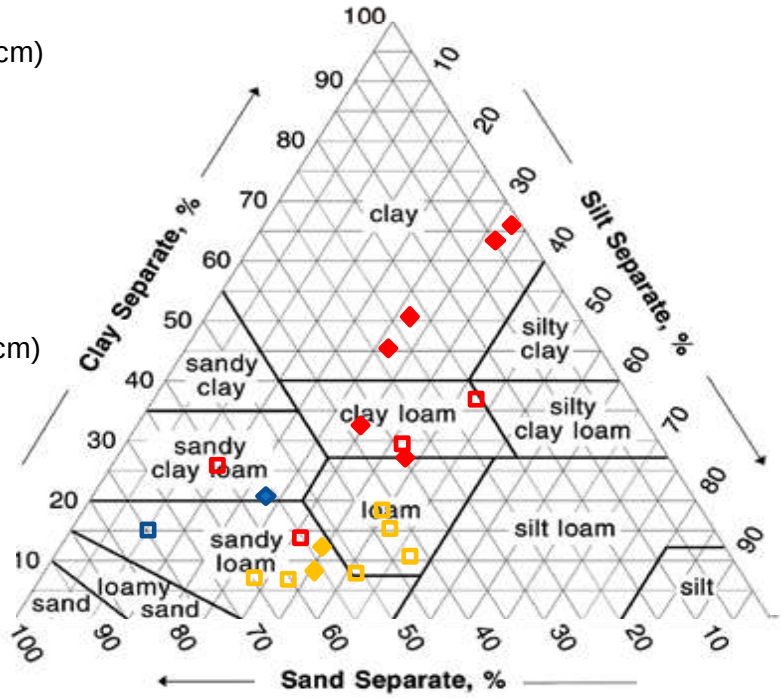


Figure 12. UF Catchment Soil Textural Analysis by Landscape Unit Type and Horizon

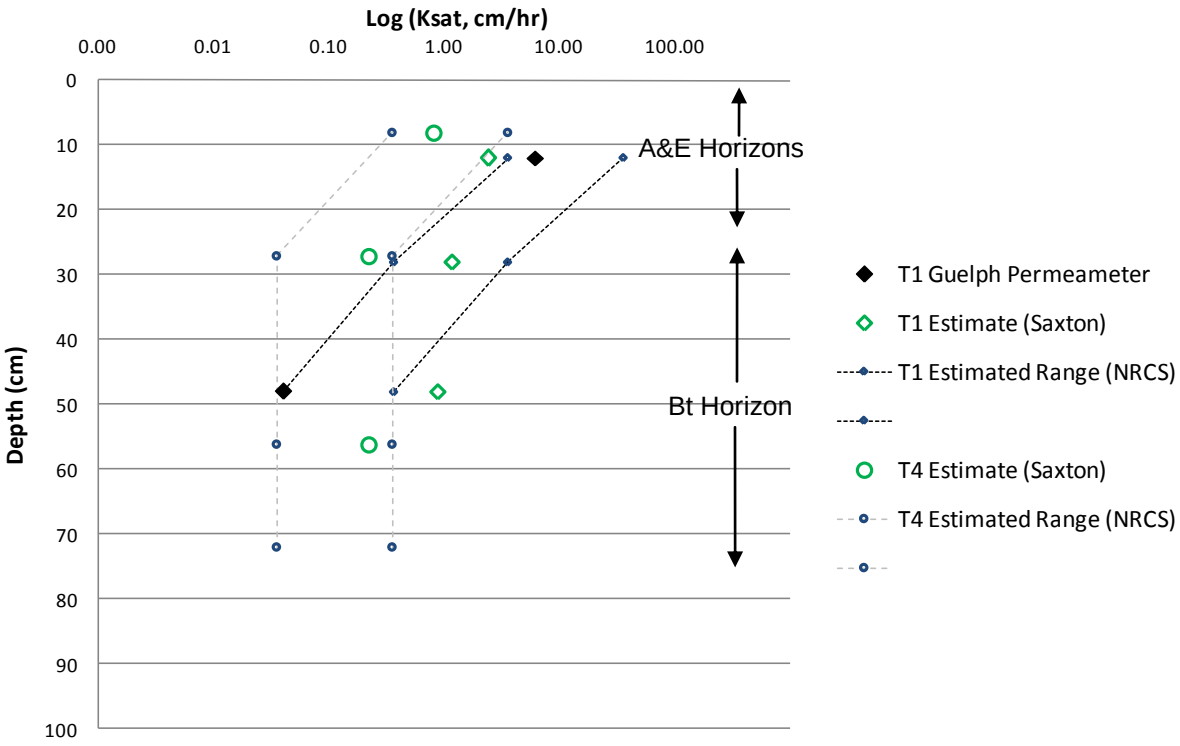


Figure 13. HF Hillslope Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities. Indirect estimates generated from Saxton (1986) and NRCS pedotransfer function analysis using texture and bulk density data.

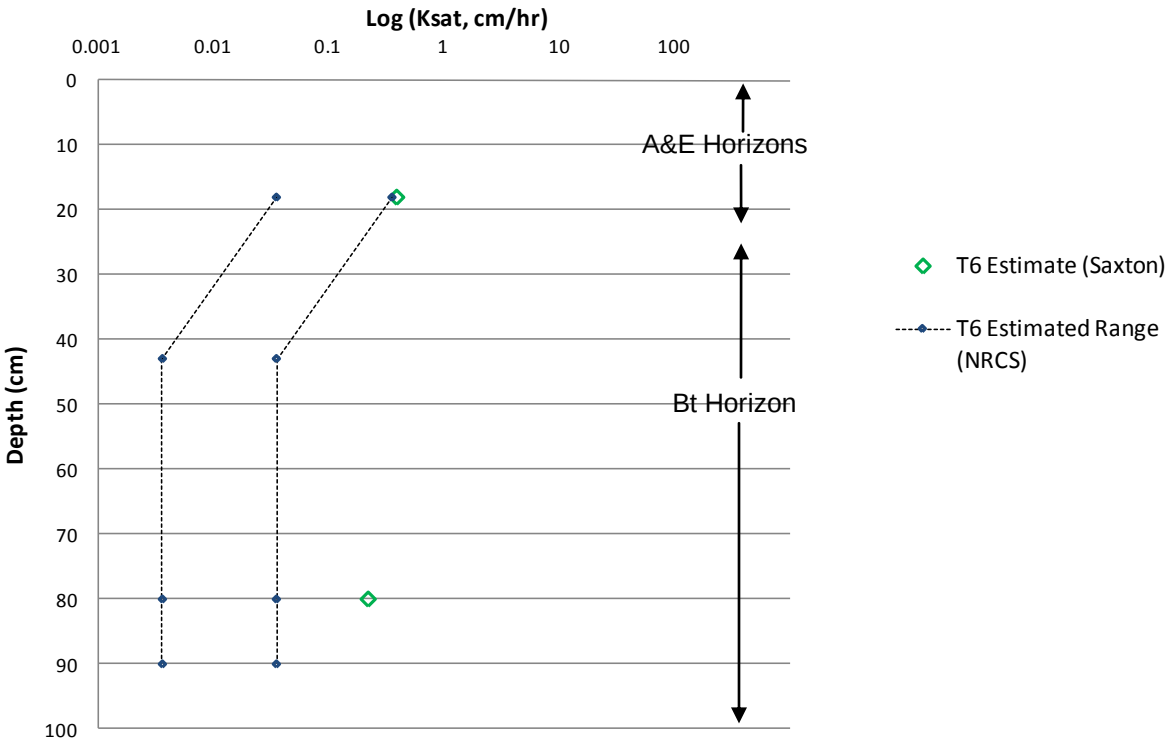


Figure 14. HF Upland Landscape Unit: Estimates of Saturated Hydraulic Conductivities. Indirect estimates generated from Saxton (1986) and NRCS pedotransfer function analysis using texture and bulk density data.

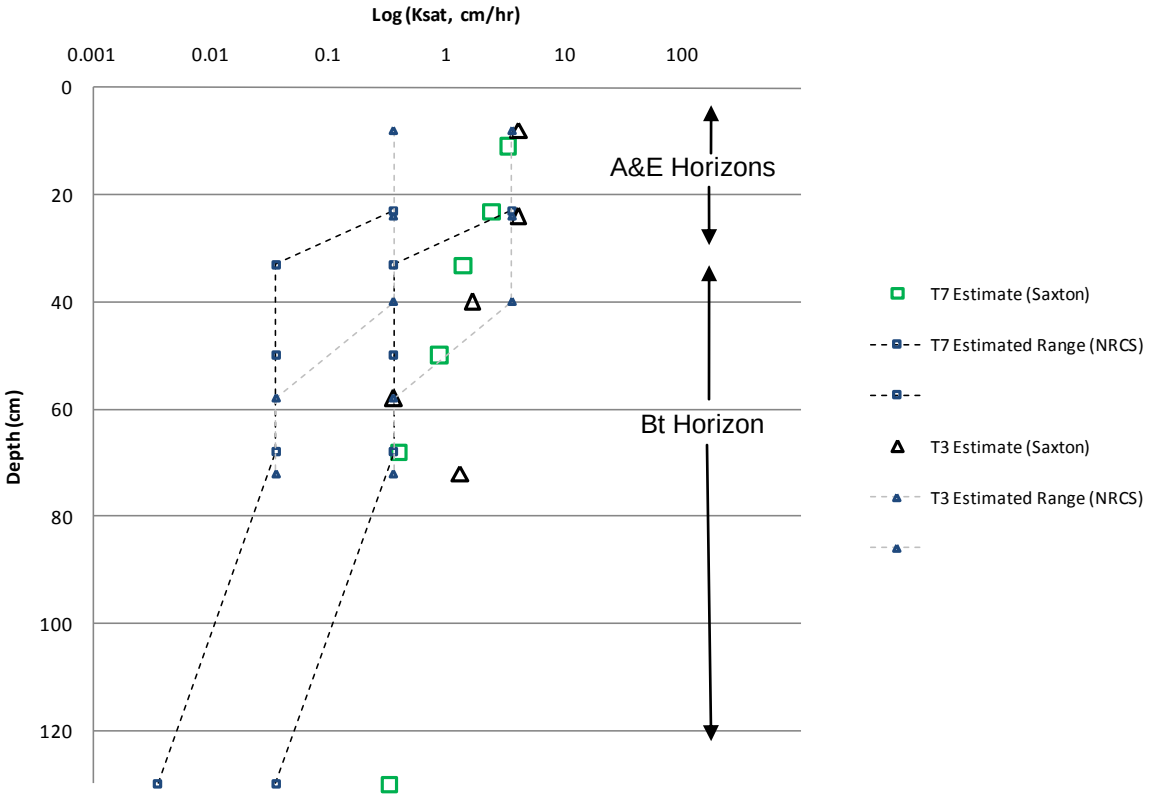


Figure 15. UF Upland Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities. Indirect estimates generated from Saxton (1986) and NRCS pedotransfer function analysis using texture and bulk density data.

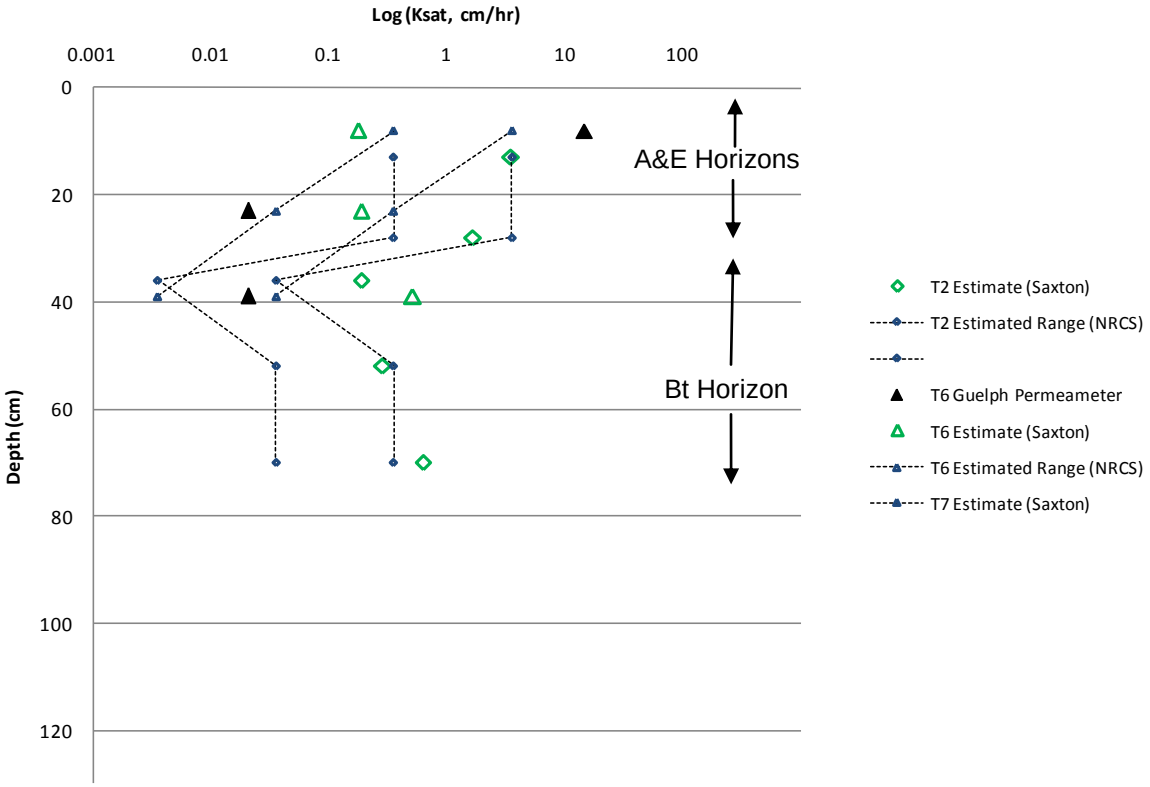


Figure 16. UF Hillslope Landscape Unit: Direct Measurements and Indirect Estimates of Saturated Hydraulic Conductivities. Indirect estimates generated from Saxton (1986) and NRCS pedotransfer function analysis using texture and bulk density data.

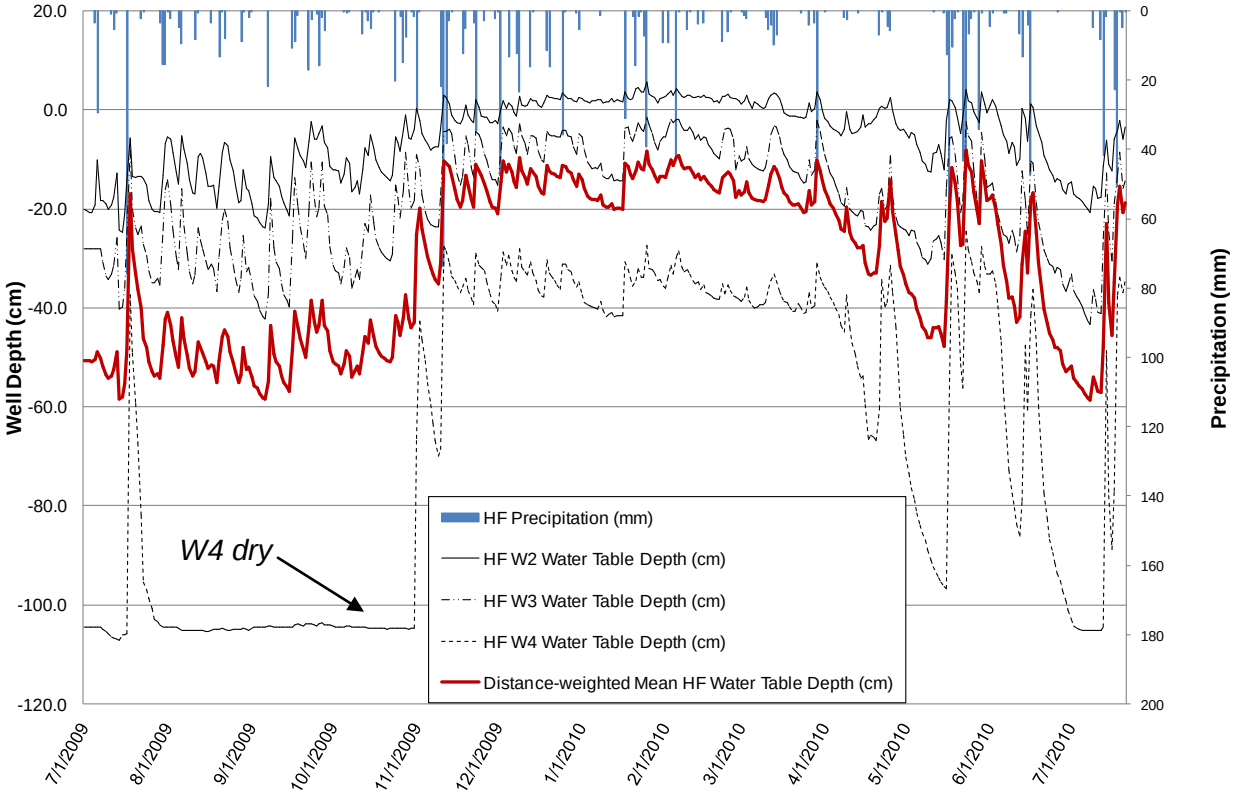


Figure 17. Daily Precipitation and Groundwater Levels for the HF Catchment for July 2009 to July 2010 (W4 dry at -107 cm)

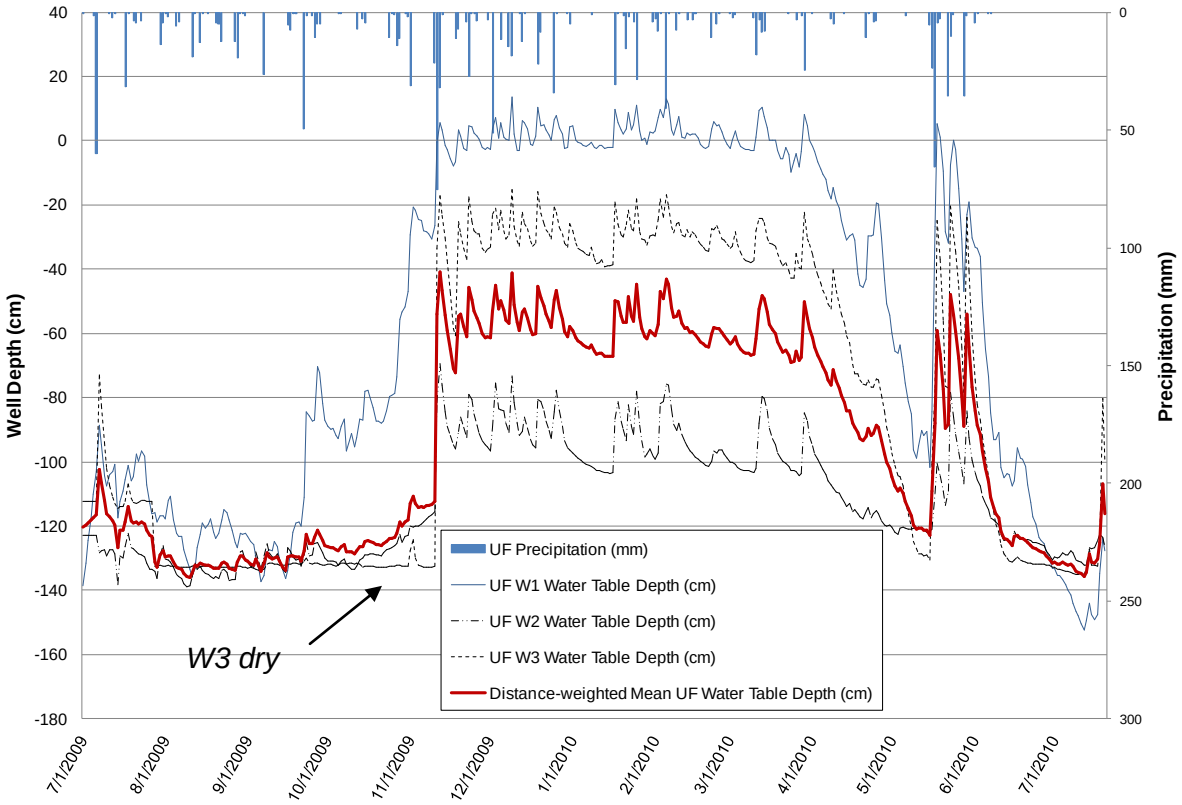


Figure 18. Daily Precipitation and Groundwater Levels for the UF Catchment for July 2009 to July 2010 (W3 dry at -133 cm)

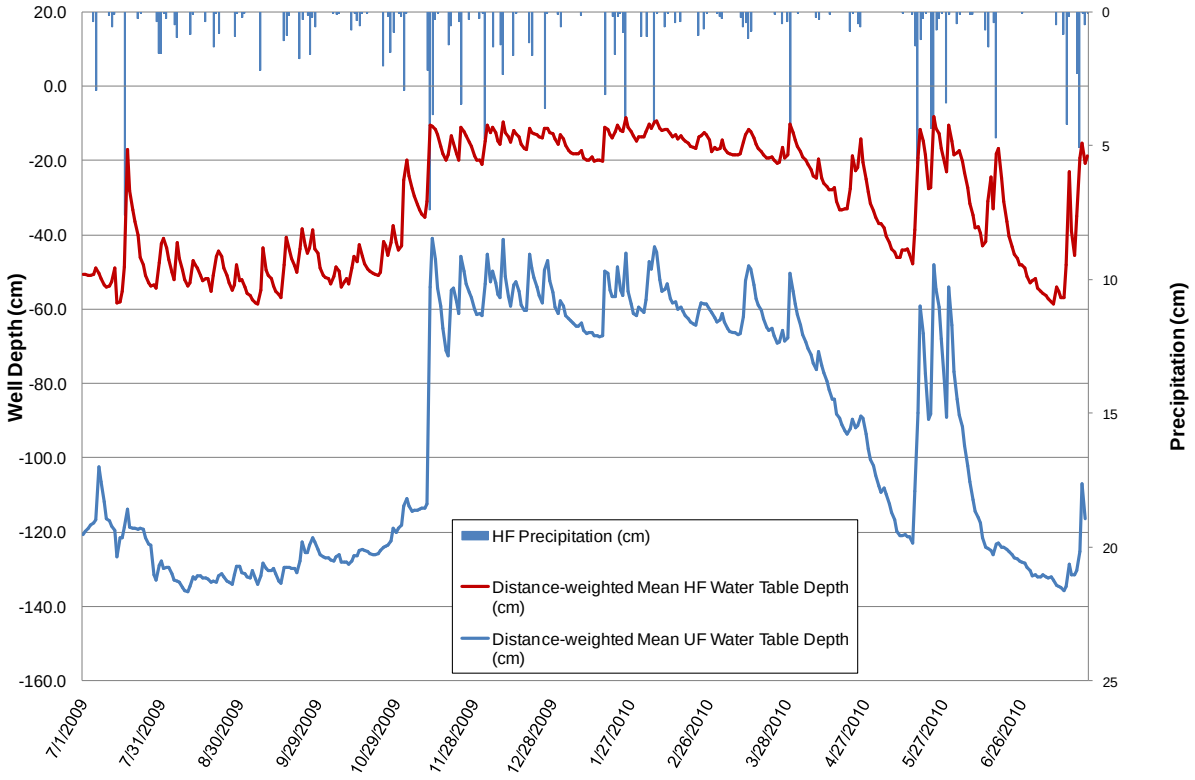


Figure 19. Average Daily Groundwater Levels Used to Represent Changing Saturated-zone Storage in HF and UF

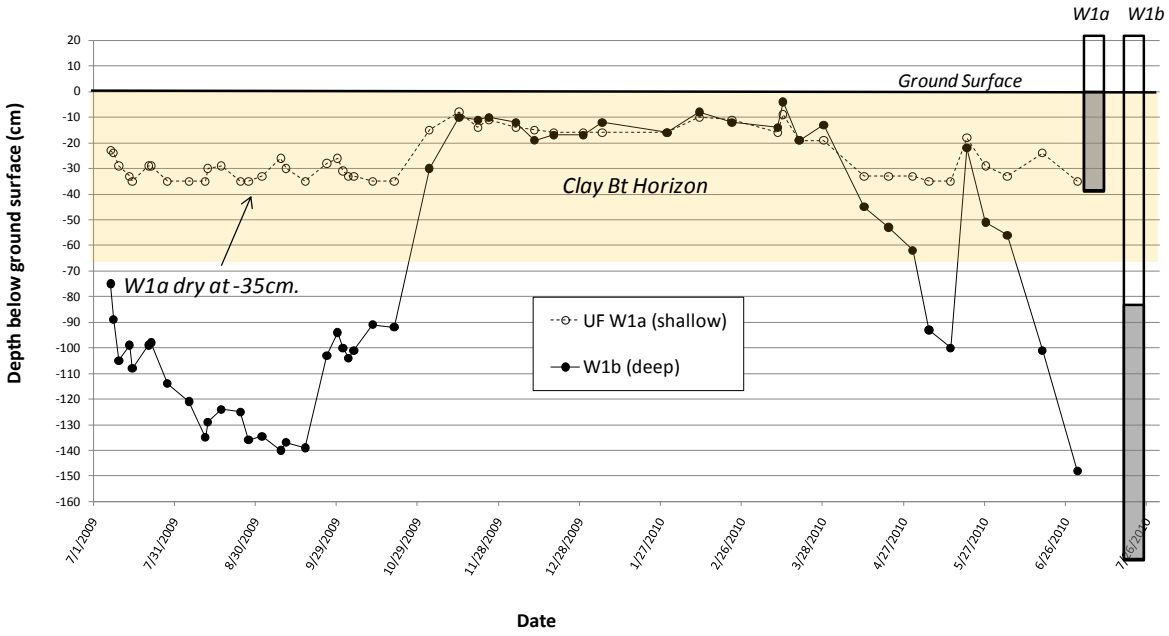


Figure 20. UF Catchment Water Table Levels below Ground Surface (wells are dry at UFW1a=35cm and UFW3a=37cm)

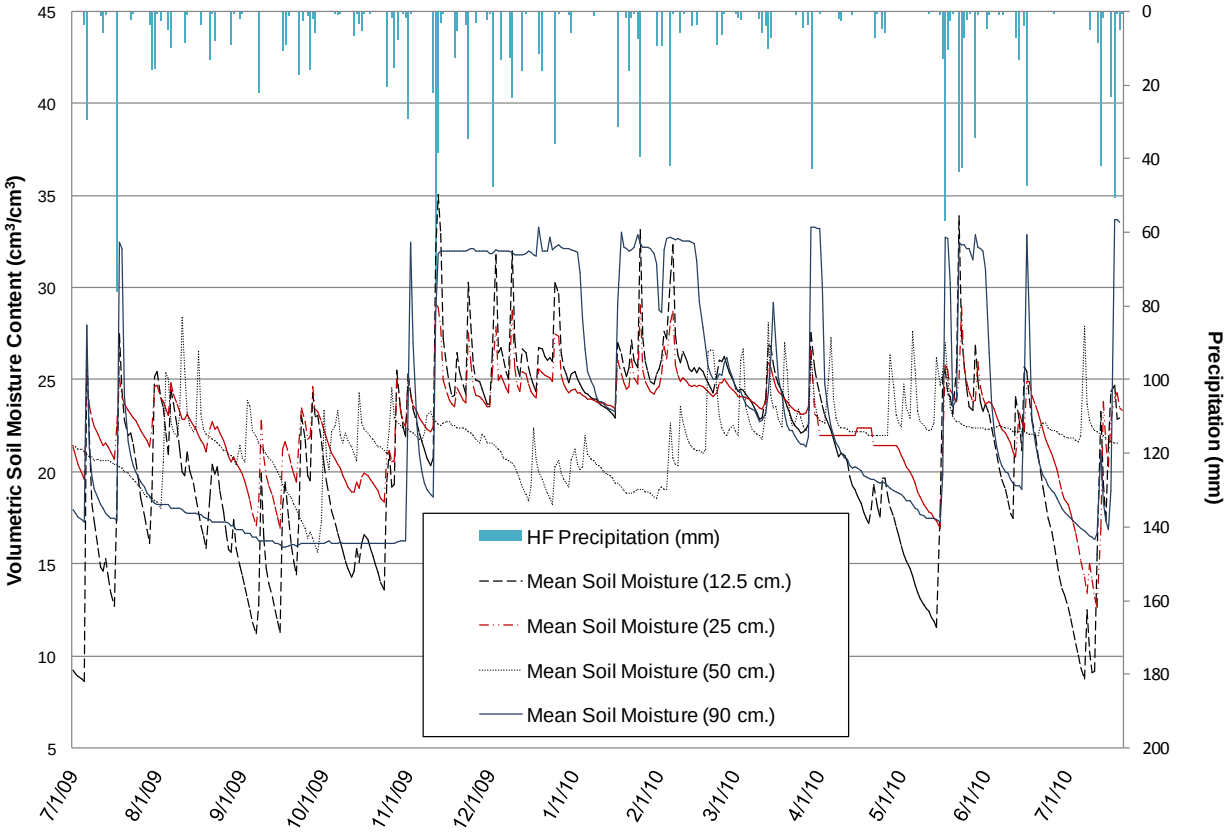


Figure 21. Daily Precipitation and Mean Daily Volumetric Soil Moisture Content of Four Depths at the HF T1 Continuous Site

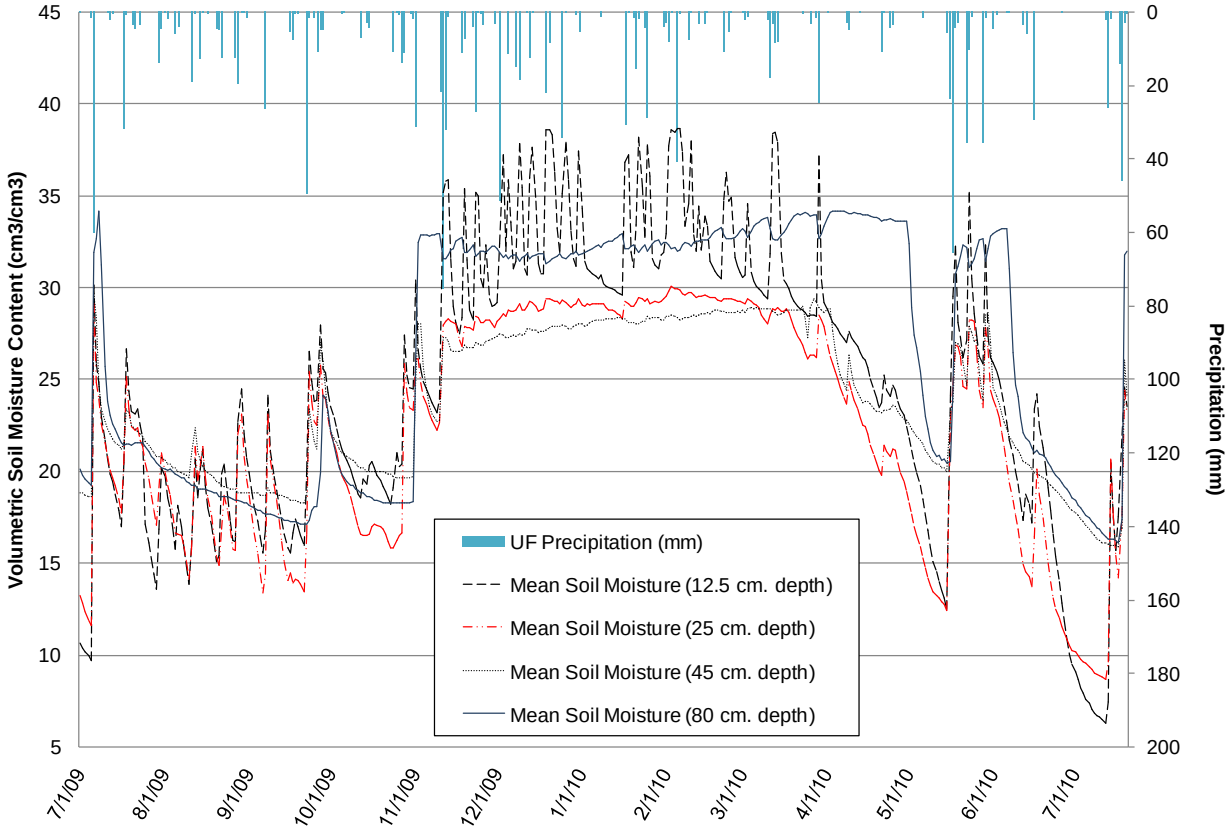


Figure 22. Daily Precipitation and Mean Daily Volumetric Soil Moisture Content of Four Depths at the UF T2 Continuous Site

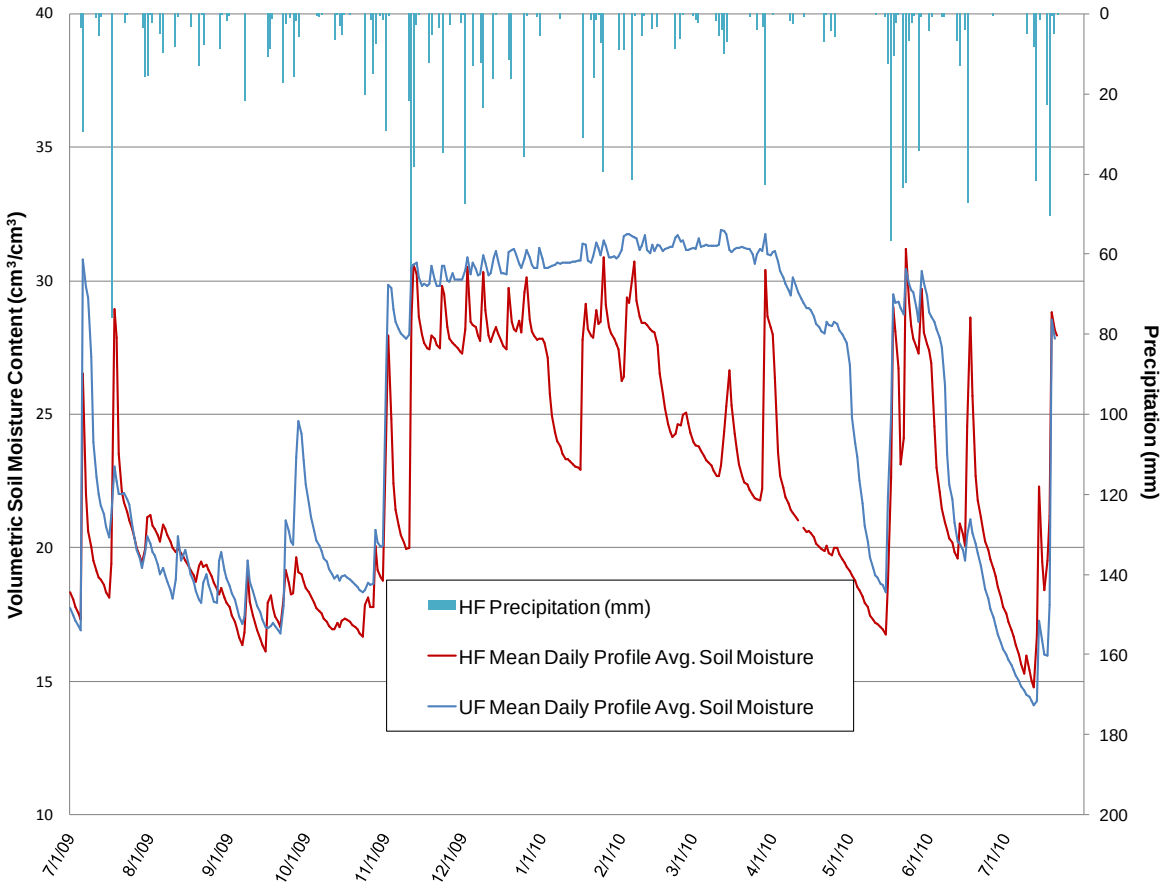


Figure 23. Daily Profile Average Soil Moisture at HF T1 and UF T2 Sites for July 2009 to July 2010

Table 7. HF and UF Seasonal Profile Average and Depth-specific VSMC at UF T2 and HF T1

	Umstead Farms (T2)					Hill Forest (T1)				
	Profile Avg.	12.5 cm	25 cm	45 cm	80 cm	Profile Avg.	12.5 cm	25 cm	50 cm	90 cm
Growing Season July 1-Oct. 31, 2009	19.8	19.5	18.6	20.5	19.8	18.9	17.8	21.4	20.9	17.5
Non-growing Season Nov. 1, 2009 - March 15, 2010	30.7	32.4	28.5	27.7	32.3	26.6	25.6	24.7	23.0	29.1
Growing Season March 16 - July 31, 2010	24.4	21.6	19.5	22.6	27.3	21.2	19.3	21.4	20.7	21.8

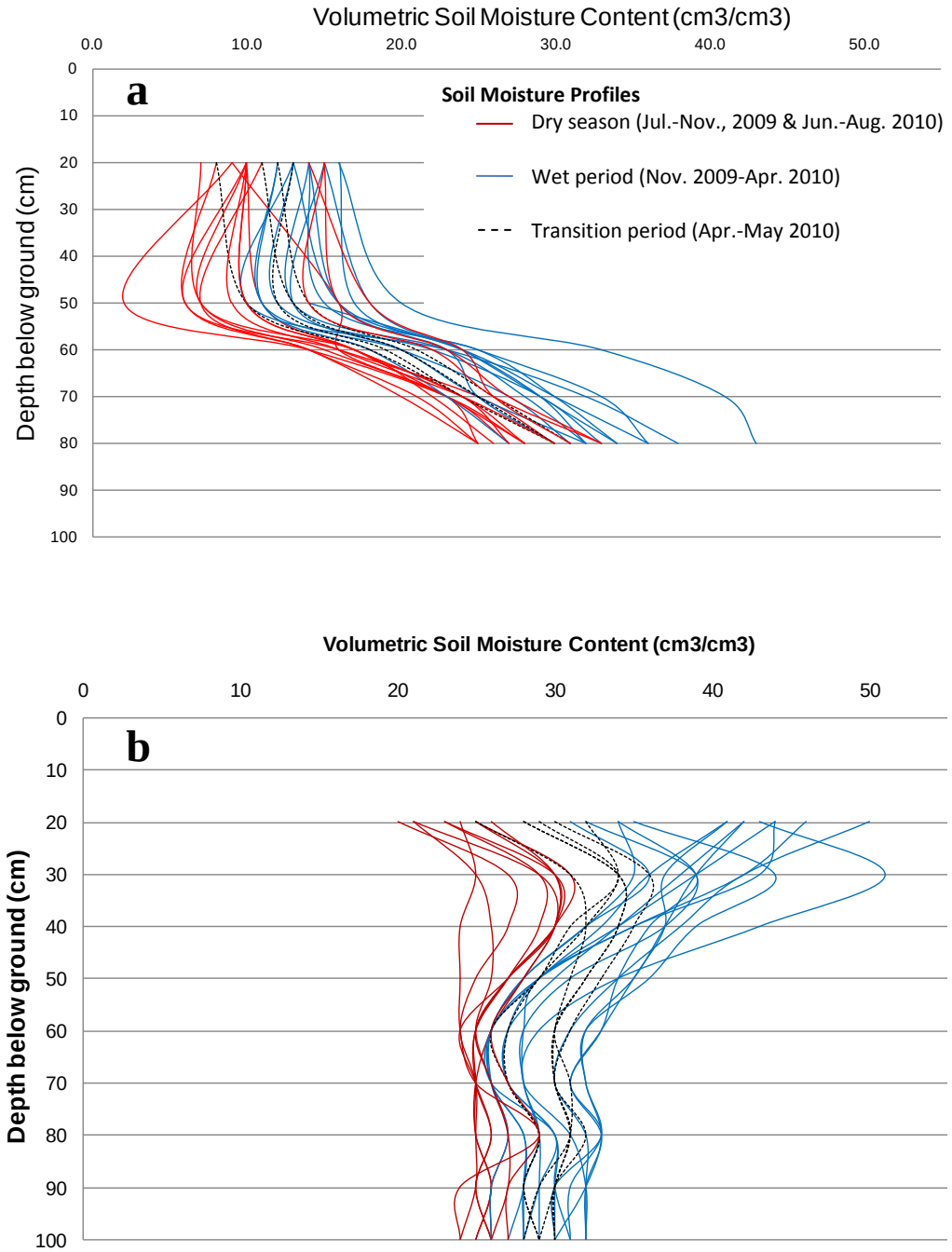


Figure 24. Bi-monthly Soil Moisture Profiles (access tubes) at the HF T1 (a) and UF T6 (b) Sites

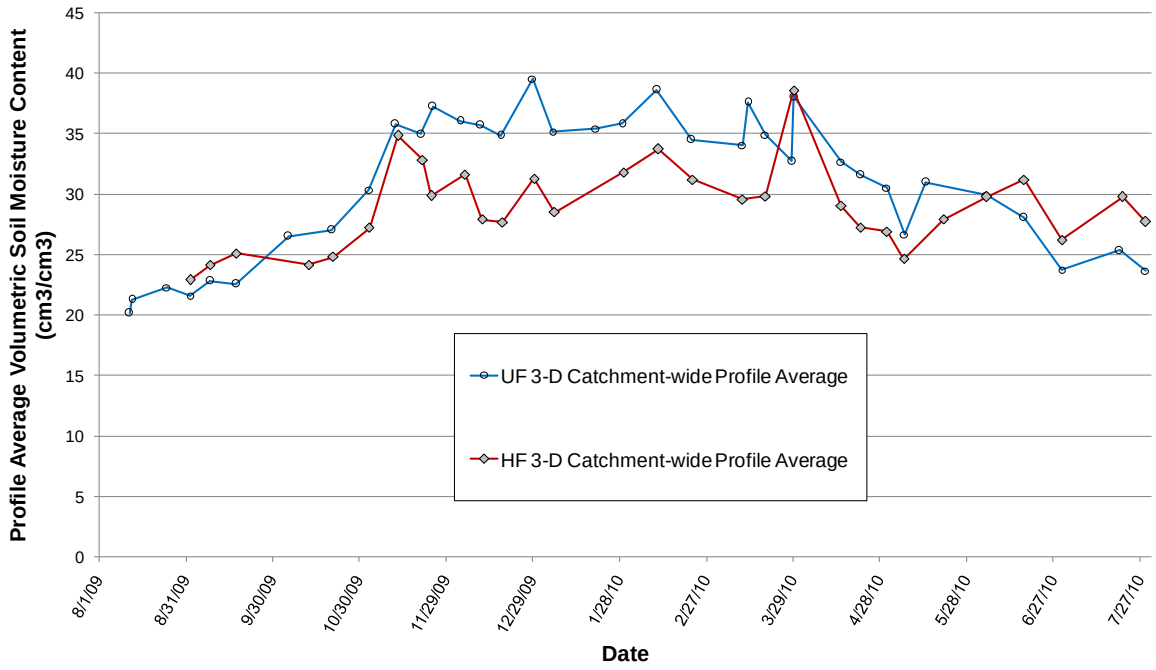


Figure 25. HF and UF Soil Moisture Profile Averages Using 3-D Approach

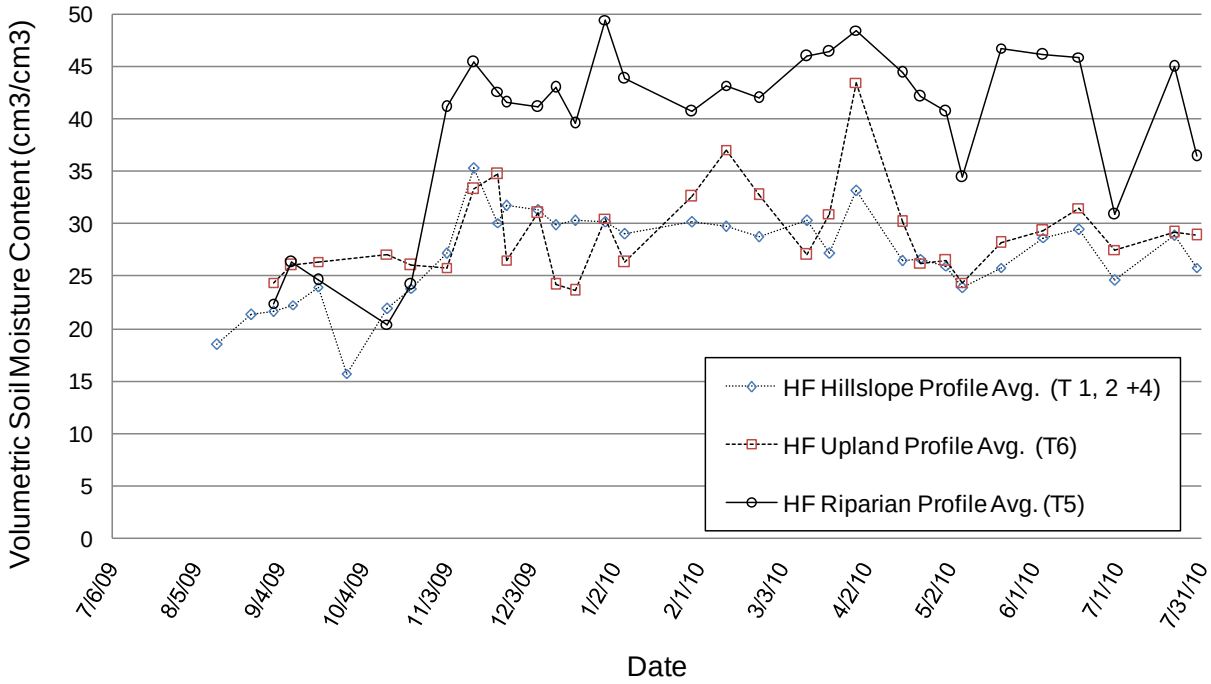


Figure 26. HF Hillslope, Upland, and Riparian Soil Moisture Profile Averages Based on the 3-D Synoptic Analysis

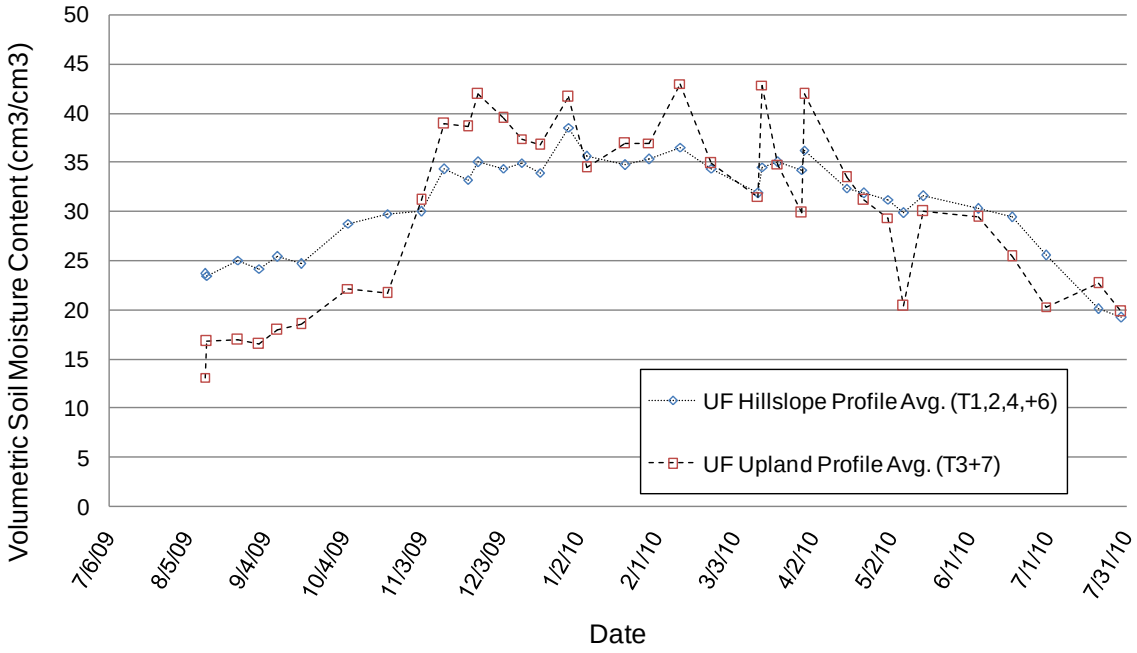


Figure 27. UF Hillslope and Upland Soil Moisture Profile Averages Based on the 3-D Synoptic Analysis

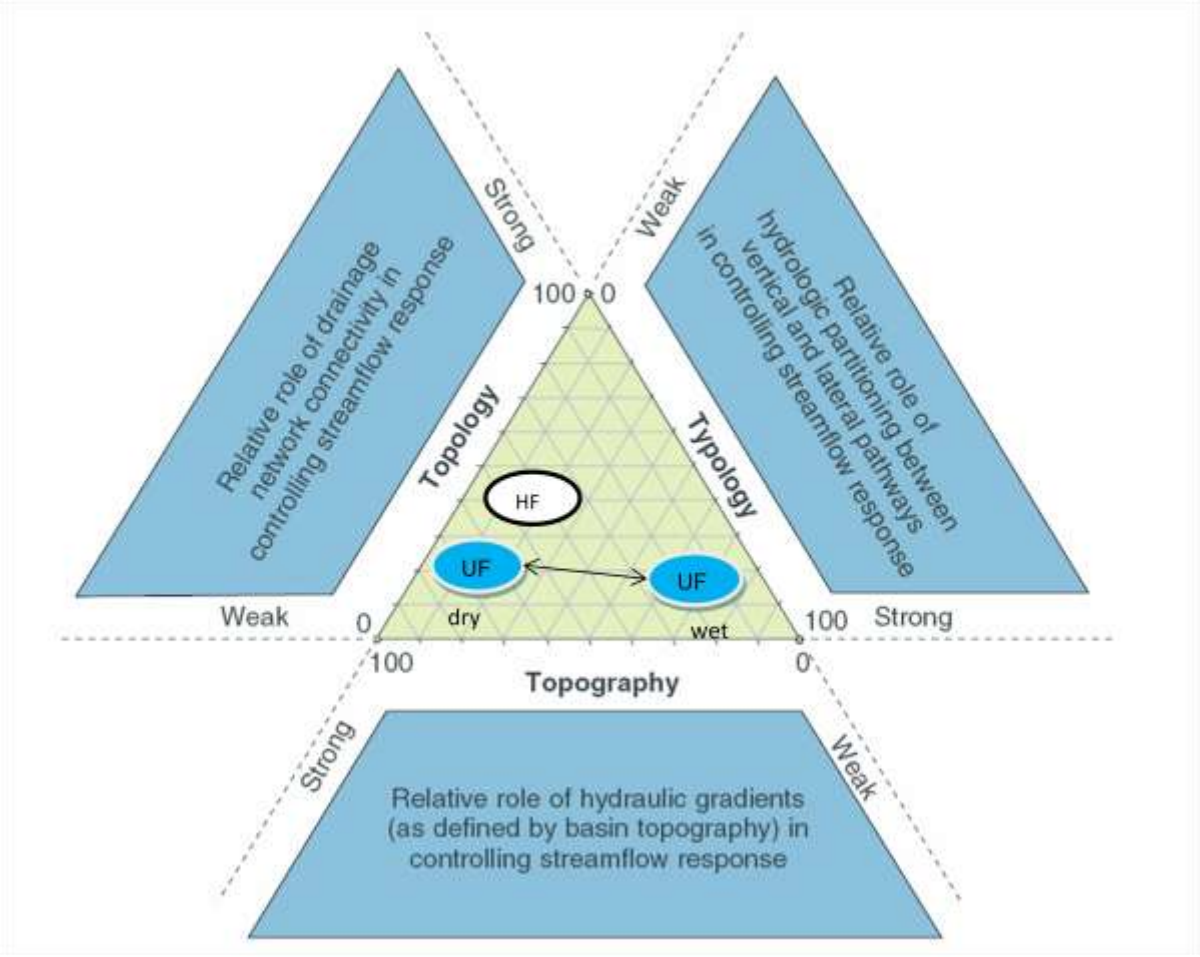


Figure 28. T3 Template Characterizing the HF and UF Catchments (based on Buttle 2006)

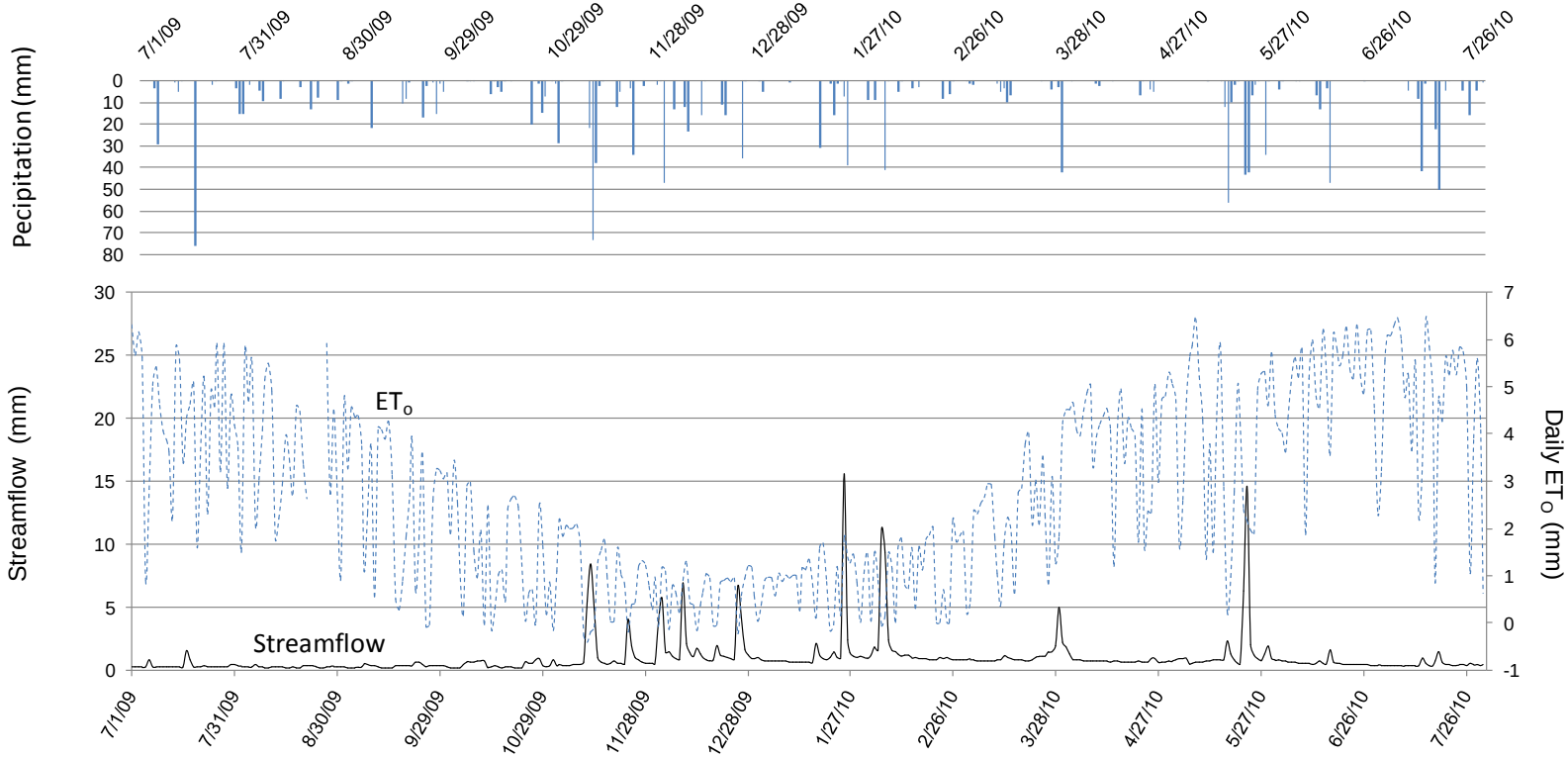


Figure 29. HF Daily Precipitation, ET_O, and Streamflow

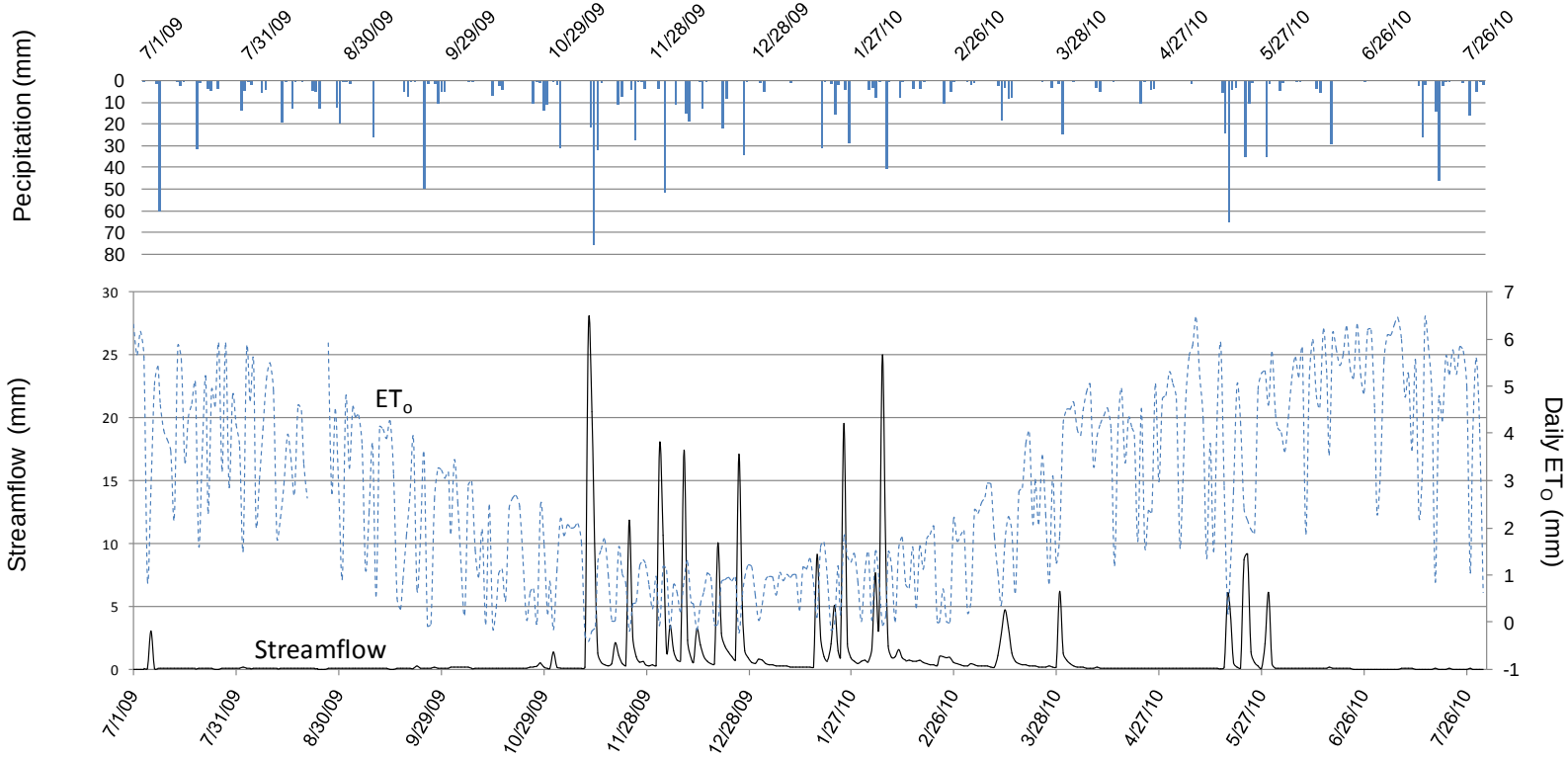


Figure 30. UF Daily Precipitation, ET_o, and Streamflow

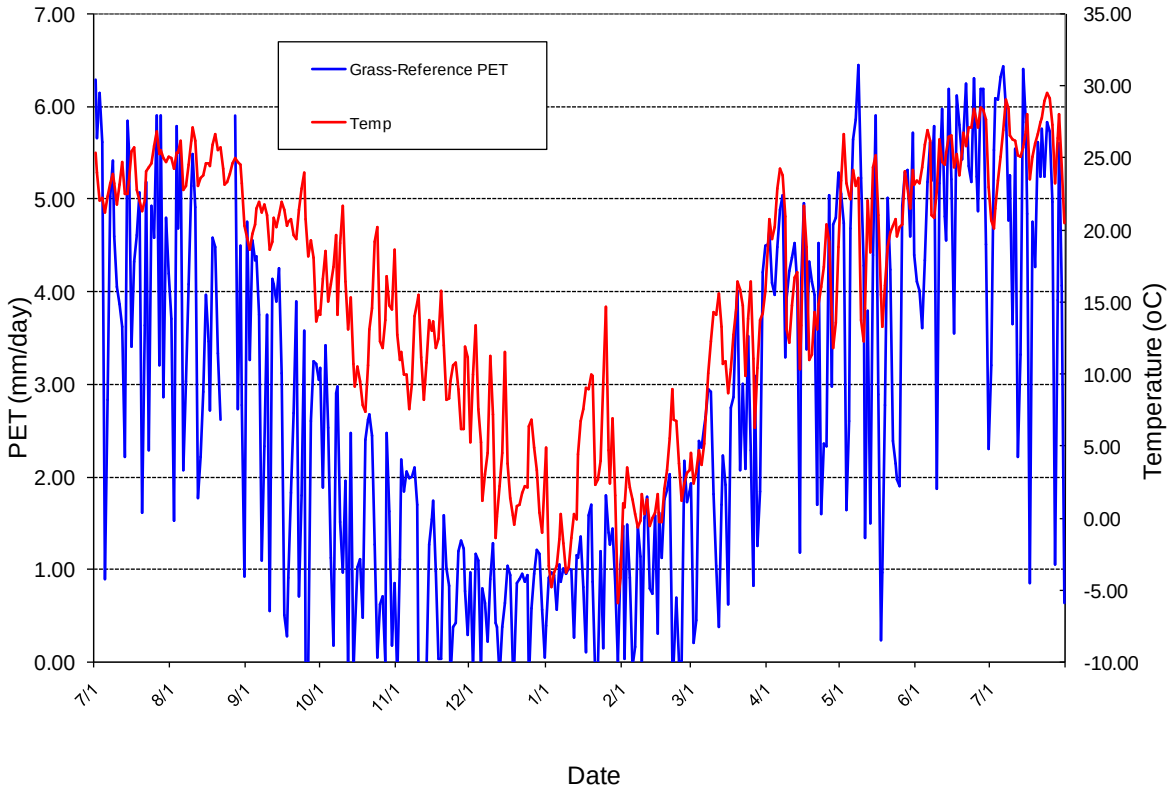


Figure 31. FAO Grass-reference ETo, using NC Climate Office data to fill gaps. Data are missing for the period of Aug. 8- Nov. 22, 2009.

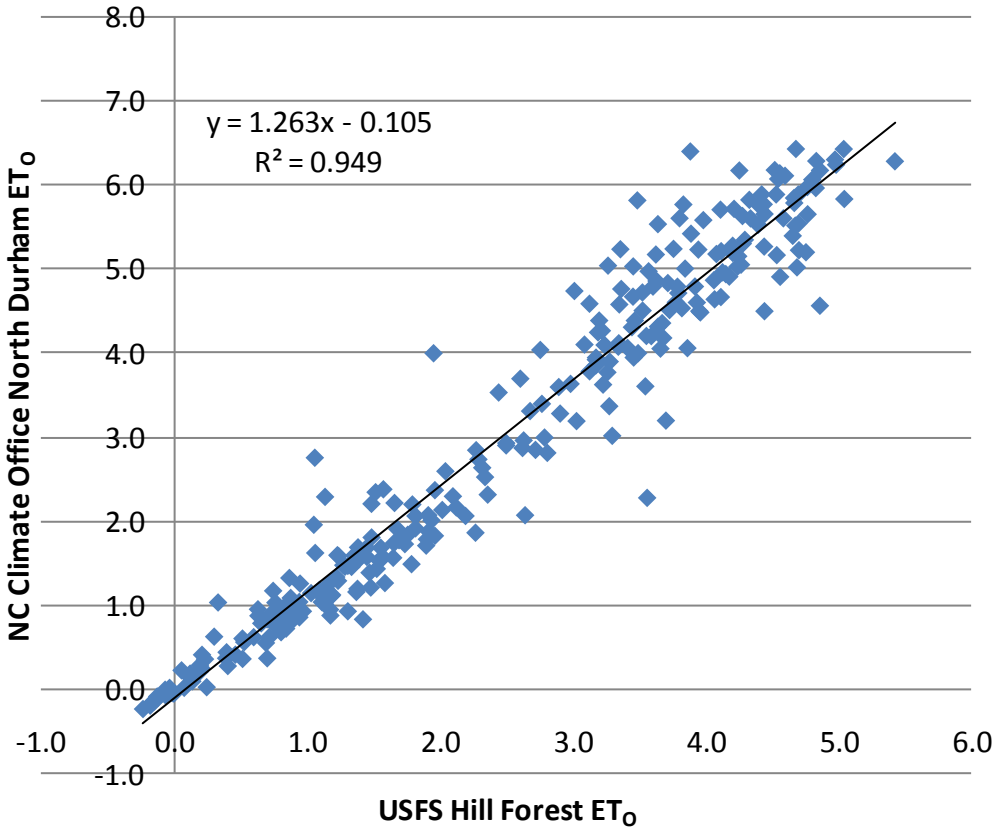


Figure 32. Comparison of Daily FAO Grass-reference ET_o Values Derived from NC Climate Office and Hill Forest Climate Data for the Period of Aug. 1, 2009 to Jul. 31, 2010.

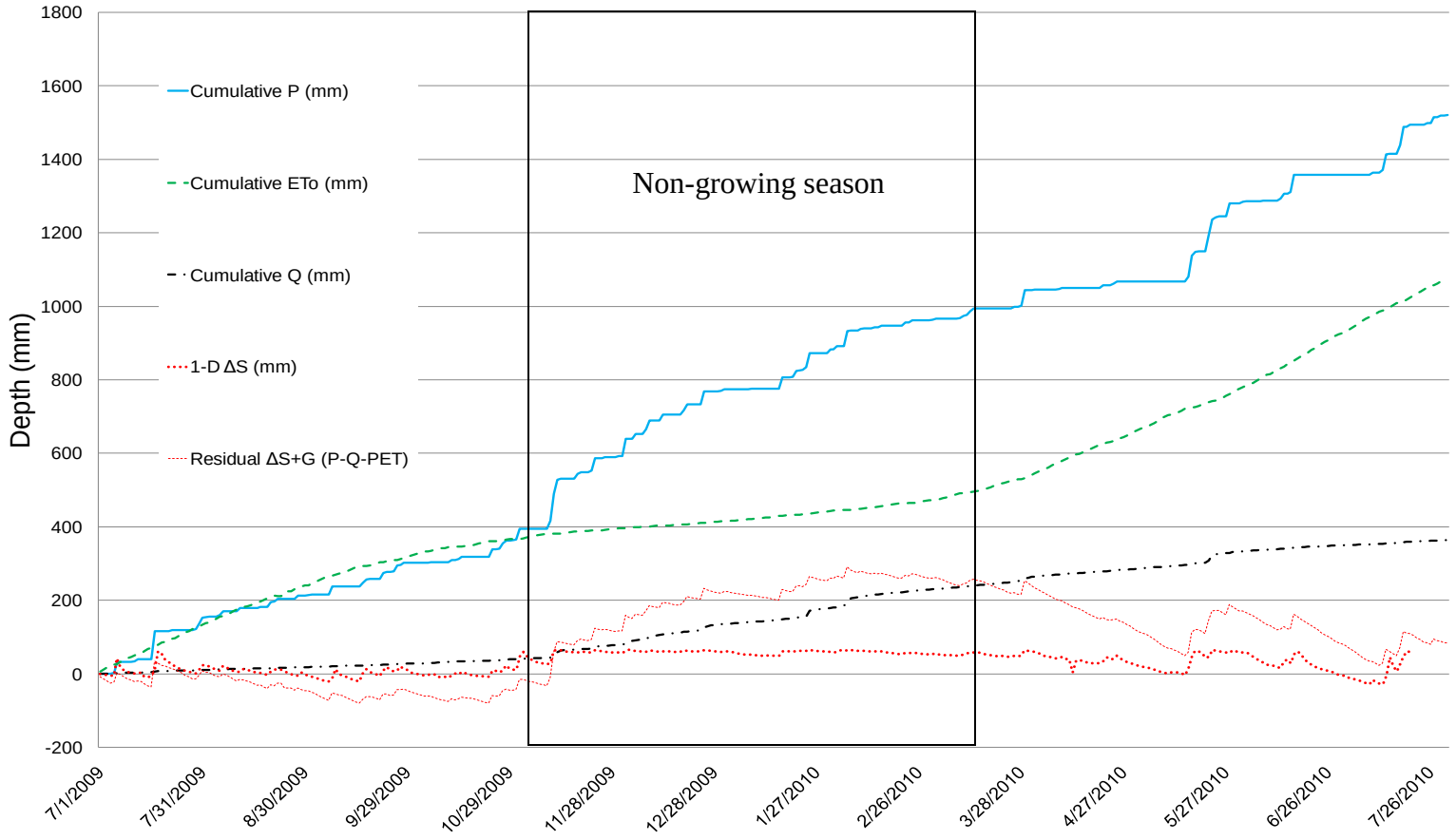


Figure 33. Cumulative Daily Water Balance for the HF Catchment

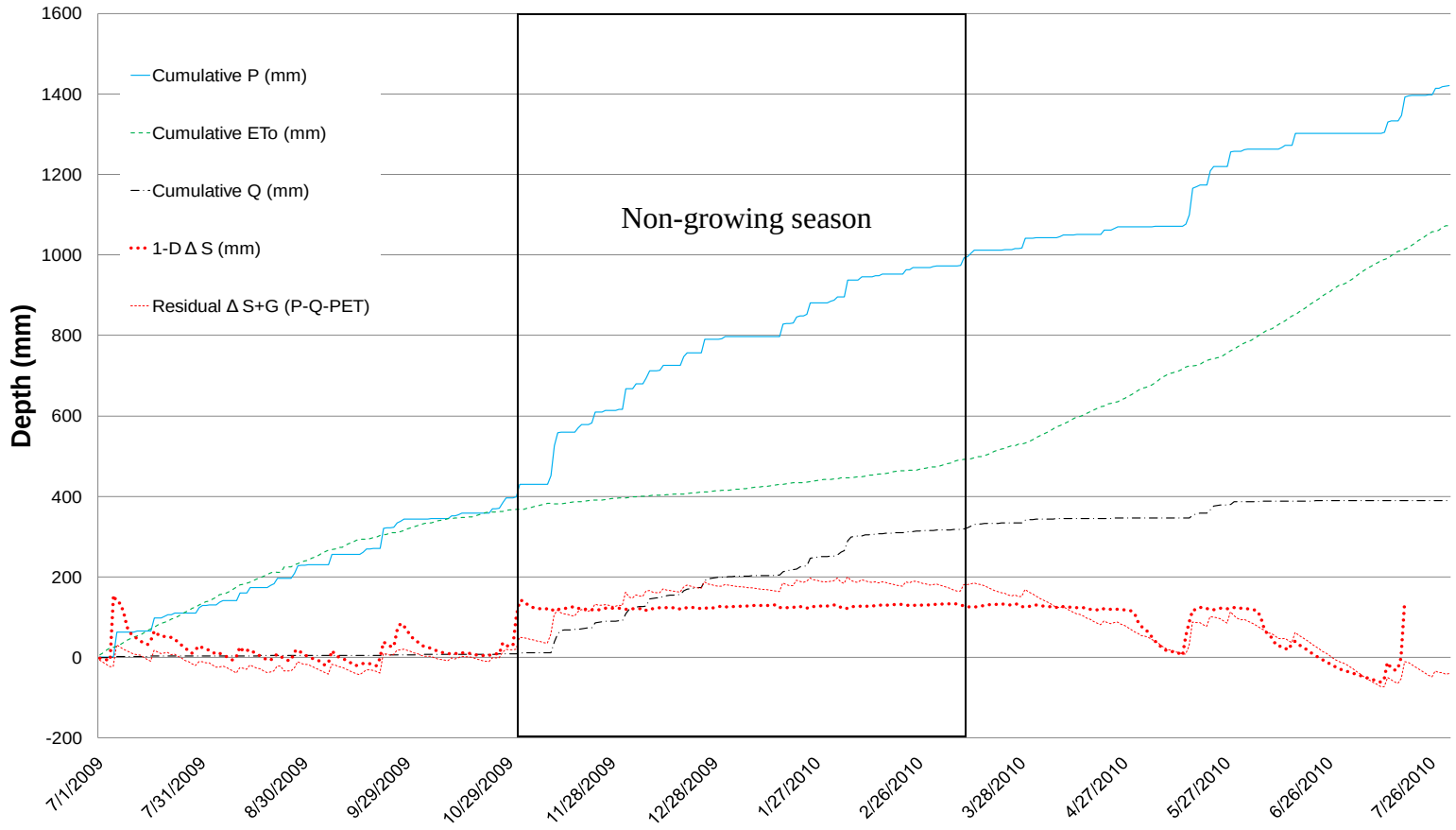


Figure 34. Cumulative Daily Water Balance for the UF Catchment

Table 8. Monthly, Seasonal, and Annual Water Balances of the HF Catchment in mm and % of P (uncertainties rounded to closest single digit)

Month	P (mm)	Q (mm)		1-D ΔS (mm)		3-D Δ S (mm)		ET (mm)		G, residual (mm)	
August '09	62 ± 2	8 ± 0	13%	-26 ± 6	-42%	-43 ± 11	-70%	79 ± 11	128%	0 ± 13	1%
September '09	87 ± 3	9 ± 0	11%	6 ± 1	7%	12 ± 3	14%	64 ± 9	73%	8 ± 10	9%
October '09	63 ± 3	12 ± 1	19%	67 ± 17	105%	96 ± 24	152%	41 ± 9	65%	-57 ± 19	-90%
November '09	227 ± 9	39 ± 2	17%	9 ± 2	4%	19 ± 5	8%	37 ± 9	16%	142 ± 13	62%
December '09	183 ± 7	57 ± 3	31%	31 ± 8	17%	34 ± 9	19%	28 ± 9	15%	66 ± 14	36%
January '10	108 ± 4	44 ± 2	41%	3 ± 1	3%	2 ± 1	2%	28 ± 9	26%	33 ± 11	31%
February '10	79 ± 3	49 ± 2	62%	-10 ± 2	-12%	-16 ± 4	-20%	27 ± 8	33%	13 ± 10	17%
March '10	83 ± 3	35 ± 2	42%	-3 ± 1	-3%	5 ± 1	6%	45 ± 9	54%	6 ± 10	7%
April '10	22 ± 1	22 ± 1	97%	-47 ± 12	-209%	-77 ± 19	-345%	70 ± 9	313%	-22 ± 15	-100%
May '10	213 ± 9	48 ± 2	22%	41 ± 10	19%	68 ± 17	32%	140 ± 11	66%	-15 ± 18	-7%
June '10	78 ± 3	17 ± 1	22%	-86 ± 21	-110%	-142 ± 36	-182%	110 ± 11	141%	37 ± 24	47%
July '10	162 ± 6	14 ± 1	9%	81 ± 20	50%	138 ± 35	85%	143 ± 11	88%	-76 ± 24	-47%
Late Growing Season '09	212 ± 8	29 ± 1	14%	47 ± 12	22%	56 ± 14	27%	184 ± 30	87%	-48 ± 33	-23%
Non-growing Season	680 ± 27	224 ± 11	33%	28 ± 7	4%	96 ± 24	14%	165 ± 45	24%	261 ± 54	38%
Early Growing Season '10	476 ± 19	100 ± 5	21%	-11 ± 3	-2%	-14 ± 4	-3%	463 ± 43	97%	-77 ± 47	-16%
Annual (Aug.09-Jul.10)	**1368 ± 55**	**354 ± 18**	**26%**	**64 ± 16**	**5%**	**91 ± 23**	**7%**	**812 ± 118**	**59%**	**136 ± 132**	**10%**

Table 9. Monthly, Seasonal, and Annual Water Balances of the UF Catchment in mm and % of P (uncertainties rounded to closest single digit)

Month	P (mm)	Q (mm)		1-D ΔS (mm)		3-D ΔS. (mm)		ET (mm)		G, residual (mm)		
August '09	102 ± 4	1 ± 0	1%	17 ± 4	17%	-4 ± 1	-4%	89 ± 11	88%	-6	± 13	-6%
September '09	114 ± 5	2 ± 0	1%	-36 ± 9	-32%	13 ± 3	12%	75 ± 9	66%	73	± 14	64%
October '09	55 ± 2	3 ± 0	5%	-4 ± 1	-7%	48 ± 12	87%	43 ± 9	78%	13	± 10	24%
November '09	219 ± 9	81 ± 4	37%	154 ± 39	71%	219 ± 55	100%	40 ± 9	18%	-57	± 41	-26%
December '09	180 ± 7	109 ± 5	61%	8 ± 2	4%	17 ± 4	9%	32 ± 9	18%	31	± 13	17%
January '10	88 ± 4	52 ± 3	59%	-5 ± 1	-6%	-5 ± 1	-6%	30 ± 9	34%	12	± 10	14%
February '10	84 ± 3	63 ± 3	76%	-11 ± 3	-13%	-12 ± 3	-14%	30 ± 8	36%	1	± 10	2%
March '10	73 ± 3	28 ± 1	38%	9 ± 2	12%	8 ± 2	12%	49 ± 9	67%	-12	± 10	-16%
April '10	27 ± 1	3 ± 0	12%	-124 ± 31	-456%	-171 ± 43	-627%	81 ± 9	297%	67	± 32	246%
May '10	188 ± 8	41 ± 2	22%	54 ± 13	29%	75 ± 19	40%	130 ± 11	69%	-37	± 19	-19%
June '10	45 ± 2	2 ± 0	4%	-5 ± 1	-11%	-166 ± 42	-368%	109 ± 11	242%	-61	± 11	-135%
July '10	118 ± 5	1 ± 0	0%	-101 ± 25	-85%	49 ± 12	41%	128 ± 11	108%	91	± 28	77%
Late Growing Season '09	270 ± 11	6 ± 0	2%	-23 ± 6	-9%	57 ± 14	21%	207 ± 30	77%	80	± 32	30%
Non-growing Season	644 ± 26	333 ± 17	52%	154 ± 39	24%	227 ± 57	35%	180 ± 45	28%	-24	± 67	-4%
Early Growing Season '10	379 ± 15	47 ± 2	12%	-176 ± 44	-47%	-213 ± 53	-56%	448 ± 43	118%	61	± 63	16%
Annual Aug.09-Jul.10	**1293 ± 52**	**386 ± 19**	**30%**	**-51 ± 13**	**-4%**	**50 ± 12**	4%	**836 ± 118**	**65%**	**123**	**± 131**	**9%**

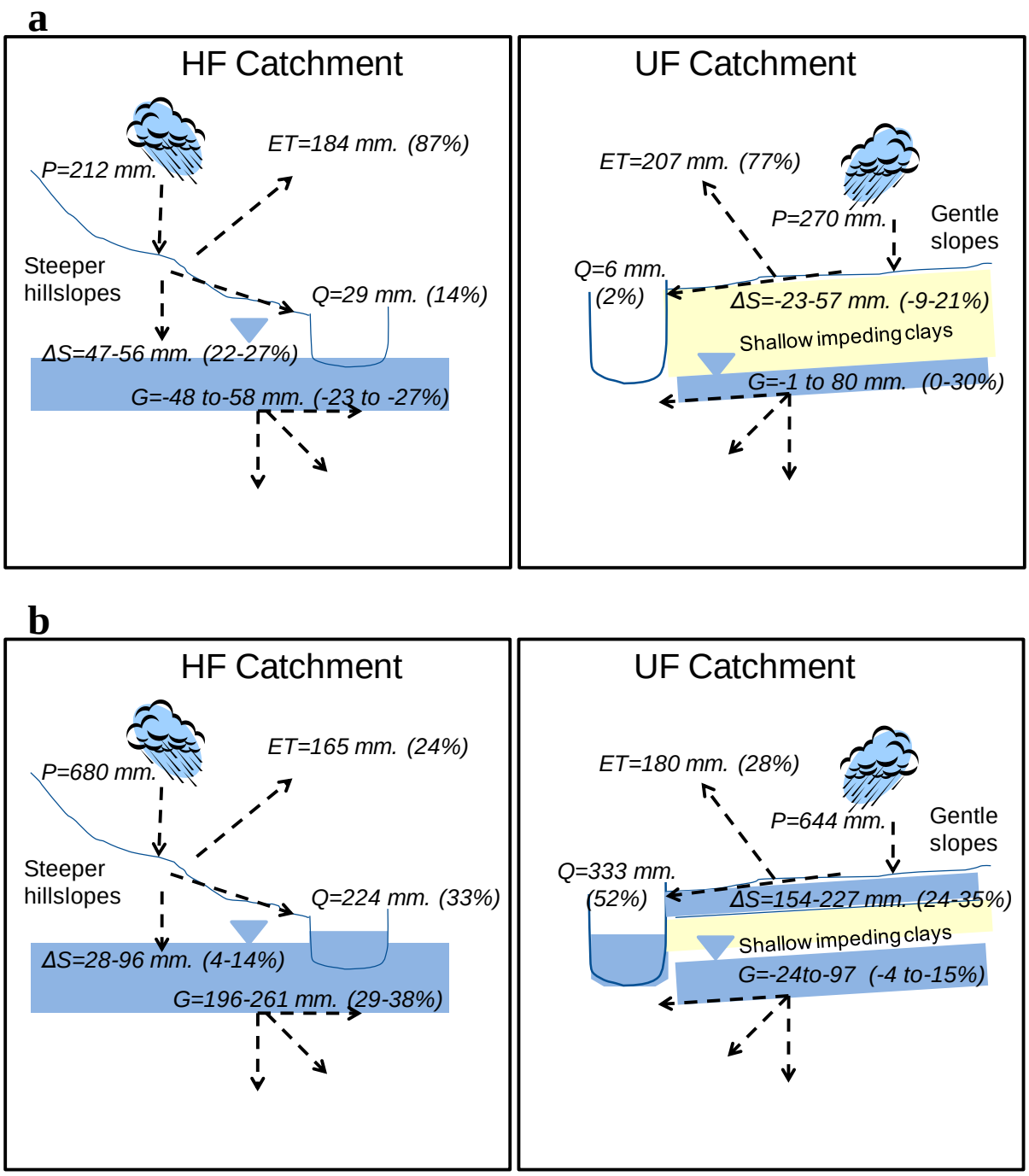


Figure 35. Conceptual, Growing Season (a) and Non-growing Season (b) Water Balance Models of the HF and UF Catchments

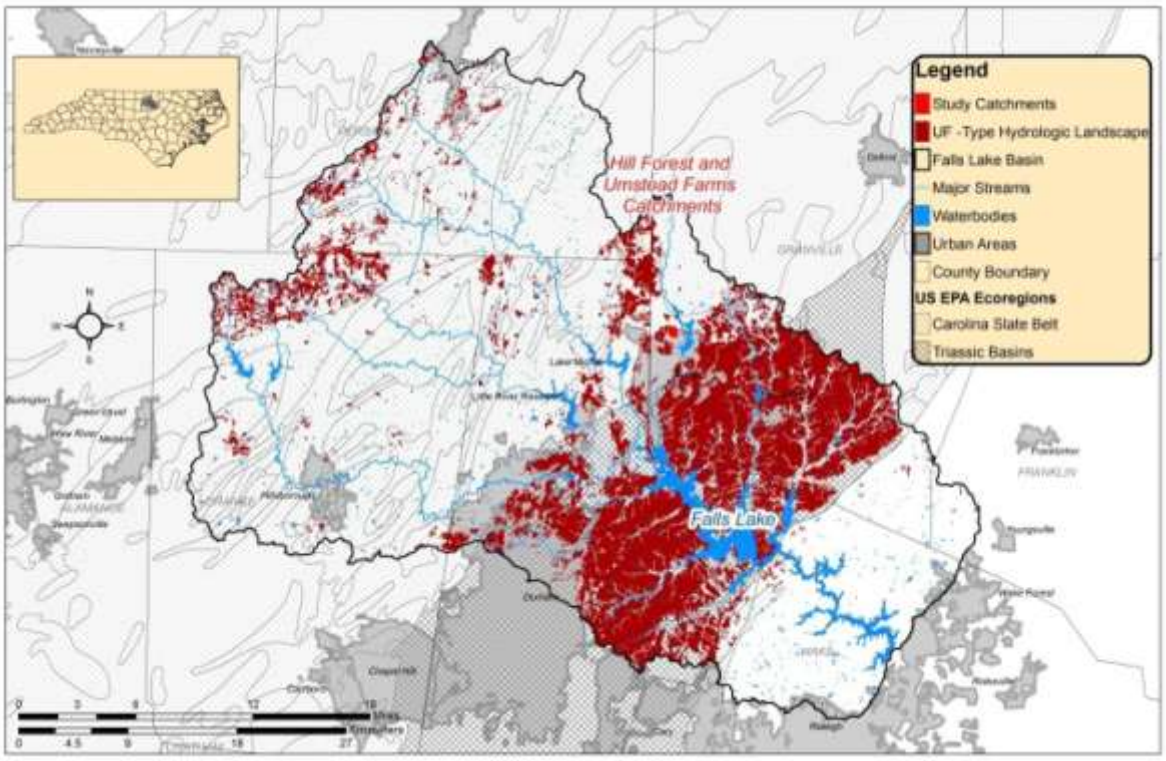


Figure 36. UF Catchment-Type Hydrologic Landscapes in the Falls Lake Basin

APPENDICES

APPENDIX 1

Soil Profile Descriptions and well drawings for HF and UF Monitoring Locations

Hill Forest Catchment

HF Riparian Well 2 Site Soils

Soil Series

Location HF2 shallow well #2

County Durham

Parent Material Colluvial / Alluvial

Moisture Status

Classification

Aspect

Landscape Position

Date 5-13-09

Drainage (wetness) Class Poorly

Slope Percent

Vegetative Cover

Described by

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
A	0-3"	Dk. Brown	—	Loam	Weak		Gran.				
B_{g1}	3-10	Gray Brown		SCL			S.B				
B_{g2}	10-24	DK. Gray		SC			S.B				
B_{tg}	24-30	Gray		Clay			SB				
C	30-33	Lt. Gray		Soil			Gr.				
A b	33-38	Dk. Brown		SCL			SB				
BC_{tg}	38-51	Light Gray	Common Orange	SC			Massive				Gravel

HF Riparian Well 3 Site Soils

Soil Series well 3

Location HF2 potential site #7 just downstream of spring (70ft)

County Durham

Parent Material Carolina Slate Belt

Moisture Status Saturated soil, rain yesterday

Classification

Aspect

Landscape Position Riparian 30 ft. from stream.

Date 5/12/09

Drainage (wetness) Class Poorly drained

Slope Percent 3-5

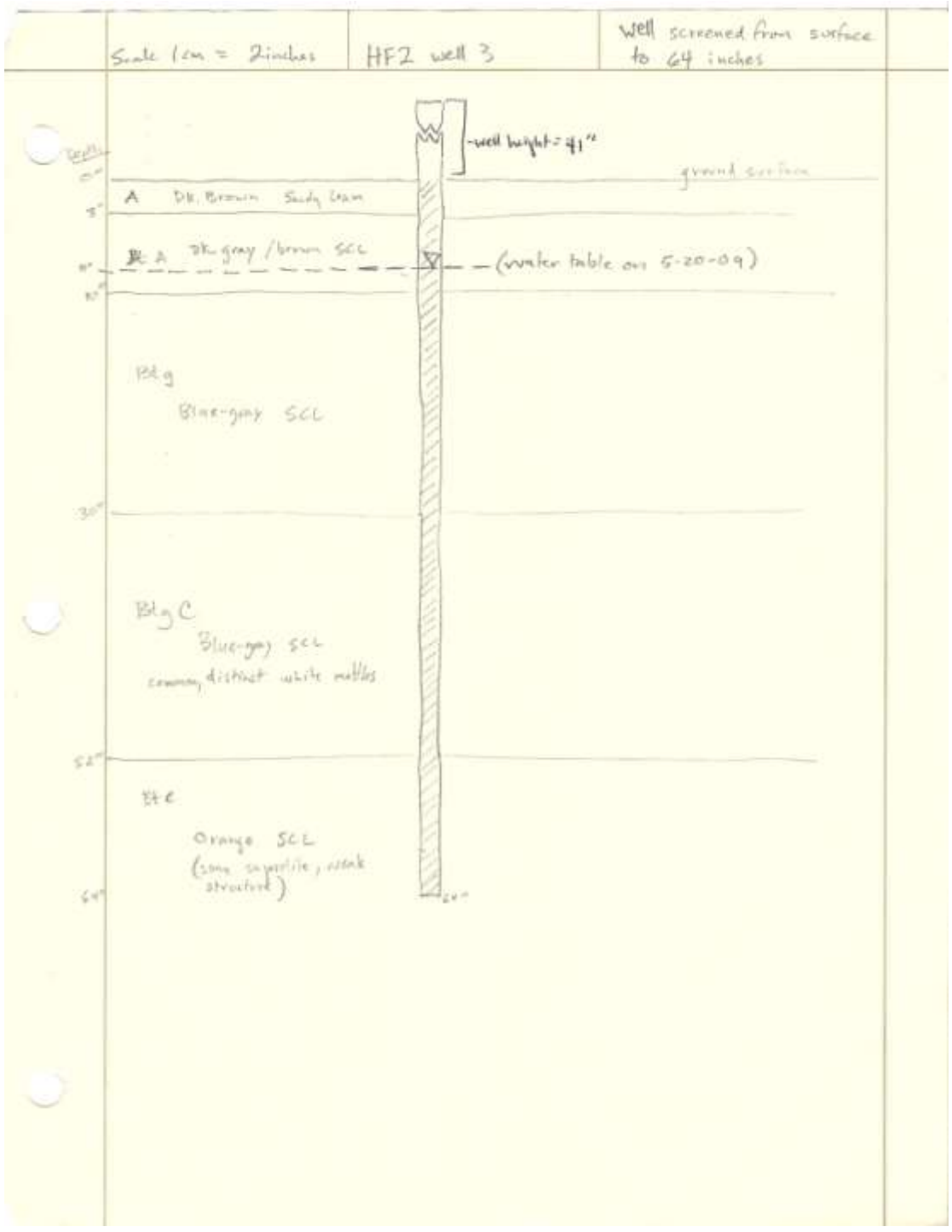
Vegetative Cover Forest

Described by C.D.

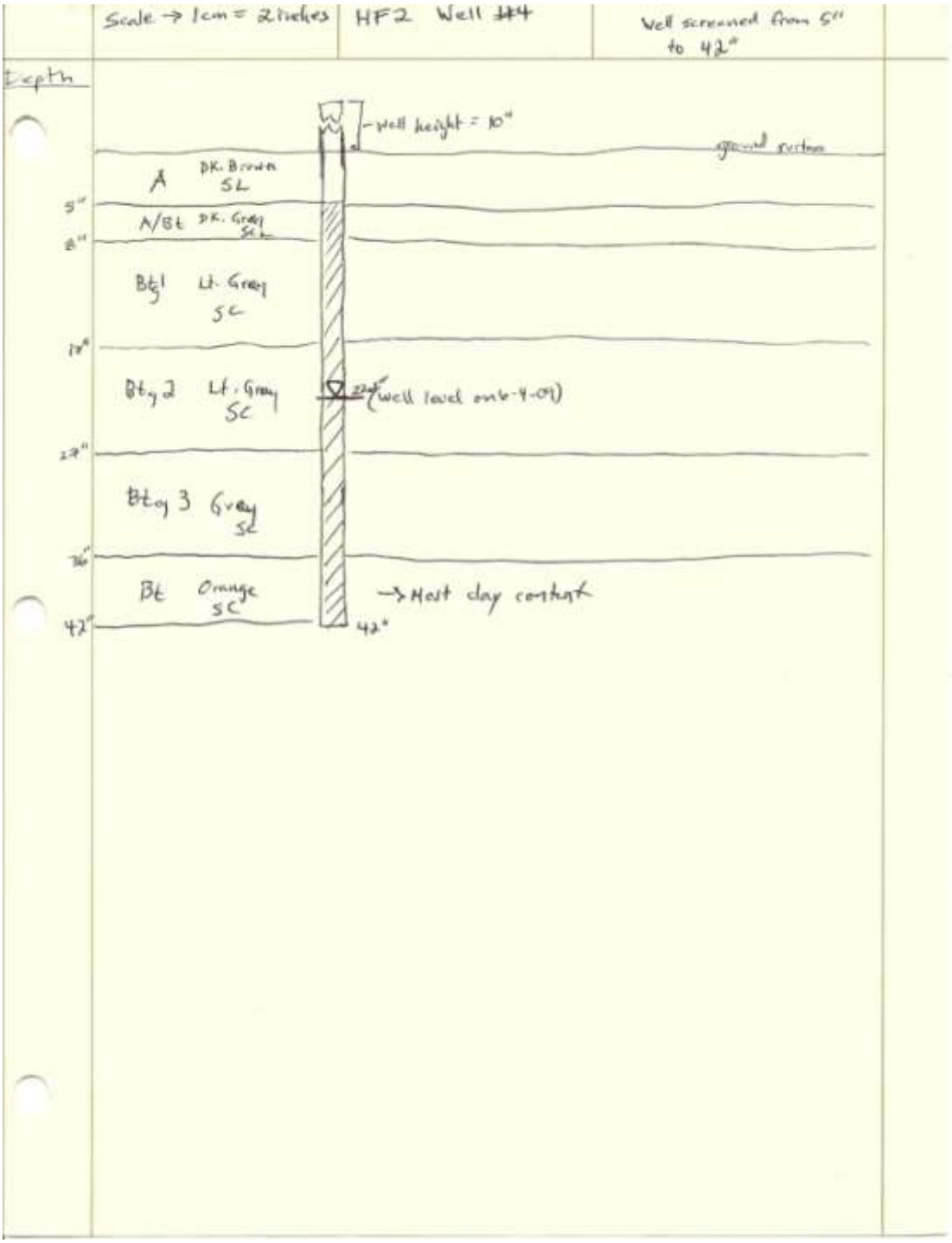
Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure Grade	Structure Class	Structure Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-3	Dk Brown	—	Sandy Loam			Granular	—	—	clear	
AB	3-10	dark gray (a bit brown)		SCL	weak		SB	slightly sticky, sp		grad.	saturated (mud pie)
Btg	10-30	Blue-gray		SCL	weak	med	SB	ss, sp		gradual	saturated (mud pie)
BtgC	30-52	Blue-gray	reddish mottles common	SCL	med.	med.	SB	ss, sp		clear/grad.	saturated
BC	52-64	ORANGE	—	SCL	weak	med	SB	ss, sp			some saprolite

Took photos

HF Riparian Well 3 Site Soils and Well



HF Riparian Well 4 Site Soils and Well

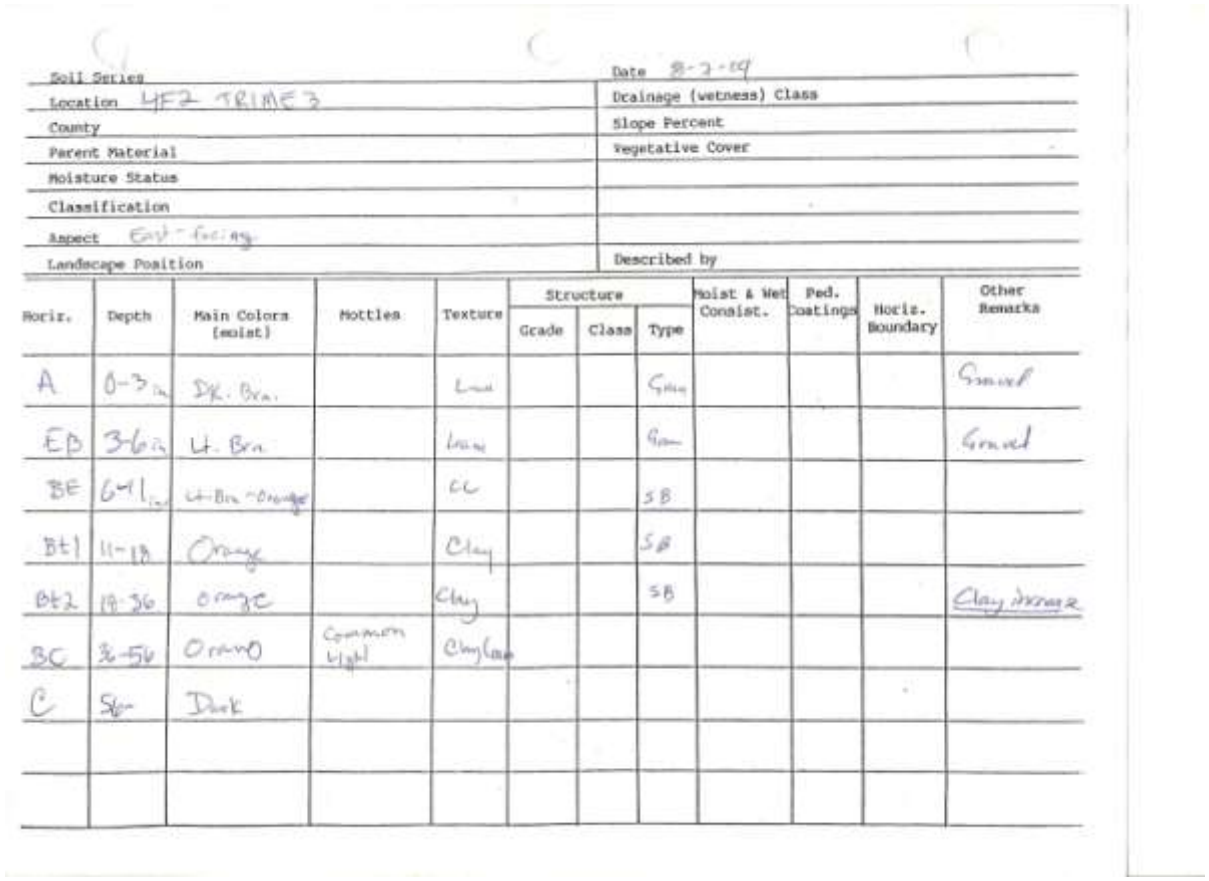


HF TRIME (Hillslope Synoptic Site) 2 Soils

Soil Series	Date 7 Aug 09
Location HF2 TRIME2	Drainage (wetness) Class
County	Slope Percent
Parent Material	Vegetative Cover
Moisture Status	
Classification	
Aspect	
Landscape Position Upland mid → transect 1	Described by

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
A	0-3	DK Brown	—	OL	Mod	Fine	Gran				Gravel
E	3-12	Lt Brown	—	OL							Gravel
B	12-24										

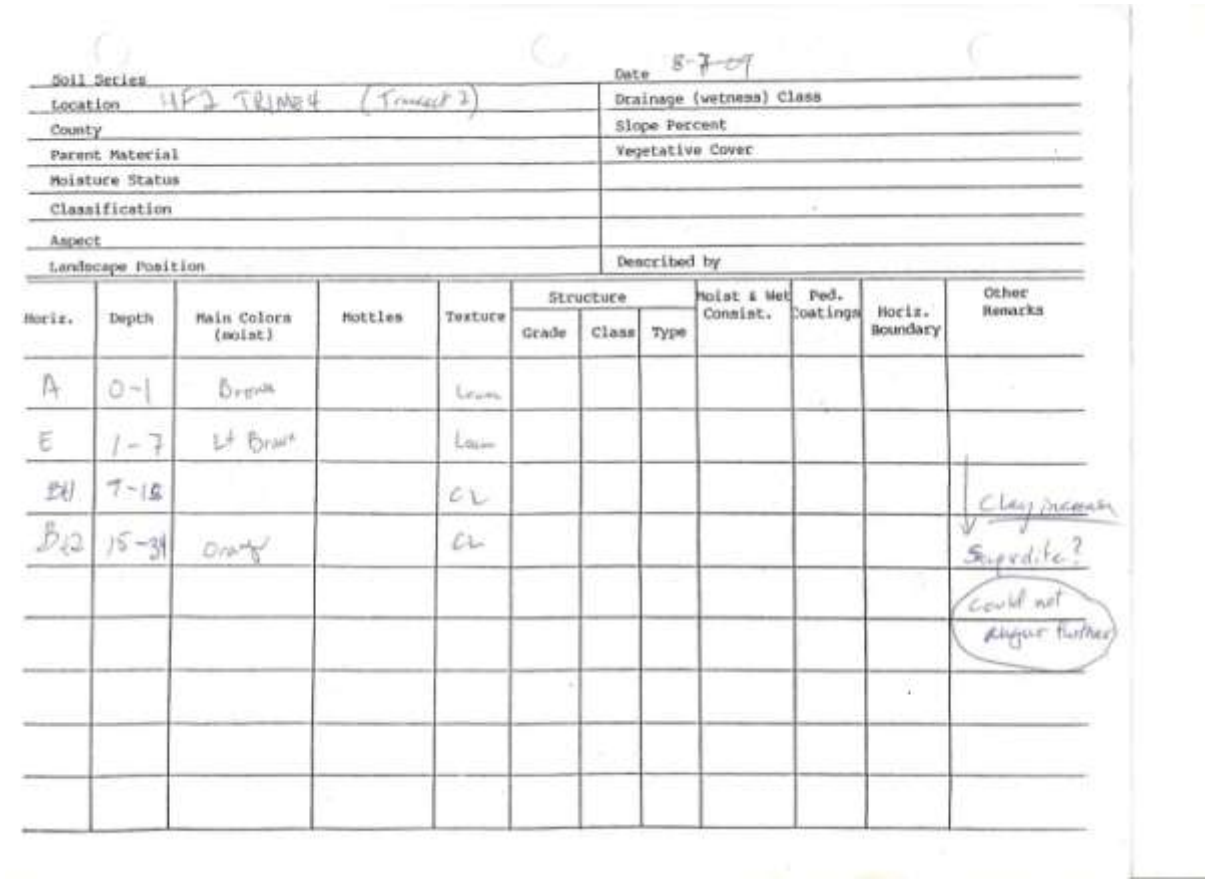
HF TRIME (Hillslope ABANDONED Synoptic Site) 3 Soils



Soil Series												
Location HF2 TRIME 3												
County												
Parent Material												
Moisture Status												
Classification												
Aspect East - facing												
Landscape Position												

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
A	0-3 in	Dk. Bra.		Loam			Gran				Gravel
EB	3-6 in	Lt. Bra.		loam			Gran				Gravel
BE	6-11 in	Lt Bra - Orange		cc			SB				
Bt1	11-18	Orange		Clay			SB				
Bt2	18-36	orange		Clay			SB				Clay increase
BC	36-56	Orang	Common Light	Clay Loam							
C	56+	Dark									

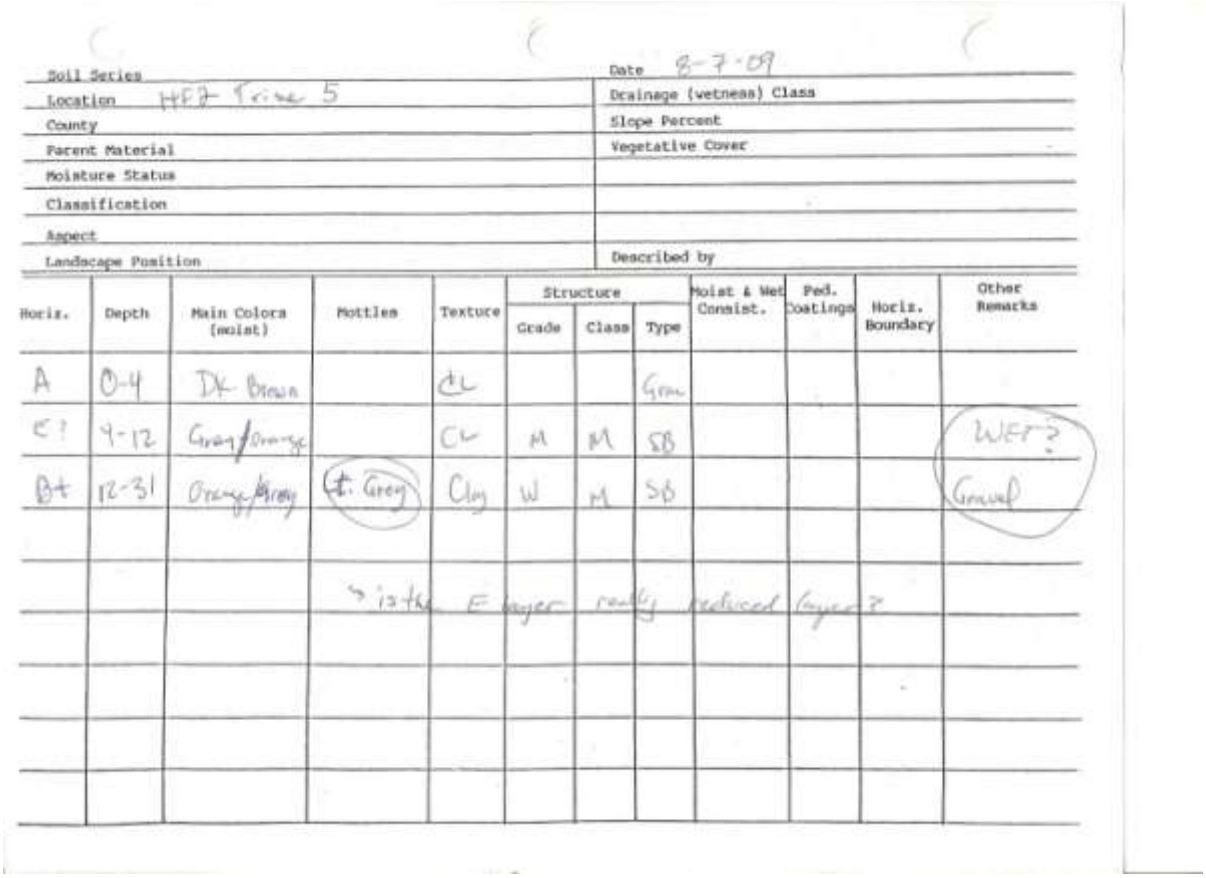
HF TRIME (Hillslope Synoptic Site) 4 Soils



Soil Series		Date 8-7-09
Location HF2 TRIME4 (Transect 2)		Drainage (wetness) Class
County		Slope Percent
Parent Material		Vegetative Cover
Moisture Status		
Classification		
Aspect		
Landscape Position		Described by

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
A	0-1	Brown		Loam							
E	1-7	Lt Brown		Loam							
B1	7-15			CL							Clay increase
B2	15-31	Orange		CL							Saprolite?
											could not dig/go further

HF TRIME (Riparian Synoptic Site) 5 Soils

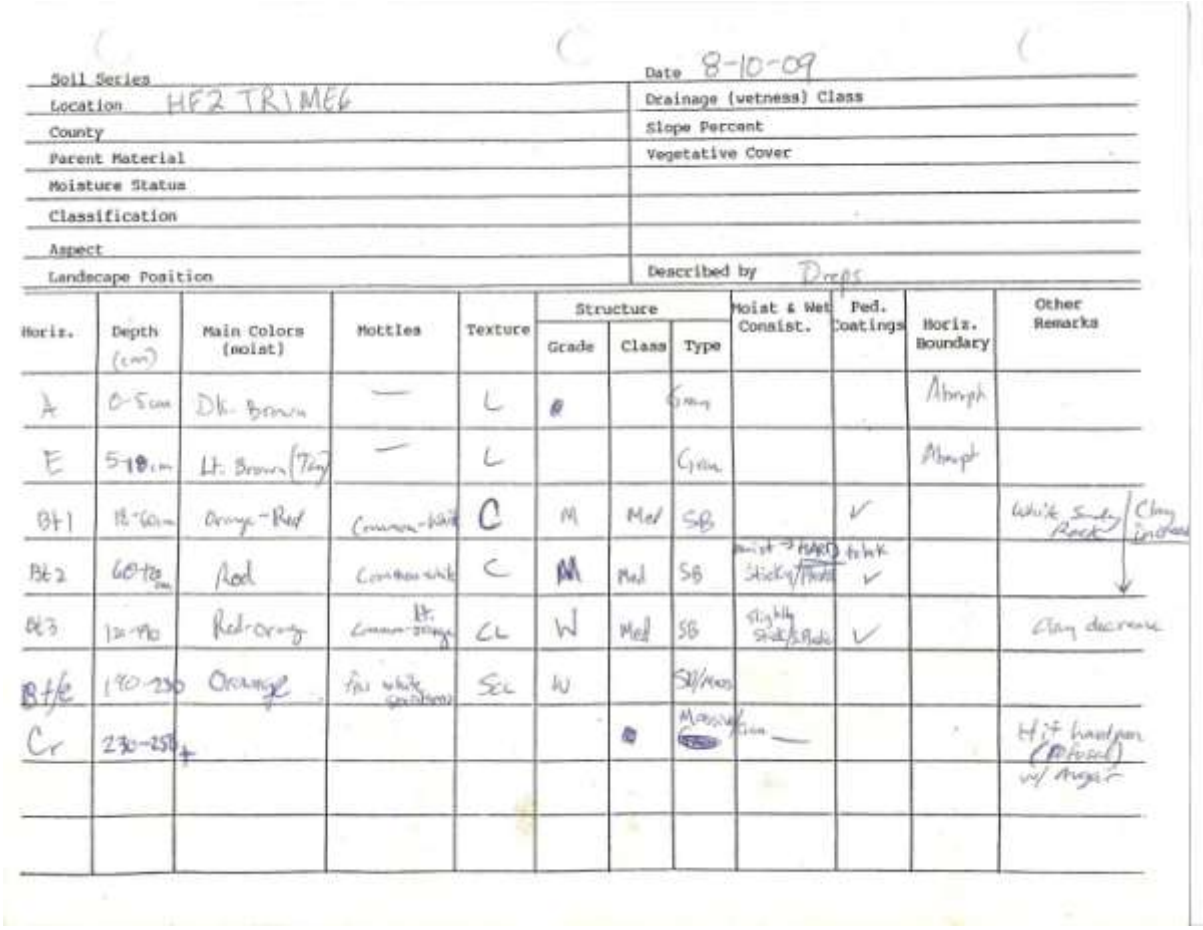


Soil Series
Location HF TRime 5
County
Parent Material
Moisture Status
Classification
Aspect
Landscape Position

Date 8-7-09
Drainage (wetness) Class
Slope Percent
Vegetative Cover
Described by

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure: Grade	Structure: Class	Structure: Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-4	Dk Brown		CL			Gran				
E?	4-12	Gray/Orange		CL	M	M	SB				WET?
Bt	12-31	Orange/Gray	Lt. Grey	Clay	W	M	SB				Gravel
			3 in th	E layer	really	reduced	layer?				

HF TRIME (Upland Synoptic Site) 6 Soils



Soil Series
Location HF2 TRIME6
County
Parent Material
Moisture Status
Classification
Aspect
Landscape Position

Date 8-10-09
Drainage (wetness) Class
Slope Percent
Vegetative Cover
Described by Deeps

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure: Grade	Structure: Class	Structure: Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-5cm	Dk. Brown	—	L	0		Gran			Abrupt	
E	5-18cm	Lt. Brown (Tan)	—	L			Gran			Abrupt	
Bt1	18-60cm	Orange-Red	Common-Many	C	M	Med	SB		✓		White Sandy Rock / Clay increase
Bt2	60-120cm	Red	Common-Many	C	M	Med	SB	moist → HARD to wet Sticky/Plastic	✓		
Bt3	120-190	Red-orange	Lt. Common-Many	CL	W	Med	SB	Slightly Sticky/Plastic	✓		Clay decrease
Bt/E	190-230	Orange	Few white sandstone	SCL	W		SB/Mass				
Cr	230-250+					0	Massive	—			Hit hardpan (Bedrock) w/ Auger

Umstead Farms Catchment

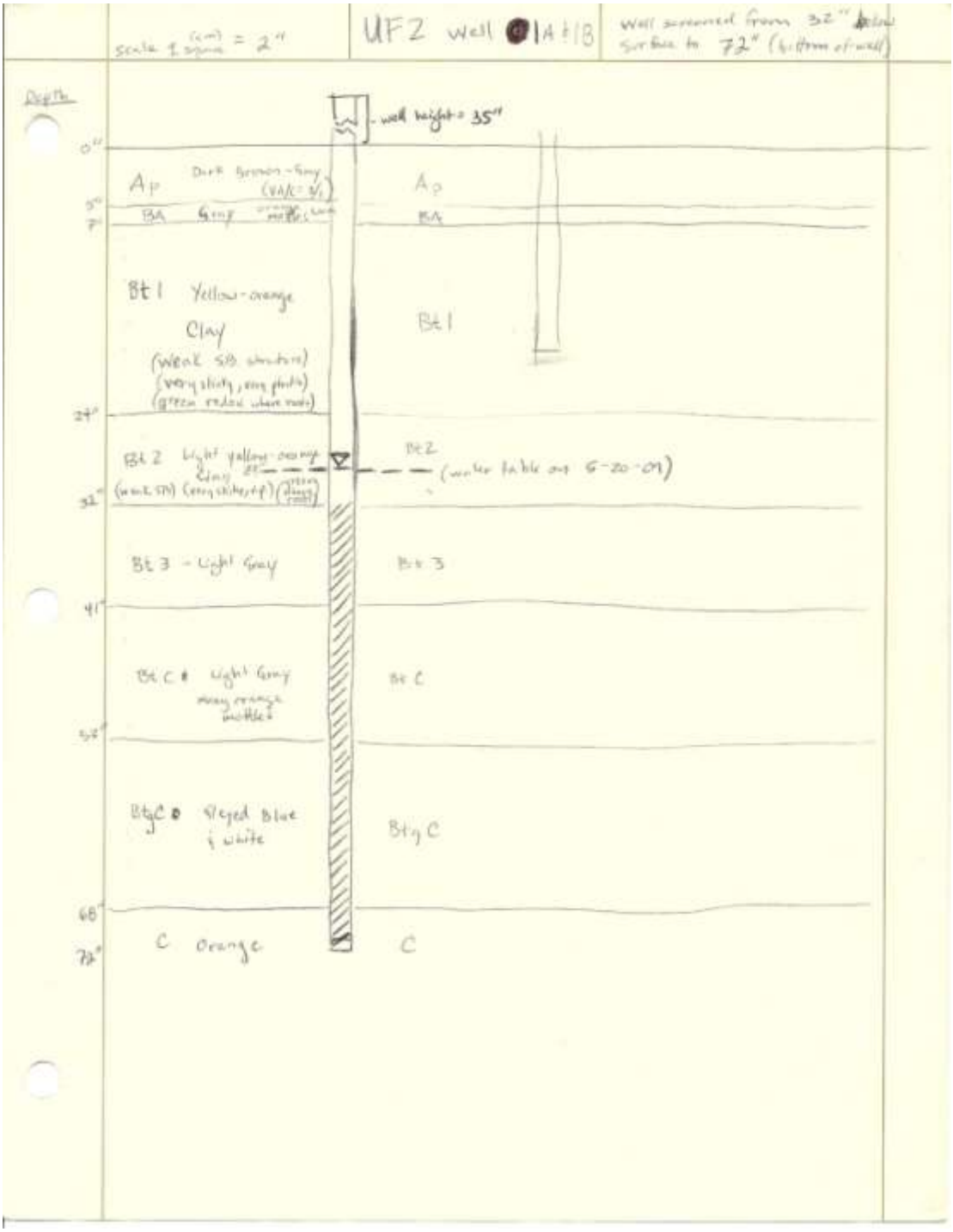
UF Riparian Well 1b Soils

Soil Series	Date 5-8-09
Location UF 2 - Soil Sample #1	Drainage (wetness) Class
County	Slope Percent ~ 1-2%
Parent Material Triassic Seds.	Vegetative Cover Forested
Moisture Status	
Classification Alfisol?	
Aspect	
Landscape Position ~50 ft. from stream bank - near slope bottom	Described by Chris Treps

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure Grade	Structure Class	Structure Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
Ap	0-5"	3/1	—	Silt Loam	weak	Med.	[illegible]	—	-	Abrupt	
[illegible]	5-7"	5/1	Common distinct orange	Loam							
Bt 1	7-24"	Yellow orange	some depletions in root channels	Clay	weak	med.	S.B.	Firm very sticky, very plastic	Yes common	diffuse	gray reduced where roots appear
Bt 2	24-32"	Light yellow orange	—	Clay	weak	med	S.B	firm V.S., V.P	Yes		Green redox small specs in matrix
Bt3	32-41	Light gray			Mod		SB				(*) Hit Rock - could not continue →
BtC	41-53	Light gray	[illegible]		Weak		SB				diabase? → Nearby diabase sill appears
BC	53-68	orange	Mixed Blue/ white		Weak		Massive				in stream channel
C	68-71	Blue	[illegible]		—		Massive				→ Some sand (saprolite?) in Bt2

(*) Photos (4) taken of soil profile sample

UF Well 1a and 1b Site Soils and Wells



UF Well 2 Site Soils

Soil Series

Location UF2 well 2

County

Parent Material Triassic

Moisture Status

Classification

Aspect

Landscape Position Floodplain

Date 5-20-09

Drainage (wetness) Class

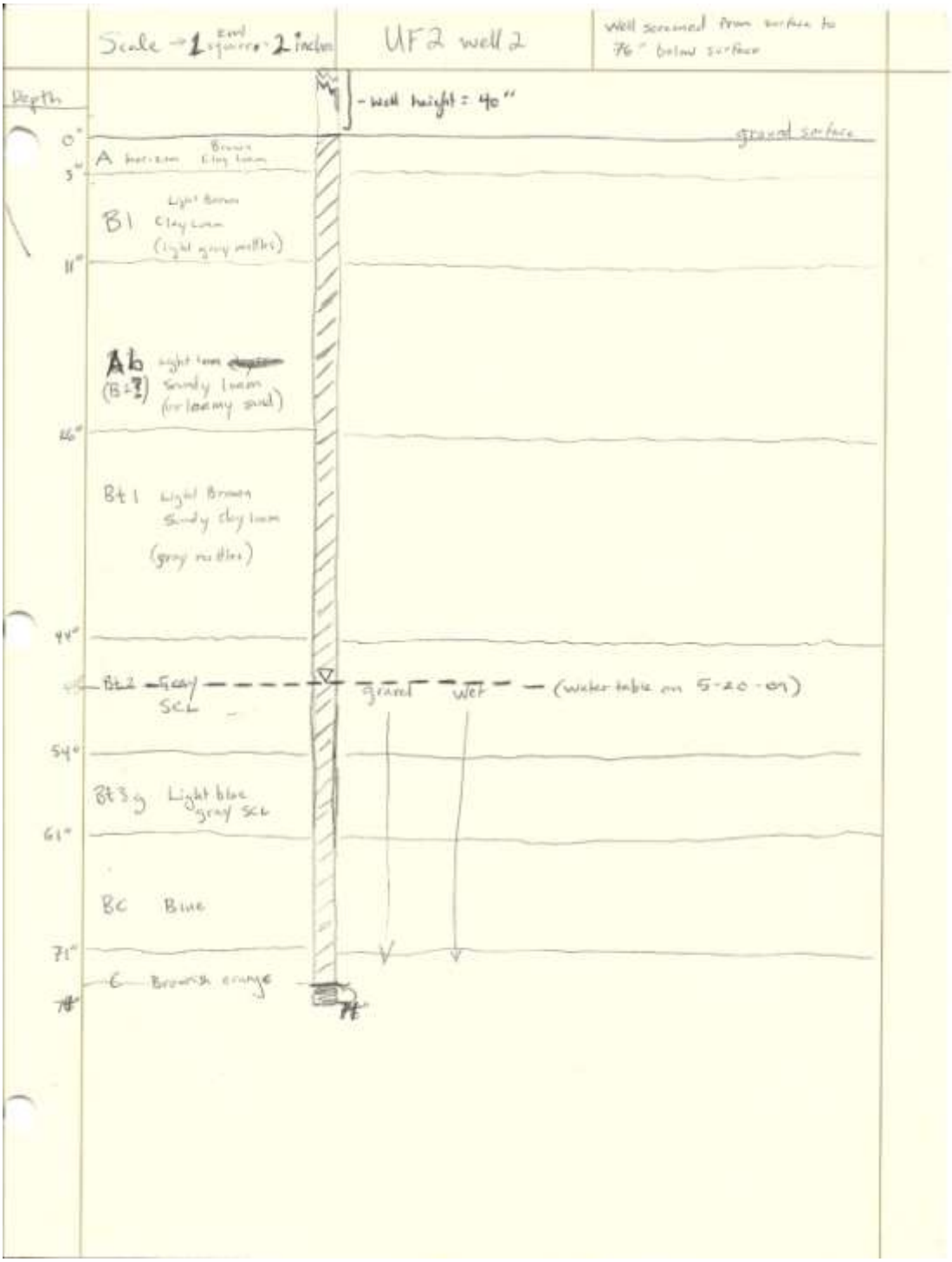
Slope Percent 0-1%

Vegetative Cover

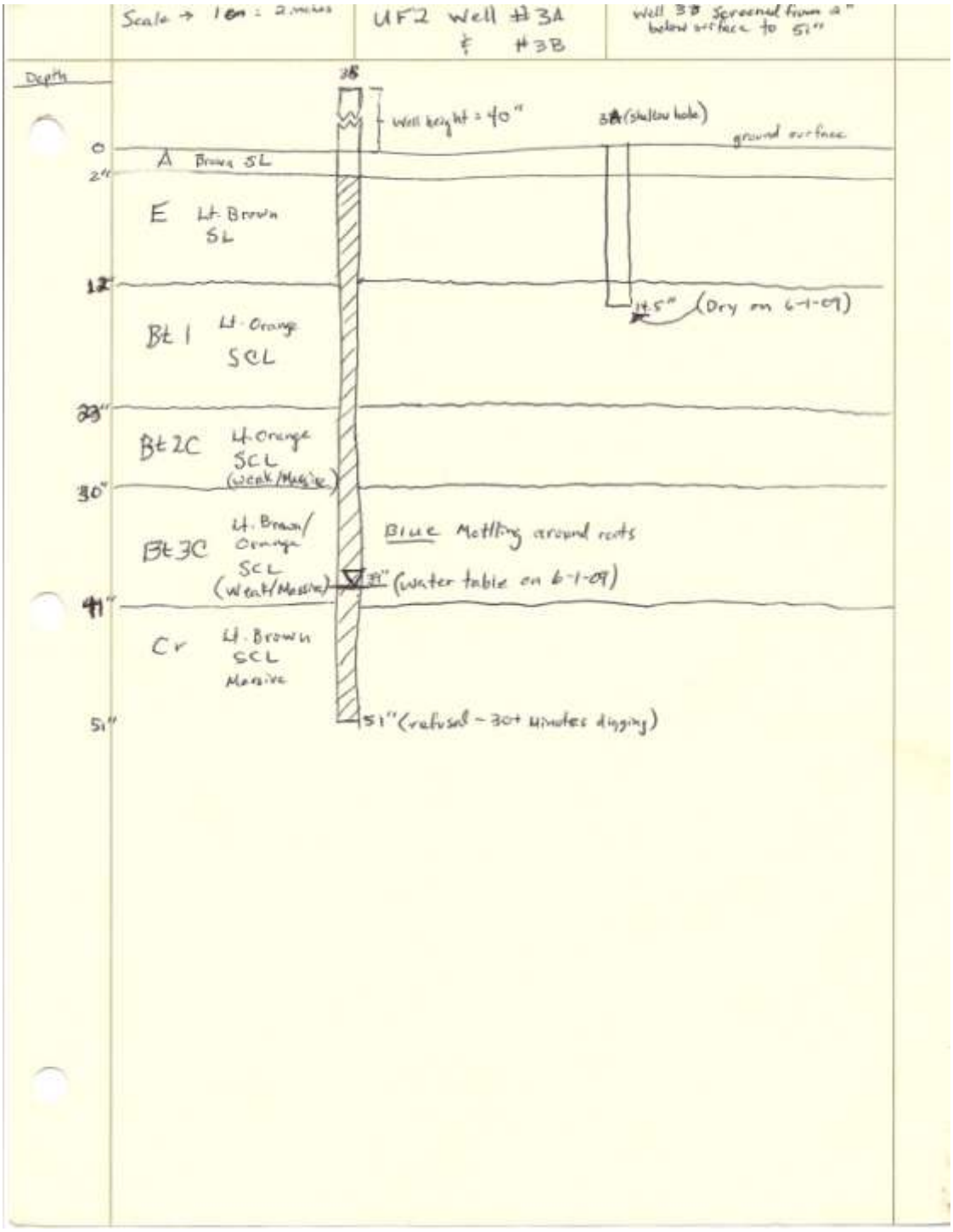
Described by

Horiz.	Depth	Main Colors (moist)	Mottles	Texture	Structure Grade	Structure Class	Structure Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-3"	Brown		Clay loam	Mod	Fine	S.B.				
B1	3-11"	[illegible] (tan) light brown	Light Gray	CL	Mod	Med.	S.B.				
B2	11-26	light tan	—	Sandy (clay) Loam			Gran.				
Bt1	26-44	Light Brown	Gray	SCL	M	M	S.B				
Bt2	44-54	Gray		SCL	M	M	SB.			Gravel Wet	
Bt3g	54-61	Light Blue-Gray		[illegible] SC,	W	M	SB			↓	Blue just like at other UF sites at depth.
BC	61-71	Blue					SB			↓	
C	71-76	Brownish Orange					SB/Massive				Compact Gravel

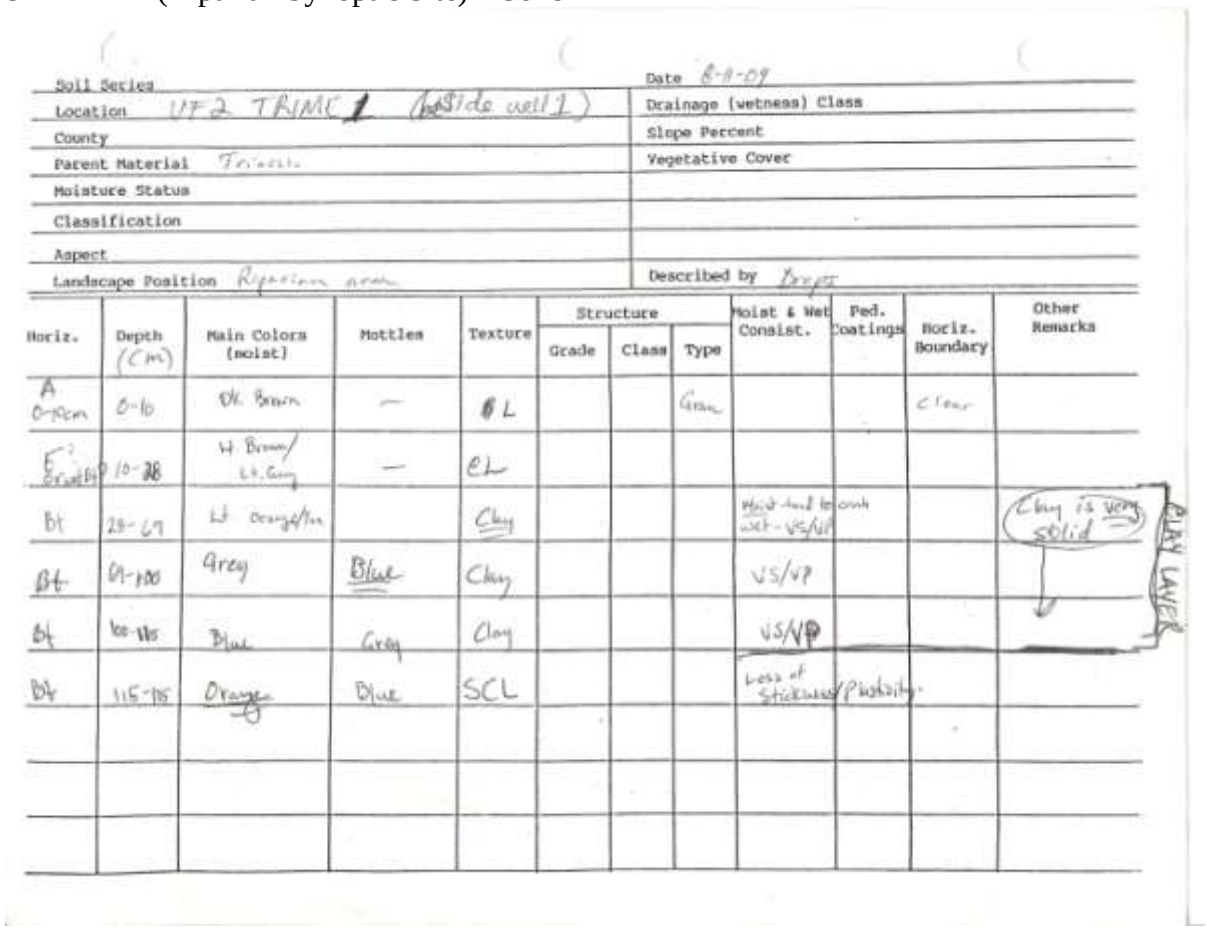
UF Well 2 Site Soils and Well



UF Well 3a and 3b Site Soils and Wells


Scale → 1cm : 2 inches
UF2 Well #3A & #3B
Well 3B Screened from 2" below surface to 51"
Depth
3B
Well height = 40"
3A (shallow hole)
ground surface
0
A Brown SL
2"
E Lt. Brown SL
12"
14.5" (Dry on 6-1-09)
Bt1 Lt. Orange SCL
29"
Bt2C Lt. Orange SCL (weak/Massive)
30"
Bt3C Lt. Brown/Orange SCL (Weak/Massive)
Blue Mottling around roots
39" (water table on 6-1-09)
41"
Cr Lt. Brown SCL Massive
51" (refusal - 30+ minutes digging)

UF TRIME (Riparian Synoptic Site) 1 Soils

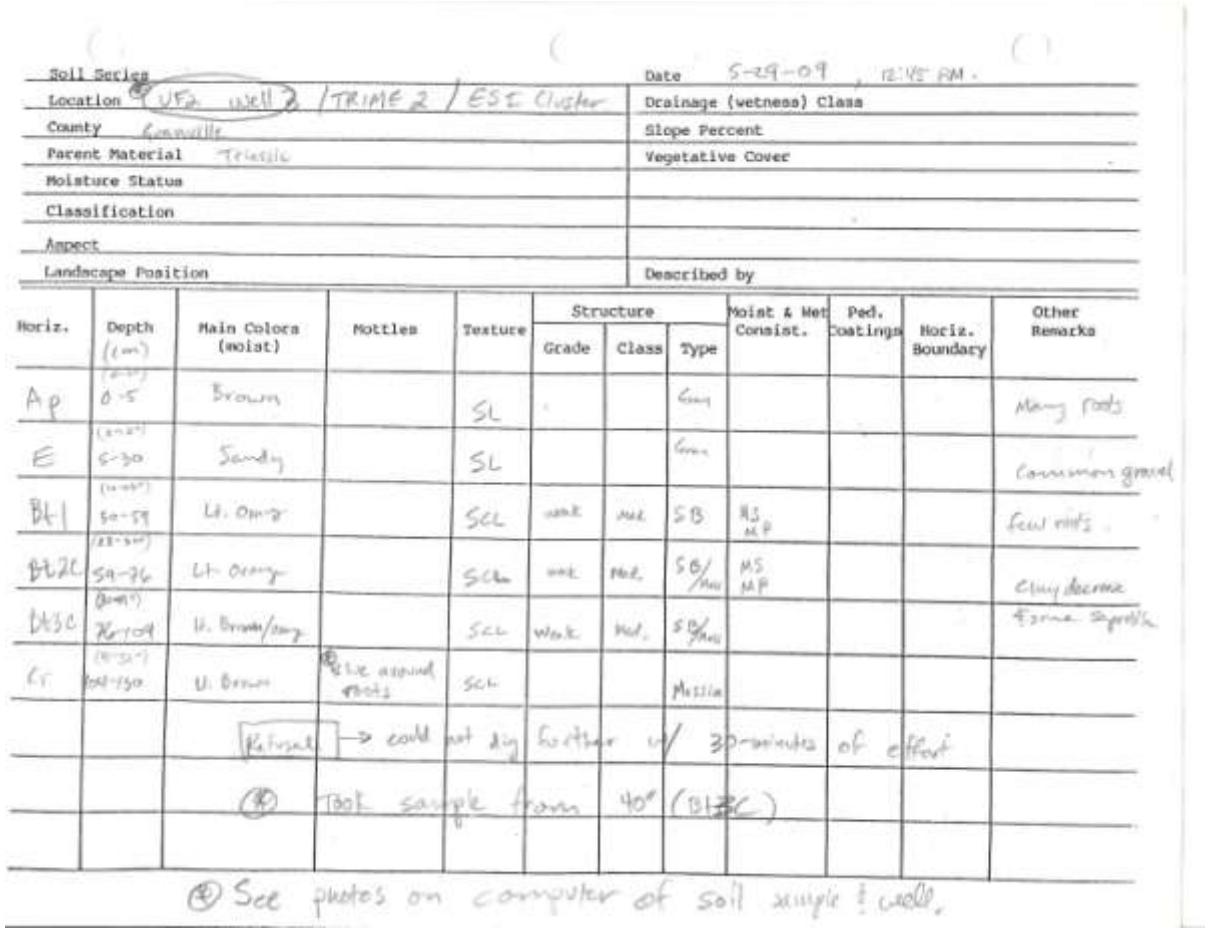


Soil Series
Location UF2 TRIME 1 (inside well 7)
County
Parent Material Terrace
Moisture Status
Classification
Aspect
Landscape Position Riparian area

Date 8-8-09
Drainage (wetness) Class
Slope Percent
Vegetative Cover
Described by Brett

Horiz.	Depth (Cm)	Main Colors (moist)	Mottles	Texture	Structure: Grade	Structure: Class	Structure: Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A 0-5cm	0-10	Dk. Brown	—	SL			Gran			clear	
E? Eroded?	10-28	M Brown/ Lt. Gray	—	eL							
Bt	28-69	Lt Orange/Tan		Clay				Moist hard to crush wet - VS/VP			Clay is very solid — CLAY LAYER
Bt	69-100	Grey	Blue	Clay				VS/VP			
Bt	100-115	Blue	Grey	Clay				VS/VP			
Bt	115-125	Orange	Blue	SCL				Less of stickiness/Plasticity			

UF TRIME (Hillslope Synoptic Site) 2 Site Soils



Soil Series
Location UF well 2 / TRIME 2 / ESE Cluster
County Gainesville
Parent Material Terrestic
Moisture Status
Classification
Aspect
Landscape Position

Date 5-29-09, 12:45 PM.
Drainage (wetness) Class
Slope Percent
Vegetative Cover
Described by

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure: Grade	Structure: Class	Structure: Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
Ap	0-5	Brown		SL			Gran				Many roots
E	5-30	Sandy		SL			Gran				Common gravel
Bt1	30-59	Lt. Orange		SCL	weak	med	SB	MS MP			few roots
Bt2C	59-76	Lt. Orange		SCL	weak	med.	SB/Ang	MS MP			clay decrease
Bt3C	76-109	Lt. Brown/Gray		SCL	Weak	Med.	SB/Ang				Some Spodic
Cr	109-150	Lt. Brown	® Blue around roots	SCL			Massive				
		Refusal	→ could not dig further w/ 30 minutes of effort								
		®	Took sample from 40" (Bt3C)								

® See photos on computer of soil sample & auger.

UF TRIME (Upland Synoptic Site) 3 Soils

Soil Series

Location UF2 TRIME 3 (Edge of field → see field [illegible])

County

Parent Material TRIASSIC BASIN

Moisture Status

Classification

Aspect

Landscape Position Upland → edge of field

Date 8-11-09

Drainage (wetness) Class

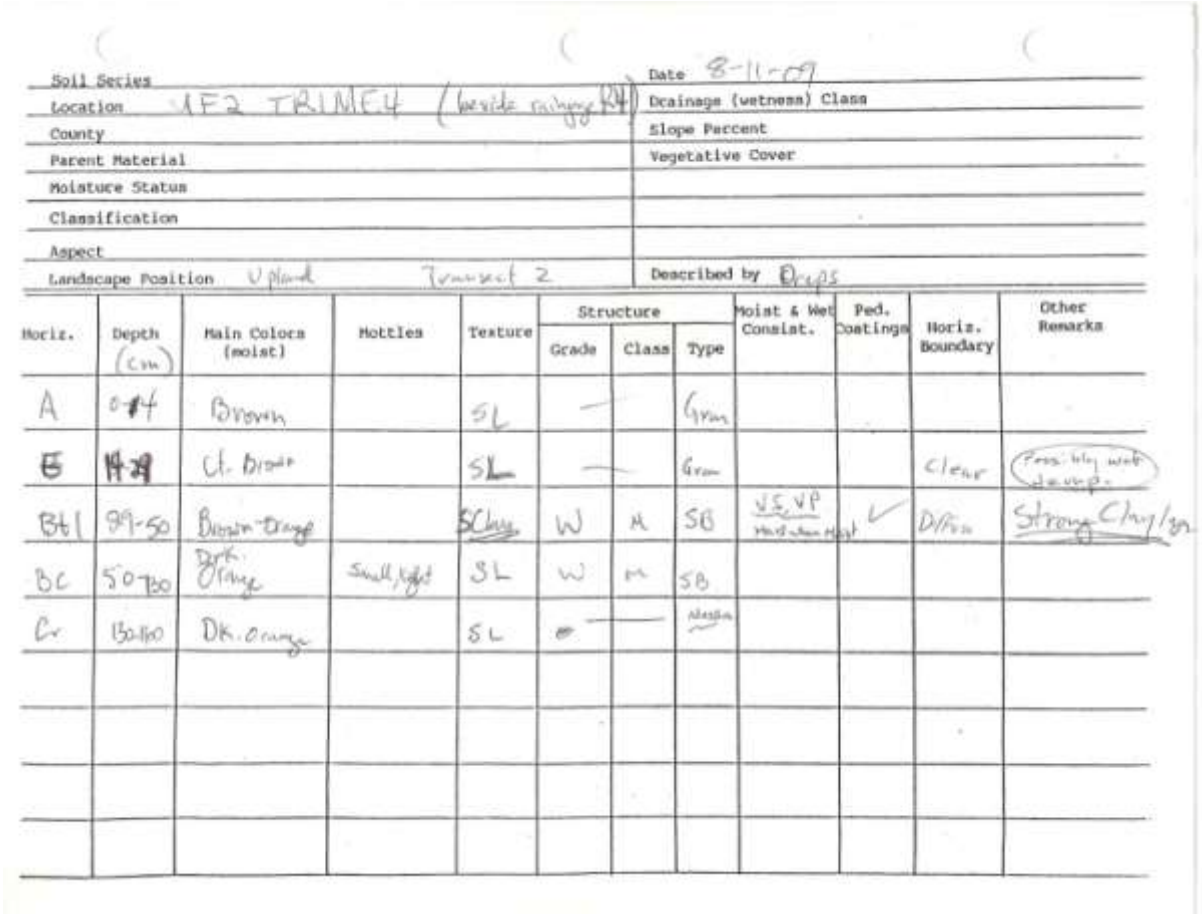
Slope Percent

Vegetative Cover

Described by Drex PS

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
A	0-5cm	Lt. Brown	—	SL	W		Gran				
E?	5-50cm			SL	W		Gran			Clear [illegible]	Gravelly
Bt/C!	50+cm ([illegible])			SCL	W		SB	Moist → hard [illegible]			Clay is very hard in this dry weather — also, mixed w/ rock → [illegible]

UF TRIME (Hillslope Synoptic Site) 4 Soils



Soil Series
Location UF2 TRIME4 (beside ridge RT)
County
Parent Material
Moisture Status
Classification
Aspect
Landscape Position Upland Transect 2

Date 8-11-09
Drainage (wetness) Class
Slope Percent
Vegetative Cover
Described by Briggs

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure: Grade	Structure: Class	Structure: Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-4	Brown		SL	—		Gran				
E	4-29	Lt. Brown		SL	—		Gran			Clear	Possibly worm channels
Bt1	29-50	Brown-Orange		SCl	W	M	SB	VS, VP	✓	Diffuse	Strong Clay/Sa
BC	50-130	Dark Orange	Small, light	SL	W	M	SB				
Cr	130+	DK. Orange		SL	—	—	Massive				

UF TRIME (Hillslope Synoptic Site) 6 Soils

Soil Series

Location UF2 TRIME6 (in "transect 2")

County

Parent Material

Moisture Status

Classification

Aspect

Landscape Position Upland

Date 8-17-09

Drainage (wetness) Class

Slope Percent 3-6

Vegetative Cover Wooded.

Described by Dreps

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure			Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
					Grade	Class	Type				
Ap	0-5	Lt. Brown	—	SL			Gran			Clear	Gravel
E	5-20cm	Lt. Tan (sandy)		SL			Gran			Clear	
Bt1	20-40	Lt Brown/orange		S Clay	Weak	[illegible]	SB	Moist * Very difficult [illegible] Wet →		Clear	strong clay layer (Plow pan?)
B[illegible]1	40-70	Lt. Orange		SCL	Weak	Med.	SB				
B[illegible]	70-110	Lt. Orange		SL			Gran.				
C	110-123	Orange									

UF TRIME (Upland Synoptic Site) 7 Soils

Soil Series

Location UF2 TRIME 7 (Bottle Raingauge RS)

County Granville

Parent Material Triassic basin

Moisture Status Rain ± 1 inch (2.5cm) over last 3 days

Classification

Aspect

Landscape Position Upland- highest location in WS.

Date 8-12-09

Drainage (wetness) Class

Slope Percent

Vegetative Cover

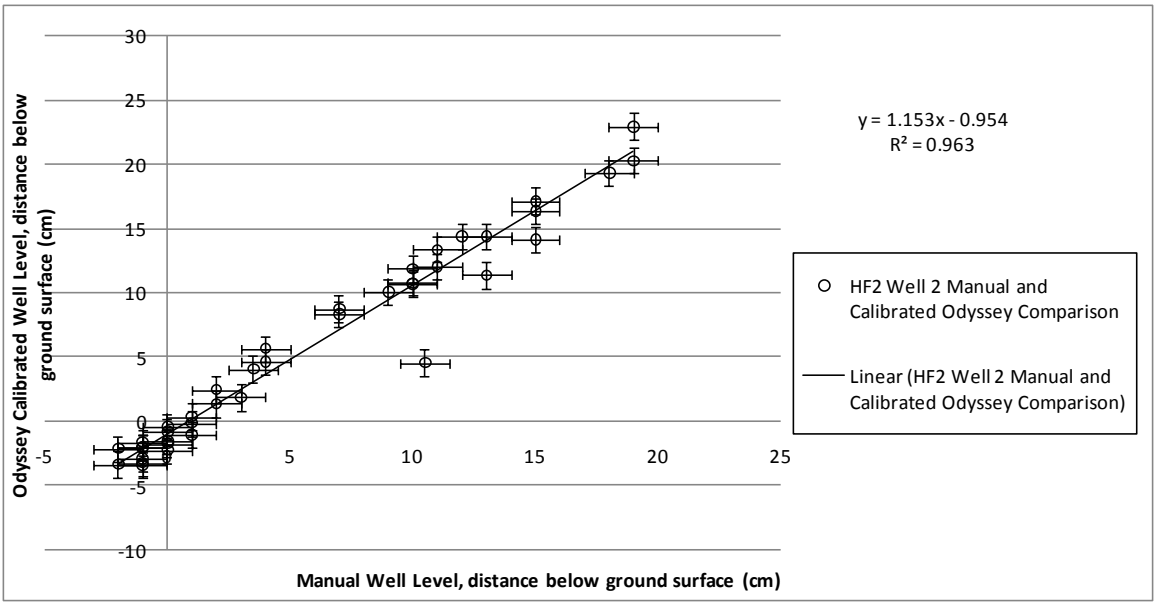
Described by [illegible]

Horiz.	Depth (cm)	Main Colors (moist)	Mottles	Texture	Structure Grade	Structure Class	Structure Type	Moist & Wet Consist.	Ped. Coatings	Horiz. Boundary	Other Remarks
A	0-5 cm	Brown		SL						~~[illegible]~~ Clear	
E	5-33 cm	Tan-Lt. Orange		SL						Clear	
Bt1	33-48	Lt. Orange	Lt. Gray	SCL	M	M	SB			Clear	
Bt2	48-64	Lt. Orange Gray	Lt. Gray/Dk. Orange	SCL	M	M	SB			[illegible]	
Bt2	64-86	Orange	—	C	W	M	SB				
Bt3	86-116	Lt. Gray	Orange	C		M	SB				Wet? (dry now)
BC 1	116-136	Lt. Gray (almost white)	Common Orange	C		Smaller peds	SB				See sample; clay decrease below 116cm
		HIT REFUSAL AT 137cm									

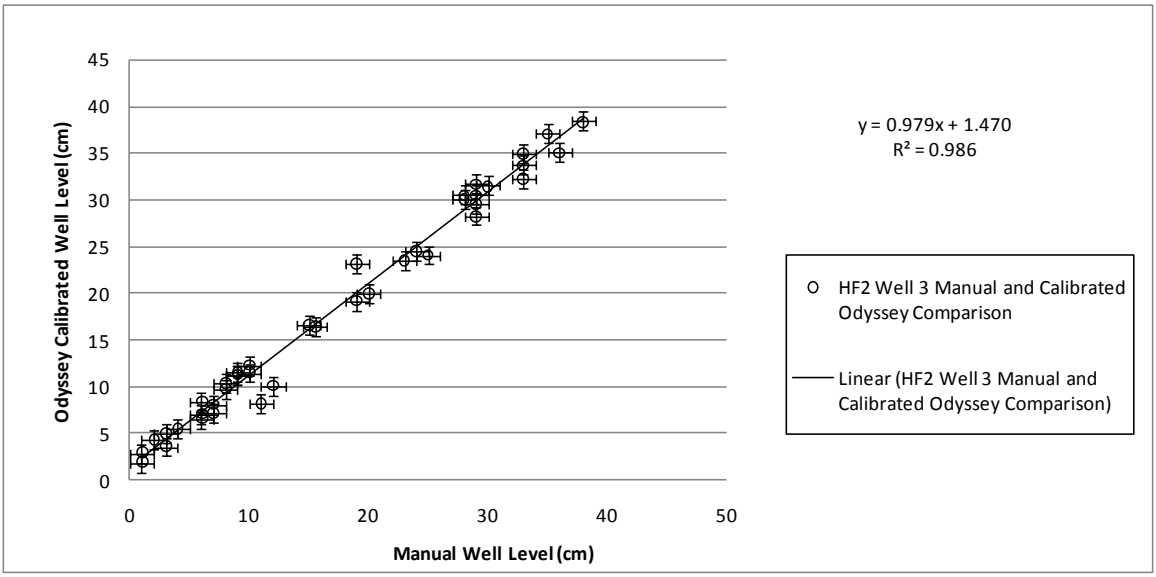
APPENDIX 2

Well Calibration Results (estimated error for each well equals 1 cm)

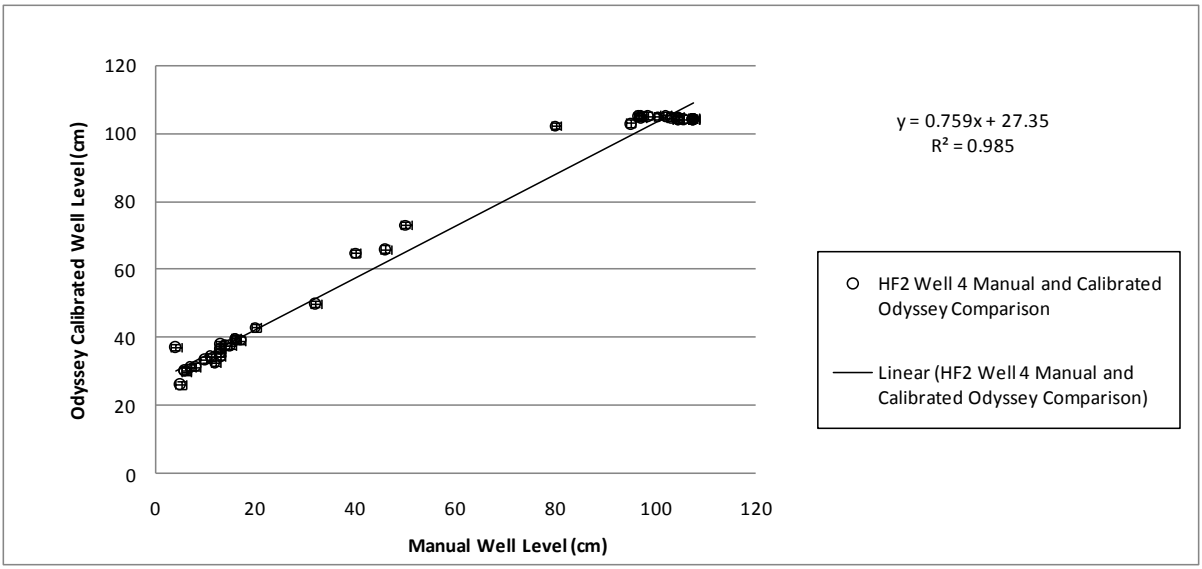
HF Well 2



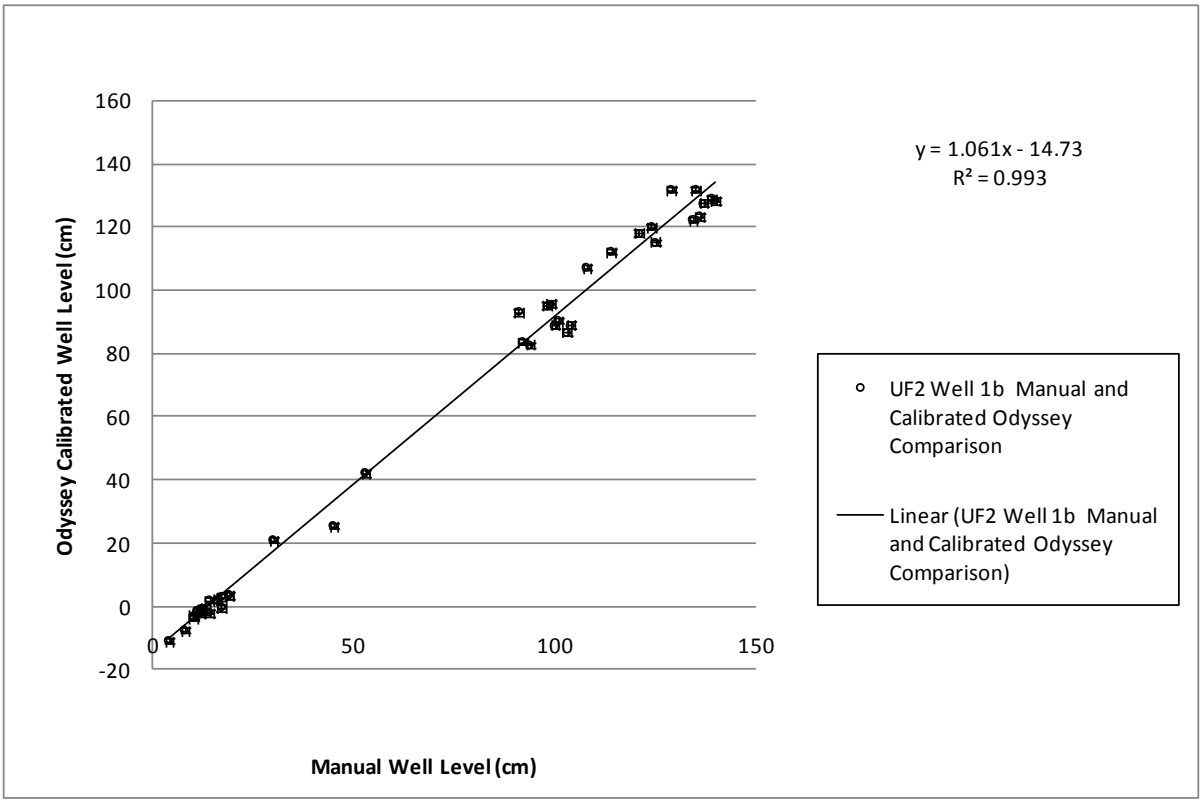
HF Well 3



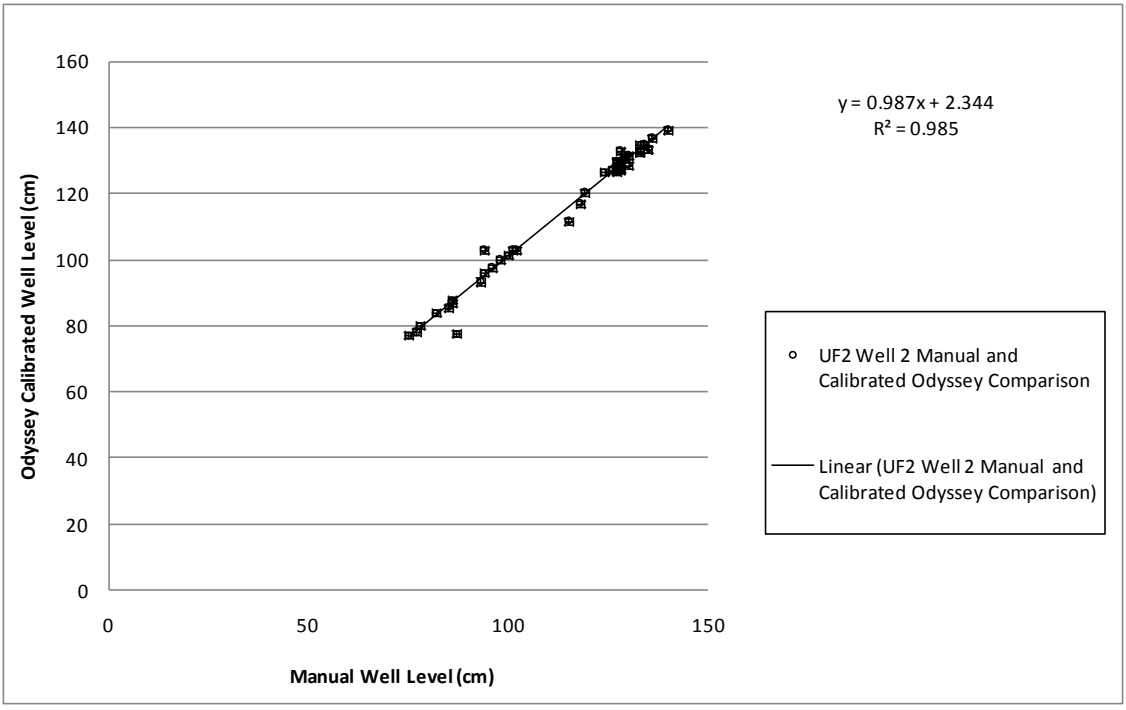
HF Well 4



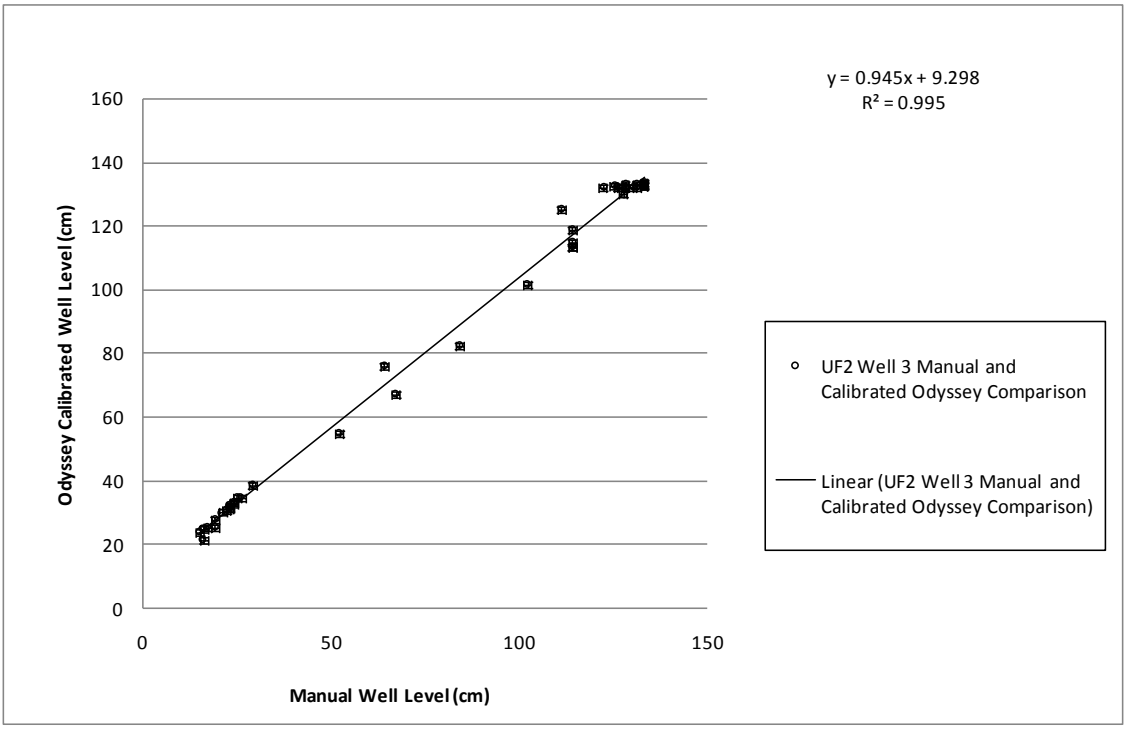
UF Well 1b



UF Well 2

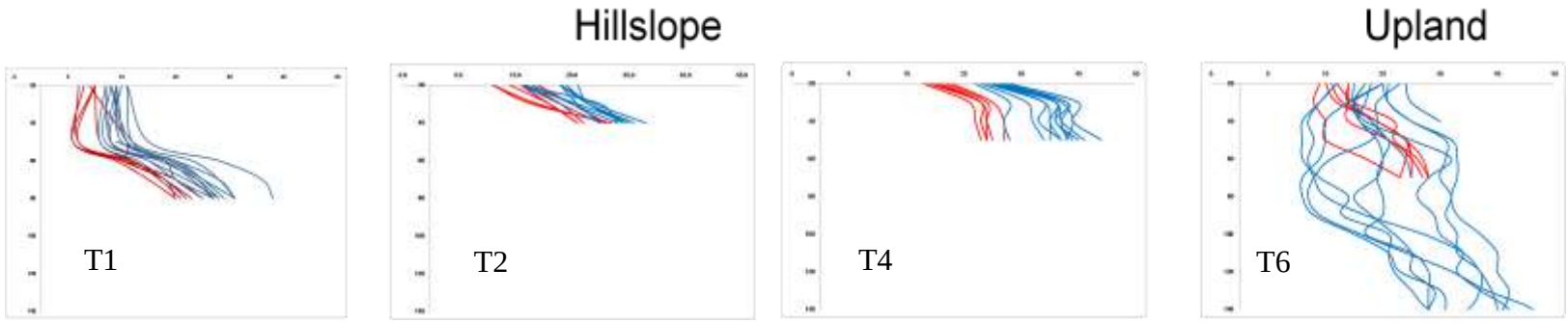

y = 0.987x + 2.344
R² = 0.985
Odyssey Calibrated Well Level (cm)
Manual Well Level (cm)
0
20
40
60
80
100
120
140
160
0
50
100
150
UF2 Well 2 Manual and Calibrated Odyssey Comparison
Linear (UF2 Well 2 Manual and Calibrated Odyssey Comparison)

UF Well 3b


y = 0.945x + 9.298
R² = 0.995
Odyssey Calibrated Well Level (cm)
Manual Well Level (cm)
0
20
40
60
80
100
120
140
160
0
50
100
150
UF2 Well 3 Manual and Calibrated Odyssey Comparison
Linear (UF2 Well 3 Manual and Calibrated Odyssey Comparison)

APPENDIX 3
HF and UF Bi-monthly soil moisture profiles for hillslope and upland sites (ranges are 0-50% VSMC and depths are 0-1.5 m. in HF and 0-1 m. in UF)

HF Catchment



UF Catchment