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Seasonal rainfall–runoff relationships in a lowland forested watershed in the southeastern USA

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Abstract:

Hydrological processes of lowland watersheds of the southern USA are not well understood compared to a hilly landscape due to their unique topography, soil compositions, and climate. This study describes the seasonal relationships between rainfall patterns and runoff (sum of storm flow and base flow) using 13 years (1964–1976) of rainfall and stream flow data for a low-gradient, third-order forested watershed. It was hypothesized that runoff–rainfall ratios (R/P) are smaller during the dry periods (summer and fall) and greater during the wet periods (winter and spring). We found a large seasonal variability in event R/P potentially due to differences in forest evapotranspiration that affected seasonal soil moisture conditions. Linear regression analysis results revealed a significant relationship between rainfall and runoff for wet ($r^2 = 0{\cdot}68$; $p < 0{\cdot}01$) and dry ($r^2 = 0{\cdot}19$; $p = 0{\cdot}02$) periods. Rainfall-runoff relationships based on a 5-day antecedent precipitation index (API) showed significant ($r^2 = 0{\cdot}39$; $p < 0{\cdot}01$) correspondence for wet but not ($r^2 = 0{\cdot}02$; $p = 0{\cdot}56$) for dry conditions. The same was true for rainfall-runoff relationships based on 30-day API ($r^2 = 0{\cdot}39$; $p < 0{\cdot}01$ for wet and $r^2 = 0{\cdot}00$; $p = 0{\cdot}79$ for dry). Stepwise regression analyses suggested that runoff was controlled mainly by rainfall amount and initial soil moisture conditions as represented by the initial flow rate of a storm event. Mean event R/P were higher for the wet period (R/P = 0·33), and the wet antecedent soil moisture condition based on 5-day (R/P = 0·25) and 30-day (R/P = 0·26) prior API than those for the dry period conditions. This study suggests that soil water status, i.e. antecedent soil moisture and groundwater table level, is important besides the rainfall to seasonal runoff generation in the coastal plain region with shallow soil argillic horizons. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS stream flow; base flow; peak flow rates; runoff-rainfall ratio; evapotranspiration; antecedent precipitation index; antecedent soil moisture conditions

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INTRODUCTION

The hydrologic dynamics of low-gradient, forested watersheds in coastal plains differ considerably from upland environments primarily due to climate and land topography (Sun *et al*., 2002, 2008a). Understanding the differences and the hydrologic processes of these systems is fundamental to provide reference data for designing Best Management Practices (BMPs) in developing landscapes in the region. Hydrologic processes in upland areas are mainly influenced by steep gradient profiles and hillslope processes (i.e. interflow, sheetflow, and overland flow) and less influenced by soil composition (Markewich *et al*., 1990). Nonetheless, soil composition in Lower Coastal Plain (LCP) environments plays a major role in runoff responses due to the presence of very to moderately poorly drained soils in a low-topographic relief area with argillic horizons ranging from 2 to 8 m (Markewich *et al*., 1990; Skaggs *et al*., 1991; Amatya *et al*., 1996, 2002; Slattery *et al*., 2006). Soil composition determines the movement of throughfall through the soil whether it is by absolute infiltration or in a form of infiltration excess such as Hortonian overland flow, subsurface storm flow, or saturation excess overland flow (Wickel *et al*., 2008). The probability of rapid overland flow in response to a storm event is low due to the low-topographic gradient characteristic of LCP watersheds (see Gonzales *et al*., 2009, for example), whereas the effect is more likely in mountainous watersheds where subsurface quick flows are the major sources of stream flow (Sun *et al*., 2008b). Conversely, saturation excess overland flow becomes more important to stream flow contribution due to shallow water table positions distinctive of the coastal plain region (Amatya and Radecki-Pawlik, 2007; Harder *et al*., 2007; Sun *et al*., 2008b; Amatya *et al*., 2009).

Another factor that influences the hydrologic dynamics of LCP watersheds with shallow water tables is evapotranspiration (ET). ET is mainly influenced by solar energy, and also by soil properties and vegetation type and seasonal dynamics (Amatya and Trettin, 2007; Sun *et al*., 2010). The LCP environment is generally characterized by a dense distribution of pine forest stands in the uplands and mixed pine and deciduous forest in

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the low-lying areas. On average, 70% of the annual precipitation can be lost to the atmosphere as ET in these landscapes (Amatya *et al.*, 2002, 2009; Lu *et al.*, 2005; Amatya and Trettin, 2007; Sun *et al.*, 2010), thus only 30% of the remaining water could be distributed as storm flow and/or drainage from the subsurface system. Sun *et al.* (2010) found that annual ET is significantly higher (1011–1226 mm/year) in a loblolly pine plantation than at a clear cut site (755–855 mm/year) due to a higher reception of net radiation related to its lower averaged albedo. This is consistent with past studies that suggested that the 'water rich' state of the Atlantic Coastal Plain of the U.S., with shallow water table conditions, results in low stream flow due to high water loss through ET (Sun *et al.*, 2005; Amatya *et al.*, 1996, 2002; Amatya and Trettin, 2007). Other studies have shown that the removal of trees in a forested watershed temporarily reduces ET and causes an increase in stream flow and elevated water table (Amatya *et al.*, 2006a; Lu *et al.*, 2009; Sun *et al.*, 2010). A cross-regional study suggests that higher stream flows and R/P typically are associated with mountainous areas (Sun *et al.*, 2002), whereas smaller R/P are expected for the LCP (Amatya *et al.*, 1997, 2000) due to differences in climate, topography, and soil water storage capacity. Sun *et al.* (2008a,b) argue that runoff in the LCP has a much larger variability than upland watersheds due to the wide range of variable source area, including ephemeral water storage in depressions in a low gradient terrain.

In addition to ET the water table position, as influenced by soil properties and ET rates, is also important in controlling runoff responses in a low-topographic gradient watershed. Water table depth influences soil saturation and the hydrologic response to storm events (Wei *et al.*, 2007). Studies have found that depending on the soil moisture condition, watersheds were highly responsive to rainfall by producing more frequent and greater amounts of runoff, with peak flow rates also depending upon the surface depressional storage (Amatya *et al.*, 1997, 2000; Slattery *et al.*, 2006; Harder *et al.*, 2007). Furthermore, some rainfall–runoff simulation models have demonstrated that the antecedent soil moisture condition (ASMC) correlated to the portioning of rainfall into infiltration and storm flow (Ye *et al.*, 1997; Wei *et al.*, 2007; Tramblay *et al.*, 2010). Seasonal climate variability influences both the soil moisture and the characteristics of the storm events that in turn affect the runoff generation pattern. Some of these characteristics are rainfall volume, intensity, frequency, duration, and direction (Singh, 1997). In South Carolina USA, average annual rainfall ranges from 1168 to 1270 mm and is generally greatest near the coast (Newcome, 1988). During a wet season more than 50% of the rainfall can be routed to stream flow under low evaporative demand (i.e. winter months) and high ASMC compared to only 20% during the summer period with high ET, except during tropical storms (Amatya *et al.*, 1996, 2000, 2006b). For this reason, to predict the runoff response to the rainfall at a seasonal scale it is important to know the meteorological patterns and a threshold value for ASMC for a specific location (Mahanama *et al.*, 2008). Although the antecedent condition of the watershed influences water availability for runoff, ET, and infiltration via soil water storage, it is highly variable and uncertain because of the difficulty in separating the functions of topography, soils, vegetation, and climate affecting water yield values (Sun *et al.*, 2002).

Dating back to the early 1960s, studies in the LCP have essentially focused on documenting the effects of watershed size on rainfall–runoff relations of forested watersheds Young and Klawitter (1964). Recently, the hydrology and water quality dynamics as affected by forest vegetation type at two first-order LCP watersheds of 160 ha each were studied by Amatya *et al.* (2006c) and Amatya *et al.* (2007). Similarly, Miwa *et al.* (2003) examined the role of drainage patterns on hydrologic dynamics of the same two watersheds. These authors observed that runoff was strongly influenced by precipitation and watershed characteristics like vegetation, as well by ASMC. Additional studies examined the stream flow and flooding dynamics of three forested watersheds (first-, second-, and third-order; Amatya and Radecki-Pawlik, 2007) and found that greater R/P were associated with the largest watershed due to longer sustained base flow. For the first-order watershed (160 ha), Harder *et al.* (2007) found that runoff was sensitive to rainfall event size, frequency, and water table position prior to storm events.

To date, the relationship between rainfall and runoff has not been examined for larger forested watersheds in the LCP. Recently, Bradley (2010) has postulated that the type of flooding pattern in (upper) Coastal Plain watersheds can affect interchange between stream water and groundwater; in a watershed where heavy sub-soils limited infiltration, hydraulic gradients were positive (stream-to-groundwater), whereas a separate site dominated by sandy soils saw groundwater flooding, represented by groundwater-to-stream water gradients (Bradley, 2010). For the watershed under investigation in this study, most soils at the site have a substantial argillic horizon and therefore a soil moisture storage capacity. Methodology from previous studies in small watersheds (Swindel *et al.*, 1983; Amatya *et al.*, 2000, 2006c; Miwa *et al.*, 2003) for identifying a runoff event as a result of a given rain storm was adapted for a 7260 ha third-order forested watershed, Turkey Creek near Huger, South Carolina. Upscaling existing analytical methods were feasible for the Turkey Creek watershed (Figure 1), as it is a relatively undisturbed forested watershed (Amatya and Radecki-Pawlik, 2007; Amatya *et al.*, 2009).

The main goal of this project was to provide baseline information on rainfall–runoff dynamics at varying temporal scales using 13 years (1964–1976) of historic data from a forested watershed. It was hypothesized that R/P are smaller during the dry (summer–fall) period due to generally reduced flows as a result of increased ET from the forests during the warmer months, as opposed to saturated soils leading to higher ratios due to sustained stream flows in the cooler wet (winter–spring) months of

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the year with low ET demand. Additionally, we postulate that R/P for individual storm events may be directly proportional to the ASMC that could be represented by the initial flow rate of an event and the 5- and 30-day antecedent precipitation index (API) preceding the storm event (Water Harvesting, 1991). Additionally, the same hypotheses were assessed for peak flow rates and rainfall relationships.

METHODS

Site characteristics

The study site is the Turkey Creek watershed (WS 78) (Figure 1) located mainly within and along the USDA Forest Service Francis Marion National Forest (FMNF). FMNF is located along the southeastern coast of South Carolina, which is within the Lower Atlantic Coastal Plain (LCP) physiographic region, covering 1683 km^2 of Berkeley, Charleston, and Dorchester counties (Figure 1). The Turkey Creek watershed is a third-order forested watershed with a topographical relief of 3–15 m above mean sea level, and drains approximately 7260 ha (72·6 km^2). It is located at 33°08′N latitude and 79°47′W longitude approximately 60 km northwest of Charleston near Huger, in Berkeley County of South Carolina (Figure 1).

Climate is classified on the Köppen scale as Temperate and Humid Sub-tropical (Cfa): ‘C’ denotes the temperate zone (one of five major zones ranging from polar to equatorial latitudes); ‘f’ denotes an area that is moist (precipitation); and ‘a’ denotes that the mean temperature of the warmest month is 22 °C, which is characterized by hot, humid summers and mild winters. Long-term (1951–2000) annual air temperature values, recorded at the Santee Experimental Forest (SEF), ranged from −8·5 °C to 37·7 °C, with an average daily temperature of 18·4 °C (Amatya *et al*., 2009). Precipitation occurs uniformly throughout the year and is derived primarily from mid-latitude cyclones (Okolowicz, 1976). Long-term rainfall data (1964–2005) from the station at the SEF showed annual rainfalls varying between 834 and 2106 mm, with July representing the wettest month (187 mm) and November representing the driest month (69 mm) on average (Harder *et al*., 2007). Low intensity, long duration storm events are observed during winter months, whereas high intensity and short duration storms are characteristic of the summer months (Amatya *et al*., 2009; Bosch *et al*., 1999).

Land cover within the watershed consists of 40% pine forest, mostly loblolly (*Pinus taeda L.*) and longleaf pine (*Pinus palustris*), 35% thinned forest, 17% forested wetlands, 5% mixed forest, and 3% agricultural, roads, open, and impervious areas (La Torre Torres, 2008). The author also provided a detailed classification of various types of vegetation on the forest. Overall, the watershed consists of 97% forest vegetation with only about 3% open areas contributing a substantial portion of precipitation to ET. There was only a very little change in land use of this forest during the study period (Amatya and Trettin (2007)). The authors reported the annual ET (as a difference between annual precipitation and streamflow) variation from as low as 830 mm to as high

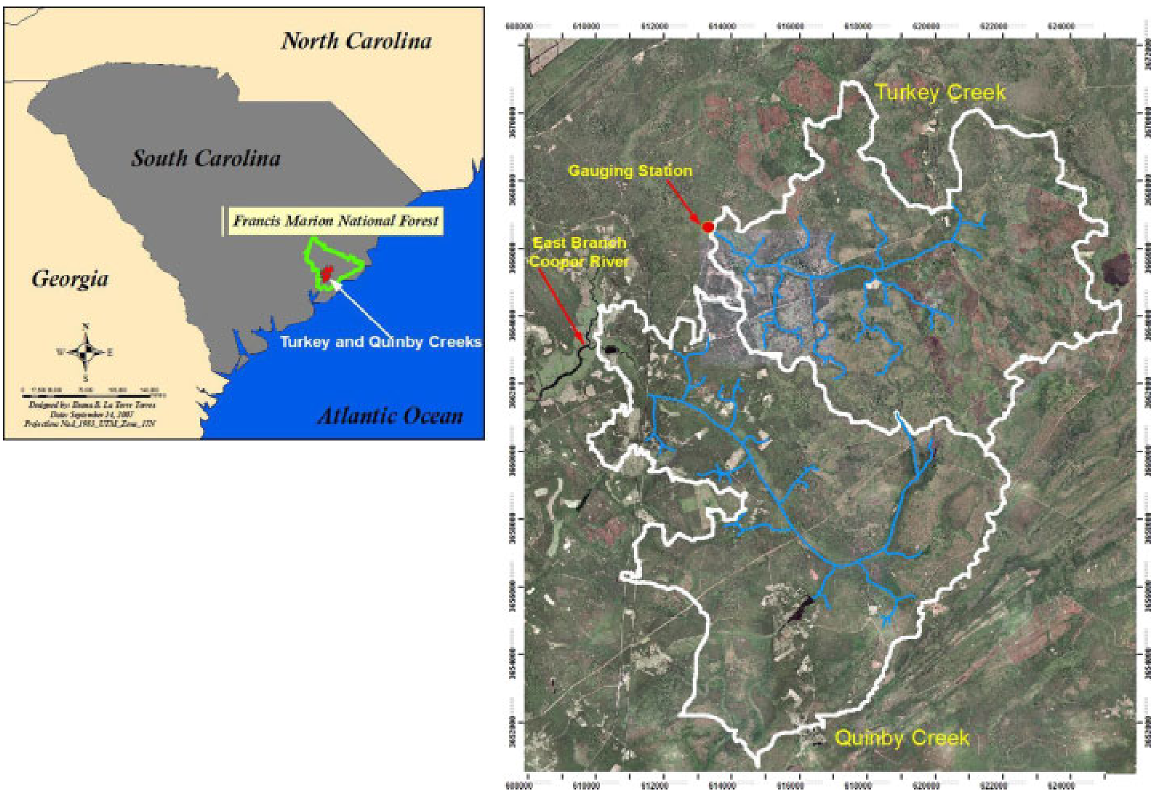

Figure 1. Location map of the Turkey Creek watershed within the southeastern limits of the Francis Marion National Forest, South Carolina

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as 1333 mm with an average of 983 mm for the mean annual precipitation of 1320 mm for the 1964–1976 period same as in this study. This yields an average annual ET of about 74·5% of mean annual rainfall leaving 25·5% for stream flow (runoff). In a similar adjacent control watershed, Harder *et al.* (2007) reported 12% of the precipitation as canopy interception, a part of total ET.

In addition, soil composition is dominated by poorly drained sandy loams of Lynchburg, Wahee, Rains, and Coxville series and very poorly drained loam soils of Byars series (Soil Survey of Berkeley County SC, 1980). All these soil types are of *Ultisol* order with depths of argillic horizons varying from 185 to 203 cm. This shallow depth generally defines the dynamic subsurface storage of this system that receives throughfall infiltration during wet periods and loses water to ET and drainage during dry periods. Permeability ranges from slow to moderate on these soil series, and some soils (Byars) have an average water table position near the ground surface as much as 6 months in most years in undisturbed lands (NRCS, 2009). Water table depths for these soil series, specifically Lynchburg and Rains, are near the surface (<7 cm) for high flow conditions (Amatya *et al.*, 2009). It is these shallow water table depths as a surrogate of soil moisture that drive stream flow (as subsurface flow) and ET in low-gradient system.

Data collection

Rainfall and stream flow data for the period 1964–1976 were obtained from the USDA Forest Service, Center for Forested Wetland Research, and analysed for the Turkey Creek watershed. Rainfall was measured using a manual gauge located on Lotti Road at about 2 km from the stream guage from 1971 onwards (Figure 1). For dates prior to 1971, data were obtained from a weather station located at the Forest Service SEF Headquarters adjacent to the study site, about 5 km from the stream guage (Figure 1). The measurements were mostly on a daily basis except for the holidays and weekends when the rainfall was totaled on the subsequent day. There were eight gauges distributed along the Turkey Creek watershed that collected rainfall data only on a weekly basis for the study period. Uniform rainfall was assumed for event analysis on this study watershed based on the results of the analysis of variance statistical analysis (SAS 9·1·3, 2000–2004), where the seasonal mean rainfall data were found to be statistically insignificant ($\alpha = 0{\cdot}05$) among these gauges (La Torre Torres, 2008).

Stream flow data were collected from a flow gauging station established in 1964 about 800 m downstream of the existing Turkey Creek bridge on Highway 41N, a few kilometers north of Huger, SC (Figure 1). Runoff data were collected at 15-min intervals when the flow occurred otherwise on a 24-h basis (Amatya and Radecki-Pawlik, 2007). Due to the difference in the temporal resolution of the historically collected stream flow and rainfall data, an accurate interpretation of results of rainfall–runoff-analysis conducted herein may pose a challenge. The event-specific stream flow rates (historically reported in ft^3/s) were converted to m^3/s. These data were further integrated to obtain daily flow with respect to watershed area-based depth (mm) by dividing daily runoff volume (m^3) by the watershed area (7260 ha) calculated in a Geographic Information System (La Torre Torres, 2008).

Data assessments

Rainfall and stream flow data from 1964 to 1976 were processed and analysed to study seasonal event rainfall and runoff dynamics as influenced by ASMC. Event runoff characteristics such as initial flow rate, runoff event duration, peak flow rate, time to peak, runoff volume, associated event rainfall amount and R/P were calculated. R/P correspond to the proportion of the associated rainfall that is converted into runoff and is calculated as the ratio of runoff depth by rainfall amounts for individual events (La Torre Torres, 2008). After a detailed examination of the available 13 years of daily rainfall and 15-min stream flow data, we selected storm events based on outflow rates greater than 0·30 m^3/s, total rainfall values greater than 20 mm, and periods of 48 h or more in between rain events (La Torre Torres, 2008). These criteria were arbitrarily selected to identify detectible single peaked events and minimize influence of prior storms on multiple peaks. On these forested watersheds due to their high canopy interception as well as high surface and subsurface storage during dry summer events, there may not be any detectable stream flow for rain amounts of as much as 15–20 mm. Multiple peak events were excluded from this analysis so as not to complicate the identification of storm duration and total storm volume. Similar methodology was used by Swindel *et al.* (1983), Amatya *et al.* (1997; 2000), Swank *et al.* (2001), and Sheridan (2002). Single event peak discharges can also be modelled easier as described by Ogden and Dawdy (2003). Most storm events simulated by SCS TR-55 model are also single events (SCS, 1986). Seasons were grouped as wet (winter–spring: December–May) and dry (summer–fall: June–November) as defined by precipitation patterns, evaporative demands, and water table positions generally distinct in terms of wet and dry seasons for LCP watersheds. Ground water table measurements were not available for the historical period of this study. ASMC was categorized as wet or dry based on an API, defined as the presence of any amount of rain (wet) or complete absence of rainfall (dry) 5 days prior to the start of the runoff event. Additionally, ASMC was also inspected for 30 days prior to the event to explain exceptions to the initial hypothesis that R/P are higher for wet soil conditions compared to dry (based on the 5-day API). Wet conditions for the 30-day period were defined as total rainfall amounts over 100 mm.

Using the above criteria a total of only 41 storm events were identified and evaluated for the 13-year period. La Torre Torres (2008) used 51 storms for only a 10-year (1964–1973) period that included events with multiple peaks also. In other studies Swank *et al.* (2001) used

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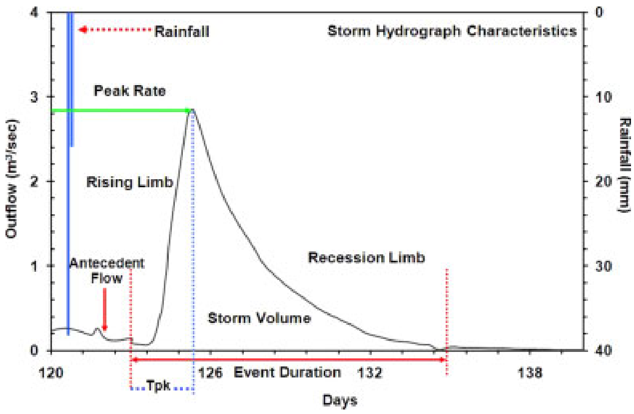

Figure 2. Graphical illustration of storm hydrograph characteristics evaluated in this study (1964–1976). Storm hydrograph represents a summer storm event in 1964 (day = 123·8) with rainfall in mm/day

75 events, Amatya *et al.* (2000) used 29 events, Slattery *et al.* (2006) used 23 events, Sheridan (2002) used 4–9 events for each watershed, and Swindel *et al.* (1983) used 55 storm events. We, therefore, believe our analysis with 41 storm events for testing our hypotheses just fall within the ranges reported in the literature. Total event runoff volumes were calculated as a sum of incremental flow in 15-min intervals divided by the watershed area to obtain runoff in depth. The runoff volume was considered to be the area under the hydrograph from the beginning of its rise until near zero flow or until the next rise as was done by Amatya *et al.* (2000) (Figure 2). Besides the above criteria, the best professional judgement had also to be used to obtain the total rainfall amount most likely contributing to the particular runoff event because the rainfall data were only on a daily basis. This was sometimes a challenge due to the difficulties in identifying an exact rainfall amount separated by 24 h that results in an outflow event. R/P were calculated using the runoff amount and the associated rainfall for the given temporal scale of the analysis. A simple linear regression analysis was used to determine the relationships between runoff and rainfall and also peak flow rate and rainfall with respect to the season and the ASMC. Due to dynamic processes of ET and rainfall affecting the storage and antecedent conditions, the relationship between these two variables will very likely be nonlinear on a small temporal scale (i.e. daily or hourly) basis. However, as the scale becomes larger (i.e. months or years), the relationship may tend to be linear possibly due to smaller change in storage. In this analysis of storm events with an average duration of 12 days, we hypothesized a linear relationship to tease out the effects of storage and ASMC. The equations of the linear regression lines and their parameters were also tested for the statistical significance at 5% level ($\alpha = 0{\cdot}05$) (La Torre Torres, 2008). Additionally, a Standard Stepwise Regression Analysis (SAS 9·1·3, 2000–2004) was used to examine the effects and significance of each of the climatic and ASMC factors on runoff volume and R/P, and reinforce the results of the simple linear regression analysis. The main objective of this analysis was to find the linear models for dependent variables, runoff as well as R/P as a function of the independent variable(s) in order of their significance in explaining the variability. Model diagnostics were calculated to help determine which variable that 'best' predicts runoff response. We incorporated multiple independent variables such as begin flow, event rainfall, 5-day rainfall, 30-day rainfall, and 5-day and 30-day prior potential evapotranspiration (PET) estimated by the Thornthwaite method (Amatya and Trettin, 2007) to better assess their importance on predicting runoff generation and its variability.

In addition, separation of storm flow and base flow for runoff events' hydrographs was conducted by a linear hydrograph separation method derived from an empirical approach developed by Swindel *et al.* (1983) for coastal Florida flatwoods. Storm flow (contributed mainly by overland flow after filling all depressions) and base flow (contributed mainly by subsurface flow when the water table is below the ground surface) were obtained by integrating the separation line with a slope of 0·09 m^3 s^{-1} day^{-1} into the hydrograph for each storm event.

RESULTS AND DISCUSSION

Runoff–rainfall relationships

Hydrologic characteristics for analysed storm events are presented in Table I. Relationships presented are for periods, 5 and 30 days prior API. Results for the linear regression analysis revealed significant ($\alpha = 0{\cdot}05$) correspondence between runoff and rainfall for wet ($r^2 = 0{\cdot}68$; $p = 0{\cdot}00$; Figure 3) and dry ($r^2 = 0{\cdot}19$; $p = 0{\cdot}02$; Figure 3) periods. R/P ranged from 0·01 to 0·80 for the dry period which exhibited a higher coefficient of variation (COV) of 0·98, compared to the wet period with a COV of 0·30 and ratios ranging from 0·17 to 0·53 (Table II). Higher variability observed during the dry period may be related to the high-intensity convective storms characteristic of the summer season ($n = 13$) as described by Bosch *et al.* (1999), in combination with an increase in ET rates during this time, which starts rising in early April in this region (Amatya *et al.*, 2000, 2009). However, this study was not only limited by lack of rainfall intensity data (only daily rainfall) for testing this variability but also by the soil moisture and water table data as the ASMC. The high variability observed in temporal rain distribution during this dry period may explain the poor correlation ($r^2 = 0{\cdot}19$; Figure 3) in its linear regression model. In addition, ET rates as indicated by the monthly variability in PET values (Figure 4) may also have played a role on this poor relationship, with $p < 0{\cdot}05$, resulting in a significant difference between wet and dry periods, and annual runoff responses (Amatya *et al.*, 2002, 2009; Sun *et al.*, 2005; Todd *et al.*, 2006; Amatya and Trettin, 2007). For example, during the dry growing season, in this type of forest part of the rainfall may not even reach the forest floor due to direct canopy interception and evaporation (Harder, 2004) that

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Table I. Basic hydrologic characteristics for analysed storm events ($n = 41$) and t-test results calculated for peak rate, runoff, rainfall, R/P, rain previous 5- and 30-days. SD = Standard Deviation

Events	Day of year	Duration (days)	Begin flow (m^3/s)	Peak rate (m^3/s)	Runoff (mm)	Rain (mm)	R/P	Rain previous 5-day (mm)	Rain previous 30-day (mm)
Spring 1964	97·85	18·5	0·16	0·59	4·1	23·7	0·17	0·0	55·1
Spring 1964	123·79	10·8	0·11	2·85	11·4	38·1	0·30	17·8	55·7
Summer 1964	224·55	6·11	0·12	0·56	2·1	32·3	0·06	0·0	421·7
Summer 1964	230·69	10·75	0·14	4·46	16·7	20·8	0·80	2·6	238·9
Fall 1964	256·88	18·73	0·13	1·19	6·0	55·8	0·11	0·0	207·0
Fall 1964	289·50	39·39	0·18	5·26	23·3	48·3	0·48	0·0	102·4
Fall 1964	339·29	9·45	0·06	0·63	6·2	48·8	0·13	0·0	21·3
Winter 1964	362·00	5·00	0·12	3·25	17·0	49·8	0·34	0·0	82·4
Summer 1965	162·44	14·00	0·03	1·84	10·1	93·4	0·11	35·3	105·4
Spring 1966	122·77	11·23	0·94	5·39	19·4	62·2	0·31	38·6	72·7
Summer 1966	169·69	13·37	0·59	36·42	47·8	165·6	0·29	60·5	186·4
Summer 1966	236·12	11·65	0·06	3·61	12·8	44·0	0·29	0·0	218·7
Spring 1967	71·37	34·25	1·03	3·53	17·7	72·9	0·24	5·6	52·7
Summer 1967	223·62	9·01	0·01	1·15	3·2	46·9	0·07	0·0	147·0
Summer 1968	190·12	21·50	0·01	4·06	26·9	43·1	0·62	0·0	107·8
Summer 1968	292·10	14·27	0·03	1·87	6·2	160·5	0·04	0·0	33·3
Fall 1968	337·37	11·38	0·04	1·51	10·1	58·2	0·17	0·0	64·5
Winter 1969	19·12	19·00	0·10	1·16	14·3	28·5	0·50	0·0	34·8
Summer 1969	195·58	11·92	0·01	1·14	1·0	77·2	0·01	15·2	89·3
Fall 1969	245·43	15·19	0·21	2·95	7·3	73·0	0·10	0·0	291·7
Fall 1969	305·67	35·32	0·01	4·62	21·7	116·8	0·19	0·0	42·2
Winter 1970	33·68	13·98	0·42	1·82	14·5	39·0	0·37	5·3	78·2
Fall 1970	303·54	11·08	0·38	0·80	5·6	26·6	0·21	24·8	90·0
Spring 1971	74·71	10·20	0·49	1·62	9·6	25·8	0·37	6·3	122·1
Spring 1971	85·00	10·75	0·33	1·82	11·7	39·4	0·30	0·7	138·3
Spring 1971	95·77	14·89	0·29	1·04	7·1	25·6	0·28	0·0	81·1
Spring 1971	141·30	7·17	0·60	2·42	10·9	32·2	0·34	44·4	137·2
Summer 1972	193·22	6·98	0·15	0·79	4·1	38·1	0·11	14·4	158·1
Fall 1972	335·08	6·13	0·07	0·73	2·0	78·8	0·03	49·5	86·5
Summer 1973	192·67	5·32	0·11	1·70	5·3	30·2	0·18	10·9	197·1
Fall 1973	215·49	12·78	0·47	7·07	30·9	98·1	0·31	0·0	123·7
Fall 1973	256·91	7·71	0·28	6·74	17·9	41·4	0·43	33·7	112·8
Summer 1974	178·01	7·99	0·03	2·53	6·8	81·0	0·08	27·9	182·0
Summer 1974	202·60	7·06	0·02	0·35	0·9	32·0	0·03	8·1	246·1
Fall 1974	249·64	11·40	0·27	6·90	19·9	39·4	0·50	0·0	153·4
Spring 1975	104·40	17·00	0·09	2·59	13·5	47·0	0·29	10·1	103·4
Spring 1975	150·60	10·00	0·01	0·82	4·7	20·3	0·23	1·3	104·9
Summer 1975	163·05	12·00	0·18	1·78	7·9	53·1	0·15	35·8	99·8
Fall 1975	265·17	13·00	0·01	0·30	1·4	22·3	0·06	42·9	100·1
Winter 1976	69·04	28·00	1·03	1·03	11·3	21·3	0·53	19·3	19·8
Fall 1976	283·09	2·91	0·01	0·38	0·4	68·6	0·01	0·0	165·0
t-test									
p-values	—	—	—	0·39	0·83	0·02	0·04	0·63	0·01
Mean	—	13·59	0·23	3·20	11·5	54·2	0·25	12·5	125·1
SD	—	8·08	0·27	5·64	9·42	34·0	0·18	17·1	79·9

is dependent upon canopy storage, a function of leaf area index. Eisenbies *et al.* (2007) specified that these characteristics, including ASMC, are key factors that determine the rates at which rivers and streams respond to rainfall events in the eastern U.S. forested watersheds. Therefore, the relationship between rainfall and runoff events on this lowland watershed may not be strictly linear due to the seasonal variations in weather parameters rainfall amounts and soil water content affected by ET rates.

A different scenario was obtained for rainfall–runoff relationships using the 5-day prior API. Results for the wet condition again showed a significant ($r^2 = 0{\cdot}39$; $p = 0{\cdot}00$; Figure 5) relationship between runoff and rainfall, nonetheless the relationship between these two variables for dry conditions was not significant ($r^2 = 0{\cdot}02$; $p = 0{\cdot}56$; Figure 5). R/P ranging from 0·03 to 0·80 for the 5-day wet conditions with a COV = 0·73 had a similar COV of 0·76 for the dry period with the ratios ranging from 0·01 to 0·62 (Table II). Similarly, relationships for wet conditions based on a 30-day prior API were significant ($r^2 = 0{\cdot}39$; $p = 0{\cdot}00$; Figure 6) between runoff and rainfall, but during dry conditions this relationship indicated no correlation ($r^2 = 0{\cdot}00$; $p = 0{\cdot}79$; Figure 6) which shows that rainfall in this case was not a good predictor of runoff. R/P for wet

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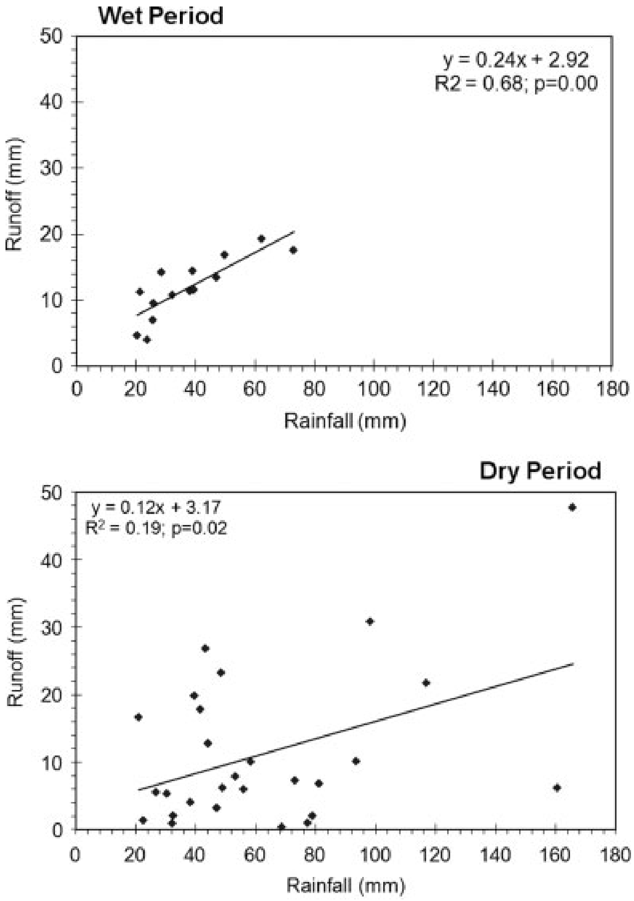

Figure 3. Event rainfall–runoff relationship for the wet (winter–spring; n = 14) and dry (summer–fall; n = 27) periods

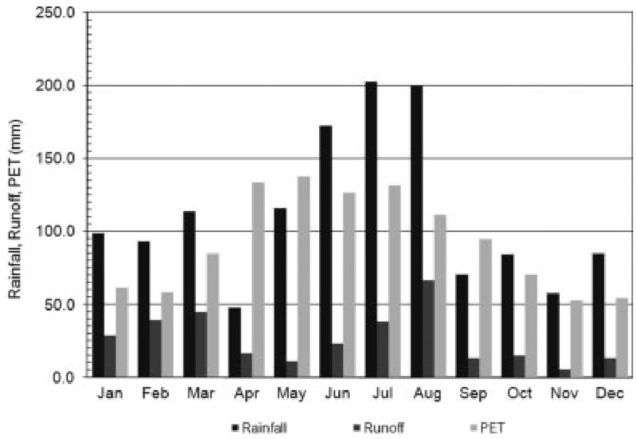

Figure 4. Mean monthly rainfall, runoff, and PET for 1974–1976 period. PET was calculated using the Thornthwaite method for a grass reference

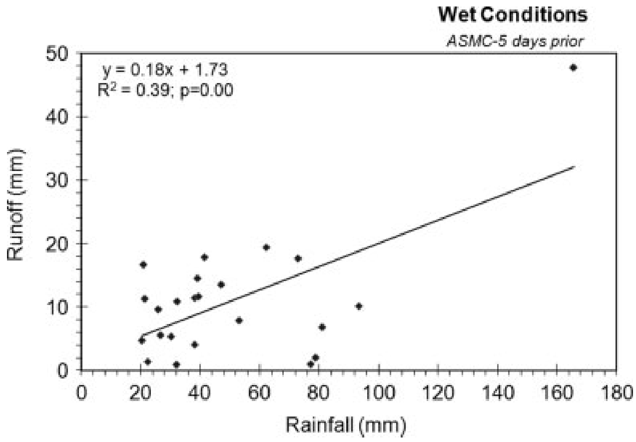

Figure 5. Rainfall–runoff relationships for events during wet (n = 23) based on 5-day API

conditions (30-day API) ranged from 0·01 to 0·80 (COV = 0·79) and from 0·01 to 0·53 (COV=0·64) for dry conditions (Table II). These results suggest that seasonal event rainfall–runoff dynamics in lowland watersheds may have been complicated due to other factors such as rainfall intensity and its aerial variability (although no difference was found on weekly basis (La Torre Torres, 2008), spatial distribution (for watersheds of this scale) of soil type and their properties, and depth to water table (i.e. soil water storage volume). In a recent study on the watershed, as a result of dry conditions (water table depth >50 cm) and high ET demands of as much as 98% of annual rainfall, Amatya *et al*. (2009) observed negligible streamflow and small R/P (0·07) for this third-order watershed from late March until November in 2007. However, in September 2006 water table positions were near the surface due to repeated rain events observed in August that saturated the soils resulting in the stream outflow and runoff–rainfall ratio of 0·26 (Amatya *et al*., 2009). These findings exemplify the disparity observed within a same period (dry period) due to the variations in rainfall, ET, and water tables in this system.

In addition to the results observed by Amatya *et al*. (2009), the mean monthly water balance plot for the study

Table II. Descriptive statistics results for R/P for the wet and dry periods, and wet and dry conditions based on both 5- and 30-day prior rainfall. p-values correspond to the significant difference in periods and conditions

Parameters	n (no. of events)	R/P Ratios range	Mean R/P	SD (±)	COV	p-values
Wet period	14	0·17–0·53	0·33	0·10	0·30	0·04
Dry period	27	0·01–0·80	0·21	0·20	0·98	
Wet conditions (5-day prior)	23	0·03–0·80	0·25	0·18	0·73	0·89
Dry conditions (5-day prior)	18	0·01–0·62	0·24	0·18	0·76	
Wet conditions (30-day prior)	24	0·01–0·80	0·26	0·20	0·79	0·68
Dry conditions (30-day prior)	17	0·01–0·53	0·23	0·15	0·64	

SD, standard deviation; COV, coefficient of variation.

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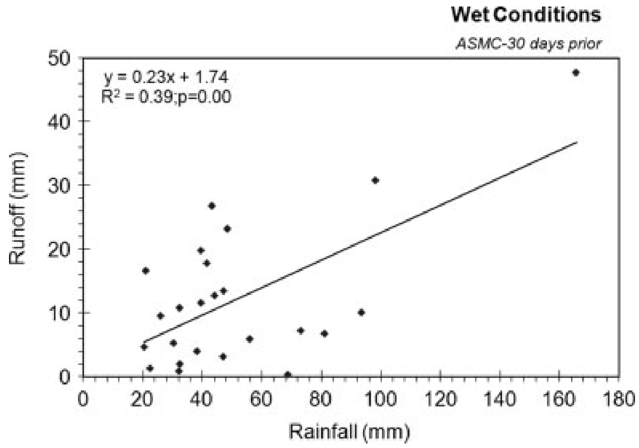

Figure 6. Rainfall–runoff relationships for events during wet ($n = 24$) based on 30-day API

period for the Turkey Creek watershed shows the trends of rainfall and runoff in relation to PET as estimated by the Thornthwaite method (Figure 4). A seasonal trend is observed in PET rates which starts increasing in April and peaks during the months of May through July. This plot suggests that the difference between rainfall and runoff is close to the PET values at least during the wet periods with unlimited soil moisture calculated for this third-order watershed (Figure 4). Additionally, *t*-test results showed that rainfall is significantly ($p < 0{\cdot}02$) higher during dry periods (mean= 62·8 mm) than for wet periods (mean= 37·6 mm) sustaining the seasonal variability expected for this variable (Table I). However, higher R/P were observed during wet ($p < 0{\cdot}04$) and rain 30 days prior API ($p = 0{\cdot}01$) with higher values observed during the wet period. In contrast, runoff, peak flow rates, and rain 5-day prior values were not significantly ($p > 0{\cdot}05$) different for wet and dry periods. Thus, it is important to examine alternative relationships that include other important variables, such as PET or water table depth as a surrogate for the ASMC, and their interactions for understanding rainfall–runoff dynamics.

Event mean R/P are presented in Table II for periods, 5 and 30 days prior API. Mean R/P were higher (R/P = 0·33) for the wet period and smaller for the dry period (R/P = 0·21; Table II). Higher coefficients were also observed for wet conditions, based on 5- and 30-day API, but these were not significantly different ($p > 0{\cdot}05$; Table II) for dry conditions. However, ratios observed in this study were consistent with ratios reported by Hewlett (1982) which ranges from 0·10 to 0·34 for rainfall events greater than 25 mm. These results support that storm event runoff response is also dependent upon seasonal weather variations for this third-order watershed. Such findings are supported by other similar studies (Miwa *et al*., 2003; Amatya *et al*., 2000; 2006c and also Harder *et al*., 2007), which concluded that runoff for a first-order watershed in the Coastal Plain was sensitive to rainfall event size, storm frequency, and ASMC (assessed from water table position) (Figure 4). We assume that the surface conditions get saturated or near saturated with shallow water table depths on most of these poorly drained soils with argillic horizons within about 2–3 m during the wet period when ET demands are low, potentially producing substantial runoff after a rainfall event on this low-gradient watershed. Shallow water tables have a direct influence on the infiltration capacity, which indicates greater hydrologic connectivity for antecedent moisture conditions, and as a result on surface runoff (Descroix *et al*., 2002; James and Routlet, 2009). Much more reduced flows are expected for similar events during dry conditions as was reported by Amatya *et al*. (2009) for a rain event in 2005 with no flows due to the dry antecedent conditions. For an adjacent poorly drained watershed, Amatya *et al*. (2006c) found highly variable stream outflows with flooding in some seasons and stated that these responses were dependent upon rainfall, ET, and ASMC. In fact, Amatya *et al*. (1996) stated that although annual ET accounts for as much as 69% of the rainfall and that the soil drainage becomes the second most important component in the annual water balance, ET may be as much as 90% of the rainfall, depending upon the season in the humid coastal plain. The drop in mean shallow soil moisture was observed during months of June and July where ET rates are close to its highest levels (Figure 4). These findings were also observed by Rouse and Wilson (1969) and Young and Klawitter (1968) where a decrease in soil moisture was also associated to the growing season (spring–summer).

Computed statistics obtained for the regression model with the event analysis are presented in Table III. The equation of the simple linear regression model showed that rainfall is a good predictor ($r^2 = 0{\cdot}68$; $p = 0{\cdot}00$) explaining as much as 65–70% of variation in runoff

Table III. Regression statistics results for runoff–rainfall relationships for the wet and dry periods, and wet and dry conditions based on both 5- and 30-day prior rainfall

Runoff–rainfall relationship

Parameters	Regression equation	r^2	*p*-value	Intercept (*p*-value)	Slope (*p*-value)
Wet period	Runoff = 0·24 × rain + 2·92	0·68	0·00	0·15	0·00
Dry period	Runoff = 0·12 × rain + 3·17	0·19	0·02	0·42	0·02
Wet conditions (5-day prior)	Runoff = 0·18 × rain + 1·73	0·39	0·00	0·57	0·00
Dry conditions (5-day prior)	Runoff = 0·03 × rain + 9·93	0·02	0·56	0·04	0·56
Wet conditions (30-daysprior)	Runoff = 0·23 × rain + 1·74	0·39	0·00	0·75	0·00
Dry conditions (30-day prior)	Runoff = 0·01 × rain + 9·74	0·00	0·79	0·00	0·79

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during the wet period, and only 20% during the dry period (Table III). Results for wet conditions based on 5- and 30-day API were also significant ($p = 0{\cdot}00$). For both of these parameters (5- and 30-day API) rainfall was able to explain about 40% of variation in the runoff generated for wet events, whereas up to only about 2% of the variation was explained by rainfall for dry conditions. Additionally, the slopes of the regression for predicting runoff volumes were highly significant for wet ($p = 0{\cdot}00$) and dry ($p = 0{\cdot}02$) periods. The same was true for wet conditions based on 5- and 30-day API ($p = 0{\cdot}00$; $\alpha = 0{\cdot}05$), although not significant for dry conditions ($p > 0{\cdot}05$). In contrast, intercepts of the regression equation for predicting runoff volumes were not significant for any of the periods ($p > 0{\cdot}05$), including wet conditions based on 5- and 30-day API ($p > 0{\cdot}05$). For dry conditions, however, intercepts were significant ($p < 0{\cdot}05$) for predicting runoff (Table III). The same was true for wet and dry conditions as determined by 5- and 30-day prior rainfall (Figures 5 and 6).

Variations in runoff response to rainfall were observed for wet and dry conditions in both cases. Eight storm events were examined in detail to test our hypotheses on the roles of rainfall amount, periods, and ASMC (as inferred from rainfall amount to runoff-generating event) on R/P (Table I). Events selected either have very small or high R/P. For example, on day 224·5 (1964) a rainfall amount of 32·3 mm produced a runoff response of only 2·1 mm (R/P = 0·06), whereas for the storm event at day 230·6 (1964) 20·8 mm produced 16·7 mm runoff (R/P = 0·80). The second event occurred directly following the return to base flow condition of the prior event and had a higher peak flow value, perhaps caused by surface runoff and shallow subsurface flow for a larger ASMC (already saturated conditions). For the event on day 224·5 with no previous rain 5 days prior, it is likely that the high ET rate including direct canopy interception during the summer caused a large subsurface storage circumventing runoff to the stream despite nearly twice as much rain observed in the 30 days before this event. Compare this with the event on day 230·6 where only 2·6 mm rain (5-days prior) produced a ratio of 0·80, whereas a ratio of 0·06 was generated for day 224·5 with no rain in the 5-day prior. Apparently the near-term soil moisture condition played a larger role in determining the runoff response during the summer season rather than a longer-term condition (30-day prior rainfall). These observations are consistent with results reported by Young and Klawitter (1968), Amatya *et al.* (2000, 2006c, 2009), Slattery *et al.* (2006), Harder *et al.* (2007), and Eisenbies *et al.* (2007) who stated that stream outflow on a lowland watershed is influenced by the moisture storage capacity of the soil prior to rainfall. Additionally, the event during a period with assumed nearly saturated soils lasted longer (10·7 days) than the event at day 224·5 (6·1 days), which influenced the runoff volumes of these events. Recently, Amatya *et al.* (2009) and Harder *et al.* (2007) reported much lower runoff ratios (0·08), as affected by antecedent conditions, during a dry year for this and a nearby first-order watershed, respectively. Similar observation was made by Amatya and Trettin (2007) in their analysis of annual ET using the same historic data from this study site. The amount and rate of runoff will be dependent upon these key controlling factors (i.e. soil hydrologic properties, soil moisture storage, and rainfall) that vary spatially and temporarily (Slattery *et al.*, 2006). However, we hypothesized that additional information on rainfall intensity, water table positions, and PET would help to more accurately determine the runoff and change in soil water storage processes.

Similar results were observed for summer events of day 223·6 in 1967 and day 283·0 in 1976. For example, on day 223·6 a rain event of 46·9 mm produced a runoff response of 3·2 mm (R/P = 0·07), and on day 283·0 a runoff response of only 0·4 mm was produced by a 68·6 mm rain event (R/P = 0·01). Both of these events were not preceded by rain 5-day prior to them, and substantial rain had occurred in the 30 days previous to these events. Most of the earlier rain (30 days prior) reported for these events is likely to be used by ET (Amatya *et al.*, 2009) and much less as runoff. This suggests that near-term soil moisture condition is certainly of great importance in determining the runoff response during dry periods. It is likely that available soil water storage was higher for these events given the relatively dry conditions as indicated by very small beginning flows prior to the event (Table I). Furthermore, part of the rainfall, depending upon the intensity, may even be directly lost to the canopy evaporation without even reaching the forest floor for infiltration (Amatya *et al.*, 1996, 2000; Amatya and Trettin, 2007; Eisenbies *et al.*, 2007). It is, therefore, important to consider that while the interpretations of this data set can be applied to similar other watersheds, event runoff dynamics in the Coastal Plain will differ in each watershed given the differences in land use/land cover, soil composition, area, and topographic gradient. However, this study provided an overview of the range of possibilities such as rain amounts, seasons, and variations in ASMC using a large set of data from a typical lowland watershed of the Coastal Plain of the Southeast USA.

As an alternative way to estimate initial soil moisture conditions, a hydrograph separation method was used to estimate base flow contribution in total event runoff. Base flow contribution was estimated for all 41 storm events used in this study. Results showed that base flow may contribute up to 57% of total runoff for this watershed. The highest mean base flow was observed during the wet period (30·0%) and the lowest during the dry period (26·3%), yet they were not statistically different ($p > 0{\cdot}05$). These estimates are consistent with the estimate obtained by Amatya *et al.* (2009) for the 2005–2008 daily stream flow. Greater base flow influence associated with wet months may be a function of the initial soil moisture conditions, which may be defined by the flow measurement at the beginning of a storm event. In the contrary, most of the runoff during the dry periods may

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have been contributed by the base flow alone because the storm flow due to quick interflow and surface runoff would be almost minimal (Amatya *et al*., 2009). These findings may provide useful insight on the role of the base flow component for runoff responses observed during different periods in this system. However, these results may have to be carefully interpreted as they are based on an arbitrary base flow-storm flow separation line developed for low gradient watersheds in coastal Florida (Swindel *et al*., 1983). Miwa *et al*. (2003) and Harder (2004) concluded that base flow influence in an adjacent first-order watershed was almost negligible. Discrepancies observed between the previous studies and this study may be related to the scaling effects (i.e. watershed size). Turkey Creek watershed is 45 times larger than the first-order watershed, with a larger hydraulic gradient from the stream channel. As such, base flow contribution may be more significant as the watershed area increases.

Peak flow rate response to rainfall

Rainfall–peak flow rate relationships for seasonal periods, 5- and 30-day prior API are presented in Figures 7–9. Linear regression results for these relationships were similar to those observed in the rainfall–runoff relationship analysis. Rainfall–peak flow rate relationships for the wet ($p = 0{\cdot}00$) and dry ($p = 0{\cdot}00$) periods were significant ($\alpha = 0{\cdot}05$). Results for the 5- and 30-day prior API showed that the relationship between rainfall and peak flow rates was significant ($p = 0{\cdot}00$) only for wet conditions, but not significant ($p > 0{\cdot}05$) for dry conditions. Although the regression analysis for rainfall and peak flow rates was similar to the results observed for the rainfall–runoff relationships, the linear regression coefficients of determination (r^2) for the wet period and wet conditions for 5- and 30-day prior API were higher than for the same condition of the rainfall–runoff relationships (Table IV).

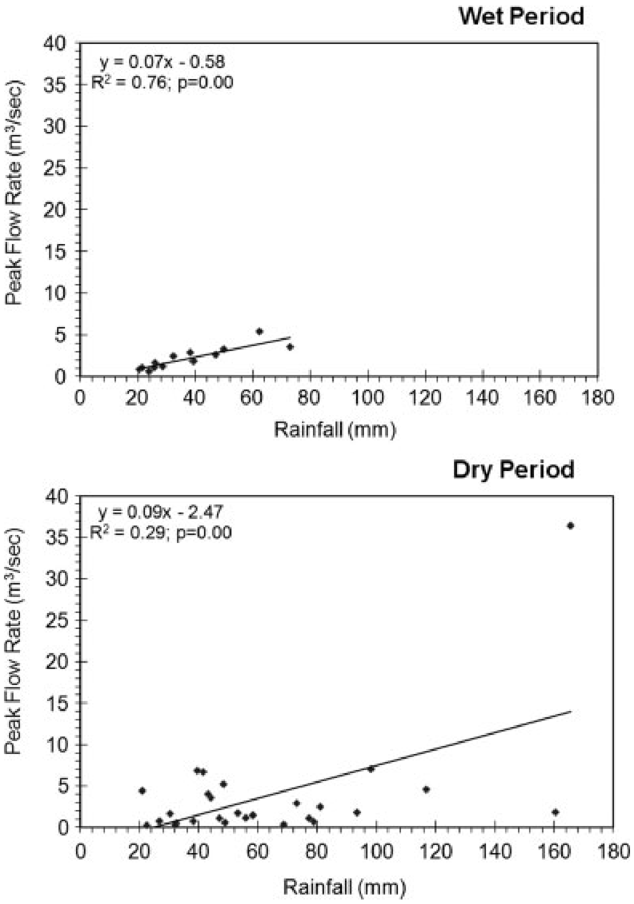

Figure 7. Event rainfall–peak flow rate relationships for the wet (winter–spring; $n = 14$) and dry (summer–fall; $n = 27$) periods

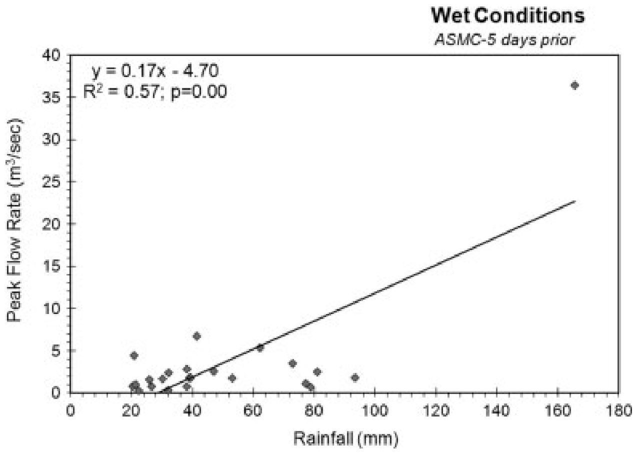

Figure 8. Rainfall–peak flow rate relationships for events during wet ($n = 23$) based on 5-day API

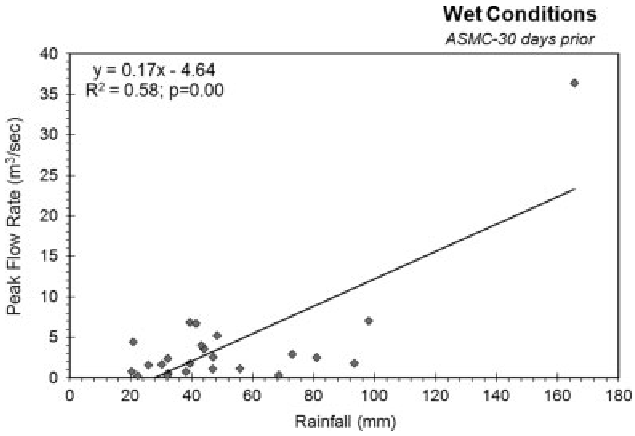

Figure 9. Rainfall–peak flow rate relationships for events during wet ($n = 24$) based on 30-day API

Results of the regression model for rainfall and peak flow rates showed that for both wet ($r^2 = 0{\cdot}76$) and dry ($r^2 = 0{\cdot}29$) periods rainfall is a good predictor of peak flow rates ($\alpha = 0{\cdot}05$; Table IV). The slopes of the regression lines in both periods were also significant ($\alpha = 0{\cdot}05$), in contrast to the observed intercepts ($p > 0{\cdot}05$). Results of the regression model, slopes, and intercepts were significant for the wet conditions ($p = 0{\cdot}00$; $\alpha = 0{\cdot}05$), while not significant ($p > 0{\cdot}05$) for the dry conditions based on 5-day prior API. Similar results were observed for the regression model, slopes, and intercepts of rainfall and peak flow rates based on the 30-day prior API, with a significance ($p < 0{\cdot}05$)

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Table IV. Regression statistics results for the wet and dry periods, and wet and dry conditions based on both 5- and 30-day prior rainfall

Peak flow rate–rainfall relationships

Parameters	Regression equation	r^2	p-value	Intercept (p-value)	Slope (p-value)
Wet period	Peak rate = 0·07 × rain − 0·58	0·76	0·00	0·25	0·00
Dry period	Peak rate = 0·09 × rain − 2·47	0·29	0·00	0·31	0·00
Wet conditions (5-day prior)	Peak rate = 0·17 × rain − 4·70	0·57	0·00	0·02	0·00
Dry conditions (5-day prior)	Peak rate = 0·03 × rain + 9·93	0·02	0·34	0·10	0·34
Wet conditions (30-day prior)	Peak rate = 0·17 × rain − 4·64	0·58	0·00	0·02	0·00
Dry conditions (30-day prior)	Peak rate = 0·01 × rain + 1·17	0·13	0·16	0·09	0·16

correspondence for wet conditions and no correlation ($p > 0{\cdot}05$) for dry conditions.

Peak flow rate responses are also associated with soil water conditions but more importantly with rainfall intensity data (McCuen, 1989). Unfortunately, we do not have the rainfall intensity data for this study. As mentioned previously, other factors such as initial water table positions (surrogated for soil moisture condition), and storm size, duration, and frequency may also influence peak flow rate response. However, although these data were not available for the time period for this study, long-term rainfall data for the region and information presented by Bosch *et al*. (1999) suggest that rainfall in the Georgia coastal plain is typically greater during the midsummer season with high-intensity convective storms, whereas frontal storms with moderate rainfall are typical of the winter and spring months. Summer storms occur more frequently than in any other season and storms yield relatively small runoff volumes (Bosch *et al*., 1999). Therefore, summer relationships seem to depend mainly on high-intensity rainfall characteristics produced by these convective thunderstorms, with high-intensity rainfall rate exceeding soil infiltration rates (Chang, 2003) and producing higher peak flow rates.

In addition to the potential effects of rainfall intensity on runoff response, water table depths as a surrogate of ASMC may also contribute to runoff and peak flow rates, and R/P as well. Harder *et al*. (2007) and Miwa *et al*. (2003) concluded that runoff response and thus peak flow rates are indeed related to the ASMC, rain event sizes, and their frequency distribution. During the summer season infiltration excess runoff may be more likely due to high-intensity storms, whereas during the winter season saturation excess runoff is expected due to the high water table positions, caused by low ET rates in this humid watershed (Figure 4). It is the surface runoff in both the cases that usually contributes to the peak flow rates. If the ASMC is relatively wet, runoff and peak flow rates will generally be high, and if this condition is dry the soil water storage capacity is also high, and less overland flow will be produced with most runoff contributed by the base flow in these low-relief systems (Harder *et al*., 2007; Amatya *et al*., 2009). The same is true for lower intensity storms, where soils have more ability to infiltrate water, producing less runoff (Chang, 2003).

Multivariate analysis of runoff generation

To further examine factors affecting runoff generation on this watershed, a stepwise regression analysis (SAS 9·1·3, 2000–2004) was performed using base flow, rainfall, 5-, and 30-day antecedent rainfall, 30-day total PET, and 5-day antecedent PET as independent variables (Table V). Results from this analysis showed that all hydrologic variables for runoff (peak flow rate, runoff volume, and R/P) were significantly ($p < 0{\cdot}10$) (only at $\alpha = 0{\cdot}10$) related to rainfall amount and antecedent stream flow conditions as indicated by the initial flow rate (begin flow). Rainfall amounts for 5- and 30-day prior to the event had some impact on runoff generation, but this was not strong. In the dry period, the three hydrologic

Table V. Results of stepwise regression analysis evaluated for all storm events ($n = 41$), and wet and dry periods

Variable	Begin flow	Rainfall	5-day rainfall	30-day rainfall
All storm events (n = 41)				
Runoff	$r^2 = 0{\cdot}33$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}17$; $p = 0{\cdot}01$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Peakflow rate	$r^2 = 0{\cdot}44$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}31$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}39$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}48$; $p = 0{\cdot}00$
R/P	$r^2 = 0{\cdot}12$; $p = 0{\cdot}02$	$r^2 = 0{\cdot}22$; $p = 0{\cdot}01$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Wet period				
Runoff	$p > 0{\cdot}10$	$r^2 = 0{\cdot}68$; $p = 0{\cdot}00$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Peakflow rate	$p > 0{\cdot}10$	$r^2 = 0{\cdot}76$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}89$; $p = 0{\cdot}00$	$p > 0{\cdot}10$
Runoff-rainfall ratios	$p > 0{\cdot}10$	$p > 0{\cdot}10$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Dry period				
Runoff	$r^2 = 0{\cdot}44$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}52$; $p = 0{\cdot}00$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Peakflow rate	$r^2 = 0{\cdot}50$; $p = 0{\cdot}00$	$r^2 = 0{\cdot}65$; $p = 0{\cdot}00$	$p > 0{\cdot}10$	$p > 0{\cdot}10$
Runoff-Rainfall ratios	$r^2 = 0{\cdot}11$; $p = 0{\cdot}09$	$r^2 = 0{\cdot}21$; $p = 0{\cdot}06$	$p > 0{\cdot}10$	$p > 0{\cdot}10$

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variables were correlated with antecedent flow conditions and event rainfall amount. However, we did not find this was the case for the wet period. Interestingly, the results did not indicate the 5- or 30-day prior PET as significant in affecting these runoff characteristics. These results confirmed that rainfall amounts and ASMC as indicated by the initial flow rate in this case are the main factors controlling the hydrologic dynamics, runoff response, in this lowland watershed of the Coastal Plain.

SUMMARY AND CONCLUSIONS

On the basis of long-term rainfall and stream flow data (1964–1976) used for 41 selected runoff events for the low-gradient forested watershed, we found that event runoff was a function of rainfall amount that explained as much as 68% for the wet periods with low evaporative demands. Although the relationship between runoff and rainfall was significant ($\alpha = 0{\cdot}05$) for wet and dry periods, it was not as strong as expected. This suggests that runoff response in these lowland watersheds is not only influenced by rainfall amounts but also by other factors such as its intensity and duration, and to the near-term soil moisture conditions created by accumulated ET and precipitation balances. Event rainfall–runoff relationships were also affected by 5- and 30-day prior rainfall under wet conditions, suggesting that soil moisture condition is an important element dictating the hydrologic dynamics of this lowland watershed in the Coastal Plain. However, this was not the case for the dry period indicating that the rainfall–runoff dynamics was more complex and variable in this system with shallow argillic horizon. We argued that this variability is most likely related to rainfall characteristics such as intensity and duration. We confirmed our hypothesis that event R/P were significantly higher during the wet period than for the dry periods. Although peak flow rate relationships with rainfall for both wet and dry periods were also significant, the wet period relationship was found to be stronger. It was also concluded that the rainfall amount and ASMC represented by the initial base flow rate were the main controlling factors for event runoff.

The results of this study showed that all event variables (runoff, R/P, and peak flow rates) were controlled by rainfall amounts and available soil water storage. Although this finding was not unique to the LCP regions (Bazemore *et al.*, 1994; Amatya *et al.*, 2000; Slattery *et al.*, 2006), it highlights and further strengthens the importance of groundwater table as a surrogate of antecedent soil moisture status in controlling storm flow generation of the lowland watershed with a shallow argillic horizon. We argue that the Variable Sources Area Concept proposed by Hewlett (1982) is valid for the LCP region which perhaps represents the extreme landscape where the saturated area can expand during wet periods and contract during dry periods over a large magnitude. Shallow saturated overland flow appears to be the dominant runoff generation mechanism for the low-gradient forested watershed in this study.

Future studies should further investigate other hydrologic indicators that affect the runoff response, such as spatial and temporal water table dynamics determined by balances of rainfall and ET. Information on depth to water table along with soil drainable porosity is necessary to determine available subsurface storage and, therefore, the ASMC at given times. Additionally, event rainfall intensity data are necessary not only to characterize the peak flow rates but also to accurately determine the rainfall amount responsible for event runoff regeneration and duration of storm events at different seasons and periods.

The results from this study site as a reference may be of great importance for regional storm water management and water quality studies, for that matter designing the BMPs such as detention ponds and restoration efforts. These data will also provide useful insight to explain the variability in storm runoff response observed for the dry period, for example. Additionally, future rainfall–runoff event analysis study at this site should take advantage of current monitoring of rainfall intensity data, water table depths, solar radiation, and other hydrometereological data, as well as modelling studies for accurately estimating soil moisture and actual ET that would help to explain the variability in runoff generation. Furthermore, water chemistry and isotope analysis may also help to identify the sources of storm flow and base flow to better understand flow generation mechanisms (McGuire *et al.*, 2007).

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