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CHARACTERIZATION OF STORM FLOW DYNAMICS OF HEADWATER STREAMS IN THE SOUTH CAROLINA LOWER COASTAL PLAIN[1]

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ABSTRACT: Hydrologic monitoring was conducted in two first-order lower coastal plain watersheds in South Carolina, United States, a region with increasing growth and land use change. Storm events over a three-year period were analyzed for direct runoff coefficients (ROC) and the total storm response (TSR) as percent rainfall. ROC calculations utilized an empirical hydrograph separation method that partitioned total streamflow into sustained base flow and direct runoff components. ROC ratios ranged from 0 to 0.32 on the Upper Debidue Creek (UDC) watershed and 0 to 0.57 on Watershed 80 (WS80); TSR results ranged from 0 to 0.93 at UDC and 0.01 to 0.74 at WS80. Variability in event runoff generation was attributed to seasonal trends in water table elevation fluctuation as regulated by evapotranspiration. Groundwater elevation breakpoints for each watershed were identified based on antecedent water table elevation, streamflow, ROCs, and TSRs. These thresholds represent the groundwater elevation above which event runoff generation increased sharply in response to rainfall. For effective coastal land use decision making, baseline watershed hydrology must be understood to serve as a benchmark for management goals, based on both seasonal and event-based surface and groundwater interactions.

(KEY TERMS: surface water/groundwater interaction; runoff; watershed management; streamflow; coastal watershed hydrology; first-order stream; hydrograph separation; South Carolina.)

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INTRODUCTION

Coastal headwater streams in undeveloped forested landscapes function as a natural storage and conveyance mechanism for groundwater discharges and streamflow (Amatya *et al.*, 2006). The lower coastal plain (LCP) of South Carolina is defined by low-gradient topography and low elevations typical of southeastern United States coastal landscapes. Shallow groundwater elevations influence soil-moisture levels and couple with surface water generation

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during rainfall events to determine stream outflows that include significant base flows (Eshleman *et al.*, 1994; Williams, 2007). The magnitude of watershed outflows is often driven by a fluctuating water table position that is regulated by the balance between evapotranspirative demand and infiltrative replenishment by rainfall (Miwa *et al.*, 2003; Amatya *et al.*, 2006; Slattery *et al.*, 2006; Harder *et al.*, 2007). High water table elevation and high soil-moisture conditions lead to higher outflow production during winter months when forest vegetation is largely dormant and evapotranspiration rates are lower (Harder *et al.*, 2007; Williams, 2007; Amatya and Skaggs, 2011; La Torre Torres *et al.*, 2011). During summer months, streamflows are intermittent in response to direct rainfall. High summer evapotranspiration rates tend to rapidly lower the water table elevation resulting in increased soil storage and decreased storm runoff (Slattery *et al.*, 2006; Harder *et al.*, 2007; Williams, 2007; Amatya and Skaggs, 2011). For low-gradient and lower elevation coastal streams, it is generally known that flow cessation occurs when the water table elevation is sufficiently low that groundwater flows are disconnected from the stream channel. Between these seasonal extremes, the rainfall response is dependent upon antecedent moisture conditions (AMC) that vary with microclimate variability and seasonal evapotranspiration shifts (Sun *et al.*, 2002; Harder *et al.*, 2007). Due to these highly variable conditions, the derivation of water budgets for coastal forested watersheds with low-gradient topographic relief can be complex. It is critical to better understand these hydrologic dynamics for the protection of water resources, flood prevention, and preservation of aquatic ecology in coastal landscapes, especially as forested areas are being converted to residential and commercial development. Developing lands are prone to increased impervious surface areas that can significantly alter site hydrology (magnitude and pathways of surface and subsurface flow) and increase pollutant loads to adjacent waters (Arnold and Gibbons, 1996; Booth *et al.*, 2002).

Land use in the region is changing rapidly with growing populations, and consequently land cover is being altered with increased impervious surface area; these changes have motivated the study of predevelopment conditions in the area to ensure water resource protection (Allen and Lu, 2003; Amatya and Skaggs, 2011; Blair *et al.*, 2011). Additionally, downstream tidal marsh ecosystems that are sensitive to impaired water quality from upstream sources are also of concern as land use changes take place in upland watersheds (Holland *et al.*, 2004). Although much work has been performed to characterize upland watersheds, more information is needed specific to the LCP with respect to regional hydrologic processes (Amatya *et al.*, 2006). Storm-event outflow production must be investigated to determine the roles that seasonal trends in evapotranspiration, water table elevation, and AMC have on LCP headwater streams.

The objective of this study is to assess the rainfall response on two headwater streams in the LCP using both total storm response (TSR) and direct runoff coefficients (ROC) to quantify storm event-based watershed outflow. This includes the differentiation between base flows associated with groundwater discharge and direct runoff that is related to surface water generation. The relationship between runoff measurements (TSR and ROC) and estimates of AMC using various methods outlined below will be determined to characterize differences in runoff generation related to seasonal trends and variable AMC from storm to storm. The role of groundwater in runoff generation will be primarily assessed in terms of water table elevation, and results will be used to assess runoff generation mechanisms in LCP headwater streams.

MATERIALS AND METHODS

Site Descriptions

The study sites (Figure 1) are located at two first-order LCP watersheds in South Carolina. Upper Debidue Creek (UDC) (33.38°N, 79.17°W), located in coastal Georgetown County, South Carolina, is a 100-ha freshwater nontidal watershed that has been slated for development. Watershed 80 (WS80), a tributary of Huger Creek located in the Francis Marion National Forest (33.15°N 79.8°W), is a 163-ha freshwater nontidal watershed that is federally protected

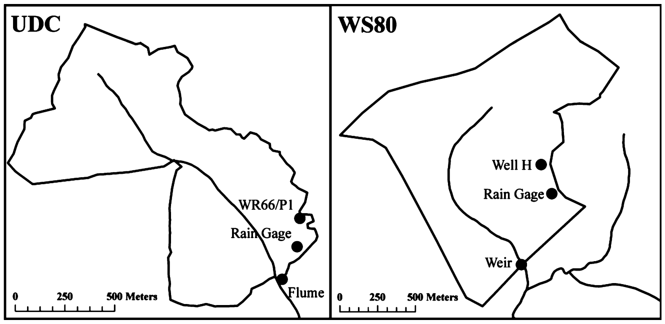

FIGURE 1. Upper Debidue Creek (UDC) Watershed and Watershed 80 (WS80) Delineations and Monitoring Networks, Including Outflow (flume or weir, respectively), Rain Gages, and Water Table Wells (WR66/P1 and Well H, respectively).

and also serves as an undeveloped reference watershed. Both watersheds are characterized by low-gradient topography and shallow water table conditions. Surface elevations at UDC range from 6.5 m above sea level (ASL) in the upland area to 2.1 m ASL at the watershed outlet. Surface elevations on WS80 range from 10 m ASL in upland areas to 3.7 m at the watershed outlet (Harder *et al.*, 2007). The landscape is currently dominated by forested wetlands with mixed hardwood lowlands and upland pine stands. The primary soils in the UDC watershed are Lynn Haven and Leon. These soils are formed of sandy marine sediment, are associated with very low-gradient conditions, are highly permeable, and poorly drained (USDA, 1980). The primary soils in WS80 are Wahee, Meggett, Craven, and Bethera. These soils are formed of clayey Coastal Plain sediments and are typical of areas with low-gradient topography (USDA, 1974). These soils are poorly drained with high available water content and have lower permeability than sandy soils. The two watersheds are about 75 km apart and in a humid subtropical climatic zone characterized by short mild winters and long hot summers (La Torre Torres *et al.*, 2011). The growing season is defined between calendar dates calculated as having a 50% probability to record the last frost of winter (sub 0°C) and first frost of fall from long-term local temperature records. These dates are from March 9 to November 25 at Charleston, South Carolina, for WS80 and from March 11 to November 20 at Georgetown for UDC (NCDC, 1988). Dates outside this range represent the dormant season.

Data Collection

Rainfall, streamflow, and groundwater elevation data from the two study watersheds were collected from 2008 to 2011 (Figure 1). Tipping bucket rain gages (Onset® Hobo™, Bourne, Massachusetts at UDC and WS80) located in both watersheds were used to quantify local hourly rainfall totals. Groundwater elevations were monitored at upland locations near the watershed boundary on both UDC and WS80. At UDC, a 3-m deep water table well (4.2 m ASL) with a pressure transducer was located in an upland pine area near the watershed boundary (WR66, Figure 1). The pressure transducer was replaced with a Solinst logger in March 2011. Groundwater elevation was monitored in the upland area at WS80 (Well H, Figure 1, 9.09 m ASL) by a WL16 logger (Global Water, Gold River, CA) deployed in a 2.8-m deep water table well. Watershed outflow in UDC was estimated using a 0.6-m modified Parshall flume located immediately downstream of a road culvert. Additional instrumentation details for UDC are provided by Hitchcock *et al.* (2009). Streamflows were corrected for submergence in the flume according to equations developed by Peck (1998). A threshold of 0.85 for submergence was set for measured outflow in accordance with the correction equations. At WS80, streamflow rate was estimated by measuring stage over a compound weir. Additional instrumentation details for flow measurement in WS80 are provided by Harder *et al.* (2007). Storm-flow rates were first converted to volumes by hydrograph integration. They were converted to equivalent depths in millimeters by dividing the runoff volume by watershed area.

Data Assessment

The storm-event rainfall response is typically referred to as runoff, and this term often has different meanings from study to study. The majority of previous studies conducted in the LCP have defined runoff as total stream outflow depth associated with a given storm event and is typically expressed as a percentage of rainfall. For analyses, total outflow depth measured as a percentage of rainfall will be referred to as the TSR in order to differentiate between different measures of storm-event runoff. Direct runoff estimates, also expressed as a percentage of rainfall, will be referred to as the direct ROC.

ROC and TSR ratios were calculated using a graphical hydrograph separation method to determine the total storm-flow depth and to distinguish the amount of direct runoff from base flow for a given rainfall event (Figure 2). The rationale for using this procedure was to calculate only the amount of flow generated as storm response quick flow, or direct runoff. The method differentiates direct runoff from the more delayed groundwater derived base-flow component of the TSR in order to obtain estimates of ROC. These two components of outflow discharge at different time scales as a

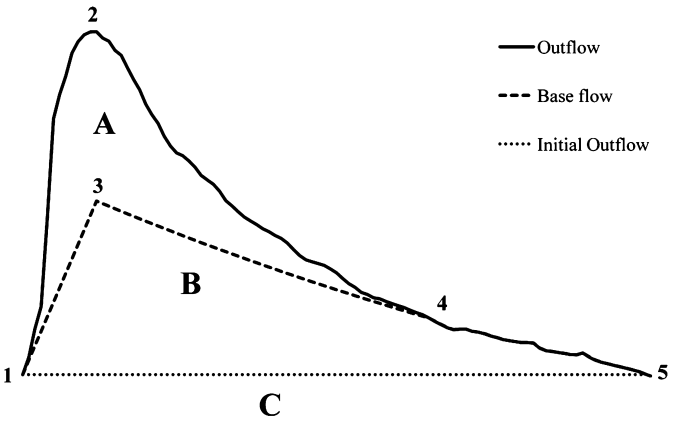

FIGURE 2. Hydrograph Separation Method for Determination of Direct Runoff Coefficients (ROC) and Total Storm Response (TSR).

signature of their generation mechanism in the rainfall response. Sustained base-flow contributions for LCP headwater streams are characteristics of groundwater elevation and watershed drainage and they may be influenced by previous storm events and AMC. ROC and TSR estimates were compared to determine differences between the methods as related to base-flow contribution.

Storm events were selected from streamflow data for 2008-2011 at both watersheds in order to assess the rainfall response over comparative local climate and moisture conditions because of their proximity. Storms were selected given that they met the following criteria: (1) rainfall >20 mm; (2) outflow was generated; and (3) event displayed a single-peaked hydrograph with a recession limb of sufficient length to perform graphical analysis. These criteria allowed for selection of a sufficient number of storms from the three-year period at both watersheds that ranged from substantial, higher frequency storm events up to larger storms of much less frequency. The AMC features measured for each storm event by compiling the initial outflow rate just prior to rainfall, the antecedent precipitation index (API) for 5 and 30 days, and the initial water table elevation prior to rainfall. The API was calculated by summing rainfall amounts for 5 and 30 days prior to the storm event (SCS, 1972).

Hydrograph separation was performed based on a method developed by Williams (2007) that emphasizes the physical processes of lower coastal hydrology, and it is represented graphically in Figure 2. This method models base-flow contributions to outflow that increase with rising water table elevation (Figure 2, Segment 1-3) in response to rainfall. Base flow increases until the peak outflow (Figure 2, Point 2) is reached. Peak base flow is followed by a sustained recession related to typical groundwater discharges (Figure 2, Segment 3-5) that result from gravity-driven watershed drainage as the water table lowers after rain ceases. This method models total outflows as the sum of two parallel linear reservoirs that discharge at different rates. A longer, slower outflow is expected for groundwater inputs and is considered here as base flow. Base-flow volumes are represented in Figure 2 as the sum of Areas B and C. The faster component, termed "quickflow," is taken as a measure of direct runoff. Direct runoff is represented by Area A in Figure 2. Williams uses the linear model of Maillet (1905) to model base-flow recession. This model describes outflow rate at a particular time as a function of initial flow rate, time, and a rate constant, which allows for the determination of the terminal point of hydrograph separation along the receding limb. The model is expressed as

$$Q_t = \mathrm{Q}_0 \exp(-t/k) \tag{1}$$

where Q_t is the outflow rate at time t, Q_0 is the outflow rate at the start of the recession, and k is a rate constant. For this exponential decay model, the log transform of Q_t ($\log Q_t$) is linearly related to time. Visual inspection of $\log Q_t$ was performed to identify the point of inflection at which the behavior of $\log Q_t$ remained linear up to the end of the storm response. This segment of the hydrograph represents outflows that are composed of the more slowly released groundwater discharges after the more quickly discharged direct runoff has exited the watershed as outflow. Linear regression results for this segment are extended back to the time of peak outflow to complete the separation of $\log Q_t$ of the recession limb, and this is transformed back from log scale for the hydrograph separation. The peak base flow (Figure 2, Point 3) is connected to the point of initial rise in the hydrograph (Figure 2, Point 1) to complete the separation into base flow and direct runoff. The quick response of the water table due to rainfall creates an initial increase in base flow as well as direct runoff in the rising limb of the hydrograph. This response is different from typical upland watersheds, where groundwater is less of an immediate influence on outflow and the hydraulic gradient is away from the stream. Total outflow volume and base-flow volume are calculated by taking the integrals under the hydrograph and hydrograph separation curve, respectively. Direct runoff depth is calculated as

$$\frac{\text{Total outflow volume} - \text{Base-flow volume}}{\text{Watershed area}} \tag{2}$$

The ROC is then calculated as the ratio of direct runoff depth to rainfall depth.

For determination of the TSR, a start and end point of the hydrograph were defined. For consistency, the start point was chosen to be 1 h prior to the initial rise of the hydrograph for the storm event (Figure 2, Point 1). The hydrograph was extended until outflow rates returned to the initial outflow rate at the start point to signify the end of the storm response (Figure 2, Point 5). Total storm-flow depth is represented in Figure 2 as the sum of Areas A and B and it is defined as

$$\frac{\text{Total outflow volume} - (\text{Duration of storm response} \times \text{Initial outflow rate})}{\text{Watershed area}} \tag{3}$$

The TSR is then calculated as the ratio of total storm-flow depth to rainfall depth. For some storm events, the recession limb was interrupted by additional rainfall before outflows returned to the initial outflow level. In these cases, the base-flow recession that was calculated by hydrograph separation for the storm was used to model outflows outward until the antecedent value was met in order to model the TSR to rainfall.

Storm-event rainfall and measures of AMC were compared with ROC and TSR values by linear regression to assess the relationship between AMC and runoff generation. Storm events were separated by growing season dates for the respective watershed locations to determine seasonal trends in mean ROC and TSR. An *F*-test was used to determine whether the seasonally grouped storm events had equal variance, and the appropriate two-sample *t*-test for equal or unequal variance was used to determine whether there was a difference between mean values of ROC and TSR. Segmented regression was performed using SegReg, a program designed to calculate a breakpoint in a dataset joining segments of separate linear regression that improves upon simple linear regression estimates for the data. This program was developed according to statistical principles outlined by Oosterbaan *et al.* (1990). Water table breakpoints estimated by segmented regression were subsequently used to separate storm events between dry and wet AMC in order to assess differences in runoff generation, and mean ROC and TSR were analyzed in the same manner used to assess seasonal mean differences. The difference between the peak outflow rate and the initial outflow rate for storm events was compared between the two watersheds to assess the difference in the magnitude of peak outflow rates in the rainfall response on the watersheds. The mean values were compared using *F*-tests and the two-sample *t*-test.

RESULTS AND DISCUSSION

For the UDC watershed, 23 storm events were analyzed, in which 20 storm events were analyzed for WS80; both sets based on selection criteria as previously described. Rainfall depth, initial outflow rate, 5- and 30-day API, initial water table elevation, peak outflow rate, total storm-flow depth, direct runoff depth as estimated by hydrograph separation, TSR, and ROC were compiled for all storms to assess outflow and direct runoff generation as it relates to AMC and water table elevation. For UDC and WS80 watersheds, storm-event sizes ranged from 20 to 154 mm with larger storms during the fall season months coinciding with tropical storms (Tables 1 and 2, respectively).

There was one noteworthy outlier related to the data. The tropical storm event that occurred on October 24, 2008 during the growing season at WS80 measured 154 mm of rain – the largest storm analyzed during the study period – with a resulting ROC of 0.57. Analyses were performed twice for WS80 storm events to determine the effect that the event on October 24, 2008 had on calculations. This large tropical storm event measured 154 mm of rain that occurred over a 13-h period with an intensity of nearly 12 mm/h. Large tropical storms that occur at the end of the growing season have the potential to produce large amounts of runoff that deviate from more typical growing season trends, mainly due to high amount of rainfall and tapered evapotranspiration demands during late fall months of October and November. Runoff generation for these large, high-intensity tropical storms is more closely related to rainfall characteristics than seasonal trends of AMC, resulting in a biased interpretation of the overall dataset. Results that include this storm in the analysis will be presented for WS80 and those that omit it will be noted accordingly.

The TSR and ROC coefficients for storms on the two watersheds varied widely. At UDC, the ROC ranged from 0 to 0.32 with a mean of 0.10, compared to a range of 0 to 0.57 with a mean of 0.17 for WS80 (Table 3). At UDC, the TSR ranged from 0 to 0.93 with a mean of 0.39, compared to a range of 0.01 to 0.74 with a mean of 0.34 at WS80. Although the two means of the TSR were similar, the calculated COV of 0.76 on WS80 shows a less variability of storm events than on UDC watershed with a COV of 0.95. Intermittent outflow and low runoff generation is typical during the summer months as shown in Tables 1 and 2 for June, July, and August storm events. This trend can be visualized in the measured ROC values plotted by Julian day over the three-year period at UDC and WS80 watersheds (Figures 3 top and 3 bottom). Mean ROC and TSR were higher on both watersheds during the dormant season. Table 3 summarizes descriptive statistics for each watershed across all storm events and separately for the dormant season and growing season events. At UDC, the mean TSR was 0.82 for the dormant season, significantly higher ($p < 0.01$) than 0.27 calculated for the growing season when high evaporative demand occurs. At WS80 also, the mean TSR of 0.49 in the dormant season was significantly higher ($p = 0.024$) than 0.25 for the growing season. These results clearly reflect the role of seasonal trends in evapotranspiration and soil-moisture conditions on runoff generation in coastal headwater streams as shown by La Torre Torres *et al.* (2011).

TABLE 1. Summary of Upper Debidue Creek (UDC) Storm-Event Characteristics for a Three-Year Period, Including Antecedent Precipitation Indices for 5 and 30 Days Prior to Event (API-5 and API-30, respectively), Direct Runoff Coefficients (ROC), and Total Storm Response (TSR).

Date	Rainfall (mm)	Initial Outflow Rate (m^3/h)	API-5 (mm)	API-30 (mm)	Water Table Elevation (m ASL)	Peak Outflow Rate (m^3/h)	Direct Runoff (mm)	Total Storm Flow (mm)	ROC	TSR
2008-07-24	30	17	11	250	NA	112	1	5	0.02	0.18
2008-09-05	87	42	0	150	NA	1,102	12	47	0.14	0.54
2008-09-11	25	166	81	231	NA	640	4	23	0.18	0.93
2008-09-16	47	159	0	171	NA	904	12	30	0.25	0.64
2008-09-25	42	134	1	175	NA	704	10	33	0.23	0.78
2009-03-01	40	16	1	33	3.19	428	3	34	0.08	0.83
2009-04-02	60	83	18	62	3.38	890	9	56	0.16	0.93
2009-08-28	68	0	0	35	2.34	99	0	3	0.00	0.04
2009-11-10	78	0	5	74	2.42	167	2	14	0.03	0.18
2010-01-16	22	119	0	74	3.60	408	2	20	0.11	0.89
2010-01-25	23	253	17	60	3.73	673	5	15	0.24	0.68
2010-02-02	27	311	20	82	3.74	896	7	22	0.25	0.82
2010-03-02	24	158	0	129	3.61	462	8	21	0.32	0.88
2010-05-04	23	2	0	30	3.25	40	0	1	0.00	0.05
2010-06-20	36	0	0	81	2.85	27	0	0	0.00	0.00
2010-06-30	35	0	36	140	2.93	64	0	1	0.00	0.02
2010-07-10	35	0	19	139	2.95	75	0	2	0.01	0.04
2010-08-01	24	0	6	130	3.03	31	0	0	0.01	0.02
2010-08-13	40	23	40	149	2.97	376	1	2	0.03	0.04
2010-08-19	25	2	36	143	3.29	85	0	2	0.01	0.09
2011-06-29	20	0	0	37	2.49	47	0	1	0.01	0.05
2011-08-06	81	24	6	179	2.66	656	3	18	0.04	0.22
2011-08-25	67	51	13	117	2.76	234	5	10	0.08	0.15

Notes: ASL, above sea level; NA, no data were available.

TABLE 2. Summary of Watershed 80 (WS80) Storm-Event Characteristics for a Three-Year Period, Including Antecedent Precipitation Indices for 5 and 30 Days Prior to Event (API-5 and API-30, respectively), Direct Runoff Coefficients (ROC), and Total Storm Response (TSR).

Date	Rainfall (mm)	Initial Outflow Rate (m^3/h)	API-5 (mm)	API-30 (mm)	Water Table Elevation (m ASL)	Peak Outflow Rate (m^3/h)	Direct Runoff (mm)	Total Storm Flow (mm)	ROC	TSR
2008-08-21	37	14	31	171	8.94	197	1	4	0.02	0.11
2008-09-05	98	0	1	167	8.26	862	2	13	0.02	0.13
2008-09-09	113	31	98	255	8.97	5,298	31	54	0.28	0.48
2008-09-25	65	0	1	218	8.62	634	5	15	0.08	0.23
2008-10-24	154	2	0	156	8.79	13,424	88	115	0.57	0.74
2008-11-29	47	2	0	27	8.64	217	4	10	0.09	0.22
2009-03-01	58	6	4	36	8.80	1,446	14	25	0.23	0.43
2009-04-02	67	49	35	61	9.02	2,619	23	46	0.34	0.69
2009-07-16	41	1	30	122	8.69	117	1	2	0.01	0.05
2009-07-22	29	1	0	153	8.80	54	0	1	0.01	0.03
2009-08-31	57	0	48	94	7.85	303	1	3	0.02	0.06
2009-11-11	70	0	2	61	7.53	22	0	1	0.00	0.01
2009-12-18	67	40	12	136	9.06	2,691	26	42	0.39	0.62
2009-12-25	31	77	3	200	9.06	967	7	18	0.22	0.57
2010-01-16	51	13	0	114	8.97	1,713	9	36	0.17	0.70
2010-01-25	42	167	25	88	9.08	2,119	19	29	0.46	0.69
2010-03-28	31	14	0	81	8.97	387	4	11	0.14	0.34
2010-05-04	52	0	0	21	8.07	13	0	0	0.00	0.01
2010-09-29	75	102	147	188	9.09	2,944	12	30	0.15	0.40
2011-02-02	66	4	12	60	8.88	231	10	14	0.15	0.22

Note: ASL, above sea level; NA.

Table 3. Descriptive Statistics for Storm Events at Upper Debidue Creek (UDC) and Watershed 80 (WS80) Watersheds Both Overall and Separately for Dormant Season and Growing Season Events, Including Direct Runoff Coefficients (ROC) and Total Storm Response (TSR).

	Overall		Dormant Season		Growing Season	
UDC	**ROC**	**TSR**	**ROC**	**TSR**	**ROC**	**TSR**
Mean	0.10	0.39	0.20	0.82	0.07	0.27
Median	0.04	0.18	0.24	0.83	0.03	0.12
SD	0.10	0.37	0.10	0.08	0.08	0.33
Min	0.00	0.00	0.08	0.68	0.00	0.00
Max	0.32	0.93	0.32	0.89	0.25	0.93
Count (n)	23	23	5	5	18	18
COV	1.06	0.95	0.51	0.10	1.25	1.21

	Overall		Dormant Season		Growing Season		Growing Season w/o 2008-10-24 Storm	
WS80	**ROC**	**TSR**	**ROC**	**TSR**	**ROC**	**TSR**	**ROC**	**TSR**
Mean	0.17	0.34	0.24	0.49	0.13	0.25	0.09	0.21
Median	0.15	0.28	0.22	0.57	0.02	0.13	0.02	0.12
SD	0.17	0.26	0.13	0.21	0.17	0.26	0.12	0.22
Min	0.00	0.01	0.09	0.22	0.00	0.01	0.00	0.01
Max	0.57	0.74	0.46	0.70	0.57	0.74	0.34	0.69
Count (n)	20	20	7	7	13	13	12	12
COV	0.99	0.78	0.54	0.42	1.36	1.02	1.28	1.05

Notes: SD, standard deviation; CV, coefficient of variation.

TABLE 4. Summary of Linear Regression Results for Relationships Between Antecedent Moisture Condition (AMC) Parameters, Direct Runoff Coefficients (ROC) and Total Storm Response (TSR), and Water Table and Initial Outflow.

	AMC Parameters			
	Initial Outflow (m^3/h)	**API-5 (mm)**	**API-30 (mm)**	**Water Table Elevation (m ASL)**
ROC regressions				
UDC				
R^2	0.78	0.00	0.02	0.54
p-Value	$p < 0.01$	0.93	0.52	$p < 0.01$
WS80				
R^2	0.25	0.01	0.01	0.31
p-Value	0.03	0.78	0.66	0.01
WS80*				
R^2	0.50	0.03	0.00	0.42
p-Value	$p < 0.01$	0.46	0.86	$p < 0.01$
TSR regressions				
UDC				
R^2	0.56	0.01	0.00	0.53
p-Value	$p < 0.01$	0.71	0.86	$p < 0.01$
WS80				
R^2	0.29	0.01	0.03	0.45
p-Value	0.01	0.69	0.50	$p < 0.01$
WS80*				
R^2	0.41	0.02	0.02	0.49
p-Value	0.00	0.52	0.62	$p < 0.01$

Water Table Vs. Initial Outflow	**UDC**	**WS80**
R^2	0.56	0.24
p-Value	$p < 0.01$	0.03

Notes: ASL, above sea level; Upper Debidue Creek (UDC); Watershed 80 (WS80); API-5 and API-30 are antecedent precipitation indices for 5 and 30 days prior to event, respectively; and WS80* indicates analyses performed omitting the storm on October 24, 2008.

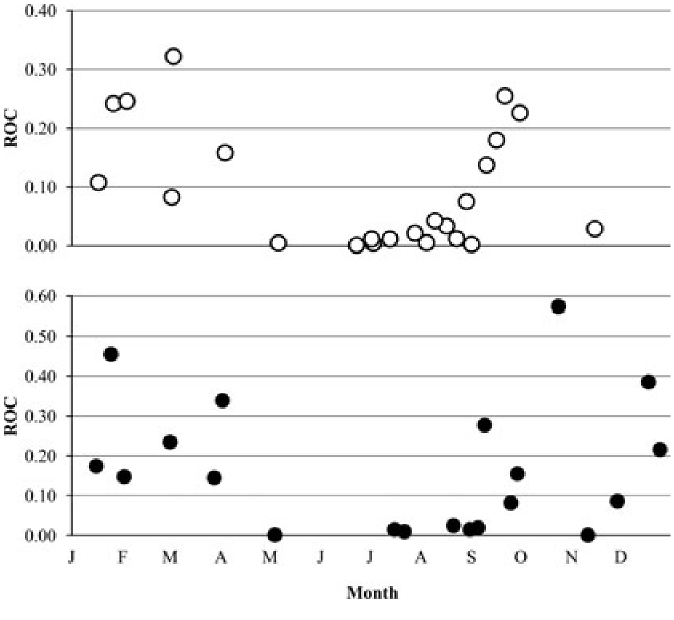

FIGURE 3. Direct Runoff Coefficients (ROC) by Month for (top) Upper Debidue Creek (UDC) and (bottom) Watershed 80 (WS80) Storm Events for the Three-Year Period.

Similarly, the mean ROC had similar seasonal differences on the two watersheds. At UDC, the dormant season mean ROC of 0.20 was higher than the 0.07 mean ROC measured for growing season storm events ($p < 0.01$). There was no difference in mean ROC between dormant (0.24) and growing season (0.13) storm events on WS80 at the 95% confidence level ($p = 0.07$). The mean ROC at WS80 for the growing season events was 0.13 and the median value was 0.02. This difference is due to the effect of the very high ROC value for this storm. By omitting the storm event on October 24, 2008 at WS80, the dormant season mean ROC of 0.24 was higher than the revised growing season mean ROC of 0.09 ($p < 0.01$). The relationships between rainfall and runoff generation measured by linear regression are summarized in Table 4. This relationship was only significant for the ROC at WS80 ($R^2 = 0.23$, $p = 0.03$). There was no significant ($\underline{\alpha} = 0.05$) relationship between rainfall and ROC at UDC or between rainfall and TSR at either watershed.

Previous studies of headwater catchments in the LCP have reported variable annual outflows as a percentage of rainfall. Amatya *et al.* (2006) measured total annual outflow depth as a percentage of rainfall over a long-term dataset covering 23 years on two first-order forested watersheds in the Francis Marion National Forest located in the LCP of South Carolina. Results ranged from 0.05 to 0.59 on the control watershed (WS80) and from 0.09 to 0.44 on the treatment watershed (Watershed 77 [WS77]). Differences in total outflow between years are due to variations both in the temporal distribution of annual rainfall and the AMC at the time of rain. In coastal forest water budgets, the relationship between rainfall and outflow production is affected by soil-moisture levels that are influenced by the shallow water table (Amatya and Skaggs, 2011). Harder *et al.* (2007) computed water budgets for WS80 over two consecutive years and measured a total outflow depth as a percentage of rainfall of 0.47 for 2003 and 0.08 for 2004. This range in outflows between years was partially due to differences in annual rainfall (1,670 and 960 mm, respectively) and partially due to differences in AMC. Several large storms during 2004 resulted in only moderate-to-low outflows, and this was linked to lower water table elevations at the time of rainfall that characterize dry AMC as was also shown by Dai *et al.* (2010) in their modeling study. In a coastal North Carolina study, Amatya *et al.* (2000) found the drainage outflow as a percentage of rainfall varying from 0.02 for a dry summer period with water table as deep as 2.3 m to as much as 0.89 for a wet winter event with near-surface water table for a drained pine forested watershed. These authors also reported that the amount of rainfall needed to generate a drainage event depends upon the AMC as represented by initial flow rate in their study. In another study, Sun *et al.* (2002) compared the hydrologic response of two flat LCP watersheds in North Carolina (NC) and Florida (FL) to a high-gradient watershed with considerable topographic relief in the Appalachian region of North Carolina (AP) using long-term precipitation and flow data. The AP watershed demonstrated higher results (0.53) compared with the two lowland watersheds (0.30 for NC, 0.13 for FL). Climate variability was one factor for the difference, with average annual precipitation of 1,730 mm for the AP watershed and 1,520 and 1,260 mm for the LCP watersheds in NC and FL, respectively. Outflow in the high-gradient watershed had consistent base-flow contributions and flowed constantly during the study period. Intermittent flow was observed on the LCP streams reflecting variable water table elevation and intermittent groundwater discharges. Variable AMC affects base flows as these conditions change and stream outflows behave accordingly. These observations are consistent with Todd *et al.* (2006) who reported that hydrologic processes in wetland-dominated basins are inconsistent with some aspects of the variable source area concept of streamflow generation. Some parts of the basin may become decoupled from the basin outlet as summer progresses. Runoff from these portions of the watershed may be lost to evaporation and infiltration or held in surface storage even before reaching the outlet.

Antecedent Moisture Conditions

The range in ROC and TSR values were hypothesized to coincide with seasonal trends in AMC. The results of linear regressions performed to assess the relationships between measures of AMC and runoff generation are summarized in Table 4. Runoff generation does not have a strong relationship to rainfall due to the variable AMC on LCP headwater streams. Variable AMC produces a range of ROC and TSR for similar rainfall depths due to differences in runoff generation mechanisms. Other studies have also shown that storm-event outflows and runoff generation on these LCP headwater catchments are not well predicted by rainfall alone (Harder *et al.*, 2007; La Torre Torres *et al.*, 2011).

The relationship between initial outflow and the ROC and TSR was significant at both UDC and WS80. At UDC, initial outflow rate explained a larger percentage of the variability for ROC ($R^2 = 0.78$, $p < 0.01$) and TSR ($R^2 = 0.56$, $p < 0.01$) than at WS80 ($R^2 = 0.25$, $p = 0.03$ for ROC; $R^2 = 0.29$, $p = 0.01$ for TSR). The relationship at WS80 was greater when the October 24, 2008 storm was omitted for both ROC ($R^2 = 0.50$, $p < 0.01$) and TSR ($R^2 = 0.41$, $p < 0.01$). Outflow in these headwater streams is a result of gravity-driven groundwater drainage and storm-event surface runoff. The magnitude of initial outflow shows a significant ($\alpha = 0.05$) relationship to runoff generation as a measure of the AMC for these streams. Because outflows are influenced by groundwater elevation, the initial water table elevation also shows a significant relationship to runoff generation. A larger portion of the variability in ROC was explained by the water table elevation as AMC at UDC ($R^2 = 0.54$, $p < 0.01$ for ROC; $R^2 = 0.53$, $p < 0.01$ for TSR) than at WS80 ($R^2 = 0.31$, $p = 0.01$ for ROC; $R^2 = 0.45$, $p < 0.01$ for TSR). This relationship improved at WS80 again with the omission of the October 24, 2008 storm for ROC ($R^2 = 0.42$, $p < 0.01$) and TSR ($R^2 = 0.49$, $p < 0.01$). These observed results are consistent with Amatya *et al.* (2000), who used the initial outflow rate as the AMC in their study.

Furthermore, there was no significant relationship between API and ROC or TSR using the 5- or 30-day API measure. Therefore, antecedent precipitation is not considered to be a good estimate of AMC as it relates to runoff generation predictions for these watersheds. Similar results were also demonstrated in the study by La Torre Torres *et al.* (2011), where selected storms from a long-term dataset at Watershed 78 (WS78) in the Francis Marion National Forest in the LCP of South Carolina were separated according to the wet (December to May) and dry seasons (June to November). Results demonstrated a significant relationship between rainfall and TSR during the wet season ($R^2 = 0.68$, $p < 0.01$) and less so during the dry season ($R^2 = 0.19$, $p = 0.02$). Rainfall accounts for a lower amount of variability in TSR during the dry months due to lower water table elevation and higher soil storage caused by increased evapotranspiration demands. The authors also suggested that the event runoff was controlled mainly by rainfall amount and the AMC represented by the initial flow rate.

Outflows from UDC and WS80 were not driven by rainfall alone because of variable AMC, consistent with Todd *et al.* (2006) who noted that the vertical water movement due to rainfall, evapotranspiration, and deep seepage was more important than the lateral groundwater flux in explaining the wetland's hydrologic behavior. Harder *et al.* (2007) showed that the temporal distribution of rainfall as related to AMC has more influence on outflow production than only rainfall total amounts alone. Sun *et al.* (2002) analyzed total outflows related to isolated storm events on the LCP FL watershed. Storms were selected to assess outflow differences generated by both small and large events and for both dry and wet AMC. The magnitude of streamflow prior to rainfall, relative to typical outflows on the watershed, was used to differentiate between dry and wet AMC. Small storms in the range of 30-59 mm demonstrated lower storm outflow depths on the FL watershed that were consistent with lower annual outflows. Large storms in the range of 102-160 mm demonstrated lower storm flows at the FL watershed for dry AMC (0.08 as a ratio of event rainfall) and much higher storm flows for wet AMC (0.58 as a ratio of event rainfall). The large increase in outflow production in the rainfall response from dry AMC to wet AMC at FL demonstrates the role of soil storage on outflow production on these LCP headwater streams. The dry AMC is associated with lower water table elevations and higher soil storage that is filled before runoff is generated. The wet AMC is characterized by high water table elevations with low soil storage, and these conditions generate runoff rapidly under saturated conditions (Amatya and Skaggs, 2011).

Influence of Water Table Elevation

For LCP watersheds, the assessment of outflow response to rainfall is often complicated by the interaction between groundwater discharges and surface water generation. Water table dynamics that are influenced by climate and evapotranspiration contribute to variable AMC on LCP headwater streams, resulting in a highly variable range of outflows as a percentage of rainfall on both an annual basis and between storm events and thus making watershed outflows difficult to predict. Higher groundwater elevations contribute to sustained base-flow conditions and higher runoff generation typically occurred during the winter months of December, January, and February (Tables 1 and 2) as previously noted. Because sustained base flow that is not directly influenced by rainfall on these headwater streams consists of groundwater discharges, initial outflows were compared with initial water table elevation to determine how closely they were related. A significant relationship was determined for both the watersheds. Initial outflow rate, ROC, and TSR all display a similar nonlinear relationship to initial water table elevation on both the watersheds (Figures 4 and 5). Lower watershed outflows are associated with low water table elevations prior to a given storm event, and low surface runoff generation remains fairly constant as water table elevation increases to the surface toward saturation. The initial water table elevation accounted for more variability in initial outflow measured on the UDC watershed ($R^2 = 0.56$, $p < 0.01$) than at WS80 ($R^2 = 0.24$, $p = 0.03$). These results may be partially due to differences in well placement between the watersheds and by differences in topography. However, the much lower gradient at UDC is likely to influence a closer relationship between groundwater fluctuations and streamflow dynamics. Analyses of these results demonstrate a significant relationship between water table elevation and outflow rates that was consistent with the relationship between water table elevation and runoff generation in these headwater streams.

A previous investigation of the rainfall response at UDC showed that groundwater elevations tracked the stream outflow hydrograph closely, and the ROC increased with consecutive storm events over a short time period that contributed to wet watershed conditions (Rogers *et al.*, 2009). A threshold groundwater elevation exists for each watershed that is typically consistent for initial outflow rate, ROC, and TSR, at which the relationship between the water table elevation and runoff generation diverges (Figures 4 and 5). This groundwater elevation is 0.84 m below ground surface (bgs) at UDC and 0.4 m bgs at WS80 at the respective monitoring wells from this study. Groundwater elevations above this level displayed a nearly linear increase in outflow and runoff generation. Segmented regression results are summarized in Table 5 and show an average breakpoint of 3.35 m ASL at UDC and 8.68 m ASL at WS80. Similar hy-

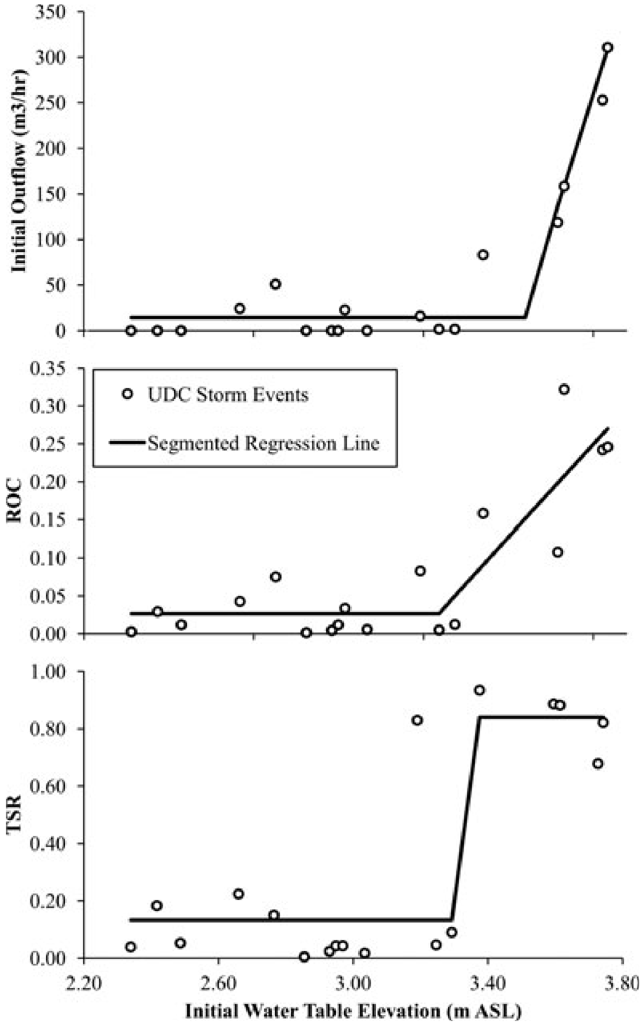

FIGURE 4. Segmented Regression Results for Upper Debidue Creek (UDC) Compared to (top) Initial Outflow Rate Plotted Against Initial Water, (middle) Direct Runoff Coefficients (ROC), and (bottom) Total Storm Response (TSR).

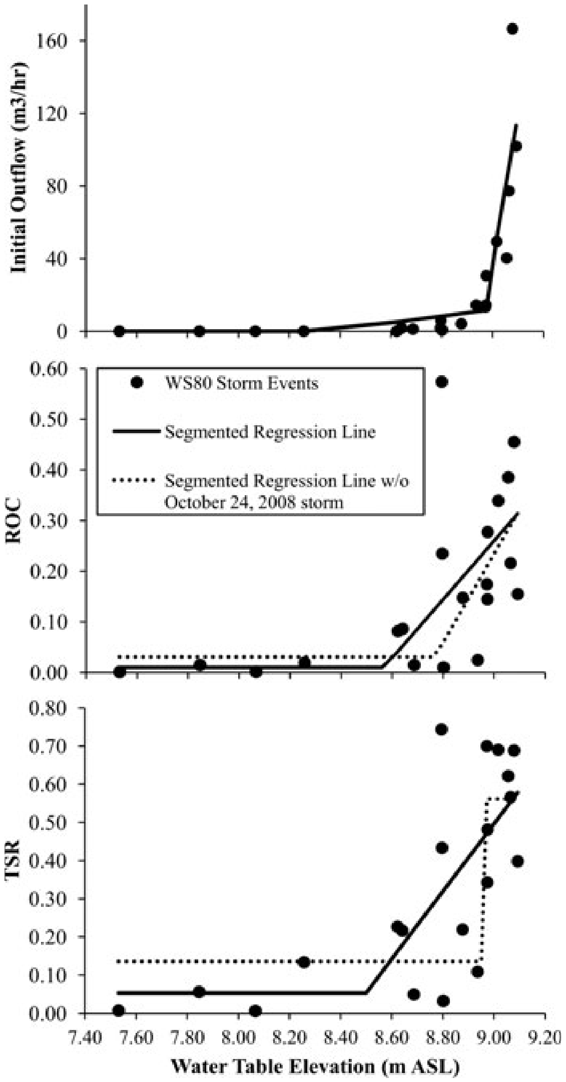

FIGURE 5. Segmented Regression Results for Watershed 80 Compared to (top) Initial Outflow Rate, (middle) Direct Runoff Coefficients (ROC), and (bottom) Total Storm Response (TSR).

drographical analyses using soil-moisture indices in other watershed studies have shown segmented relationships and provided breakpoint elevations, notably in till-mantled headwater catchments (Detty and McGuire, 2010).

Outflows were found to track groundwater elevations in close relationship for these streams as also shown by Harder *et al.* (2007) in previous studies for similar watersheds. Using 2003-2004 data, Harder *et al.* (2007) also found a significant ($\alpha = 0.05$) nonlinear power relationship between water table and outflow generation on the WS80 watershed. These results support the findings of Williams (2007) who observed that groundwater elevations below a similar threshold level (approximately 1 m bgs at the watershed divide for the coastal watershed studied near Georgetown) were associated with high soil storage capacity and low runoff generation. Williams (2007) also observed a nonlinear relationship between rainfall and direct runoff estimates in an LCP headwater stream. Runoff generation mechanisms unique to LCP hydrology were related to water table elevation. Base-flow levels were modeled by a graphical hydrograph separation method that accounts for accelerated groundwater discharges in the rainfall response. Most recently, Callahan *et al.* (2011) estimated total recharge to groundwater for the same LCP watershed studied by La Torre Torres *et al.* (2011) by analyzing water table response to storm events and the rate at which water was transferred into shallow groundwater. The authors attributed the difference found in two methods of estimating recharge – water table fluctuation method and the

TABLE 5. Summary of Segmented Regression Results for Initial Outflow Rate, Direct Runoff Coefficients (ROC), and Total Storm Response (TSR) Against Water Table Elevation.

	Initial Outflow Rate (m^3/h)	**ROC**	**TSR**	**Average Break Point (m ASL)**
UDC				
Break point	3.50	3.25	3.29	3.35
R^2	0.936	0.778	0.745	
p-Value	$p < 0.01$	$p < 0.01$	$p < 0.01$	
WS80				
Break point	8.97	8.56	8.5	8.68
R^2	0.800	0.342	0.528	
p-Value	$p < 0.01$	$p < 0.01$	$p < 0.01$	

Notes: ASL, above sea level; Upper Debidue Creek (UDC); Watershed 80 (WS80).

TABLE 6. Summary of Descriptive Statistics for Direct Runoff Coefficients (ROC), and Total Storm Response (TSR) Separated Between Dry and Wet Antecedent Moisture Conditions (AMC) According to Water Table Elevation for Upper Debidue Creek (UDC) and Watershed 80 (WS80).

	Dry AMC		**Wet AMC**	
	ROC	**TSR**	**ROC**	**TSR**
UDC				
Mean	0.02	0.13	0.22	0.84
Standard error	0.01	0.06	0.04	0.04
Median	0.01	0.05	0.24	0.88
Standard deviation	0.03	0.22	0.08	0.10
Minimum	0.00	0.00	0.11	0.68
Maximum	0.08	0.83	0.32	0.93
Count (n)	13	13	5	5
WS80				
Mean	0.03	0.11	0.23	0.43
Standard error	0.02	0.04	0.04	0.07
Median	0.02	0.10	0.19	0.46
Standard deviation	0.04	0.10	0.17	0.25
Minimum	0.00	0.01	0.01	0.03
Maximum	0.09	0.23	0.57	0.74
Count (n)	6	6	14	14

Darcy equation – to evapotranspiration and AMC not accounted for in the Darcy method.

The relationship between water table elevation and initial outflow rate, ROC, and TSR all improved when modeled by a segmented regression for both the watersheds. These results (summarized in Table 5 and displayed graphically in Figures 4 and 5) demonstrate the significance of this breakpoint water table elevation in predicting outflow and runoff generation on these LCP headwater streams. Results suggest that this groundwater elevation may have physical significance on these watersheds that is related to runoff generation. A breakpoint water table elevation could dictate the rainfall response on these watersheds between dry and wet AMC. Rain events that occur when the water table elevation is below the breakpoint could be expected to produce very moderate amounts of runoff for dry AMC. When the water table elevation is above the breakpoint, substantial runoff generation would be expected under higher water table conditions.

Storm events with water table elevation below the calculated breakpoint were designated as dry AMC, whereas those with water table elevation above the breakpoint were designated as wet AMC. Descriptive statistics of wet and dry AMC are summarized in Table 6. The mean TSR for dry AMC storms was significantly lower ($\alpha = 0.05$) than that for wet AMC storms at UDC ($p < 0.01$) and at WS80 ($p < 0.01$). Mean ROC was similarly lower for dry AMC storms than wet AMC storms at UDC ($p < 0.01$) and at WS80 ($p < 0.01$). These results were similar to the observed differences in seasonal runoff generation and highlights seasonal trends in AMC. Storms that are categorized as wet or dry AMC based on water table elevation were observed during both the dormant and growing season, but the majority of dry AMC storm events were observed during the growing season and wet AMC storms during the dormant season. Variability in rainfall patterns from year to year and also on a seasonal basis can produce variable moisture conditions on these watersheds, especially during months between periods of high and low evapotranspiration as the groundwater as soil water storage becomes depleted during the spring months or replenished in the fall. This relationship was observed in variable runoff generation at UDC and WS80 during these transitional months (Figures 3 top and 3 bottom) between the wetter winter months and the drier summer months.

La Torre Torres *et al.* (2011) hypothesized that the breakpoint water table elevation at each watershed relates to runoff generation mechanisms that are unique to low topography LCP hydrology and are defined by low gradient, groundwater influence, and soil characteristics. Water table elevations below this level represented a dry AMC associated with higher soil storage capacity that has to be filled by infiltration from a large rainfall amount before runoff responses to the rainfall occur. As water table elevations increased above this level, higher outflow rates prior to rainfall were observed and runoff generation increased for storms that occur during periods of wet AMC. Differences between clayey soils and sandy soils in soil storage capacity, infiltration, and hydraulic conductivity influence runoff generation dynamics and contribute to differences between breakpoint water table elevations at the two locations because of the effect that these soil properties have on the movement of runoff and groundwater toward the stream. Our results were also consistent with observations noted by Todd *et al.* (2006), who reported that some parts of the basin may become decoupled from the basin outlet as summer progresses and their runoff may be lost to evaporation and infiltration or held in surface storage even before reaching the outlet. Saturation excess overland flow is the dominant source for runoff generation on low-gradient forested watersheds in the LCP (Eshleman *et al.*, 1994; Slattery *et al.*, 2006; Williams, 2007). It has been postulated that, as the groundwater elevation increases, the area of saturation near the stream increases and larger areas contribute to saturated excess overland flow, producing greater runoff (Eshleman *et al.*, 1994). Accelerated groundwater contributions to outflow are also believed to increase as the water table elevation rises above this breakpoint level due to a greater hydraulic gradient toward the stream and the potential for piston flow discharges (Williams, 2007). The differences between base-flow apportionment between the TSR and ROC coefficients highlight differences in runoff generation on these two watersheds.

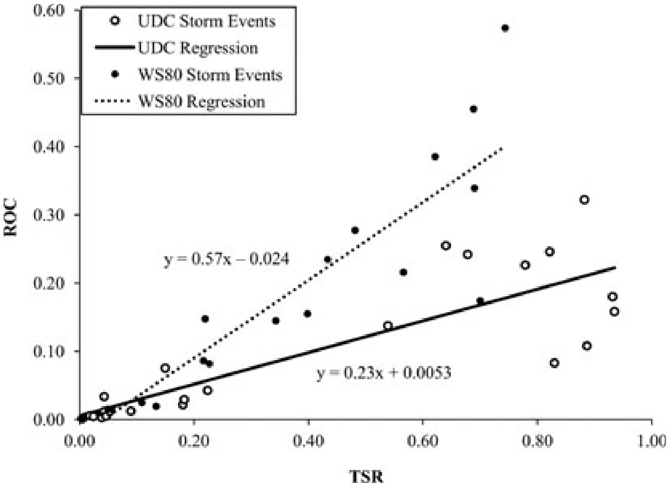

FIGURE 6. Direct Runoff Coefficients (ROC) Plotted Against Total Storm Response (TSR) for Storm Events from Both Upper Debidue Creek (UDC) and Watershed 80 (WS80) Watersheds. Coefficient of determination (R^2) values were 0.713 (p-value <0.01) and 0.814 (p-value <0.01), respectively.

Accounting for Base Flow

Linear regression results between TSR and ROC demonstrated that the two measures of runoff have good agreement for storm events at UDC ($R^2 = 0.71$, $p < 0.01$) and at WS80 ($R^2 = 0.81$, $p < 0.01$). The relationship between TSR and ROC at each watershed approximated the additional direct runoff that was calculated by the ROC model as the watershed produced more total outflow when modeled by the TSR method (Figure 6). The slope of the trend line at UDC was 0.23 (p-value <0.01), less than half that found for WS80, where the slope of the trend line was 0.57 (p-value <0.01). Estimates of direct runoff at WS80 increased more than twice as quickly than at UDC with increasing TSR. Additionally, the difference between peak outflow rate and the initial outflow rate were higher on average at WS80 than at UDC ($p = 0.01$). Higher peak outflows and greater direct runoff generation at WS80 likely result from clayey soils that are less infiltrative than sandy soils at UDC and generate greater surface-driven runoff in response to rainfall.

Mean ROC and TSR values were similar at both watersheds for dry AMC storm events (Table 6). Mean ROC was 0.02 at UDC and 0.03 at WS80, and mean TSR was 0.13 at UDC and 0.11 at WS80. No significant difference in mean ROC or mean TSR was found between UDC and WS80 ($\alpha = 0.05$). Base flows for dry AMC storms are low due to smaller groundwater contribution. The similar results for mean ROC and TSR at UDC and WS80 reflect similar runoff generation mechanisms on both watersheds for dry conditions. Mean ROC was similar on both the watersheds for wet AMC storm events, measuring 0.22 at UDC and 0.23 at WS80. No significant difference between the means was found ($\alpha = 0.05$). Although the ROC model had demonstrated similar direct runoff contributions to outflow for both the watersheds under wet conditions, the same was not true for the calculated TSR results. Mean TSR for wet AMC storms at UDC (0.84) was significantly greater than at WS80 (0.43) by comparison ($p < 0.01$). Under wet conditions with high groundwater elevation, model results demonstrated much larger total outflow generation in the rainfall response for the UDC watershed but ROC estimates were similar for both watersheds. The TSR model for runoff generation does not account for accelerated groundwater contributions in the rainfall response. The difference in results between the two watersheds based on mean TSR indicates that this base-flow component was greater at UDC than at the WS80. Groundwater contributions to outflow may not be directly attributable to new rainfall inputs for a storm event, especially when the groundwater elevation is higher during wet AMC storm events.

There was a stronger relationship between water table elevation and runoff generation measures at UDC than at WS80 (Table 4). This comparison indicates that groundwater-driven base-flow contributions were more closely tied to runoff generation at UDC than at WS80. Runoff generation for similar watersheds was better estimated by the ROC model because it accounts for accelerated base-flow contributions. The relationship between water table elevation and runoff generation is also strong at WS80 as was also shown earlier by Harder *et al.* (2007). Higher direct runoff generation and higher peak outflow rates would be the result of clayey soils that generate additional surface-driven runoff. These site-specific soil characteristics may explain the relationship between rainfall and ROC that was observed. Groundwater elevations display a significant ($\alpha = 0.05$) relationship with ROC and TSR for both of these LCP headwater streams, and seasonal trends in antecedent moisture levels related to the groundwater elevation determine the stream response to rainfall.

CONCLUSIONS

The runoff response to rainfall on LCP headwater streams is not easy to characterize due to variable moisture conditions and the range of other parameters affecting the soil moisture. Runoff generation cannot be predicted by rainfall alone for any given storm event, nor is antecedent precipitation a good indicator of the AMC. The 5- and 30-day API did not appear to have a direct relationship with runoff generation, but they likely influence water table elevations indirectly by infiltrative replenishment of the perched water table subject to evapotranspirative demands. There was a stronger relationship between initial outflow and water table elevation with the ROC and TSR coefficients at UDC than at WS80. The influence of the perched water table on outflow generation seems to best determine the rainfall response. Outflows and runoff generation were clearly related primarily to varying water table elevations. The relationship between the water table elevation, runoff amount, and event outflows on these watersheds appears to change at a given breakpoint elevation. Water table elevations below this level define dry AMC, and low runoff generation in this condition typically results due to high soil storage and possibly disconnected surface (due to microtopography) as well as groundwater. Water table elevations above this level define wet AMC, and high runoff generation occurs due to saturated conditions. Stronger relationships between water table elevation and outflows at UDC suggest that groundwater and surface water generation may be more closely related on LCP headwater streams with sandy soils than on watersheds with clayey soils like WS80. For these watersheds with sandy soil, groundwater contributions to outflow represent a greater portion of streamflows, and runoff estimates may be better predicted by the ROC. Watersheds in the LCP with clayey soils also demonstrate a strong relationship between water table elevation and runoff generation, but surface-derived runoff may occur at a more substantial level on these watersheds due to less infiltrative soils. These results can guide land use and water resource management decisions, specifically with respect to stormwater management requirements for residential and commercial development that consider not only surface water but also groundwater.

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