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EFFECT OF SOILS ON WATER QUANTITY AND QUALITY IN PIEDMONT FORESTED HEADWATER WATERSHEDS OF NORTH CAROLINA[1]

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ABSTRACT: Water quantity and quality data were compared from six headwater watersheds on two distinct soil formations, Carolina Slate Belt (CSB) and Triassic Basins (TB). CSB soils are generally thicker, less erodible, and contain less clay content than soils found in TB. TB generated significantly more discharge/precipitation ratio than CSB (0.33 *vs.* 0.24) in the 2009 dormant season. In the 2009 growing season, TB generated significantly less discharge/precipitation ratio than CSB (0.02 *vs.* 0.07). Over the entire monitoring period, differences in discharge/precipitation ratios between CSB and TB were not significantly different (0.17 *vs.* 0.20, respectively). Storm-flow rates were significantly higher in TB than CSB in both dormant and growing season. Benthic macroinvertebrate biotic index scores were excellent for all streams. Nutrient concentrations and exports in CSB and TB were within background levels for forests. Low-stream nitrate and ammonium concentrations and exports suggested that both CSB and TB were nitrogen limited. Soils appear to have had a significant influence on seasonal and storm-flow generation, but not on long-term total water yield and water quality under forested conditions. This study indicated that watersheds on TB soils might be more prone to storm-flow generation than on CSB soils when converted from forest to urban. Future urban growth in the area should consider differences in baseline hydrology and effects of landuse change on water quantity and quality.

(KEY TERMS: Triassic Basins; Carolina Slate Belt; forest hydrology; streamflow; water quality; North Carolina Piedmont.)

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INTRODUCTION

The piedmont region of the southeastern United States (U.S.) is an area under rapid urbanization and landuse changes (Wear and Gries, 2011). For example, the population of Wake County, North Carolina (NC) is projected to double in the next 30 years (North Carolina Office of State Budget and Management, 2008). Population rise, landuse change, and record droughts have increased water supply stress in the piedmont region of the southeastern U.S. (Sun *et al.*, 2008; United States Drought Monitor, 2011). Fifty-eight percent of streams in the piedmont of NC are first order headwater streams (North Carolina Division of Water Quality, 2005), which provide most of the water in rivers. Understanding streamflow dynamics and protecting these streams from degrada-

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tion through proper planning and management will help maintain quality stream channel networks and water supplies for downstream tributaries and rivers (North Carolina's Forest Resources Assessment, 2010). Falls Lake Watershed is the water supply reservoir for Raleigh, the capital of the state of NC, and surrounding towns in Wake County in the piedmont region. Knowledge about total and seasonal water quantity from the watershed can be useful in implementing long-term management, development, and land acquisition strategies (North Carolina's Forest Resources Assessment, 2010). This watershed is dominated by two very different geologic provinces, the Carolina Slate Belt (CSB) and Triassic Basins (TB) that could vary in water yield and quality. Few studies have examined the effects of geologic effects on watershed water balances and flow characteristics.

Soil thickness is one important watershed parameter that affects water storage and release. For example, thick soils tend to redistribute rainfall better and lessen lateral flow generation than thin soils (Hopp and McDonnell, 2009). Hoover and Hursh (1943) found that soil depth and storage properties may be as important as topography in storm-flow generation and stream discharge. Studies further suggest that antecedent soil moisture storage is critical to stormflow "threshold" response to rainfall events (McGuire and McDonnell, 2010) and soil thickness is linked to base-flow rates and to dynamics of other watershed hydrologic components (Ohnuki *et al.*, 2008). Soil thickness is considered a standard variable in several hydrology models that are used to further quantify catchment runoff and improve ecological modeling (Frankenberger *et al.*, 1999; Arnold and Fohrer, 2005; Pelletier and Rasmussen, 2009). Gochis *et al.* (2010) reported that accounting for small scale variants in soil depth can moderately improve land surface model energy and water flux estimates. Buttle *et al.* (2004) also noted that soil thickness was a first order control for slope runoff generation; thin soils almost always generated runoff and indicated a near linear relationship between runoff and rainfall depth. Differences in rainfall intensity and antecedent moisture explained little variability in runoff from thin soil slopes, which is consistent with limited storage capacity (Buttle *et al.*, 2004).

Discharge/precipitation ratio is one key parameter used to quantify effects of soil and landuse changes from forests to other uses on annual and seasonal streamflow. Giese and Mason (1993) found that a typical normalized mean streamflow for a piedmont urban watershed was 1.0 mm/day, which computes to a discharge/precipitation ratio of 0.33. The watershed has approximately 20% impervious surface with a mixture of CSB, TB, and Raleigh Belt (RB) soil features. Boggs and Sun (2011) compared discharge from an urbanized watershed with RB soil features and approximately 44% impervious surface and a forested watershed with CSB soil features in the piedmont of NC. They found a discharge/precipitation ratio of 0.42 for urban and 0.21 for forest. Boggs and Sun (2011) also found mean discharge of 1.2 mm/day for an urbanized watershed and 0.54 mm/day for a forested watershed.

Forests provide the best water among all land uses and risk to water quality is minimized by forest cover. Across the U.S., the range of nitrate concentration in urban areas (0-6 mg/l) is smaller than farmlands (0-10+ mg/l), but larger than in forests (0-2 mg/l) (John, 2008). Omernik (1977) found that nitrate and phosphate in streamwater draining agriculture land had nine times greater concentration than forestland. Legacy effects from 19th and 20th Century agriculture practices continue to contribute to water quality degradation due to increased channel erosion and nutrient load discharges (Binkley and Brown, 1993). Minimizing sediment and pollutant loading to source water areas can help mitigate risk to water quality. Research and practical application advances in agriculture, forest planning, and management have occurred over the past 50-60 years. However, more studies that link forest soils to watershed hydrology and define the range of natural sediment and nutrient variability in these systems are needed.

In this study, the standard paired watershed approach was used to quantify temporal hydrology and water quality conditions under forested conditions. This experimental design offers an opportunity to understand discharge and water quality variability from headwater watersheds in TB as well as compare and contrast this variability with discharge and nutrient concentrations from CSB, the predominant NC piedmont ecoregion (Cleland *et al.*, 2007). This study also offers reference or baseline data for watershed development planning and management. Our objectives are (1) to compare annual, seasonal, and storm-based watershed water quantity and water quality in contrasting NC piedmont watersheds dominated by two different soil features, and (2) to identify controls on storm-flow response variables using a multivariate analysis approach.

MATERIALS AND METHODS

Study Sites

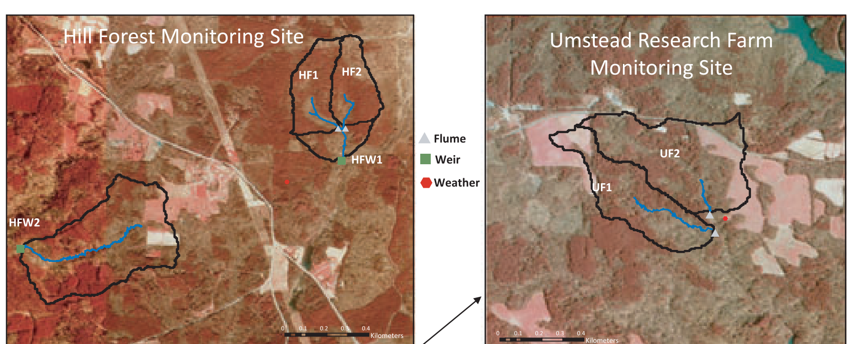
The headwater study watersheds are characterized as mixed pine-hardwood forests located in the Falls

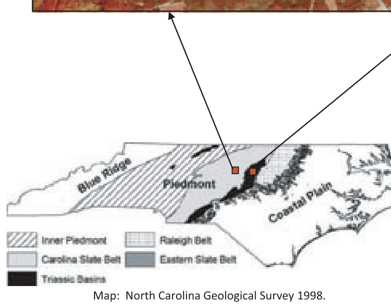
Lake Watershed of the Neuse River Basin, within the piedmont region of NC. Four watersheds (HF1, HF2, UF1, and UF2) ranging from 12 to 28 ha in size with perennial stream channels were gauged for flow monitoring and water quality sampling from November 2007 to June 2010 (Figure 1). Four 2-H type flumes were installed at the stream outlet. Stream identification and rating were determined based on geomorphic, hydrologic, and biological indicators described in the North Carolina Stream Identification Manual (North Carolina Division of Water Quality, 2005). The first watershed pair, HF1 and HF2, is located in the Flat River Watershed at North Carolina State University's Hill Demonstration Forest (HF) in northern Durham County, NC. The other pair, UF1 and UF2, is located in the Knap of Reeds Watershed at North Carolina Department of Agriculture and Consumer Services Umstead Research Farm (UF) in western Granville County, NC. The linear distance between sites is about eight kilometers. We also monitored hydrology in two larger (i.e., 29 and 40 ha) watersheds at the Hill Demonstration Forest, HFW1 and HFW2 (Figure 1). Two 90° V-notch weirs served as the gauge stations. HF1 and HF2 are nested within HFW1. Overstory vegetation, leaf area index, and meteorological conditions were similar for all sites. Dominant overstory species included *Quercus* sp. (oak), *Acer rubrum* (red maple), *Liquidambar styraciflua* (sweetgum), *Liriodendron tulipifera* (tulip poplar), *Fagus grandifolia* (American beech), and *Pinus taeda* (loblolly pine) with growing and dominant season leaf area index of 3.8 and 1.0, respectively.

Discharge and Water Quality Measurements

Discharge rates (measured in cubic feet per second, cfs) were logged every 10 min with a Sigma 900 Max water sampler (Hach Company, Loveland, Colorado). Data were downloaded at least every two weeks or within a couple of days after a storm event. Grab water samples were collected at least bi-weekly. Storm-based water samples were collected based on flow rate of change with a trigger flow point programmed in the Sigma 900 Max. Storm-based samples were collected on a stratified sampling program, intensive sampling during rising limb (six samples in 1 h), and less intense during recession limb (six samples over 6-10 h) of the hydrograph. To avoid potential to overemphasize one limb of the hydrograph, time-weighted mean concentration for each constituent was computed.

Constituents used to indicate water quality conditions included total suspended sediment (TSS), total organic carbon (TOC), ammonium (NH_4), nitrate (NO_3), total phosphorus (TP), total Kjeldahl nitrogen (TKN), stream temperature, and macroinvertebrate biodiversity. Water samples were preserved by adding 0.2 ml of sulfuric acid to grab sample bottles and 2 ml of sulfuric acid to sigma bottles prior to their placement in the sampler base. Water samples collected from the field were kept at 3.6°C prior to analysis. Constituents from each water sample (TSS, TOC, NH_4, NO_3, TP, and TKN) were determined at North Carolina State University Soil Science Analytical Laboratory in milligrams per liter (mg/l) using standard methods (Greenburg, 1992).





	HF1	HF2	UF1	UF2	HFW1	HFW2
Size (ha)	12	12	19	28	29	40
Aspect	South	South	Southeast	Southeast	South	Southwest
Geologic regions	Carolina Slate Belt	Carolina Slate Belt	Triassic Basin	Triassic Basin	Carolina Slate Belt	Carolina Slate Belt

FIGURE 1. Study Sites and Descriptive Characteristics.

Stream temperature data were logged every 10 min using Hobo Pro v2 water temperature data loggers (Onset Corporation, Southern, Massachusetts) and downloaded every few months. Two benthic macroinvertebrate assessments were completed following methods outlined by North Carolina Department of Environment and Natural Resources, Bioassessment Unit (2011) Qual 4 method. One field survey occurred in January 2010 and the other in April 2010 where a kick net, sweep net, leaf pack, and visual samples were collected from each stream and field sorted. Benthic macroinvertebrate samples were identified to the lowest possible taxonomic class and a biological index was determined from the formula in North Carolina Department of Environment and Natural Resources (2006) standard qualitative method (also see Penrose *et al.*, 1980; Crawford and Lenat, 1989 for computation and descriptive details). Precipitation was measured at HF and UF with a Hobo Data Logging Rain Gauge — RG3 (Onset Corporation) and downloaded every few months.

Data Processing and Statistical Analysis

Discharge values were divided by watershed size to normal streamflow data and converted from cfs to mm, so that units were comparable to precipitation. Annual water budget can be computed using catchment water balance equation $ET = P - Q \pm \Delta S$, where ET equals evapotranspiration, P equals precipitation, Q equals discharge, and ΔS equals change in storage. We assume that ΔS on an annual hydrologic or water year basis equaled zero mm. Therefore, annual ET was computed as $ET = P - Q$ and we also reported ET in percent (%) of P. Based on continuous water table data in CSB watersheds, we determined that April-March was the period where ΔS was close to 0 mm, varying less than any other period of the year. This period coincides with what Weaver (1998) reported as a climatic year for low-flow analysis in NC. Annual water budget for this study was computed based on water years April 2008-March 2009 (hereafter referred to as 2009) and April 2009-March 2010 (hereafter referred to as 2010).

HF1 and HF2 are paired watersheds with similar soils, topography, slope, drainage density, precipitation, and vegetation cover. This suggests that daily and annual normalized discharge should be similar between pairs. However, HF2 is spring fed contributing approximately 32% (2009) and 27% (2010) more annual discharge than its pair HF1 (which does not contain a spring). Spring flow contribution of 0.32 mm/day in HF2 was estimated based on 124 days when streamflow was 0 mm/day in HF1. We have adjusted HF2 values to account for added spring flow (column in Table 1). HF2 adjusted data were used in computations and are presented in results and discussion.

Storm parameters that included duration, peak rate, total discharge, base flow, and storm flow were derived from a standard flow separation method using a constant slope ($0.05\ ft^3/sec/mi^2/h$ or 1.1 mm/day) as described by Hewlett and Hibbert (1967). Separation analysis included 12-24 storms during monitoring period and covered dormant season (November to April) and growing season (May to October) in CSB and TB. In the study region, soil moisture is the lowest during peak growing season when potential ET is highest and highest in dormant season when potential ET is lowest (Dreps, 2011).

We analyzed mean hydrologic parameters and water quality indices between water years, regions, seasons, and months using one-way analysis of variance (JMP, 2009). The conservative post hoc Tukey HSD test was selected and significance level was set to $\alpha \leq 0.05$ in JMP 9.0 to determine which group means were statistically different from each other. Significant difference statements are $\alpha \leq 0.05$ and data presented for each region are mean values, unless otherwise stated. We used general linear regression model (GLM) procedure to test relative control of independent variables on several storm outflow response variables in CSB and TB. This procedure uses the method of least squares to fit general linear models.

Geographic Ecoregions and Soil Characteristics

A major difference between HF and UF is the ecoregion that has allowed for differences in stream channel formation, soil type, thickness, and seasonal function (Cleland *et al.*, 2007). Streams found in HF (HF1, HF2, HFW1, and HFW2) are generally shallow, and connected to their narrow floodplain, rocky substrate. These stream channels had steep upland slopes ranging from 15 to 40% with watersheds underlined by CSB soils characteristics. HF upland soils are defined as well-drained with depth to water table >6 ft and tend to function in a similar capacity in growing season and dormant season. According to the North Carolina Geological Survey (1988), CSB is comprised mostly of rocks formed through volcanic activity and deposits, and was the location of oceanic volcanic islands approximately 550 million years ago. Total land surface in CSB covers 8.5% of NC and extends into surrounding states of Virginia and South Carolina (Cleland *et al.*, 2007). Soil distribution in CSB watersheds vary slightly between catchments with Tatum and Appling being the dominate series. In contrast, streams in UF (UF1 and UF2) have

TABLE 1. Annual Water Budget-Discharge, Precipitation, ET, and Discharge to Precipitation Ratio for Water Years April 2008-March 2009 and April 2009-March 2010 in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds.

Watersheds	Geologic Regions	Discharge mm	Precipitation mm	ET mm	ET % of P	Discharge/ Precipitation Ratio	Precipitation April 2007-March 2008 (Drought Period) mm
April 2008-March 2009							
HF1	CSB	162	1,207	1,045	87	0.13	610
HF2	CSB#	279	1,207	928	77	0.23	610
HF2 adjusted	CSB##	189	1,207	1,018	84	0.16	610
HFW1	CSB	186	1,207	1,021	85	0.15	610
HFW2	CSB	200	1,207	1,007	83	0.17	610
	Mean CSB	184 (16.0)*Aa	1,207	1,023 (16.0)Aa	85 (1.7)Aa	0.15 (0.02)Aa	610
UF1	TB	235	1,279	1,044	82	0.18	708
UF2	TB	246	1,279	1,033	81	0.19	708
	Mean TB	241 (7.8)**Ba	1,279	1,039 (7.8)Aa	82 (0.7)Ba	0.19 (0.01)Ba	708
April 2009-March 2010							
HF1	CSB	205	1,351	1,146	85	0.15	
HF2	CSB#	361	1,351	990	73	0.27	
HF2 adjusted	CSB##	263	1,351	1,088	81	0.19	
HFW1	CSB	277	1,351	1,074	79	0.21	
HFW2	CSB	293	1,351	1,058	78	0.22	
	Mean CSB	260 (38.3) + Ab	1,351	1,092 (38.3)Ab	81 (2.8)Ab	0.19 (0.03)Ab	
UF1	TB	245	1,288	1,043	81	0.19	
UF2	TB	333	1,288	955	74	0.26	
	Mean TB	289 (62.2) ++ Aa	1,288	999 (62.2)Aa	78 (4.8)Aa	0.22 (0.04)Aa	

Notes: HF2 adjusted = annual spring flow contribution removed. Standard deviations are in parentheses.
Means with the same letters are not significantly different, $p < 0.05$, Tukey test; region *vs.* region within water year (uppercase); water year *vs.* water year within region (lowercase). Precipitation during drought period was added to the table to give context for precipitation input before water year April 2008-March 2009. P, precipitation.
*Discharge = 0.50 mm/day; **Discharge = 0.66 mm/day; +Discharge = 0.71 mm/day; ++Discharge = 0.79 mm/day.
#Data not used in mean calculation because of spring flow contribution. ##Data used in mean calculation because watershed streamflow has been adjusted for spring flow contribution.

incised stream channels that are detached from their wide floodplain, sandy substrate, and gentle upland slopes averaging 7% with watersheds underlined by TB soil characteristics. TB is 3.5% of NC (Cleland *et al.*, 2007) and extends down to include a small portion of South Carolina. TB was formed approximately 200 million years ago during a major rifting event. Numerous clastic and evaporitic synrift basins were formed during this event, later filling with sedimentary rocks, mud, sand, silt, and gravel (North Carolina Geological Survey, 1988). Soil distribution in TB watersheds vary between pairs with Helena being the dominate series. There is a 10-cm thick confining clay layer 30 cm below ground surface that creates an impermeable condition that results in a perched water table during dormant season. TB soils are clayey with lower permeability, higher shrink swell characteristics, and thinner soil layers than CSB soils (United States Department of Agriculture, Soil Conservation Service, 1971). These features cause variability in how TB soils store, release, and generate water between growing season and dormant season. More details on local site CSB and TB soil physical properties and hydraulic features can be found in Dreps (2011).

According to the NC Geologic map, UF watersheds fall outside of the defined TB ecoregion by about 1.6 km and are depicted in CSB class. However, on-the-ground surveys indicate that physical and chemical stream and soil features in UF watersheds are highly characteristic of TB soils as reported by Griffith *et al.* (2002). In addition, refined ecoregion maps generated by the USDA Forest Service and other government and nongovernment agencies depict UF in TB (Cleland *et al.*, 2007). Given the coarse spatial resolution of NC Geologic maps (1:24,000), it is not surprising that UF watersheds are depicted in CSB class (Colson *et al.*, 2008). These maps are generally not detailed enough for certain descriptive information in a small spatial scaled research project. Infield surveys are the most accurate method for determining stream characteristics for site-specific research purposes in small headwater watersheds (Colson *et al.*, 2008). Therefore, we consider soil features in UF watersheds to be characteristic of TB.

RESULTS

Annual Parameters

Precipitation for water year 2008 (April 2007-March 2008) was 610 mm in CSB and 708 mm in TB (Table 1). This was about 40% below a normal precipitation year (~1,100 mm) for the NC piedmont area (State Climate Office of North Carolina, 2011), resulting in a dry year. Precipitation was 1,207 mm in CSB and 1,351 in TB in 2009, and 1,279 mm in CSB and 1,288 mm in TB in 2010, resulting in wet years.

Water budget parameters varied between geographic regions and water years (Table 1). Discharge was 184 mm in CSB and 241 mm in TB in 2009, and 260 mm in CSB and 289 mm in TB in 2010. ET was 85% in CSB and 82% in TB in 2009, and 81% in CSB and 78% in TB in 2010. Discharge/precipitation ratio was 0.15 in CSB and 0.19 in TB in 2009, and 0.19 in CSB and 0.22 in TB in 2010. Daily discharge was 0.50 mm/day in CSB and 0.66 mm/day in TB in 2009, and 0.71 mm/day in CSB and 0.79 mm/day in TB in 2010.

Annual mean discharge and discharge/precipitation ratio were significantly lower, and ET was significantly higher in CSB than TB in 2009 (Table 1). No water budget parameters were significantly different between CSB and TB in 2010. TB discharged 27% (0.19 *vs*. 0.15) more water than CSB following a drought year and 16% (0.22 *vs*. 0.19) more following a wet year. Over the entire monitoring period, differences of discharge/precipitation ratio between CSB and TB were not significantly different (0.20 *vs*. 0.17).

All parameters changed significantly (increase or decrease) in CSB from 2009 to 2010. No parameters changed significantly in TB from 2009 to 2010.

Seasonal Discharge/Precipitation

Precipitation within dormant seasons and growing seasons was similar (Figure 2). Seasonal discharge/precipitation ratio expresses the percentage of precipitation that result in stream discharge. CSB and TB discharge/precipitation ratios were not significantly different in 2008 dormant season ($p = 0.77$) and 2008 growing season ($p = 0.67$) (Figure 2). Discharge/precipitation ratio was significantly higher in TB than CSB during 2009 (0.33 *vs*. 0.24) and 2010 dormant seasons (0.44 *vs*. 0.31), and significantly lower during 2009 growing season (0.02 *vs*. 0.07).

May 2007 to October 2007 (drought period) growing season precipitation was significantly lower than the typical growing season precipitation, 160 mm *vs*. 680 mm.

Storm Hydrograph Characteristics

Storm hydrology characteristics were subject to geological and seasonal influence (Table 2). Event duration, peak time, and base flow were significantly higher in TB than CSB in dormant season only. Peak rate, total discharge, storm flow, and discharge/

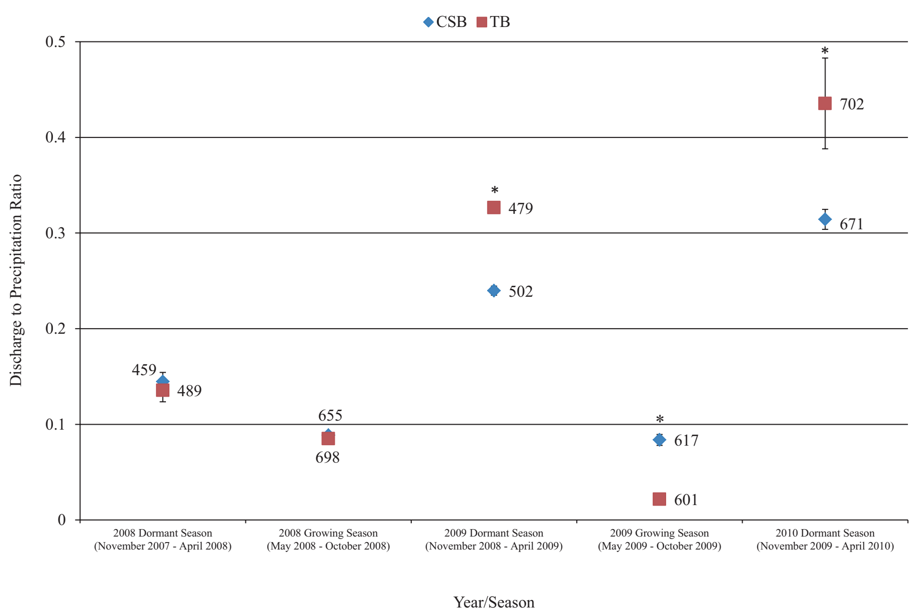


FIGURE 2. Dormant and Growing Season Discharge to Precipitation Ratio from 2007 to 2010 in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds. *Significantly different at $p < 0.05$, Tukey test. Precipitation values in mm are shown.

TABLE 2. Storm Hydrologic Characteristics in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds Derived from Standard Flow Separation Method.

Watersheds	n	Geologic Regions	Event Duration hours	Begin Flow mm/day	Peak Rate mm/day	Peak Time hours	Total Discharge mm	Base flow mm	Storm flow mm	Precipitation mm	Discharge to Precipitation Ratio
Dormant season											
HF1	24	CSB	19.3 (12.4)	0.4 (0.4)	4.3 (4.3)	8.9 (8.3)	2.1 (2.5)	0.8 (0.9)	1.3 (1.7)	25.6 (18.9)	0.07 (0.07)
HF2	24	CSB	20.3 (13.0)	0.4 (0.3)	7.8 (9.2)	8.3 (10.0)	3.5 (5.5)	0.9 (1.2)	2.5 (4.3)	26.0 (24.7)	0.11 (0.09)
HFW1	24	CSB	19.0 (14.4)	0.5 (0.3)	6.1 (7.6)	8.2 (12.0)	2.9 (4.3)	1.0 (1.3)	1.9 (3.1)	26.2 (23.2)	0.08 (0.08)
HFW2	24	CSB	23.8 (18.5)	0.4 (0.2)	8.6 (10.3)	10.0 (12.0)	4.8 (6.0)	1.3 (1.6)	3.4 (4.6)	24.7 (25.9)	0.14 (0.13)
		Mean CSB	20.6 (2.2)Aa	0.4 (0.1)Aa	6.7 (2.0)Aa	8.9 (0.8)Aa	3.3 (1.1)Aa	1.0 (0.2)Aa	2.3 (0.9)Aa	25.6 (0.6)Aa	0.10 (0.03)Aa
UF1	20	TB	30.1 (20.8)	0.4 (0.5)	25.0 (28.5)	11.7 (12.5)	10.8 (11.9)	1.8 (2.6)	9.0 (10.0)	27.3 (26.9)	0.33 (0.22)
UF2	19	TB	31.2 (19.3)	0.4 (0.3)	29.1 (27.3)	13.3 (13.0)	13.2 (13.5)	1.8 (1.4)	11.4 (12.3)	31.7 (26.5)	0.34 (0.21)
		Mean TB	30.6 (0.7)Ba	0.4 (0.0)Aa	27.0 (2.9)Ba	12.5 (1.1)Ba	12.0 (1.7)Ba	1.8 (0.0)Ba	10.2 (1.7)Ba	29.5 (3.1)Aa	0.34 (0.00)Ba
Growing season											
HF1	23	CSB	7.7 (6.5)	0.1 (0.2)	12.1 (36.2)	3.4 (6.4)	2.0 (7.5)	0.1 (0.2)	1.9 (7.3)	25.9 (25.7)	0.03 (0.06)
HF2	23	CSB	8.3 (5.8)	0.3 (0.2)	14.8 (34.8)	2.5 (2.3)	2.3 (7.4)	0.2 (0.3)	2.1 (7.1)	28.5 (25.3)	0.04 (0.06)
HFW1	22	CSB	12.6 (21.2)	0.3 (0.1)	8.1 (17.0)	2.9 (2.2)	1.7 (5.1)	0.2 (0.3)	1.5 (4.8)	29.0 (27.7)	0.03 (0.04)
HFW2	23	CSB	7.8 (8.6)	0.4 (0.5)	8.4 (22.0)	2.6 (2.1)	2.0 (6.3)	0.3 (0.4)	1.7 (6.0)	22.3 (27.6)	0.03 (0.06)
		Mean CSB	9.1 (2.3)Ab	0.3 (0.2)Aa	11.0 (3.3)Aa	2.9 (0.4)Ab	2.0 (0.3)Aa	0.2 (0.1)Ab	1.8 (0.3)Aa	26.4 (3.1)Aa	0.03 (0.01)Ab
UF1	12	TB	11.2 (9.7)	0.1 (0.1)	18.9 (37.1)	2.7 (1.9)	4.3 (10.6)	0.2 (0.3)	4.1 (10.5)	26.1 (21.4)	0.09 (0.15)
UF2	12	TB	9.8 (7.4)	0.1 (0.1)	18.9 (33.4)	3.0 (2.0)	3.9 (9.8)	0.2 (0.2)	3.7 (9.7)	31.7 (27.4)	0.06 (0.10)
		Mean TB	10.5 (1.0)Ab	0.1 (0.0)Ab	18.9 (0.0)Ba	2.9 (0.2)Ab	4.1 (0.3)Bb	0.2 (0.0)Ab	3.9 (0.3)Bb	28.9 (4.0)Aa	0.07 (0.02)Bb

Notes: Standard deviations are in parenthesis.
Means with the same letters are not significantly different, $p < 0.05$, Tukey test; region *vs.* region within season (uppercase); season *vs.* season within region (lowercase). n, number of storms.

precipitation ratio were significantly higher in TB than CSB in both dormant season and growing season. Peak rate was 300% higher in TB than CSB during dormant season, 27.0 mm *vs.* 6.8 mm, and 72% higher during growing season, 18.9 mm *vs.* 11.0 mm. Base flow was 80% higher in TB than CSB during dormant season, 1.8 mm *vs.* 1.0 mm, and the same during growing season, 0.2 mm. Storm flow was 343% higher in TB than CSB during dormant season, 10.2 mm *vs.* 2.3 mm, and 117% higher during growing season, 3.9 mm *vs.* 1.8 mm. Discharge/precipitation ratio was 240% higher in TB than CSB during dormant season, 0.34 mm *vs.* 0.10 mm, and 133% higher during growing season, 0.07 mm *vs.* 0.03 mm.

Event duration, peak time, base flow, and discharge/precipitation ratio decreased significantly in both CSB and TB from dormant to growing season (Table 2). Total discharge and storm flow decreased significantly only in TB from dormant season to growing season. For example, storm flow declined from 10.2 to 3.9 mm, a 60% decrease in channel storm flow. Precipitation intensity for storm hydrograph characteristics was not significantly different from region to region or season to season (Table 2) (e.g., 25.6 mm *vs.* 29.5 mm or 25.6 mm *vs.* 26.4 mm, respectively).

Multiple regression analysis was applied to data in Table 2 to assess relative control on response variables. Controls on watershed response variables were similar between CSB and TB, with the exception of storm flow and total discharge (Table 3). Storm flow was controlled by precipitation in CSB and by season, and precipitation in TB. Total discharge was controlled by season and precipitation in CSB, and by season, begin flow, and precipitation in TB. All other response variables including peak time, peak rate, base flow, and discharge/precipitation ratio were controlled by the same predicator variable(s) in CSB and TB.

Annual Water Quality

Annual water quality parameters were computed based on time-weighted mean concentration (TWMC) and flow-weighted mean concentration (FWMC) to account for differences in sampling time and streamflow, respectively. In general, TWMC and FWMC were similar with slight differences associated with large storm events. TWMC data are presented and discussed because they typically represent common stream and aquatic exposure conditions (Table 4).

TSS, TOC, TP, and TKN showed significant difference in concentration (Table 4) or export (Table 5) within regions or years. NO_3 and NH_4 showed no significant differences within regions and years in both

TABLE 3. General Linear Regression Model Stepwise Analysis Comparing Control of Predictor Variables (season, begin flow, and total precipitation) on Several Response Variables During Storms (5 mm to 130 mm) in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds.

Response Variables	Season	Begin Flow	Total Precipitation	r^2
		CSB		
CSB				
Peak time	0.00	ns	0.00	0.4
Peak rate	ns	ns	0.00	0.6
Base flow	0.00	0.00	0.00	0.6
Storm flow	**ns**	ns	0.00	0.6
Total discharge	0.00	**ns**	0.00	0.7
Discharge to precipitation	0.00	0.00	0.00	0.4
TB				
Peak time	0.00	ns	0.00	0.6
Peak rate	ns	ns	0.00	0.4
Base flow	0.01	0.00	0.00	0.6
Storm flow	**0.00**	ns	0.00	0.8
Total discharge	0.00	**0.02**	0.00	0.8
Discharge to precipitation	0.00	0.00	0.00	0.6

Notes: p values are shown for columns titled Season, Begin Flow, and Total Precipitation. ns, not significant at $p < 0.05$, Tukey test. Bolded and underlined values and characters indicate where predictor variables differed between CSB and TB in terms of significant support in the model.

concentration and export. TSS concentration increased significantly from 2008 to 2009, 18.8-32.0 mg/l in CSB and 20.7-38.3 mg/l in TB. TOC concentration was significantly higher in TB when compared with CSB in 2008, 11.3 mg/l *vs.* 6.6 mg/l and 2009, 11.2 mg/l *vs.* 6.0 mg/l. On an individual watershed basis, UF2 had higher NO_3 concentrations when compared with all other watersheds in 2008 and 2009. In 2009, UF2 had the highest concentrations of all measured constituents except TP (Table 4). HFW2 had a slightly higher TP concentration. Exceedance or reference concentrations reported in other studies are found in Table 4.

TSS export was significantly higher in TB than CSB in 2009, 121 kg/ha/yr *vs.* 81 kg/ha/yr. TOC export was significantly higher in TB than CSB, 19.0 kg/ha/yr *vs.* 9.7 kg/ha/yr in 2008 and 35.4 kg/ha/yr *vs.* 15.3 kg/ha/yr in 2009. TP export increased significantly from 2008 to 2009, 0.10-0.22 kg/ha/yr in CSB and 0.08 kg/ha/yr to 0.31 kg/ha/yr in TB. TKN export increased significantly from 2008 to 2009, 0.70-1.58 kg/ha/yr in CSB.

Seasonal Water Quality

NO_3 revealed a moderate seasonal pattern where most daily peak concentrations were observed during growing season in CSB and TB (Figure 3). Daily maximum peak NO_3 concentration was 0.34 in CSB and 1.0 mg/l in TB. Although UF2 and HFW2 maximum peak NO_3 concentration were relatively low, 1.6 and 0.65 mg/l, respectively, data from UF2 and HFW2 were not incorporated in Figure 3. Small amounts of NO_3 drain from the agriculture field and pasture in these two watersheds year round and would confound seasonal NO_3 signal. There was no seasonal pattern for TSS, TOC, NH_4, TP, and TKN concentrations in CSB and TB (data not shown). TSS, TP, and TKN concentrations generally peaked during high storm flow (>6 mm) and precipitation events (>30 mm).

A seasonal comparison example that depicts discharge and TSS relationship in CSB and in TB is shown in Figure 4. Both dormant and growing season patterns were a clockwise hysteresis. TB showed considerably more limb separation than CSB during dormant season (Figure 4a). TB highest TSS concentration occurred with the highest rate of discharge. In contrast, CSB highest TSS concentration occurred before maximum rate of discharge, TSS concentration was diluted as water flow peaked. TB and CSB limb separation was less in growing season than dormant season (Figures 4a and 4b). TB highest TSS concentration occurred before maximum rate of discharge. TSS concentrations in both watersheds and seasons returned to base levels once discharge was close to prestorm rates. Dormant season TSS concentration was 46 mg/l in CSB and 113 mg/l in TB. Growing season TSS concentration was 81 mg/l in CSB and 99 mg/l in TB.

A clear seasonal pattern was observed in monthly maximum stream temperature. Stream temperature fluctuated from 9.5 to 24.0°C in CSB and 9.3 to 26.2°C in TB over monitored period. Summer values were slightly higher in TB than in CSB. Winter values were slightly higher in CSB than in TB.

Benthic Macroinvertebrate

Benthic metric results were not significantly different between CSB and TB in January survey (Table 6). Total EPT (Ephemeroptera, Plecoptera, and Trichoptera) taxa richness and EPT abundance were significantly higher in CSB when compared with TB in April survey. Biotic index was significantly lower in CSB than TB (3.1 *vs.* 4.4) in April survey.

Total taxa richness and total EPT taxa richness declined significantly in TB between January and April survey. EPT abundance stayed the same in CSB (i.e., 82 and 82), but decreased in TB (i.e., 60 and 36) between surveys. Biotic index declined (improved) in CSB and TB between surveys, but the improvement was only significant in CSB.

Mean 14-day streamflow (more related to presence or absence of aquatic species than instantaneous

TABLE 4. Annual Time-Weighted Total Suspended Sediment and Nutrient Concentrations in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds for 2008 and 2009.

Watersheds	Geologic Regions	TSS	TOC	NH_4	NO_3	TP	TKN
				mg/l			
2008							
HF1	CSB	17.3 (22.6)	7.2 (4.4)	0.01 (0.02)	0.01 (0.04)	0.04 (0.04)	0.40 (0.36)
HF2	CSB	25.0 (41.1)	7.4 (5.7)	0.00 (0.01)	0.01 (0.03)	0.07 (0.09)	0.51 (0.55)
HFW1	CSB	15.1 (19.1)	6.2 (4.0)	0.01 (0.03)	0.02 (0.13)	0.05 (0.04)	0.42 (0.33)
HFW2	CSB	17.6 (26.8)	5.7 (3.9)	0.04 (0.20)	0.05 (0.11)	0.12 (0.32)	0.58 (0.78)
	Mean CSB	18.8 (27.4)Aa	6.6 (4.5)Aa	0.02 (0.07)Aa	0.02 (0.08)Aa	0.07 (0.12)Aa	0.48 (0.51)Aa
UF1	TB	19.0 (27.7)	10.7 (6.9)	0.02 (0.08)	0.02 (0.07)	0.06 (0.06)	0.51 (0.56)
UF2	TB	22.3 (28.0)	11.8 (7.4)	0.02 (0.08)	0.20 (0.25)	0.04 (0.04)	0.66 (0.47)
	Mean TB	20.7 (27.9)Aa	11.3 (7.2)Ba	0.02 (0.08)Aa	0.11 (0.16)Aa	0.05 (0.05)Aa	0.59 (0.52)Aa
2009							
HF1	CSB	38.8 (34.1)	5.6 (3.1)	0.01 (0.03)	0.00 (0.01)	0.09 (0.11)	0.79 (0.98)
HF2	CSB	30.1 (24.1)	6.8 (4.3)	0.01 (0.03)	0.00 (0.01)	0.07 (0.08)	0.64 (0.62)
HFW1	CSB	26.8 (18.6)	6.2 (3.6)	0.00 (0.00)	0.02 (0.10)	0.06 (0.05)	0.46 (0.28)
HFW2	CSB	32.4 (32.7)	5.5 (3.7)	0.02 (0.10)	0.04 (0.07)	0.12 (0.14)	0.63 (0.63)
	Mean CSB	32.0 (27.4)Ab	6.0 (3.7)Aa	0.01 (0.04)Aa	0.02 (0.05)Aa	0.09 (0.10)Aa	0.63 (0.63)Aa
UF1	TB	34.7 (20.7)	10.1 (5.6)	0.01 (0.03)	0.00 (0.02)	0.09 (0.08)	0.70 (0.49)
#UF2	TB	41.9 (32.7)	12.3 (6.6)	0.07 (0.44)	0.23 (0.41)	0.11 (0.12)	0.97 (0.98)
	Mean TB	38.3 (26.7)Ab	11.2 (6.1)Ba	0.04 (0.24)Aa	0.12 (0.22)Aa	0.10 (0.10)Aa	0.84 (0.74)Aa
Exceedance value				2.0[1]	10*/1.0**	0.05[2]/0.10[3]	
Reference value					0.13***	0.04[4]	0.3[5]

Notes: Standard deviations are in parentheses.
TSS, total suspended sediment; TOC, total organic carbon; NH_4, ammonium; NO_3, nitrate; TP, total phosphorus; TKN, total Kjeldahl nitrogen.
Means with the same letters are not significantly different, $p < 0.05$, Tukey test; region *vs*. region within year (uppercase); year *vs*. year within region (lowercase).
*Drinking water criteria, USEPA, 2000b; **Preserve biological integrity, USEPA, 2000b; ***Reference conditions, USEPA, 2000a.
#UF2 = 10% of watershed is covered by agriculture field.
[1]Exceed chronic exposure criteria for fish, reported in Mueller and Helsel, 1996.
[2]Criterion for the prevention of eutrophication of stream where phosphorus enters a lake or reservoir, reported in Mueller and Helsel, 1996.
[3]Criterion for the prevention of eutrophication of stream where phosphorus does not directly enter a lake or reservoir, reported in Mueller and Helsel, 1996.
[4]Reference conditions, USEPA, 2000a.
[5]Reference stream and river water conditions, USEPA, 2000a.

streamflow at survey time) and mean monthly TOC concentration (indicator of plant detritus or food source in streamwater) prior to surveys varied between CSB and TB (Table 6). Streamflow was 0.82 mm/day in CSB and 1.26 mm/day in TB prior to January survey and 0.65 mm/day in CSB and 0.15 mm/day in TB prior to April survey. TOC concentration was 5.2 mg/l in CSB and 9.1 mg/l in TB prior to January survey and 5.2 mg/l in CSB and 7.8 mg/l in TB prior to April survey.

DISCUSSION

Annual Parameters

Quantifying stream discharge and water quality data at various temporal scales (annual-, seasonal-, and storm-based) from forests with different soil characteristics can provide useful information to water resource managers and modelers to mitigate changes in storm-flow dynamics, following land conversions from forests to other uses. Monitoring for this study began in November 2007, near the end of a record drought year for the southeastern U.S. (United States Drought Monitor, 2011). The southeast regional drought reduced soil moisture, groundwater storage, and base flow in study watersheds resulting in no flow for 70% of the early monitoring period, November 2007 to February 2008. Annual parameters were affected by drought conditions.

In 2009, which followed a drought year, most water balance parameters between CSB and TB were significantly different with CSB producing significantly less discharge/precipitation than TB, 15% *vs*. 19%. By 2010, which followed a wet year, CSB water balance parameters increased (improved) and were no longer significantly different from TB. Variation in relationship between CSB and TB discharge/precipitation from 2009 to 2010 was due, in part, to consequences of

TABLE 5. Annual Time-Weighted Total Suspended Sediment and Nutrient Export from Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds for 2008 and 2009.

Watersheds	Geologic Regions	TSS	TOC	NH_4	NO_3	TP	TKN	Discharge
		kg/ha/yr						l/s
2008								
HF1	CSB	21	8.7	0.01	0.01	0.05	0.48	0.5
HF2	CSB	37	12.3	0.00	0.01	0.10	0.80	0.6
HFW1	CSB	22	9.2	0.01	0.03	0.08	0.62	1.4
HFW2	CSB	27	8.7	0.06	0.08	0.19	0.88	1.9
	Mean CSB	27 (7)Aa	9.7 (1.7)Aa	0.02 (0.03)Aa	0.03 (0.03)Aa	0.10 (0.06)Aa	0.70 (0.18)Aa	1.1 (0.7)Aa
UF1	TB	30	16.8	0.02	0.03	0.09	0.80	0.9
UF2	TB	40	21.2	0.03	0.35	0.08	1.18	1.6
	Mean TB	35 (7)Aa	19.0 (3.1)Ba	0.03 (0.00)Aa	0.19 (0.22)Aa	0.08 (0.01)Aa	0.99 (0.26)Aa	1.2 (0.5)Aa
2009								
HF1	CSB	84	12.0	0.02	0.01	0.20	1.71	0.8
HF2	CSB	80	17.9	0.03	0.01	0.20	1.67	1.0
HFW1	CSB	72	16.5	0.00	0.04	0.16	1.24	2.5
HFW2	CSB	87	14.8	0.06	0.11	0.32	1.68	3.4
	Mean CSB	81 (7)Ab	15.3 (2.5)Ab	0.03 (0.02)Aa	0.04 (0.05)Aa	0.22 (0.07)Ab	1.58 (0.22)Ab	1.9 (1.2)Aa
UF1	TB	99	29.0	0.02	0.01	0.25	2.01	1.7
#UF2	TB	142	41.8	0.24	0.78	0.36	3.30	3.1
	Mean TB	121 (30)Bb	35.4 (9.1)Ba	0.13 (0.16)Aa	0.40 (0.54)Aa	0.31 (0.08)Bb	2.66 (0.91)Aa	2.4 (1.0)Aa

Notes: Standard deviations are in parentheses.
TSS, total suspended sediment; TOC, total organic carbon; NH_4, ammonium; NO_3, nitrate; TP, total phosphorus; TKN, total Kjeldahl nitrogen.
Means with the same letters are not significantly different, $p < 0.05$, Tukey test; region *vs*. region within year (uppercase); year *vs*. year within region (lowercase).
#UF2 = 10% of watershed is covered by agriculture field.

cumulative drought on soil water dynamics and how CSB and TB stored and released water following a dry year and a wet year. Risser *et al.* (2005) found that recharge or storage in a wet year can be 3-5 times that of a dry year. Cumulative drought affects appear to have had a greater influence on CSB parameters when compared with TB as reflected by significant increase or improved discharge from 2009 to 2010 (184-260 mm) (Table 1). Although TB streams have low-flow characteristics and are considered to have the lowest base flows in NC due to low infiltration rates and low topographic relief (Weaver and Pope, 2001; North Carolina Department of Environment and Natural Resources, Division of Water Quality Planning Branch, 2003), drought does not appear to significantly exacerbate these annual streamflow dynamics beyond those of CSB. TB discharge was not significantly different from 2009 to 2010 (241-289 mm). Study discharge and discharge/precipitation ratios were low compared with values found in western NC forests. Swank *et al.* (2001) found that annual discharge was 990 mm, which computed to 55% of precipitation in a 12 ha mixed hardwood forest in the Southern Appalachian Mountains. Western piedmont and mountains are areas considered to have high potential to sustain low flow or base flow in NC because of deeper soil storage capacity and underlying geologic features (Weaver and Fine, 2003). In contrast, CSB and TB in central piedmont NC have minimal potential for sustained base flow due to low permeability associated with area rock type (Weaver and Fine, 2003). Giese and Mason (1993) found that both piedmont CSB and TB have relatively low base flow with TB being distinctive in that its base-flow rates and annual discharge are some of the lowest in NC.

Estimated ET values in this study were considered high (≥78% of P) (Table 1) and may be over estimates. Based on a general ET equation developed by Sun *et al.* (2011) as a function of potential ET, precipitation, and leaf area index, Dreps (2011) found that ET was 60% in CSB and 65% in TB. Differences in ET estimates by this study and Dreps (2011) were probably a result of the catchment water balance equation ($ET = P - Q$) not fully accounting for change in soil water storage. The equation also did not account for water lost to deep seepage. ET remains the most uncertain variable to quantify on a small scale, although it represents about 70% of annual precipitation across the U.S. (Brooks *et al.*, 1997). Annual ET from forested watersheds in the southeastern U.S. can range from 50% in Appalachian Mountains, 85% in coastal Florida Flatwoods (Sun *et al.*, 2002), and 60% in piedmont, NC (Stoy *et al.*, 2006; Oishi *et al.*, 2008).

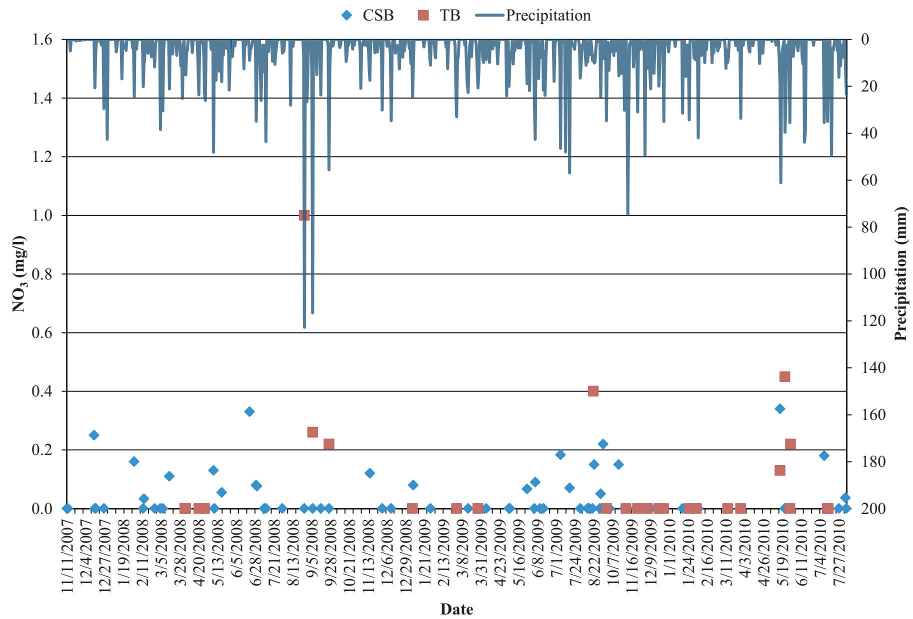


FIGURE 3. Daily Peak Concentration of Nitrate (NO_3) in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds. Dormant season is November-April and growing season is May-October.

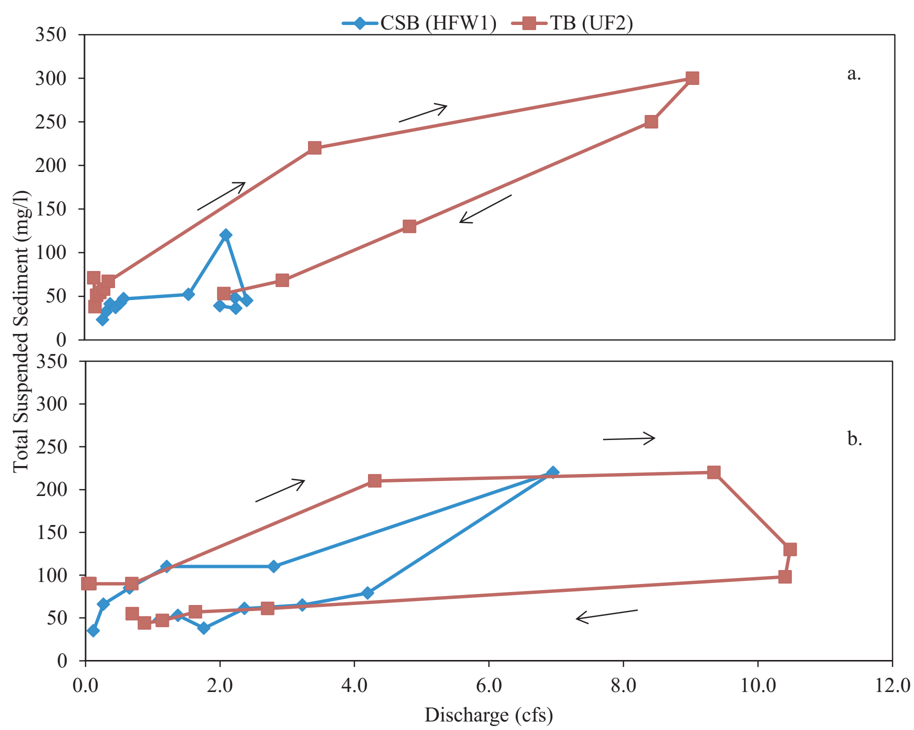


FIGURE 4. Example of Relationship Between Discharge and Total Suspended Sediment (TSS) in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds in (a) Dormant Season and (b) Growing Season. Data are from high precipitation event (>35 mm) that generated significant storm flow (2.5 cfs or 6.0 mm).

Seasonal Discharge/Precipitation

Under normal climate conditions, precipitation in the southeastern U.S. is fairly evenly distributed throughout the year (State Climate Office of North Carolina, 2011) and discharge has a seasonal pattern linked to ET (Sun *et al.*, 2002). Following the May 2007-October 2007 growing season drought, watershed

TABLE 6. Macroinvertebrate Benthic Metric Results in Carolina Slate Belt (CSB) and Triassic Basin (TB) Watersheds Surveyed in January 2010 and April 2010.

Watersheds	Geologic Regions	Total Taxa Richness	Total EPT Taxa Richness	EPT Abundance	Biotic Index	Water Quality	Streamflow (mm/day)[1]	TOC (mg/l)[2]
January								
HF1	CSB	32	13	41	4.5	Excellent	0.63	4.0
HF2	CSB	43	21	83	3.8	Excellent	0.82	5.9
HFW1	CSB	50	24	110	4.0	Excellent	0.89	5.2
HFW2	CSB	34	20	95	4.1	Excellent	0.93	5.6
	Mean CSB	40 (8.3)Aa	20 (4.7)Aa	82 (29.6)Aa	4.1 (0.3)Aa	Excellent	0.82 (0.13)Aa	5.2 (0.9)Aa
UF1	TB	35	16	44	4.8	Excellent	0.97	8.7
UF2	TB	38	18	75	4.5	Excellent	1.56	9.5
	Mean TB	37 (2.1)Aa	17 (1.4)Aa	60 (21.9)Aa	4.7 (0.2)Aa	Excellent	1.26 (0.42)Aa	9.1 (0.6)Ba
April								
HF1	CSB	26	16	74	3.3	Excellent	0.49	4.7
HF2	CSB	35	17	88	3.0	Excellent	0.58	6.9
HFW1	CSB	43	22	106	3.3	Excellent	0.85	4.8
HFW2	CSB	29	17	58	2.8	Excellent	0.70	4.2
	Mean CSB	33 (8.5)Aa	18 (32.2)Aa	82 (16.0)Aa	3.1 (0.2)Ab	Excellent	0.65 (0.16)Aa	5.2 (1.2)Aa
UF1	TB	25	12	36	4.8	Excellent	0.11	7.4
UF2	TB	25	10	36	4.0	Excellent	0.19	8.2
	Mean TB	25 (0.0)Ab	11 (1.4)Bb	36 (0.0)Ba	4.4 (0.6)Ba	Excellent	0.15 (0.06)Ba	7.8 (0.6)Ba

Notes: Standard deviations are in parentheses. Criteria for NC Biotic Index: Excellent < 5.24, Good 5.25-5.95, Good-Fair 5.96-6.67, Fair 6.68-7.70, Poor > 7.71 (Source: Lenat, 1993).
EPT, ephemeroptera, plecoptera, and trichoptera.
Means with the same letters are not significantly different, $p < 0.05$, Tukey test; region *vs*. region within month (uppercase); month *vs*. month within region (lowercase).
[1]Mean 14-day streamflow prior to survey.
[2]Mean monthly TOC concentration prior to survey.

storage and release patterns were altered and discharge rates no longer followed a clear seasonal pattern. Long-term drought is cumulative, so hydrologic effects during exceptional drought period are dependent on current precipitation inputs plus precipitation in previous months or seasons. Therefore, we observed limited discharge and no statistical differences between CSB and TB discharge/precipitation ratio in 2008 dormant season and 2008 growing season (Figure 2). By 2009 dormant season, hydrologic conditions had improved and TB generated significantly more discharge/precipitation (0.33 *vs*. 0.24) than CSB. TB, however, generated significantly less discharge/precipitation (0.02 *vs*. 0.07) than CSB in 2009 growing season. This lower discharge/precipitation ratio during 2009 growing season in TB has implications for growing season target water budgets, drinking water supplies during drought conditions, aquatic recreation, and aquatic species. Differences in seasonal flow dynamics was driven by how CSB and TB soils stored, processed, and released water seasonally. CSB soils were thick and stored water and drained it gradually, which resulted in more continuous base flow across seasons when compared with TB. Woolhiser *et al.* (2006) found that stream runoff and infiltration rates were sensitive to a 20% increase in soil depth, resulting in greater capacity for infiltration into the soil compared with thinner soil. TB soils were thin, clayey, and had a confining layer that prevented continued infiltration, thus allowing shallow soil water contribution to base flow (Hutchinson and Moore, 2000). This contribution was usually short lived during the growing season as the soil became dry and hard, deactivating the confining layer that allowed increased vertical water flow. Consequently, TB gentle slope gradient became the controlling factor on base-flow rates as most water was stored in bedrock (McGuire *et al.*, 2005). TB growing season soil storage capacity increased when compared with dormant season. During dormant season and rainfall accumulation, TB confining layer was reactivated as soils swelled and saturated. Saturation occurred from the perched water table over the confining layer rather than deep water table. Under saturated conditions, thin soil features became the dominant control on storm-flow generation. As a result, storm-flow generation from TB watersheds with moderate slopes (~10%) were more than CSB watersheds with steep slopes (~25%) (Baumann *et al.*, 2008).

TB discharge/precipitation appeared more sensitive to seasonal precipitation fluctuations when compared with CSB as reflected by a wider spread in ratio values in 2009 seasons (Figure 2). Effects from precipitation intensity were also more evident in TB than CSB during 2008 and 2009 growing seasons. Precipitation totals were similar during 2008 (698 mm) and 2009

(601 mm) growing seasons, however, a higher frequency of large storms (>25 mm) occurred in 2008 growing season. This resulted in significantly more TB discharge/precipitation in 2008 growing season than 2009 growing season (0.09 *vs.* 0.02, respectively) due to rapid rainfall accumulation, decreased infiltration, and increased lateral or overland flow (Figure 2). Mohamoud (2004) reported that clay content was a good predictor of high streamflow and could indicate the presence of impeding soil layer and occurrence of high subsurface lateral flow. CSB discharge/precipitation in 2008 growing season and 2009 growing season were statistically similar (0.09 *vs.* 0.08, respectively), indicating a different response than TB to the same changes in precipitation intensity.

Kuntukova (2011) found that significant discharge (≥5 mm) occurred when precipitation inputs were larger than 32 mm in CSB and 30 mm in TB, suggesting that TB was slightly more sensitive to inputs than CSB. Buttle *et al.* (2004) also found lower estimated rainfall thresholds required to generate 1 mm discharge in thin soils when compared with thick soils. Integrated seasonal affects of soil thickness and consequences of a confined clay layer on parameters into hydrologic models may help capture the influence these factors play in storm-flow generation. In addition, quantifying seasonal discharge targets across regions and precipitation inputs can aid water resource planners and modelers in formulating and setting seasonal maximum allowable budgets for human and agricultural water consumption. Consumption limits are particularly important in annual or seasonal drought. During exceptional drought periods as designated by NC Drought Management Advisory Council, water users shall reduce consumption by 20% below the month prior (15A NCAC 02E.0614). A better understanding of seasonal discharge dynamics draining from hydrologically different source areas to water supply reservoirs may increase or decrease this consumption percentage during exceptional drought periods.

Storm Hydrograph Characteristics

Various mathematical methods or chemical tracers can be used to evaluate storm hydrograph dynamics. A standard flow separation method was used with a constant slope (1.1 mm/day), as described by Hewlett and Hibbert (1967). The standard flow separation method and Kuntukova (2011) isotope hydrograph separation method with various tracers produced similar patterns in flow response between CSB and TB. Both methods found that storm flow was larger in TB than CSB. However, flow separation in this study indicated that storm flow accounted for a maximum 85% of total discharge in TB and 65% in CSB. Kuntukova (2011) found that storm flow accounted for a maximum 75% of total discharge in TB and 52% in CSB.

Moderately high to high storm events (22-32 mm) produced storm discharge that was significantly higher in TB than CSB in both dormant and growing season. The largest differences occurred in dormant season (Table 2). For example, TB total discharge was 250% higher than CSB total discharge during dormant season, 12.0 mm *vs.* 3.3 mm, and 100% higher during growing season, 4.1 mm *vs.* 2.0 mm. Dreps (2011) reported that in dormant season, TB storm-flow response was controlled by or "turned on" due to highly expansive clay subsoil, increased lateral flow, and low ET. CSB have nonexpansive soils that allow for deeper infiltration and consequently significantly shorter event duration and peak time, and more base flow during dormant season. Forested watershed hydrology changes with varying degrees and controls. Controls on storm hydrograph characteristics include soil, topography, antecedent moisture conditions, and season (Freer *et al.*, 1997; James and Roulet, 2007; Vano *et al.*, 2008).

This study revealed many statistical similarities around which predictor variable controlled storm response in CSB and TB (Table 3). Controls on storm flow and total discharge, however, varied between geographic regions. For example, the best-fit model to explain storm-flow response in CSB included precipitation only, but season and precipitation in TB. This suggests that watershed response parameters were more sensitive to moisture conditions and season in TB than CSB. Soil influence on storm-flow generation varied more from growing season to dormant season in TB than CSB due to TB thin soil, high shrink swell soil features, and less dormant season rainfall redistribution. Hopp and McDonnell (2009) noted that soil thickness was a critical driver in rainfall redistribution and water storage. CSB thick soils drained water slowly throughout the year due to large amounts of stored water in bedrock and topographic control. TB thin soils drained water slowly in growing season when soils were dry with an inactive confining clay layer, and fast in dormant season when soils were wet with an active confining layer. Ohnuki *et al.* (2008) found that a similar seasonal switch in soil features influenced water storage capacity and discharge generation. Jencso and McGlynn (2011) also found that predictor variables (i.e., topography, land cover vegetation, and geology) of annual, peak, transition, and base-flow periods changed seasonally. Kuntukova (2011) reported that TB soils were more sensitive to antecedent moisture conditions and time of year than CSB soils when explaining magnitude of discharge response in these upland forests. La Torre

Torres *et al.* (2011) found that discharge and seasonal soil moisture conditions were significantly correlated in forested lowland watersheds as well.

Annual Water Quality

Our annual nutrient concentrations were similar or lower than forested watershed values summarized in Binkley *et al.* (1999); further verifying that water quality from forests is high and represents baseline conditions. Baseline stream nutrient and TSS concentrations and exports are valuable water quality characteristics to understand, particularly to quantify and model changes following landuse changes or land management activities. These baseline data help capture and refine the natural range of nutrient variability in a forested system and define background source conditions. For example, Binkley and Brown (1993) reported that NO_3 concentrations range from 0.002 to 1.0 mg/l in water that drains forested watersheds. Swank and Vose (1994) found that NO_3 concentration was 0.004 mg/l in streamwater draining a mature mixed hardwood stand in the Southern Appalachian. Study of annual mean NO_3 concentrations fell within the range, 0.02-0.12 mg/l. Low stream NO_3 and NH_4 concentrations and exports suggested that both CSB and TB are nitrogen limited. Low concentrations are generally driven by vegetation cover, soil development factor, and biogeochemistry that effects mineralization, nitrification, and denitrification rates in forested watersheds. Forest management activities in the Southern Appalachian that include harvesting have been shown to cause minimal NO_3 concentration increases (0-0.15 mg/l) in streamwater (Swank *et al.*, 1989). When these concentrations are combined with increased discharge from harvesting, however, significant increases in nutrient export can occur (Swank and Johnson, 1994).

Most annual TSS and nutrient concentrations were not significantly different between CSB and TB or between 2008 and 2009. Exports showed slightly more significant differences than concentration, particularly between CSB and TB in 2009. TSS export, for example, was significantly higher in TB than CSB in 2009, 81 kg/ha/yr *vs*. 121 kg/ha/yr, because of higher discharge and higher erodible soil features. However, overland soil erosion was not observed at either site; indicating that higher TSS exports in TB was tied to the mobilization of relic stream sediments following increased stream discharge. Several forestry best management practices effectiveness studies have documented similar sediment transport relationships following forest harvesting, which was accompanied with temporary increases in stream discharge (summarized in Anderson and Lockaby, 2011). According to several studies, TSS export in undisturbed forested watersheds range from 20 to 340 kg/ha/yr (Ursic, 1970; Douglass and Van Lear, 1983). This TSS export range has been linked to different vegetation cover, geology, soil type, flow regime, and topography (Swank *et al.*, 1989). Harvesting activity that used forestry BMPs during operation have yielded average sediment loads of 340/ha/yr over a 10-year period after closure (Swank *et al.*, 2001) in the Southern Appalachians. This sediment export load is on the high-end when compared with similar forestry studies in the southeastern U.S.

TP export was strongly associated with TSS export as reflected by the same statistical arrangement within geographic regions and years (Table 5). TSS and TP exports were significantly higher in 2009 when compared with 2008 in CSB and TB. In addition, both TSS and TP exports were significantly higher in TB when compared with CSB in 2009. Changes in TP export tend to follow changes in TSS export given that phosphorus often attaches to small particles of sediment (Brady, 1990; Ice, 1999).

TOC concentrations (Table 4) and exports (Table 5) were significantly higher in TB when compared with CSB due to differences in seasonal streamflow dynamics and channel morphology. Deep and incised streambanks that are detached from their wide floodplain in TB reduce flushing of leaves, detritus, and other plant material from stream channel during storm events. The highest differences in TOC concentration between TB and CSB are typically seen in late fall when TB streamflow response to precipitation is smaller than CSB. Consequently, material in TB streams is not flushed out and adds to the streamwater carbon pool. In contrast, CSB streambanks are shallow and connected to their narrow floodplain and respond more rapidly to precipitation during this period. Thus, more detritus material is removed from CSB streams compared with TB streams.

Investigating impacts of land management activities that include fertilization on water quality were not part of our original research scope. However, fertilization of an agriculture field in UF2 watershed allowed us to generally assess this management practice. About 10% of UF2 is agriculture land. This agricultural field has been used for research test plots by the NC Department of Transportation that focused on invasive weed control and wildflower production. To establish and maintain field crop productivity, various annual rates of fertilizer were applied to this field prior to this hydrology and water quality study. Fertilizer application contributed to higher stream nutrient concentrations in UF2 than UF1 through leaching and lateral flow. NO_3, a highly mobile nutrient, showed the largest nutrient concentration difference between UF2 and UF1, 0.23 mg/l *vs*. 0.00 mg/l, respectively (Table 4). NO_3 concentration in UF2 still fell below drinking water standard of 10 mg/l and biological integrity preservation value of 1.0 mg/l as set by the U.S. Environmental Protection Agency (USEPA, 2000b). Research studies have shown that forest fertilization affect on annual streamwater NO_3 is typically low, increasing from <1.0 to <5 mg/l (Aubertin *et al.*, 1973; Fredriksen *et al.*, 1975; Norton *et al.*, 1994; Binkley *et al.*, 1999). Forested buffers have been shown to capture 80% or more of nitrate draining from agriculture lands (summarized in Comerford *et al.*, 1992). Exceptions to low NO_3 stream response following fertilization are forests that are nitrogen saturated, such as Fernow Experimental Forest, West Virginia (Adams *et al.*, 1997). Applying fertilizer as a standard management practice, however, is not likely in the mixed hardwood, mixed mesophytic forests at Fernow.

Seasonal Water Quality

There was no strong relationship between most nutrients and season. The majority of daily peak NO_3 concentrations, however, occurred during growing season in CSB and TB (Figure 3). Daily peak NO_3 concentrations were zero or at acceptable limit (1.0 mg/l) to preserve biological integrity (i.e., NC Biotic Index of ≤5.0 in Lenat, 1993; USEPA, 2000b) even during high rainfall events in growing or dormant season. TB peak NO_3 concentration reached 1.0 mg/l on 8/27/08 after a 110-mm storm event with a maximum intensity of 23.6 mm/hr. This peak NO_3 concentration was atypical as the next highest peak NO_3 concentration in TB was 0.45 mg/l from a 50-mm storm with a maximum intensity of 23.8 mm/hr. Daily peak NO_3 concentrations were consistent with others findings that tree uptake or biogeochemistry regulates nutrient losses as reflected by low peak concentrations (Vitousek and Reiners, 1975; Knoepp and Clinton, 2009). Binkley *et al.* (1999) compiled data from several water quality studies and reported that peak NO_3 concentrations in most forested watershed streams were <1.0 mg/l. U.S. hardwood forests are generally considered nitrogen limited, thus the potential for stream NO_3 leaching is minimal. Forest soils generally have a high capacity to retain or process nutrient inputs through physical and chemical buffering, microbial nitrogen (N) transformation, and plant uptake. A kriging exercise using ArcGIS geostatistical analyst revealed that N deposition at our sites was 11.8 kg/ha/yr and total N export over the monitoring period was 1.2 kg/ha/yr in CSB and 1.4 kg/ha/yr in TB. Retention of N was 90% in CSB and 88% in TB of atmospheric input. Lovett *et al.* (2000) found that N retention in Catskills, New York forests, that exhibit signs of N saturation, was about 70%.

Our results suggest that sediment source in CSB and TB during both dormant and growing season was in-channel (Figure 4). In-channel source for TSS is characterized by clockwise hysteresis while distant or overland flow channel source is characterized by counterclockwise hysteresis (Walling and Webb, 1982; Klein, 1984; Baca, 2002). Clockwise loop forms when instream or near-stream soil particles are resuspended in water column during high storm-flow events. Conversely, counterclockwise loop forms when precipitation inputs exceed soil infiltration capacity and overland flow occurs or source is from upper watershed slope. If ground cover is not sufficient to reduce overland flow rates, sediment can be carried directly into the channel.

Monthly maximum stream temperature showed a typical seasonal pattern with low temperatures in winter and high temperatures in summer. Monthly maximum stream temperature did not exceed the 29°C threshold to maintain healthy stream habitat for aquatic life as set by NC regulatory limits during any portion of the monitoring period. Monthly maximum stream temperature reached 24.0°C in CSB and 26.2°C in TB. Retaining sufficient streamside tree cover helps mitigate wide seasonal stream temperature fluctuations and shifts (Beschta, 1997).

Benthic Macroinvertebrate

January and April 2010 benthic macroinvertebrate surveys indicated that water quality was excellent in CSB and TB (Table 6). However, there were significant differences in most benthic metric results between CSB and TB in April survey. CSB had significantly higher total EPT taxa richness and EPT abundance and significantly lower (improved) biotic index than TB. TOC, an indicator of plant detritus or food source in streamwater, was significantly higher in TB compared with CSB. It did not, however, appear to influence biotic index. For example, TOC increased significantly (5.2-7.8 mg/l) between CSB and TB in April survey, but biotic index increased significantly or worsened (3.1-4.4). Streamflow followed biotic index trend where it declined significantly between CSB and TB in April survey (0.65 mm/day in CSB and 0.15 mm/day in TB). Therefore, the higher biotic index values found in TB during the April sample were likely due to lower flows and not related to water quality conditions.

CSB biotic index decreased significantly from January to April survey, suggesting that stream conditions were more favorable for aquatics in April. In contrast, TB total taxa richness and total EPT taxa richness decreased significantly from January to April, suggesting that aquatic habitat conditions declined from January to April. These data indicated that CSB was on the lower or healthier end of the biotic index spectrum and streamflow patterns in CSB may have reduced negative effects on aquatic habitat.

Macroinvertebrate indices are influenced by a range of factors including stream sedimentation, dissolved oxygen levels, and stream temperature (Lenat and Crawford, 1994). Variant in benthic metric results between surveys might have been due to seasonal fluctuations associated with shifts in streamflow. Additional surveys and longer monitoring will help to further explain and account for seasonal changes.

CONCLUSIONS

This study represents the most complete paired watershed study in the piedmont region. It appears that soil features influenced hydrologic processes such as storm-flow generation and soil water storage dynamics and to a lesser extent water quality conditions. The magnitude of streamflow differences between CSB and TB were linked to seasonal and storm event antecedent moisture conditions. Seasonal discharge/precipitation ratios varied between CSB and TB with TB generating significantly higher dormant season discharge/precipitation ratios than CSB. TB tended to have significantly higher dormant season streamflow and lower growing season streamflow than CSB due to thinner soils and seasonally dynamic clay layer. TB soils had low permeability and were thin, highly erodible with highly expansive clays. CSB soils were well drained, thick, and less erodible, particularly in the uplands. Stepwise regression analysis revealed that storm flow and total discharge in TB were more sensitive to soil moisture conditions and season than CSB. These findings and differences in hydrologic response between geographic regions were linked to expansive clay subsoil and increased lateral flow in TB and topography in CSB.

Benthic macroinvertebrate biotic index score was excellent for all streams, indicating high water quality for CSB and TB. Annual, seasonal, and peak TSS and nutrient concentrations and exports in CSB and TB were within background levels for forests and represent baseline forest conditions. They were also considered within suitable exposure limits to maintain aquatic species health. Low stream NO_3 and NH_4 concentrations and exports suggested that both CSB and TB are nitrogen limited. Quantifying nutrient baseline values and enrichment can provide land managers with information to improve best management practices and development planning. These baseline values may also be useful for water quality model calibration in association with the development of pollutant management strategies.

This study's hydrology and water quality results can be considered reference or baseline hydrology and water quality data for small (~40 ha) forested headwater watersheds in the piedmont. Although the study's temporal and spatial dataset is limited, these data are relevant to forests with CSB and TB as the dominant underlying geologic structure that have similar soil characteristics. As the monitoring period covered a dry (660 mm/yr) and a wet (1,200 mm/yr) year, these data can contribute to refining the range of variability of forest hydrology and water quality conditions and assist water resource managers with setting stream recovery targets. Also, the piedmont of North Carolina is the most rapidly expanding region of the state, and record droughts in the last decade have placed a strain on water supplies in some areas. Given the observed relationships between soils and streamflow and differences between geological ecoregions, landuse changes from forests to urban and other uses could influence timing, volume, and quality of downstream water supplies, which can vary according to soils and geology. Future urban growth in the area should consider differences in baseline hydrology in the region and the effects of landuse change, and severe and extreme drought on water quantity and quality.

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