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WATER BALANCES OF TWO PIEDMONT HEADWATER CATCHMENTS: IMPLICATIONS FOR REGIONAL HYDROLOGIC LANDSCAPE CLASSIFICATION[1]

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ABSTRACT: In the Piedmont of North Carolina, a traditionally water-rich region, reservoirs that serve over 1 million people are under increasing pressure due to naturally occurring droughts and increasing land development. Innovative development approaches aim to maintain hydrologic conditions of the undisturbed landscape, but are based on insufficient target information. This study uses the hydrologic landscape concept to evaluate reference hydrology in small headwater catchments surrounding Falls Lake, a reservoir serving Raleigh and the greater Triangle area. Researchers collected one year of detailed data on water balance components, including precipitation, evapotranspiration, streamflow, and shallow subsurface storage from two headwater catchments representative of two hydrologic landscapes defined by differences in soils and topographic characteristics. The two catchments are similar in size and lie within the same physiographic region, and during the study period they showed similar water balances of 26-30% Q, -4 to 5% ΔS, 59-65% evapotranspiration, and 9-10% G. However, the steeper, more elevated catchment exhibited perennial streamflow and nongrowing season runoff ratios (Q/P) of 33%, whereas the flat, low-lying stream was drier during the growing season and exhibited Q/P ratios of 52% during the nongrowing season. A hydrologic landscape defined by topography and soil characteristics helps characterize local-scale reference hydrology and may contribute to better land management decisions.

(KEY TERMS: surface water hydrology; headwaters; surface water/groundwater interactions; water balance; streamflow generation; stormwater management; runoff.)

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INTRODUCTION

The Piedmont region of the eastern United States (U.S.) is the most densely populated region of the country and includes the major metropolitan areas of Atlanta, Raleigh-Durham, Richmond, Washington D.C., Philadelphia, and New York City. In North Carolina, population is projected to grow by 40% by 2030, and water consumption is projected to increase from 912 to 1,270 Mm^3/yr (NCREDC, 2006). In the Piedmont region of North Carolina, droughts already occur despite an average annual rainfall of over 1,100 mm, and many communities face low reservoir levels and water restrictions each summer. Furthermore, many U.S. Piedmont reservoirs currently fail to meet federal water quality standards.

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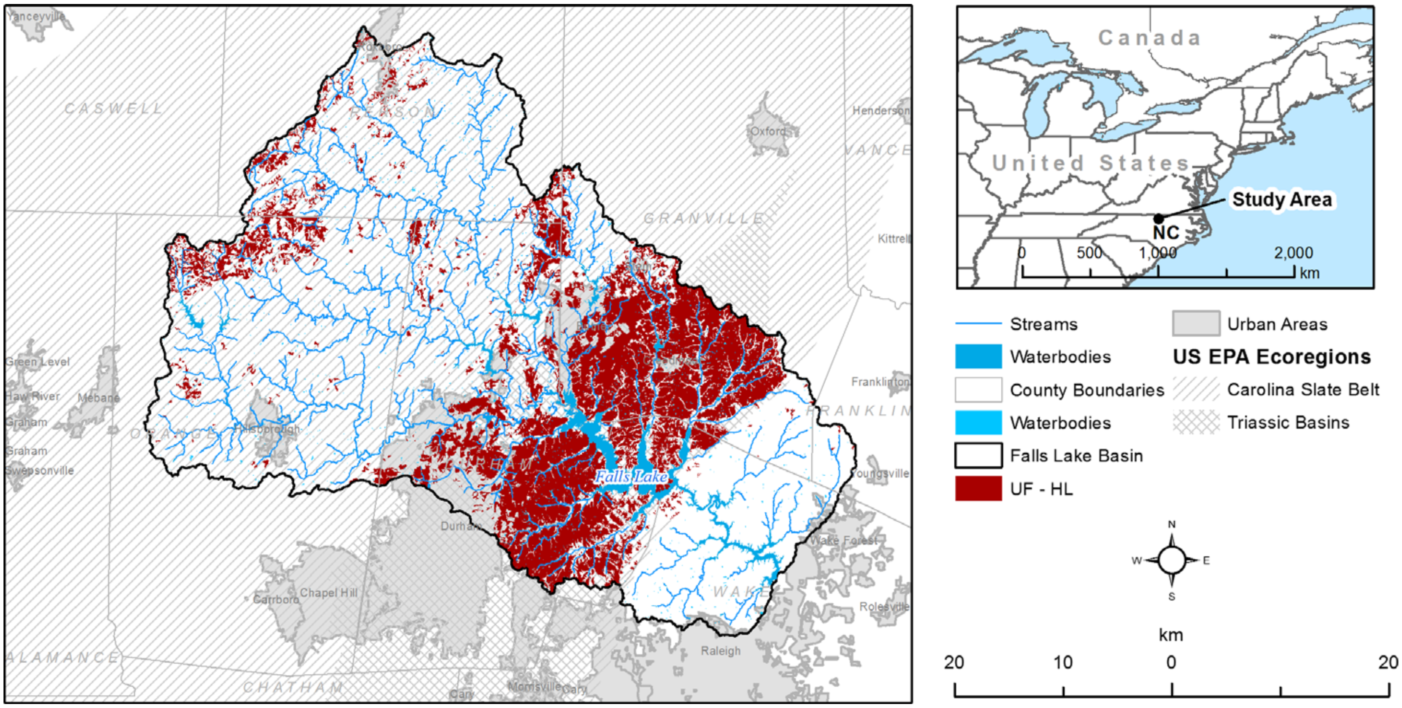

FIGURE 1. Two Hydrologic Landscapes Based on Soil Type and Slope in the Falls Lake Basin, in the Piedmont of North Carolina: Umstead Farms-Type Hydrologic Landscape, or UF-HL Identifies a Hydrologic Landscape Defined by Low-Gradient Soils Forming Seasonal Perched Water Tables above Expansive Clay Layers. Note that these do not correspond completely with USEPA ecoregions.

Innovative stormwater management offers some hope for both the water demand and stream-water quality challenges. Such approaches attempt to maintain or restore "pre-development hydrologic conditions" using engineering and landscaping practices to match a built site's hydrology to its original, pre-built conditions in disturbed areas by mimicking forested hydrologic conditions (USEPA, 2000; Dietz, 2007; Roy *et al.*, 2008; NC DENR, 2009). However, such practices, undertaken at the scale of the developed site, suffer from a dearth of practical information about the pre-built or reference hydrology to guide their implementation at the small watershed scale (Dietz and Clausen, 2005; Roy *et al.*, 2008). Although research shows that land-use changes strongly affect headwater stream hydrology (Burns *et al.*, 2005; Freeman *et al.*, 2007), and headwater streams represent between 53% (Nadeau and Rains, 2007) and 70% (Leopold *et al.*, 1964) of the U.S. river network, there is a lack of understanding of their variable characteristics (Bishop *et al.*, 2008). Recent attempts to study the effects of innovative stormwater management in small, urbanized watersheds (Thurston *et al.*, 2008) have not set watershed-scale targets for key parameters based on reference hydrologic conditions. Bishop *et al.* (2008) used the term "aqua incognita" to describe the lack of understanding of headwater systems.

Classification approaches exist for characterizing hydrologic functions across the landscape, but testing of these approaches against empirical evidence is needed. Winter (2001) defined the hydrologic landscape concept as "a complete hydrologic system consisting of surface runoff, ground-water flow, and interaction with atmospheric water" and envisioned it as a conceptual framework invaluable to design of future process-based studies and their intercomparison. Wolock *et al.* (2004) generated hydrologic landscape regions across the U.S., and Santhi *et al.* (2008) used these to make regional estimations of base flow. However, these large-scale analyses would not be expected to accurately capture important spatial variability of local headwater catchments. For small watershed scales, Buttle (2006) offers a classification approach to compare relative controls exerted on catchment hydrology by topography, typology (controls on lateral flow), and topology (connectedness of the surface drainage network), the three T conceptual framework.

In North Carolina's Piedmont region, application of the hierarchical classification framework of environmental controls (e.g., climate, geology, soil type, depth, topography, and drainage network) described by Devito *et al.* (2005) at the regional scale suggests that focusing on differences in soils and topography may be useful for characterizing important differences in reference hydrology relevant to the management of headwaters. Figure 1 shows low-gradient soils (<10% slopes) reported as forming seasonal perched water tables above expansive clay layers

(USDA, 1971, 1997). This region, trending northeast and in direct connection to the Falls Lake reservoir, illustrates a hypothesized hydrologic landscape that may result in strongly contrasting hydrologic response compared to the surrounding area.

This study uses a water balance approach to compare the catchment-scale daily cumulative, monthly, and seasonal water balances of two Piedmont catchments and presents results in the context of the hydrologic landscape framework. Headwater scale studies in the Piedmont region are lacking, and similarly scaled studies from the adjacent mountains and coastal plains physiographic regions (e.g. Sun *et al.* 2002; Harder *et al.*, 2007) underscore the need for spatially and temporally detailed water balances. Using the water balance, we address the following research questions: (1) does the hydrology of these two reference headwater catchments differ; (2) do differences exist in hydrologic response across various time scales of interest (i.e., seasonal, monthly, daily); and (3) are differences in hydrologic response attributable to difference in soils and topography, as used to define the hypothesized hydrologic landscapes? In other words, is this local-scale classification useful?

STUDY CATCHMENTS

The Hill Forest (HF) and Umstead Farm (UF) study sites, each 29 ha in area, are first-order headwater catchments located within 5 miles of each other in the upper Neuse River Basin and Falls Lake watershed in the Piedmont region of North Carolina (Figure 2). These two catchments are part of a study evaluating the effectiveness of stream management zones in improving water quality in headwater streams (Boggs *et al.*, 2012). Table 1 summarizes key characteristics of the two study catchments. Climate in the region is temperate with hot summers (Peel *et al.*, 2007), with 115-year average temperatures for January and June of 4.3°C and 24.5°C, respectively (NCCO, 2010). Average annual precipitation is 1,130 mm and falls primarily in the form of rain, with occasional winter (December-March) snows.

Three types of landscape-based classification describing these sites already exist (Table 1). Both catchments overlay Carolina Slate Belt geology (McConnell and Glover, 1982; Griffith *et al.*, 2002). However, USDA Forest Service ecological subunits based on geology, topography, soils, and vegetation (Cleland *et al.*, 2007) classify HF as Carolina Slate Belt and UF as Southern Triassic Uplands (e.g. Boggs *et al.*, 2012; see discussion to follow). As noted by Wolock *et al.* (2004), ecological unit definitions are not focused on classification of hydrologic response. The large-scale (200 km^2 watershed) analysis of hydrologic landscape regions of Wolock *et al.* (2004) characterizes the region, in which the HF and UF catchments lie as a combination of HRL 11 (humid plateaus with impermeable soils and bedrock) and HRL 7 (humid plains with permeable soils and impermeable bedrock).

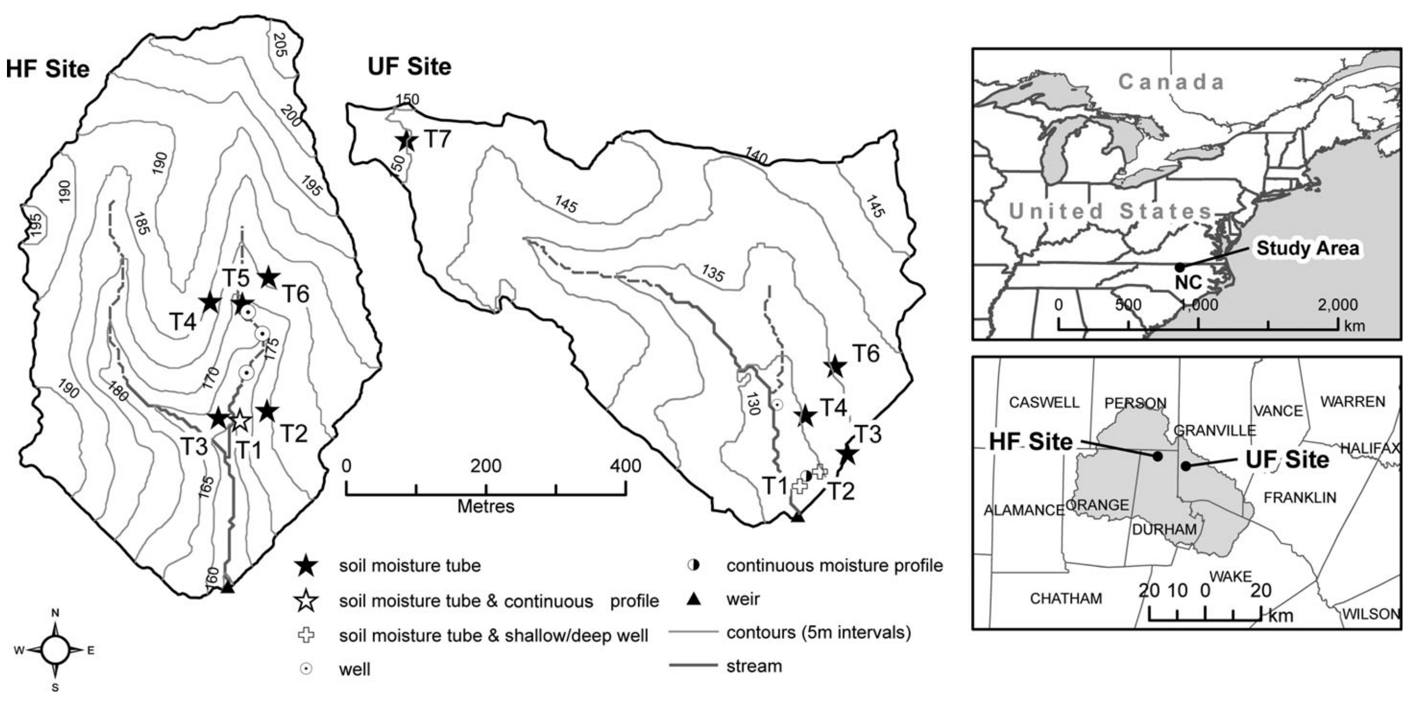

FIGURE 2. Hill Forest (HF) and Umstead Farms (UF) Catchment Locations and Instrumentation.

TABLE 1. Characteristics of Hill Forest (HF) and Umstead Farm (UF) Catchments.

Characteristics	HF	UF
Area (ha)	29	29
USEPA ecoregion[1]	Carolina Slate Belt	Carolina Slate Belt
USDA ecological subunit[2]	Carolina Slate Belt	Southern Triassic Uplands
Hydrologic landscape region[3]	HLR11	HLR7
Land cover (%forest/%Ag)	100/0	92/8
Forest age and type	30-35 years, mixed pine-hardwood	65-70 years, mixed pine-hardwood
Total relief (m)	49	29
Avg slope (%)	13.1	7.6
Drainage density (km/km^2)	3.51	3.89
Expansive clays	No	Yes
Shallow perched water	No	Yes

[1]Griffith *et al.* (2002); McConnell and Glover (1982).
[2]Cleland *et al.* (2007).
[3]Wolock *et al.* (2004).

Land cover for the two catchments is typical of forests in the Piedmont. Tree ages in HF are 30-35 years (Boggs *et al.*, 2010), and the major species are plantation loblolly pine (Hazel *et al.*, 1989), white oak, mockernut hickory, American beech, and sourwood, with Virginia pine and chestnut oak in the upland areas. UF is primarily a mixed forest of loblolly pine, white oak, tulip poplar, and sourwood, with some stands up to 65-70 years old (Boggs *et al.*, 2010). During the period of study, the 8% agricultural area of the UF catchment was fallow, with a mix of grasses.

The combination of soils and topography offers a strong contrast between HF and UF study catchments. The topography of the HF catchment is rolling, with average slopes of 13%, and total relief is 49 m. The Tatum soil series (fine, mixed, semiactive, thermic Typic Hapludults) covers 55% of the catchment, primarily on hillslopes around stream areas. The Tatum E series has 15-25% slopes (USDA, 1971, 2010), and many hillslope locations have slopes greater than 40% and semiactive clays described as having moderate shrink-swell potential. The remaining 45% of the HF catchment is covered by hydrologically similar fine, kaolinitic, thermic Typic Kanhapludults (Appling, Cecil, and Georgeville series) (USDA, 1971) that are deep and have low shrink-swell potentials in the subsurface and depths to bedrock greater than five feet (USDA, 1971). Initial field observations and laboratory analysis suggest that the riparian soils are morphologically distinct from the surrounding Tatum soils, and are likely Entisols with less developed, sandier surface and subsurface horizons.

The UF catchment is flatter, with an average slope of 7% and total catchment relief of 29 m. The Helena soils series (fine, mixed, semiactive, thermic Aquic Hapludult) is dominant (USDA, 1997), covering 55% of the catchment, and almost all near-stream, riparian areas. Helena's mafic parent material and resulting mixed mineralogy are likely products of post-metamorphic diabase dikes of probable Triassic age (McConnell and Glover, 1982) that developed a layer of highly expansive, plastic, and sticky soils that reportedly causes a perched water table during the nongrowing season, November 1-March 15 (USDA, 1997, 2010). Initial soil profiles and textural analysis confirm expansive clay subsoils, and low soil chromas in shallow (A and E) horizons suggest long-term saturation during the growing season, March 15-October 31. No such seasonal perched water tables are reported for any of the HF soils (USDA, 1971, 2010), and soils analyses confirm that HF soils are well drained. In the UF catchment's upland areas, 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).

WATER BALANCE CALCULATION

Comparison of reference hydrology between the HF and UF catchments was based on the water balance equation,

$$P = \mathrm{ET} + \Delta S + Q + G, \tag{1}$$

where P is precipitation, ET is evapotranspiration, ΔS is change in soil water storage, Q is streamflow, and G is net groundwater flux. Daily, monthly, seasonal, and annual water balances were generated from empirical observations for each catchment over the period of August 2009 to July 2010. Field instrumentation measured key hydrologic fluxes and storage at the small catchment scale (Figure 2). Precipitation was recorded in each catchment using a manual rain gage and a Hobo tipping-bucket (Onset Corporation, Bourne, Massachusetts) recording each 0.2 mm of rainfall. Total rainfall from manual and tipping-bucket gages were compared for consistency. Where losses of tipping-bucket data occurred, manual rain gage data were substituted. Snow events (7.5-15 cm) occurred on December 18 and 30, 2009 and January 29, February 12, and March 2, 2010. The

USDA recorded streamflow every 10 min at gaging stations. UF was instrumented with a 2-H flume, a stilling well and pressure transducer; in HF, an existing 90° V-notch weir was used with identical stage recording instrumentation.

One meteorological station (Onset Corporation), located at HF, provided supporting data, including hourly solar radiation, wind speed and direction, air temperature, and relative humidity, for daily and monthly ET estimates. Data needed for calculations of net radiation were unavailable from August 8 to November 12, 2009 and thus were gap filled with radiation from the NC Climate Office North Durham Water Reclamation Facility, approximately 19 km south of the catchments. Existing radiation data from the two weather stations compared favorably, with $R^2 = 0.94$. The daily grass-reference evapotranspiration formula (Allen *et al.*, 1994) adapted from the Penman-Monteith method (Monteith, 1965) provided an estimation of actual daily ET of a hypothetical well-watered grass (ET_O) assuming 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. The result is an estimation of ET for a hypothetical grassed location under local weather conditions, not an estimation of actual water loss for forests. We used a second empirical relationship developed from eddy flux data (Sun *et al.*, 2011) to estimate actual monthly ET for deciduous forests,

$$\begin{aligned}\mathrm{ET} =& 11.94 + 4.76\,\mathrm{LAI} \\ &+ \mathrm{ET_O}(0.032\,\mathrm{LAI} + 0.0026P + 0.15)\end{aligned} \tag{2}$$

where P is monthly precipitation (mm), and LAI is mean monthly leaf area index calculated using 10-day incremental data from U.S. 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). Daily cumulative water balance uses daily values of grass-reference ET_O because actual ET could only be calculated as monthly values (Equation 2). Monthly, seasonal, and annual water balances used actual ET (Equation 2).

Daily changes in shallow (<2 m) subsurface water storage (ΔS) were estimated in each catchment using methodology presented by Spence and Woo (2003) and Guan *et al.* (2010).

$$\begin{aligned}\Delta S = \Delta S_U + \Delta S_S =& \Delta\theta[z_w(t) - z_w(t-1)] \\ &+ S_y[-z_w(t) + z_w(t-1)]\end{aligned} \tag{3}$$

where ΔS_U is change in unsaturated storage and ΔS_S is change in saturated storage, also referred to as net recharge (Healy and Cook, 2002). $\Delta\theta$ is the change in volumetric soil moisture content (VSMC) 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 ground surface at any given point in time, with t and $t-1$ being the present and previous time step, respectively.

Change in catchment-scale shallow saturated water storage (ΔS_S) was calculated using a network of riparian water table wells (1.5-2.5 m in depth) (Figure 2). These riparian wells were equipped with Odyssey capacitance water level loggers housed in 5-cm perforated PVC pipe and collected water table levels at 15-min intervals and were screened to just below ground surface. In UF, two locations within the Helena soils (with known shallow expansive clay [Bt] horizon and seasonal perched water table) were instrumented with two wells each, one screened above and one below the shallow confining clay layer. The deeper wells were equipped with the continuous capacitance loggers, and the shallow wells screened above the clay layer were measured manually three to four times monthly. Data from all capacitance loggers were calibrated three to four times monthly using manual measurements (50 total manual measurements). Linear best fit equations of these calibrations yielded R^2 values ranging from 0.96 to 0.99. A mean daily water table depth (z_w) was calculated for each well to minimize diurnal effects on the water table depth (Coes *et al.*, 2007).

Specific yield, S_y, was estimated as the difference between saturated conditions and field capacity (Fetter, 2001).

$$S_y = \theta_S - \theta_{FC} \tag{4}$$

where θ_S is the saturated VSMC (equivalent to porosity) and θ_{FC} is the VSMC at field capacity, both in cm^3/cm^3. Using soil moisture data collected from continuous time domain transmissivity (TDT) profiles (see discussion below) colocated with wells (T1 in HF and T2 in UF), θ_S was estimated as the maximum soil moisture observed during the period of record and θ_{FC} was estimated during an essentially rain-free period at the end of December 26-January 15 (<8 mm), allowing for soil drainage but with minimum effects from ET during the nongrowing season (Figure 3). A distance-weighted average of daily ΔS_S calculated for each well was used to represent daily catchment ΔS_S.

Daily change in shallow unsaturated-zone storage (ΔS_U) was calculated using two separate methods. The first, referred to as the "1-D" method, calculates change in VSMC ($\Delta\theta$) based on hourly measurements from a single hillslope location in each catchment (Figure 2, locations HF T1 and UF T2) instrumented

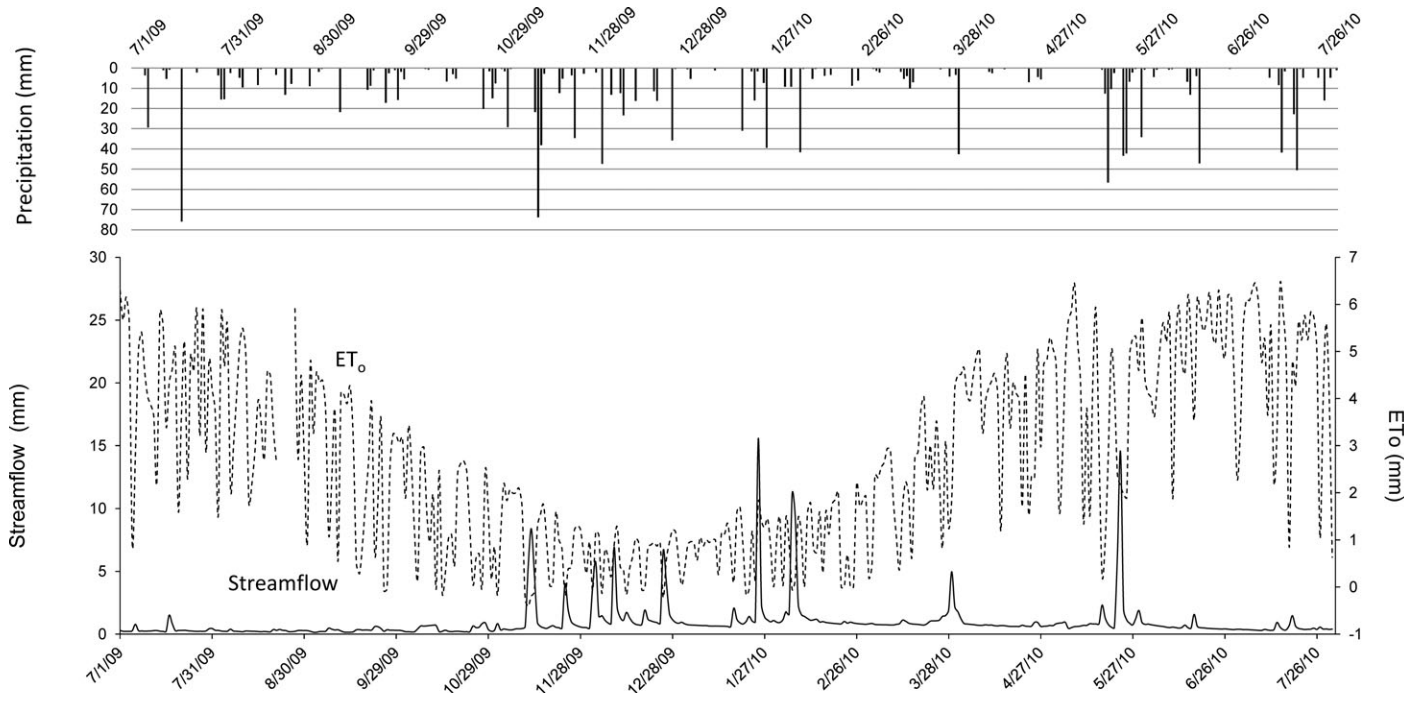

FIGURE 3. Hill Forest Catchment Daily Precipitation, Grass-Reference Evapotranspiration (ET_O), and Streamflow.

with a cluster of four TDT volumetric soil moisture probes in profile (depths of 12.5, 25, 50, and 90 cm) and connected to a data logger (Environmental Systems Incorporated, ESI). A profile average soil moisture was calculated using depth integration similar to Tromp-van Meerveld and McDonnell (2006) and Moroizumi *et al.* (2008) and 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 riparian well colocated with the hillslope location. A daily average ΔS_U was generated for use in Equation (3), and the resulting 1-D ΔS was used in the daily cumulative, monthly, and seasonal water balances.

The second "3-D" method incorporates spatially distributed soil moisture profiles categorized by position (riparian, hillslope, and upland) into a single representative $\Delta\theta$ value for use in monthly and seasonal water balances. Using two transects of 2-inch PVC profile access tubes installed vertically to refusal (0.5-1.5 m), perpendicular to the stream channel and spanning topographic position (upland, hillslope, and riparian) in each catchment (Figure 2), a moisture profile was collected three to four times per month with a portable IMKO TRIME Gro-Point Time Domain Reflectometry (TDR) probe (IMKO, Ettlingen, Germany). The TRIME TDR probe was used to record soil moisture, θ at 0.1-m intervals and a profile average generated using the same approach as for the 1-D method.

Catchment area was categorized into riparian, hillslope, or upland units using factors of slope, soil type and texture, depth to water table, reported existence of perched water table by state soil surveys, and saturated hydraulic conductivity of confining layer (Table 2), a similar approach to that of Peters *et al.* (2003) and England and Holtan (1969). Resulting upland and hillslope units correspond to upland and hillslope soils types on soils maps (USDA, 1971, 1997). The HF riparian unit, too small to be mapped at the soil survey scale (1:20,000), was hand delineated in ArcMAP based on field observations of sandy loam soils in the flat (<12% slope) stream valley bottom. No riparian units were mapped in UF because hillslope soils with Helena-series properties are adjacent to nonflooding, highly incised streambeds throughout most of the catchment. Within each unit, distance-weighted profile average soil moisture (Moroizumi *et al.*, 2008) was calculated using the corresponding access tubes (Table 2). Percent area of hillslope, riparian, and upland units were then used to prorate unsaturated-zone profile average moisture content from the representative distance-weighted average to the catchment scale. As described in Equation (3), unit-representative soil moisture content was then multiplied by depth to get total unsaturated-zone storage. Unsaturated zones of the upland and hillslope units were assumed to extend through the full soil thickness, with unit average thickness estimated from soil surveys and official soil series descriptions (USDA, 1971, 1997, 2010) and soil profiles collected during site installation. The resulting catchment-scale average θ was used to calculate

TABLE 2. Criteria Defining Hill Forest (HF) and Umstead Farms (UF) Upland, Hillslope, and Riparian Units.

	HF Catchment			UF Catchment	
Area Type	Upland	Hillslope	Riparian	Upland	Hillslope
Access tube location	T4, T6	T1, T2	T5	T7, T3	T1, T2, T4, T6
Distance from stream (m)	80, 110	20, 100	20	240, 120	20, 80, 100, 120
Slope (%)[1]	0-16	12-50	0-12	0-12	0-37
Soil type	Cecil, Appling, Georgeville	Tatum	Tatum[2]	Vance	Helena, Tatum
Unsaturated-zone depth (cm)	180[1]	180[1]	30[3]	180[1]	45-90[1]
Depth to expansive Bt (cm)	N/A	N/A	N/A	N/A	45
Presence of perched water	No	No	No	No	Yes
Depth to bedrock (cm)[1]	>197	135	>135	>263	>263

[1]From USDA (2010).
[2]Riparian soils not mapped at a scale of USDA NRCS Soil Survey Maps (1:20,000).
[3]Riparian unsaturated-zone depth calculated as mean water table depth of study period (August 1, 2009-July 31, 2010).

change in storage included in Equation (3). The resulting 3-D ΔS was used in monthly and seasonal water balance calculations.

Any groundwater flux (G) across catchment boundaries are estimated as the residual of input (P), outputs (Q, ET), and changes in shallow storage (ΔS) identified above. As a result, estimates include cumulative error of all individual components. Uncertainty of the groundwater flux was estimated using standard techniques for propagation of uncertainty through calculations (Lesack, 1993; Genereux *et al.*, 2005).

$$W_G = \sqrt{(W_P)^2 + (W_Q)^2 + (W_{\Delta S})^2 + (W_{\mathrm{ET}})^2} \tag{5}$$

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

Based on guidance from Winter (1981), for catchments of areas less than 26 ha (0.26 km^2) uncertainty in annual, seasonal, and monthly precipitation was estimated to be 4%. Uncertainty in annual Q for flumes and weirs with high temporal resolution recording instrumentation is typically ~5% (Winter, 1981; Lesack, 1993; Genereux *et al.*, 2005). Monthly reference Penman-Monteith ET estimates were shown by Allen *et al.* (1989) to have standard errors of 0.36 mm/day with greater daily error estimates, on the order of 0.77 mm/day.

Uncertainty in 1-D and 3-D estimates of catchments-scale change in storage is more difficult to infer. Contributing factors include (1) soil moisture measurements by TDR and TDT probes, (2) water table measurements, (3) assumption of unsaturated-zone thickness, and (4) uncertainty associated with the regionalization of point data to represent catchment-wide changes in storage. Manufacturer information estimates uncertainty of the TDT continuous probes as ~1% (ESI, 2008). A conservative estimate of uncertainty in TRIME TDR profile averages (considering they could not account for daily fluctuations) is to assume uncertainty can be no greater than the daily fluctuations of θ, an uncertainty of ~5%. Uncertainty in absolute water table measurements has been shown to be less than 1%. Although the range in θ across catchments at any point in time 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. 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%. 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 14, 2010 (nongrowing season 2010), and March 15-July 31, 2010 (early growing season 2010) for seasonal intra- and cross-catchment comparisons.

RESULTS

*Precipitation (P), Streamflow (Q), and Evapotranspiration (*ET*)*

The period of study exhibited precipitation and temperatures close to the 115-year climatic norms (NCCO, 2010) (Tables 3 and 4). Annual precipitation was 1,368 ± 55 mm and 1,293 ± 52 mm, for HF and UF, respectively, 12 and 6% above the 111-year Durham County climate norm of 1,219 mm (NCCO, 2010). Monthly rainfalls during this period were typical except during November 2009, when rainfall (>220 mm), was almost twice the monthly average of 114 mm (NCCO, 2010).

TABLE 3. Monthly, Seasonal, and Annual Water Balance for the Hill Forest Catchment in mm and % of Precipitation, 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	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%
Nongrowing 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 (August ’09-July ’10)	1,368 ± 55	354 ± 18	26%	67 ± 16	5%	95 ± 23	7%	812 ± 118	59%	136 ± 132	10%

Note: P, tipping-bucket precipitation; Q, measured streamflow; 1-D ΔS, changes in soil moisture storage measured hourly by single location (ESI) probes; 3-D ΔS, changes in soil moisture storage measured by spatially distributed (TRIME) probes; ET, evapotranspiration estimated using Sun *et al.* (2008); G, groundwater flux across catchment boundary, calculated as residual of measured components (uses 1-D ΔS).

TABLE 4. Monthly, Seasonal, and Annual Water Balance for the Umstead Farms Catchment in mm and % of Precipitation, 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%
Nongrowing 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 (August ’09-July ’10)	1,293 ± 52	386 ± 19	30%	−45 ± 13	−4%	71 ± 12	4%	836 ± 118	65%	116 ± 131	9%

Note: P, tipping-bucket precipitation; Q, measured streamflow; 1-D ΔS, changes in soil moisture storage measured hourly by single location (ESI) probes; 3-D ΔS, changes in soil moisture storage measured by spatially distributed (TRIME) probes; ET, evapotranspiration estimated using Sun *et al.* (2008); G, groundwater flux across catchment boundary, calculated as residual of measured components (uses 1-D ΔS).

Cumulative annual Q values for the two catchments were similar, with 354 ± 18 mm (26% of P) and 386 ± 19 mm (30% of P) for HF and UF, respectively. However, monthly variation in Q was much greater for UF (1-109 mm) than HF (8-57 mm). UF showed more extreme flow conditions, with lower Q in all growing season months (March-October) and higher Q during all nongrowing season months. Growing season daily base flow (periods >48 h after rain events) in UF was ephemeral, approaching 0.01 mm/day, while that of HF was perennial and ranged between 0.2 and 0.5 mm/day (Figures 3 and

4). In early November, at the end of the growing season, UF base flow increased to levels similar to those of HF, and daily storm-related discharge levels became much higher in UF than in HF. As shown in Tables 3 and 4, the total growing season Q was higher in HF (14% in late 2009 and 21% in early 2010) than in UF (2 and 12%, respectively). This was reversed during the nongrowing season, when Q in HF was 33% of P, and 52% of P in UF.

Daily FAO grass-reference ET (ET_O) dynamics were similar to both sites (Figures 3 and 4). Annual total ET generated using Sun *et al.* (2008) was 812 ± 118 mm (59% of P) and 836 ± 118 mm (65% of P) for HF and UF, respectively (Tables 3 and 4). Note, application of the empirical relationship between forest-based ET and grass-reference ET_O, LAI, and P generated by Sun *et al.* (2011) resulted in lowering annual ET estimates from the ET_O grass reference by 13 and 11% for HF and UF sites, respectively.

Monthly and seasonal ET values in Tables 3 and 4 show the varying seasonal shift in ET in both catchments. For the two catchments, the uncertainty range of all monthly values overlapped. Monthly growing season ET ranged from 41 to 143 mm (1.4-4.8 mm/day), whereas monthly nongrowing season ET ranged from 27 to 49 mm (0.9-1.6 mm/day). In May 2010, ET in both catchments experienced large increases from April 2010.

Changes in Soil Moisture Storage at the Catchment Scale

The HF and UF profile average θ for the late growing season (August-October) 2009 were 19 and 20%, respectively (Figure 5). A marked shift from dry to wet conditions corresponding to the end of the growing season occurred in early November 2009 with HF and UF profile averages increasing to 27 and 31%, respectively. In late March 2010, a shift back from wet to dry conditions began, with both profiles briefly falling below 20%, temporarily rising with May storms and then dropping once again in June 2010. During the nongrowing season, the UF profile was consistently wetter than that HF, and varied less than 3%, while HF soil moisture fell and rose by almost 9% in response to interstorm and storm periods.

Results from the access tube soil moisture profiles provide additional insights into seasonal unsaturated soil water storage dynamics. Figure 6 shows soil moisture profiles at selected hillslope sites to illustrate differences in soil moisture dynamics between catchments. Each line in Figure 6 represents the soil moisture profile at a single point in time. In HF, θ was lowest near the surface and highest at depth, with greatest variations between dry and wet seasons (about 20%) observed at the 80-cm depth. All five profiles collected in the HF catchment except the

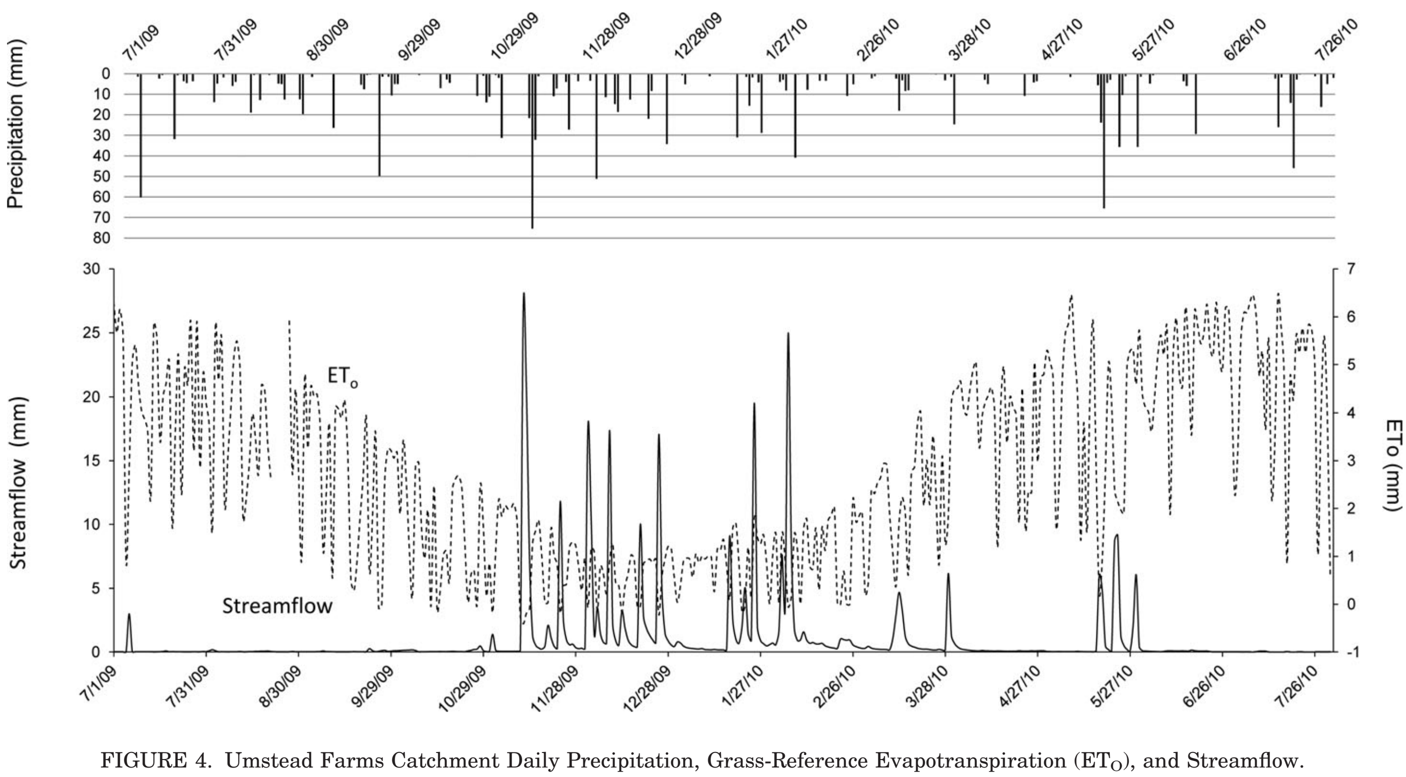

FIGURE 4. Umstead Farms Catchment Daily Precipitation, Grass-Reference Evapotranspiration (ET_O), and Streamflow.

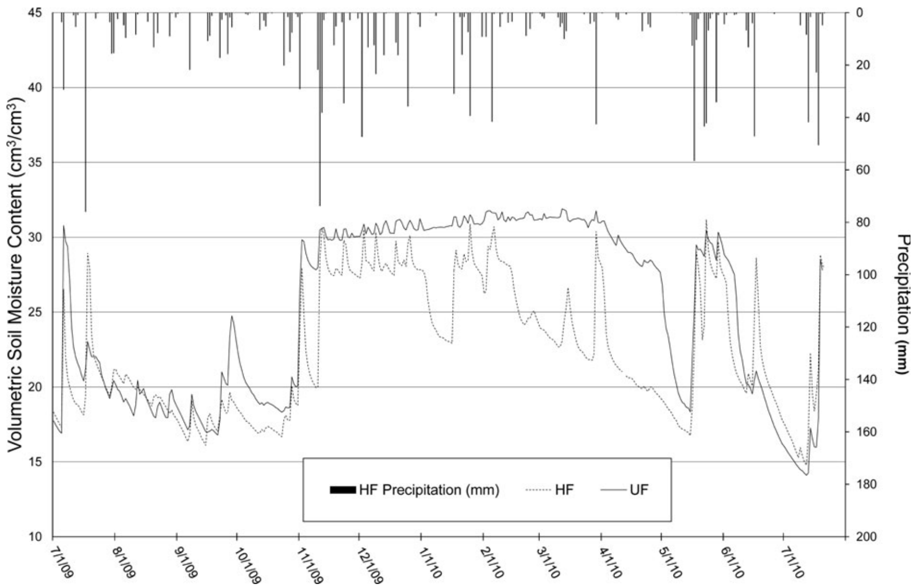

FIGURE 5. Daily Profile Average Soil Moisture at Hill Forest (HF) T1 and Umstead Farms (UF) T2 Sites (July 2009 to July 2010).

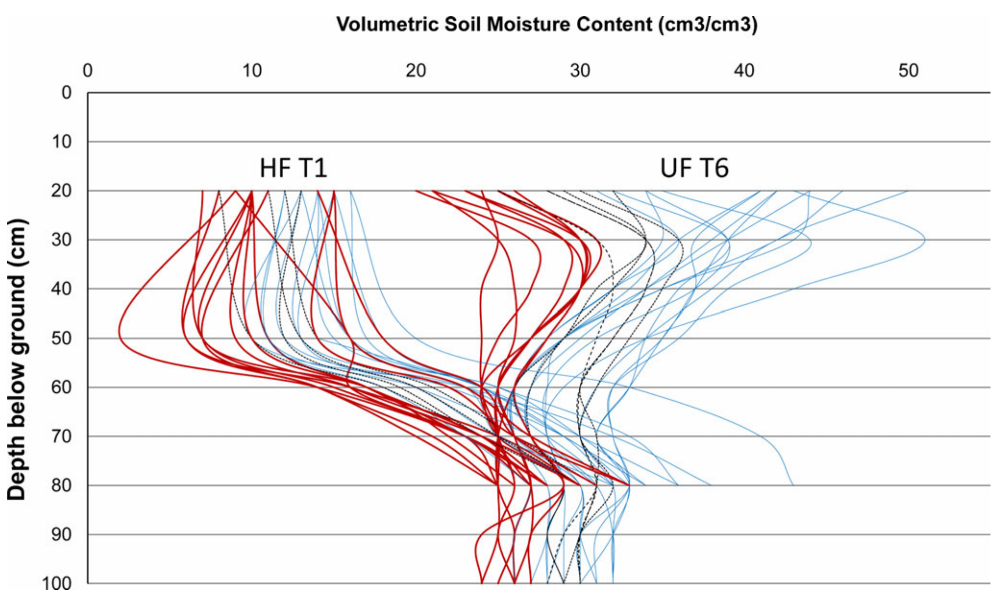

FIGURE 6. Bimonthly Soil Moisture Profiles (access tubes) at Hill Forest (HF) T1 and Umstead Farms (UF) T6 Sites. Blue indicates profiles from October 2009 to March 15, 2010 (nongrowing season); dotted black lines indicate profiles from March 15 to May 30, 2010 (transition period); red indicates profiles collected during the growing season (July-October 2009; June-July 2010).

riparian site (T5) exhibit the same shape, drier at the top and wetter at the bottom, throughout the study period. In contrast, the typical UF hillslope site demonstrates a much different pattern than those of HF hillslopes. Just as in HF, there was an increase in θ between growing and nongrowing season. However, in UF, θ was higher through the nongrowing season and never 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 the lower depths, corresponding to the soil's BT horizon. During the nongrowing season in UF, hillslope profile θ steadily increased between the ~50-60 cm (Bt horizon) and 20 cm (A horizon) depths, corresponding to saturation of shallow wells. There were also examples when θ 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. In contrast, θ at the UF upland synoptic sites in Vance soils (T3 and T7) increased with depth.

Comparison of 3-D catchment-wide mean θ in HF and UF (data not shown) also reflects the differences in unsaturated-zone behavior of the two catchments seen in profile (Figure 5). In HF, 3-D catchment-wide mean θ was between 23 and 25% during late growing season 2009. The moisture shift was 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 to 25% during late growing season 2009, and then staying above 35% during the nongrowing season. Both catchments returned to the dry state after May 2010.

Estimates of changes in catchment storage using 1-D and 3-D ΔS approaches are provided in Tables 3 and 4 for HF and UF, respectively. During the late growing season of 2009 (August-October), the 1-D HF unsaturated-zone change in storage was 47 mm, a gain of 22%, whereas the UF change in storage was −23 mm, a loss of 9%. During the nongrowing season (November 1-March 15, as defined in USDA, 2010), HF shows a 28 mm gain (4%), whereas the UF catchment 1-D change in storage was 154 mm, a gain of 24%. Both catchments show losses in storage during the early part of the growing season of 2010 (March 16-July 31). HF change in storage was −11 mm (−2%), whereas UF change in storage was −176 mm (−47%). The annual 1-D change in storage in HF was 67 mm (5%), whereas that of UF was −45 mm (−4%).

In HF, estimates of annual 3-D ΔS (95 ± 23 mm) and 1-D ΔS (67 mm ± 16) were similar, considering uncertainties. Monthly 1-D and 3-D ΔS exhibit corresponding increases and decreases throughout the study period, though their absolute values vary. Although the 1-D ΔS analysis is spatially limited, it appears consistent with the 3-D analysis in the HF catchment. In UF, however, 3-D ΔS was 71 ± 12 mm, whereas 1-D ΔS was −45 ± 13 mm. Here, uncertainties cannot account for differences between these two numbers. Monthly 1-D and 3-D totals in UF followed similar patterns during the nongrowing season in particular, although growing season patterns diverged (e.g. August-October, 2009 and June-July, 2010). The less frequent monitoring of access tube sites used in the 3-D analysis may lead to overrepresenting extreme events. For example, data were collected from access tube sites only twice in July 2010, so the 46-mm rain event that occurred on July 18 (Figure 4) leads to an overestimation of θ and water table.

Water Balances

Figures 7 and 8 show the daily cumulative water balance components for HF and UF catchments, respectively. During the late growing season of 2009 (August-October 2009), P was slightly higher than ET in both catchments, and there were negative or near-zero ΔS and low Q. In UF, ΔS were typically zero, only increasing in response to the largest storms, and Q for the entire three-month period totaled only 6 mm. When P increased in November 2009, this accompanied the leaf loss and reductions in ET (relative flattening of the cumulative ET curve) and both ΔS and Q increased. In UF, ΔS and Q were higher than in HF, and Q/P for the nongrowing season was 52% and then trended back toward zero when ET values increased starting in April. From April 2010, ET rose with a similar slope to that of P, and ΔS dropped near zero. By June 2010, HF Q and ΔS were low, but cumulative Q continued to increase. In UF, ΔS became negative and Q reduced to zero. From this point forward P in the UF catchment resulted in positive ΔS (e.g., July), but did not result in Q.

Monthly, seasonal, and annual water balances for HF and UF are shown in Tables 3 and 4, respectively. The annual HF and UF balances are similar, showing only slight variations in the percentages of Q (difference of 4%), 1-D ΔS (difference of 9%), ET (difference of 6%), and G (difference of 1%). However, monthly and seasonal water balances illustrate differences in seasonal changes that occurred in the catchments. In UF, 219 ± 9 mm of rainfall in November 2009 caused strong monthly ΔS of 154 ± 39 mm and 219 ± 55 mm (a 17-100% increase), for 1-D and 3-D estimates, respectively. In HF, similar P totals in November 2009 (227 ± 9 mm) had less effect on November ΔS, which increased by 9-19 mm in November and 31-34 mm in December (a 4-19% increase). The overall October-December, 2009, increases in Q with respect to September, 2009, Q, were much greater in UF (3-109 mm, or 54× larger) than in HF (12-57 mm, or 5× larger).

A seasonal breakdown also further suggests important differences in inferred net groundwater gains or losses (calculated by residual) for the HF and UF catchments (Tables 3 and 4, Figure 9). For HF, late growing season 2009 Q and ET were 14 and 87% of P, respectively. A positive change in storage of 22-27% thus infers a net gain from groundwater of 48 to 53 ± 33 mm (−23 to −27%) during this period. During the nongrowing season that followed, ET reduced to 24% while Q increased to 33% of total P. Slight increases in storage (4-14%) occurred, and 261 ± 54 mm, or 38% of the precipitation is estimated lost as deep seepage (G). After March, in the

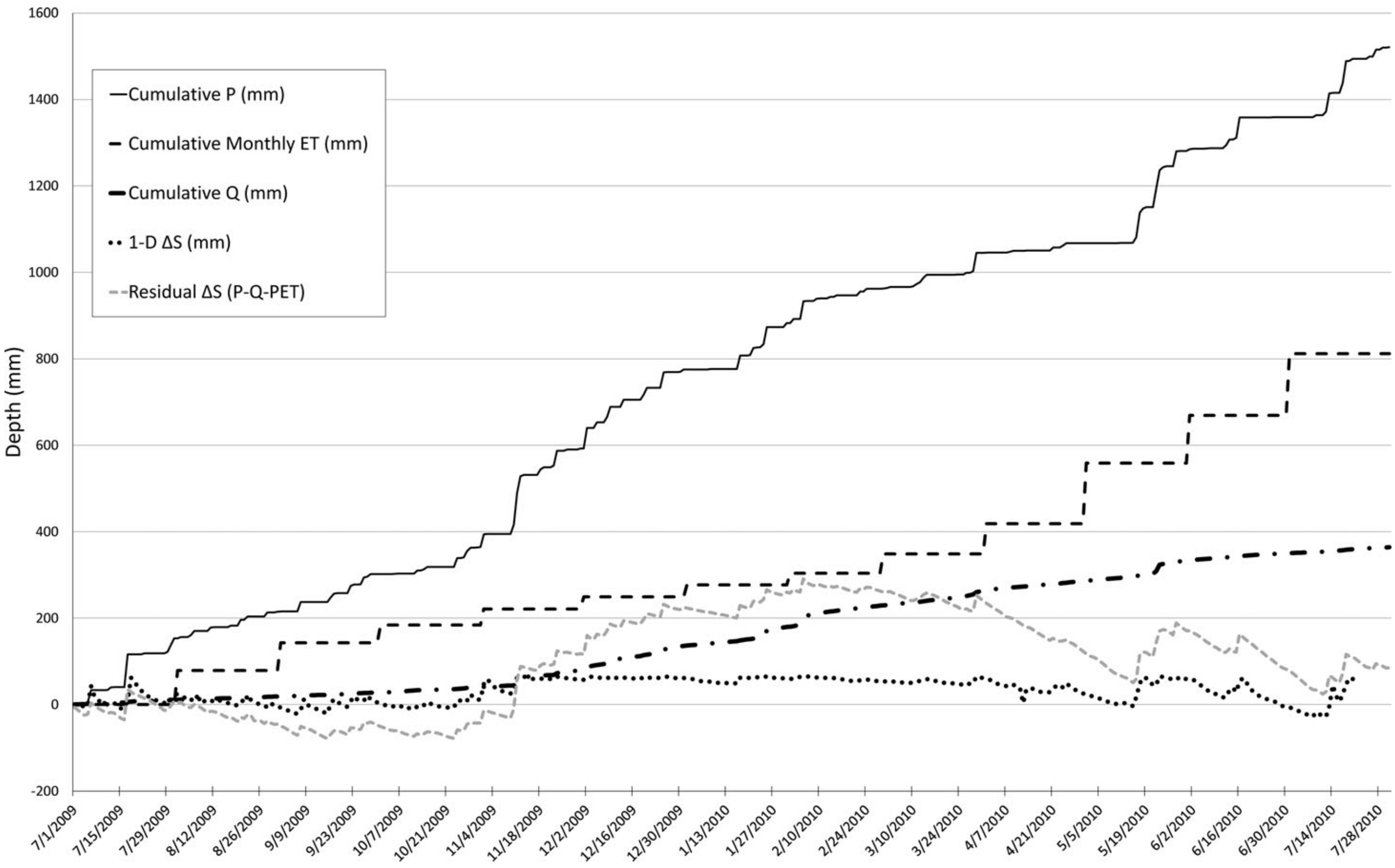

FIGURE 7. Hill Forest Cumulative Daily Water Balance.

early growing season of 2010, Q fell to 21% and ET rose to 97% of P, while losses in storage (-2 to 3%) occurred. Based on this balance, we estimate a net gain from groundwater of 77 ± 47 mm (-16%) during this period. Seasonal patterns in water balance components differed in UF. During late growing season 2009, total Q was 2% of P, while ET was 77% of P. Storage changes ranged from -9 to 21%, and G was estimated to be between 0 and a net loss to deep seepage of 30%. When ET fell to 28% during the nongrowing season, UF Q increased to 52% of P, and ΔS increased to between 24 and 35%, inferring a small net gain from groundwater ranging between 4 and 15%. Once ET increased (to 118% of P) during early growing season 2010, Q fell to 12% of P, shallow storage showed losses (ΔS was -47 to -56%), and there was a 0-16% net loss to deep seepage (G).

The annual estimations of G were a net loss to depth (deep seepage + groundwater recharge) of 136 ± 132 mm (10 ± 10% of P) in HF and 116 ± 131 mm (9 ± 10% of P) in UF. The uncertainties in annual G are large, ~100%, equal to the estimates themselves and no discernible differences can be made between HF and UF catchment systems over this time scale. The generally accepted annual models of groundwater recharge in North Carolina (Heath, 1994) suggests that the statewide annual average of G is 16% of total P. Seasonal estimates of G provide some useful contrasts between UF and HF catchment behavior. Considering only the 1-D analysis in HF, G was calculated to be a net loss to depth (recharge) of 261 ± 54 mm (38%) during the nongrowing season and smaller net gains (discharge) of 48 ± 33 mm and 77 ± 47 mm to the shallow subsurface system during the late 2009 and early 2010 growing seasons. This pattern of groundwater recharge (loss to depth) during the low-ET nongrowing season is consistent with general models of Piedmont hydrology (Heath, 1994). In November-February, when ET was low (16-33% of P), monthly G ranged from net losses (recharge) of 17-62% of P. During these months, 1-D storage changes in HF were low (-12 to 17%), suggesting that excess rainfall moved vertically through the relatively well-drained unsaturated zone, as supported by the direct observation of persistent patterns in vertical soil moisture profiles (Figure 8). At UF, monthly data show small net losses and/or potentially net gains in G (-26 to 17%) and high Q (37-76%) during the nongrowing season. Higher net losses to depth of G in September (73 ± 14 mm,

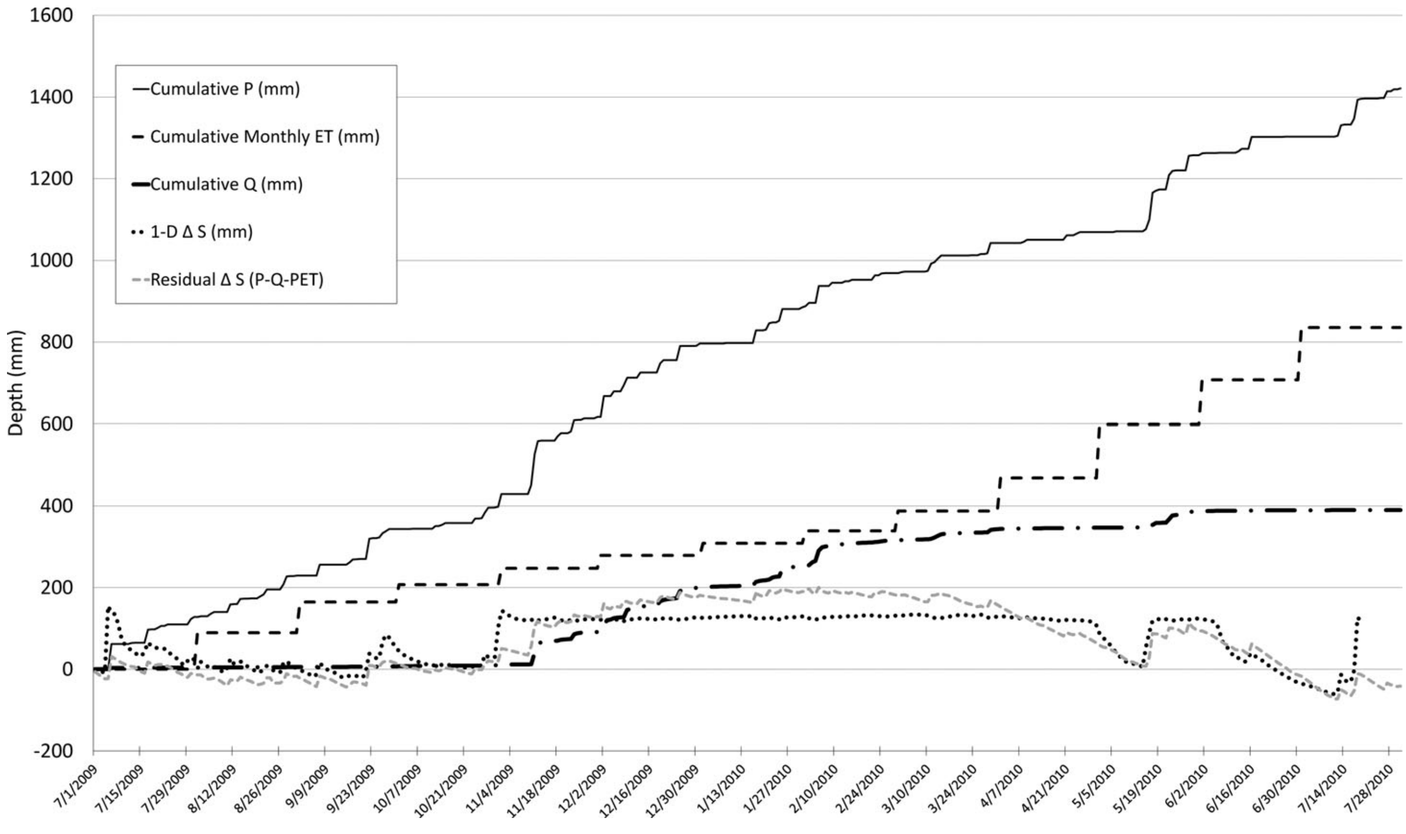

FIGURE 8. Umstead Farms Cumulative Daily Water Balance.

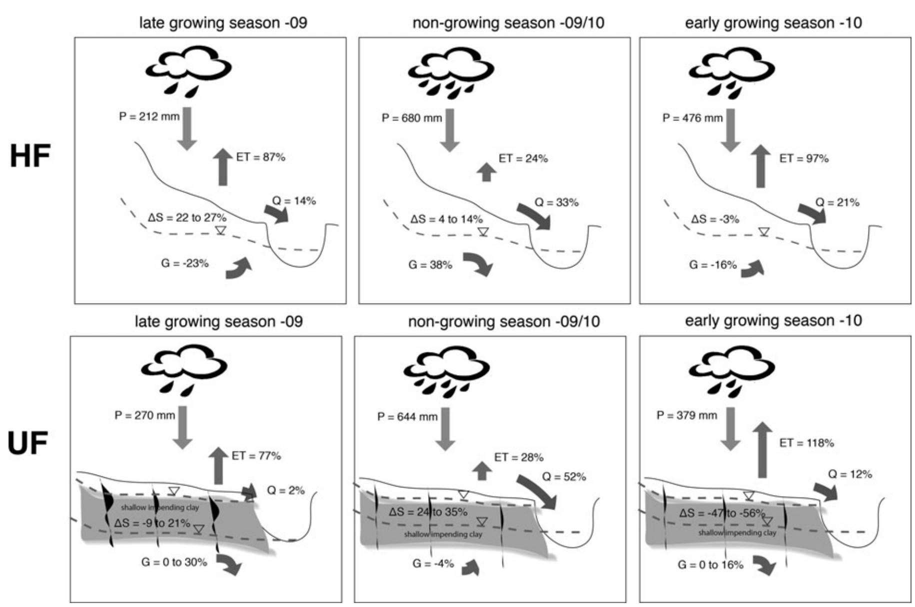

FIGURE 9. Conceptual Growing Season (left and right panels) and Nongrowing Season (middle panels) Water Balance Models for Hill Forest (HF) and Umstead Farms (UF) Catchments. Arrows in individual panels are scaled relative to precipitation. Illustration of the UF includes the shallow impeding clay, the seasonal development of vertical cracks, and the nongrowing and early growing season perched water table.

or 64%), April (67 ± 32 mm, or 246%), and July (91 ± 28 mm, or 77%) suggest downward vertical fluxes occurred during the growing season when perched water existed but little rainfall occurred (April 2010), or during drier periods when large amounts of rain occurred and the expansive clay horizons were not saturated, allowing vertical flow through cracks and macropores promoted by drier conditions (September 2009 and July 2009).

DISCUSSION

Does Reference Hydrology Differ between the Catchments?

The 12-month water balance was similar for the HF and UF catchments, and consistent with annual catchment water balances cited in the Piedmont region. For comparative purposes, Schäfer *et al.* (2002) calculated that ET in a pine-dominated stand in nearby Duke Forest, derived from eddy-covariance trace gas observations (1998-2000) ranged from 537 to 614 mm. Stoy *et al.* (2006) used eddy-covariance measurements to calculate a range of 560-740 mm at the same stand and a range of 580-640 mm for a Duke Forest hardwood-dominated stand during 2001-2004. Using the residual of 30-year average precipitation minus streamflow at a USGS gaging station, Lu *et al.* (2005) estimated an ET of 791 mm, or 72% of the average annual P (1,122 mm) in the 386-km^2 Flat River watershed, in which the HF catchment is nested. Considering uncertainties, ET estimates in the current study overlap the ranges observed by Lu *et al.* (2005) and Stoy *et al.* (2006), and they are slightly higher than the calculations of Schäfer *et al.* (2002).

However, seasonal, monthly, and daily water balance varied (Figure 9), suggesting important differences in reference hydrology for subannual time scales. During growing seasons, HF generated more streamflow (Q/P of 14 and 21%, respectively) than did UF (2 and 12%, respectively). During the nongrowing season, this was reversed, with UF streamflow increasing dramatically (Q/P of 52%) accompanied by high shallow storage. HF streamflow increased to a lesser extent (33%), with greater estimated losses to groundwater (G).

Soil water storage increases during the nongrowing season and reductions in ET appear to cause increases in stream discharge in both catchments. This pattern is consistent with other studies describing dry and wet state changes in catchment hydrology (Grayson *et al.*, 1997; Tromp-van Meerveld and McDonnell, 2006). However, strong differences in shallow storage dynamics are clearly visible between the two catchments (Figure 9). These differences are not explained by topography alone, as the low-lying, flat watershed (UF) consistently exhibited higher flows and storm response during the nongrowing season, and requires additional information such as soil type to explain catchment behavior. Soil moisture profiles (Figure 6) demonstrate that in UF hillslope soils, nongrowing θ increases occurred above the clay horizon, whereas in HF, θ was lowest near the surface and highest at depth. The cumulative water balances (Figures 7 and 8) also illustrate these differences. In UF, 1-D and residual ΔS (the same as $P - [\text{ET} + Q]$) tracked closely throughout the study period, diverging only slightly (>40 mm) during the nongrowing season. However, as shown in Figure 9, in HF the 1-D and residual ΔS differed by around 200 mm during the nongrowing season, suggesting a difference between water not becoming ET or Q and the amount of storage detected by this analysis, which assumes that the top 1 m represents the unsaturated zone. The greater similarities in residual and measured ΔS in UF likely reflect that the shallow (<2 m) probes better captured the soil moisture storage occurring in UF, where much of the storage was trapped in the shallow surface of hillslope soils, than in HF, where storage moved vertically through upland and hillslope soils.

The UF values for G were zero or negative during the nongrowing season, while the HF value for G was 29-39% of total P. This suggests that nongrowing season subsurface flux and deep seepage were important in HF but not in UF. The nongrowing season values for G in the HF catchment are consistent with models of recharge in the Carolina Slate Belt physiographic province, whereas those in the UF catchment are more consistent with values for Triassic Basin recharge posited by Heath (1994).

Are Differences in Reference Hydrology Attributable to Differing Hydrologic Landscapes?

The UF and HF catchments both lie over crystalline-metamorphic geology typical of the Carolina Slate Belt (Table 1), but the differences in their seasonal water balances suggest distinct hydrologic landscapes, although we argue for a local-scale replacement of the large-scale classification of Wolock *et al.* (2004). Buttle's (2006) T3 conceptual framework of primary first-order controls on hydrologic response can be used to compare these two landscapes. In UF, typology exerts strong seasonal controls on the water balance due to the dominance of expansive clay Bt soil horizons and low slopes, allowing infiltration of P during the growing season through cracks, but becoming impermeable, perching water, and promoting lateral flow and thus higher Q, during the nongrowing season (Figures 4 and 5). In HF, where the clays are less expansive, typology appears to be less of a controlling factor, and topography is likely more important, as steeper hillslopes drain to depth quickly between storm events throughout the year (Figures 3 and 5). These results can be likened to models demonstrating that thin, low-slope soils develop large, connected areas of saturation above impermeable bedrock, similar to the UF impermeable clay soil horizon, while thicker soils like those in HF tend to move water vertically to depth and dampen lateral flow response (Hopp and McDonnell, 2009).

Evapotranspiration appears to play a minor role in variability between the catchments. Monthly leaf area index (LAI) values, a major component of the catchment-level ET calculation, were higher in the UF catchment, which has more mature trees. LAI values were higher in UF during the nongrowing season when UF runoff was much higher, which suggests that it was not a driving factor in the differences in streamflow generation. Conversely, LAI values were higher in HF during August ’09 and May ’10, and streamflow was also higher. This suggests that HF soils are thicker, store more water, and drain throughout the year. These results suggest that, despite having the same underlying geology, and identical climate and precipitation, the HF and UF catchments can be defined as having different hydrologic landscapes driven primarily by differences in soil type and slope and not as strongly by variation in vegetation.

Implications for Development and Future Considerations

Future testing of local-scale hydrologic landscape maps, such as that proposed in Figure 1, may offer more spatially and temporally refined information to guide the development of reference hydrologic targets. Increasingly, management practices that target reference conditions (e.g., so-called green infrastructure and stormwater low-impact development [LID]) are being used with the hope of achieving water quality standards. For example, the local stormwater management strategies in North Carolina allow the use of stormwater “LID” (NCAC, 2011), and the North Carolina LID Guidebook sets target annual water balance criteria for the Mountain, Piedmont (including the Piedmont’s Triassic Basin), and Coastal Plain physiographic provinces based on long-term hydrologic data from research stations in the Mountain and Coastal Plain physiographic provinces (Coweeta NC and Santee SC), and states that future targets could be developed for other areas when data become available (Perrin *et al.*, 2009). Currently, target hydrology for Piedmont “undisturbed woods with clay-influenced soils” is an annual water balance of 68.7% ET, 2.7% runoff (defined as overland flow), and 28.7% infiltration (sic), defined as the sum of shallow interflow and deep seepage (Perrin *et al.*, 2009).

The current research suggests that the targets may be too coarse in both space and time. To work effectively at the headwater scale, innovative stormwater planning may need refinement using a more spatially detailed reference hydrology such as one based on hydrologic landscape units (e.g., Winter, 2001). A hydrologic landscape map of the U.S. exists (Wolock *et al.*, 2004), but the description of regions requires local-scale revising. In addition, findings from both catchments demonstrate a strong seasonal influence on the water balance of headwater catchments in this region, suggesting seasonal targets may also be warranted.

Limited to a single year of observations, findings presented here would be strengthened by more data collection. Storm-based analyses by Kuntukova (2011) show significantly higher total flow, runoff ratios, and peak flow rates at UF site subcatchments, compared to HF sites, giving additional support for the findings presented here. To further investigate the validity of the UF-type hydrologic landscape (Figure 1) as a predictive tool, we recommend additional small watershed observations from the region. Extended testing would allow further comment on variability of the subannual water balance that may result from within-watershed heterogeneity in soils and their connection to the stream channel, as well as differences in % land cover.

CONCLUSIONS

Comparing the water balance during a one-year period in two headwater catchments of identical climate and geological setting in the Piedmont region of North Carolina suggests that the soils and topography of the catchments are controlling factors representing two unique hydrologic landscapes. Differences in daily cumulative, monthly, and seasonal water balances demonstrate important differences in processing and storage of water. Topography (slopes) and soil properties (clay layer) are important in affecting seasonal catchment water balances and groundwater recharge. The proposed hydrologic landscapes based on soils and topography alone appear to reflect an important distinction between regional-scale reference hydrology of these representative catchments. Our study suggests that current hydrologic landscape mapping is too coarse to characterize watershed hydrologic differences. This study could be used to inform future iterations of criteria to guide innovative, performance-based development design.

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