Received: 27 October 2017 | Accepted: 22 February 2018
DOI: 10.1002/hyp.11488

SPECIAL ISSUE: WATER IN THE CRITICAL ZONE

WILEY

Run-off processes from mountains to foothills: The role of soil stratigraphy and structure in influencing run-off characteristics across high to low relief landscapes

Margaret A. Zimmer[1] | John P. Gannon[2]

[1] Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA, USA

[2] Department of Geosciences and Natural Resources, Western Carolina University, Cullowhee, NC, USA

Correspondence
Margaret A. Zimmer, Department of Earth and Planetary Sciences, University of California, Santa Cruz, USA.
Email: margaret.zimmer@ucsc.edu

Abstract

The critical zone features that control run-off generation, specifically at the regional watershed scale, are not well understood. Here, we addressed this knowledge gap by quantitatively and conceptually linking regional watershed-scale run-off regimes with critical zone structure and climate gradients across two physiographic provinces in the Southeastern United States. We characterized long-term (~20 years) discharge and precipitation regimes for 73 watersheds with United States Geological Survey in-stream gaging stations across the Appalachian Mountain and Piedmont physiographic provinces of North Carolina. Watersheds included in this analysis had <10% developed land and ranged in size from 14.1–4,390 km^2. Thirty-four watersheds were located in the Piedmont physiographic province, which is typically classified as a low relief landscape with deep, highly weathered soils and regolith. Thirty-nine watersheds were located in the Appalachian Mountain physiographic province, which is typically classified as a steeper landscape with highly weathered, but shallower soils and regolith. From the United States Geological Survey daily mean run-off time series, we calculated annual and seasonal baseflow indices (BFI), minimum, mean, and maximum daily run-off, and Pearson's correlation coefficients between precipitation and baseflow. Our results showed that Appalachian Mountain watersheds systematically had higher minimum daily flows and BFI values. Piedmont watersheds displayed much larger deviations from mean annual BFI in response to year-to-year variability in precipitation. A series of linear regression models between 21 landscape metrics and annual BFIs showed non-linear and complex terrestrial–hydrological relationships across the two provinces. From these results, we discuss how distinct features of critical zone architecture, with specific focus on soil depth and stratigraphy, may be dominating the regulation of hydrological processes and run-off regimes across these provinces.

KEYWORDS

baseflow, critical zone, regional watershed, run-off, storage

1 | INTRODUCTION

Past research has highlighted the temporal and spatial variability possible in rainfall–run-off responses within and between watersheds. Through time, changes in land-use/land-cover (Pierce, Hornbeck, Likens, & Borman, 1970; Rose & Peters, 2001) or hydroclimatic conditions (Nippgen, Mcglynn, Emanuel, & Vose, 2016) can affect run-off generation processes across landscapes year-to-year. Across space, variability in physical, biological, or climatic characteristics between watersheds can affect how much precipitation ultimately contributes to run-off (Jones et al., 2012). Several studies have worked to classify which critical zone, defined as the surface of the Earth from the top of competent bedrock to the tree canopy (Brantley, Goldhaber, & Vala, 2007), factors and climatic forcings are most important in determining hydrologic response across a range of watershed types (Botter, Basso, Rodriguez-Iturbe, & Rinaldo, 2013; Carmona, Sivapalan, Yaeger, & Poveda, 2014; Sawicz, Wagener, Sivapalan, Troch, & Carrillo, 2011), spatial scales (Gaál et al., 2012; Trancoso, Phinn, McVicar, Larsen, & McAlpine, 2017), and antecedent wetness conditions (Price, 2011). Yet our understanding of how the subsurface critical zone structure regulates run-off generation is still not well understood, especially at larger spatial scales. This is partly due to an ever-evolving understanding of the subsurface as it is relevant to run-off generation, influenced by recent scientific and technological advancements focused on understanding subsurface structure and evolution (e.g., Rempe & Dietrich, 2014; St. Clair et al., 2015). In light of these advancements, there is still much to learn about the balance between surficial (e.g., topography and vegetation) and subsurface (e.g., soil and regolith depth and subsurface stratigraphy) critical zone properties as drivers of spatial and temporal run-off characteristics.

Due to the spatial heterogeneity in landscapes, process-based hydrology is often conducted at the headwater catchment scale where hydroclimatic forcings and biophysical characteristics are relatively uniform. Great strides have been made at this scale to understand how the critical zone passively regulates the movement of water across our landscapes (Detty & McGuire, 2010; Du et al., 2016; Hutchinson & Moore, 2000; Jencso & McGlynn, 2011). However, water resources are most often managed at the regional scale. Linking similarities between critical zone characteristics and water fluxes across these two spatial scales is complex, which makes discerning regional hydrology based on a catchment scale process-based understanding difficult (Bracken et al., 2013). That difficulty is partly because spatial heterogeneity in critical zone characteristics increases with watershed size and many critical zone characteristics co-evolve through time. This makes it difficult to tease apart complex relationships and feedbacks between run-off controls in the critical zone (Troch et al., 2017). Researchers have worked to address this challenge through the classification of hydrological regimes across different watersheds (e.g., Jones et al., 2012; Sawicz et al., 2014; Trancoso, Larsen, McAlpine, McVicar, & Phinn, 2016; Troch et al., 2017). Many of these classification schemes work to decipher which landscape characteristics within specific climates dominate run-off regimes and, from this, infer the underpinning hydrological mechanisms. This has improved understanding and prediction of run-off responses to precipitation inputs in specific landscapes. An important next step is to better understand the specific hydrological mechanisms underlying these classification systems and watershed run-off regimes.

To address this next step, we sought to characterize the surface and subsurface critical zones across a regional geomorphic gradient and investigate how these critical zone characteristics may regulate the distribution of water across these landscapes. To do this, we investigated regional watershed-scale run-off regimes in the Piedmont and Appalachian Mountain physiographic provinces in North Carolina, United States. Previous regional-scale hydrologic studies in the Piedmont and Appalachian Mountains have focused on characterizing event- to annual-scale run-off regimes across land-use or geomorphic gradients (Price et al., 2011; Rose & Peters, 2001). Rose and Peters (2001) showed that annual run-off coefficients and annual daily low-flows were consistently higher in both natural and human-developed watersheds in the Appalachian Mountains than the Piedmont. Price et al. (2011) used a multivariate regression analysis to isolate watershed characteristics correlated with low-flow variability. From their regression results, the authors suggested watershed characteristics that enhance or sustain infiltration and recharge, such as forest cover, may be important for sustaining low-flow during droughts. Although these studies are important for understanding flow response to environmental change, they do not address the specific mechanisms associated with critical zone characteristics that drive such landscape–run-off relationships. Here, we took the next step to link hydrological processes in the critical zone to regional scale hydrological behaviour.

In this study, we sought to compare and contrast differences in regional scale run-off regimes and critical zone characteristics at the Piedmont and Appalachian Mountain physiographic province scale, in an effort to address the overarching question: "How does critical zone structure influence regional scale runoff differences across physiographic provinces with contrasting geomorphology?"

Specifically, we analysed 20 years of regional daily precipitation (NOAA, 2017) and daily run-off from 73 United States Geological Survey (USGS) stream gaging stations across a range of watersheds in the high gradient Appalachian Mountain and low gradient Piedmont physiographic provinces. We investigated how daily, seasonal, and annual run-off magnitudes across watersheds responded to variability in precipitation inputs. Using the USGS Geospatial Attributes of Gages for Evaluating Streamflow II landscape characteristic database (Falcone, 2011), we conducted a series of linear regressions to identify critical zone and climate properties that were correlated to watershed run-off regimes. Given our results, we discuss three hypotheses for how the critical zone may play an active role in regulating the movement of water across these landscapes. The three hypotheses discussed are:

Hypothesis 1. *Variations in climate, weather, and evapotranspiration across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

Hypothesis 2. *Variations in subsurface critical zone depth across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

Hypothesis 3. *Variations in subsurface critical zone stratigraphy across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

2 | CRITICAL ZONE DESCRIPTION AND CONCEPTUAL UNDERSTANDING OF HEADWATER CATCHMENT SCALE RUN-OFF GENERATION IN THE APPALACHIAN AND PIEDMONT PHYSIOGRAPHIC REGIONS

The Appalachian Mountain and Piedmont physiographic provinces represent an elongated area of land in the Southeastern United States from Pennsylvania to Georgia. For this study, we focused on the North Carolina portion of these provinces (Figure 1). This region is currently weathering under a humid, warm climate. The soil depth is variable, but is roughly 1–1.5 m and is underlain by 1–10 m of saprolite, or highly weathered and porous bedrock (Buol & Weed, 1991). The Appalachian Mountain province represents the crest of the topographic uplift that corresponds to the eastern continental drainage divide. The topographic gradient shifts from steep to moderate to low relief along the transition from the Appalachian Mountains to the Piedmont (Figure 2). Along this gradient, colluvial and creep-moved material make the unconsolidated material thicker in the Mountain toe slopes and Piedmont (Buol & Weed, 1991). Chemical weathering rates increase along this geomorphic gradient due to a coincident, albeit slight, climate gradient. These characteristics are reflected in the watersheds used in our study, where soil depth is significantly shallower in the Appalachian Mountains and deeper in the Piedmont (Figures 2 and 3). This correlation between soil depth and landscape slope is a common geomorphic relationship identified in a range of landscapes (McKenzie & Ryan, 1999).

The Appalachian Mountains are generalized by the Blue Ridge Belt, which houses a complex mixture of igneous, sedimentary, and metamorphic rock that has been squeezed, folded, and fractured for the last 1–1.5 billion years (North Carolina Geological Survey, 1985). The Piedmont is similarly composed of a complex mixture of parent material and is categorized by a series of geological belts that represent similar rock types and geologic histories. The most prominent are the Inner Piedmont Belt, composed mostly of 500–750 million-year-old (myo) metamorphosed rock, the Charlotte Belt composed of 300–500 myo igneous rocks, and the Carolina Slate Belt, which is composed of 550–650 myo deformed volcanic and sedimentary rocks (North Carolina Geological Survey, 1985).

The Appalachian Mountain physiographic province of North Carolina is classified as a steep landscape with deep, highly weathered soils. Soils are predominantly classified with moderate to high infiltration capacities (Figure 3a,b). Mean annual precipitation as downloaded from NOAAs Climate Divisional Database (nCLIMDIV) during the study period ranged from 1,274 mm in the Northern Mountains to 1,438 mm in the Southern Mountains (Table 1; NOAA (2017)). Long term (1971–2000) mean annual potential evapotranspiration as calculated from the Hamon Method (Hamon, 1961) ranged from 713 mm in the Southern Mountains to 660 mm in the Northern Mountains (Di Luzio, Johnson, Daly, Eischeid, & Arnold, 2008). The Appalachian Mountain Region is generally classified with warm summers, mild winters, and relatively uniform monthly precipitation across the year (Figure 4).

The Piedmont physiographic province of North Carolina is classified as a low relief landscape with deep, highly weathered soils. Soils are composed of a mix of low to high infiltration soils (Figure 3e,f). Climate is characterized as humid subtropical. Mean annual precipitation as downloaded from NOAAs Climate Divisional Database (nCLIMDIV) during the study period ranged from 1,136 mm in the Northern Piedmont to 1,185 mm in the Southern Piedmont (Table 1; NOAA (2017)). Long term (1971–2000) mean annual potential evapotranspiration as calculated from the Hamon Method (Hamon, 1961) ranged from 796 mm in the Northern Piedmont to 827 mm in the Southern Piedmont (Di Luzio et al., 2008). Similar to the Appalachian Mountains, the Piedmont is generally classified with warm summers, mild winters, and relatively uniform monthly precipitation across the year (Figure 4).

Due to extensive weathering in these regions, clay-rich argillic soil horizons are present in both provinces, but dominate in the Piedmont (Buol & Weed, 1991; Daniels, Everett, & Zelazny, 1987). Accumulation of low hydraulic conductivity clays across the mineral soil created these argillic layers that can act as barriers for water percolation at both the A/B and B/C soil horizon interfaces. In the Mountains, perturbations driven by climate (e.g., frost and thaw) and topography (e.g., creep) create widespread discontinuities in the shallow clay-rich impeding layers (Buol & Weed, 1991). Given the subtropical climate and the lower gradient topography, discontinuities in impeding layers are not as common in the Piedmont. While both landscapes have historically undergone widespread human development of land, the Piedmont region in particular has lost centimetres of topsoil due to intensive agricultural practices (e.g., cotton and tobacco farming)

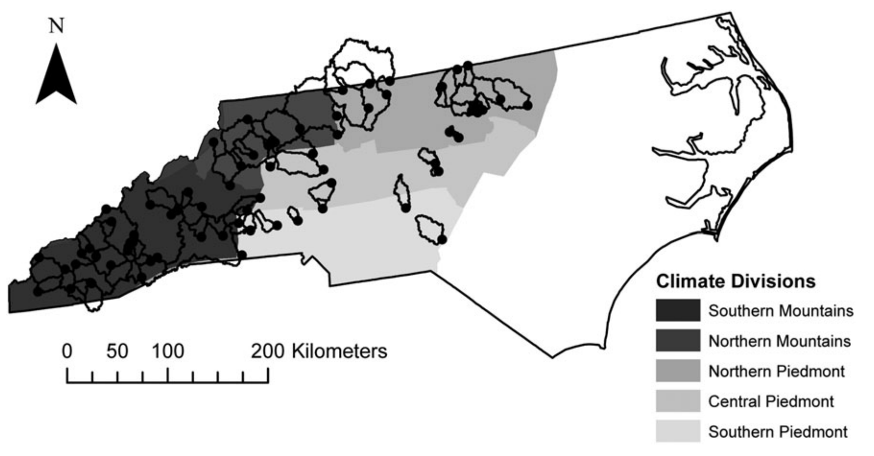

FIGURE 1 United States Geological Survey in-stream gaging stations with contributing watersheds outlined. Shaded areas represent climate divisions (physiographic subregions)

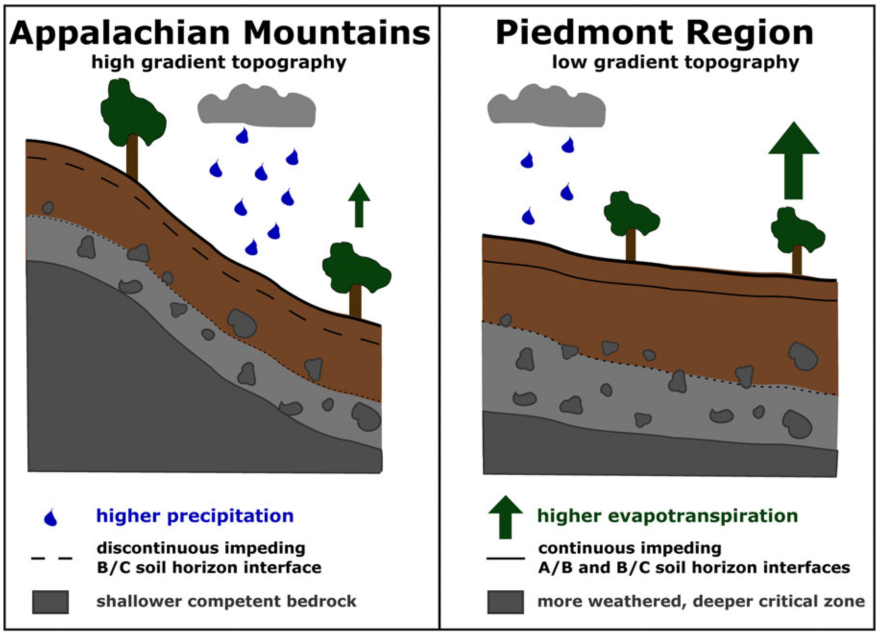

FIGURE 2 Conceptual diagram of key climate and critical zone characteristics across the Appalachian Mountains and Piedmont physiographic regions

throughout the 19th and 20th centuries (Richter, Markewitz, Trumbore, & Wells, 1999; Trimble, Weirich, & Hoag, 1987). As a result, the argillic layer can be closer to the ground surface in the Piedmont. Depth to the interface between saprolite (weathered parent material) and competent bedrock is deep (2–26 m) across these regions, but weathering rates and lateral movement of materials over geologic time has resulted in deeper weathering fronts (and thus more soil and saprolite) in the Piedmont province (Figure 2; Buol & Weed, 1991)

There is a rich history of catchment scale rainfall–run-off research from these provinces. Much of this work has focused on understanding flowpaths of water through the critical zone and into the stream during individual precipitation events (Brammer & McDonnell, 1996; Burns et al., 2001; Hewlett & Hibbert, 1967; Hooper, Christophersen, & Peters, 1990; Scanlon, Raffensperger, Hornberger, & Clapp, 2000). At the event scale, Piedmont watersheds have been shown to produce higher peak flows than Appalachian Mountain watersheds. For example, from multi-year studies, researchers have reported peak event run-off rates at ~20–40 mm/day (Nippgen et al., 2016) in Appalachian Mountain streams and much higher (>100 mm/day) in Piedmont streams (Burns et al., 2001; Zimmer & McGlynn, 2017). Although more work is needed to quantitatively compare peak stormflow variability in these systems, it is clear that there are systematic differences in how water is routed to the stream channel at the event scale. The partitioning of precipitation into fast and slow pathways across these landscapes likely has great implications for baseflow partitioning and longer term run-off characteristics (e.g., monthly and annual), but few comparisons have been made. Further, the similarities and differences between critical zone characteristics across these physiographic regions have not been thoroughly studied at the regional scale. In this study, we sought to bridge these two knowledge gaps.

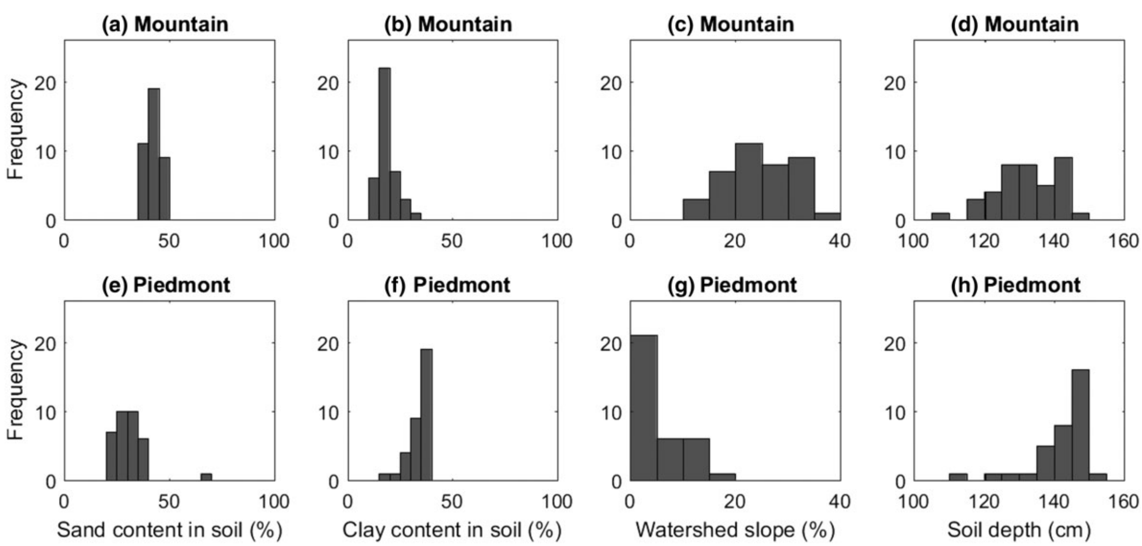

FIGURE 3 Histograms of soil particle size characteristics (a,b and e,f), median watershed slopes (c,g), and mean soil depths (d,h) in Mountain and Piedmont watersheds

TABLE 1 Mountain and Piedmont climate subregions characteristics

Subregion	Number of USGS gaging stations	Average precipitation, mm	Potential evapotranspiration, mm	Expected run-off coefficient (average precip - potential evapotranspiration)/ average precip	Calculated run-off coefficient (measured run-off/average precip.)	Range in watershed areas, km^2	Watershed slope, (%)
Northern Mountains	8	1,274 (200)	713 (38.4)	0.44 (0.30–0.54)	0.4	74.07–4,390	18.5 (4.2)
Southern Mountains	31	1438 (239)	660 (63.1)	0.54 (0.40–0.64)	0.55	14.08–4,390	26.3 (6.3)
Northern Piedmont	19	1,136 (192)	798 (34.7)	0.30 (.11–.43)	0.25	19.57–2,707	5.2 (3.1)
Central Piedmont	7	1,178 (190)	794 (26.3)	0.33 (0.17–0.44)	0.27	39.62–789.9	7.3 (4.6)
Southern Piedmont	8	1,185 (202)	827 (29.2)	0.30 (0.13–0.43)	0.30	58.94–2,260	7.3 (5.4)

Note. All data from GAGES II database, except precipitation from NOAA. Reported values are averages across all sites in each subregion with standard deviation and minimum/maximum ranges in parenthesis.

3 | METHODS

3.1 | Data description

In this study, we utilized 73 USGS stream gaging stations and NOAA regional precipitation datasets from the Appalachian Mountains and Piedmont physiographic provinces in North Carolina, United States (Figure 1). Thirty-four gaging stations were located in the Piedmont and 39 stations were located in the Appalachian Mountains. Each province was further broken into subregions based on slight differences in hydroclimatic conditions (Figure 1; Table 1). Gaging stations included in this analysis drained watersheds with <10% developed land and ranged in size from 14.1–4,390 km^2 (Table 1).

We downloaded monthly precipitation totals and Palmer Drought Severity Index (PDI) for each climate subregion from NOAAs Climate Divisional Database (nCLIMDIV; NOAA, 2017) across the 20-year study period. The PDI is an indicator of landscape dryness based on recent precipitation and temperature (Palmer, 1965), where a negative value indicates drought conditions. We downloaded 21 landscape metrics for each watershed from the USGS Geospatial Attributes of Gages for Evaluating Streamflow II database (Falcone, 2011) as described in Table 2 to use in a linear regression analysis. The explanatory variables used in this analysis were selected on the basis of variables used in a similar study conducted in the southern Blue Ridge Mountains of Georgia and North Carolina (Price et al., 2011).

3.2 | Hydrometric measurements and analysis

We downloaded daily run-off data using the USGS R dataRetrieval package (Hirsch & De Cicco, 2015). Baseflow separation was carried out using the method of Nathan and McMahon (1990), as

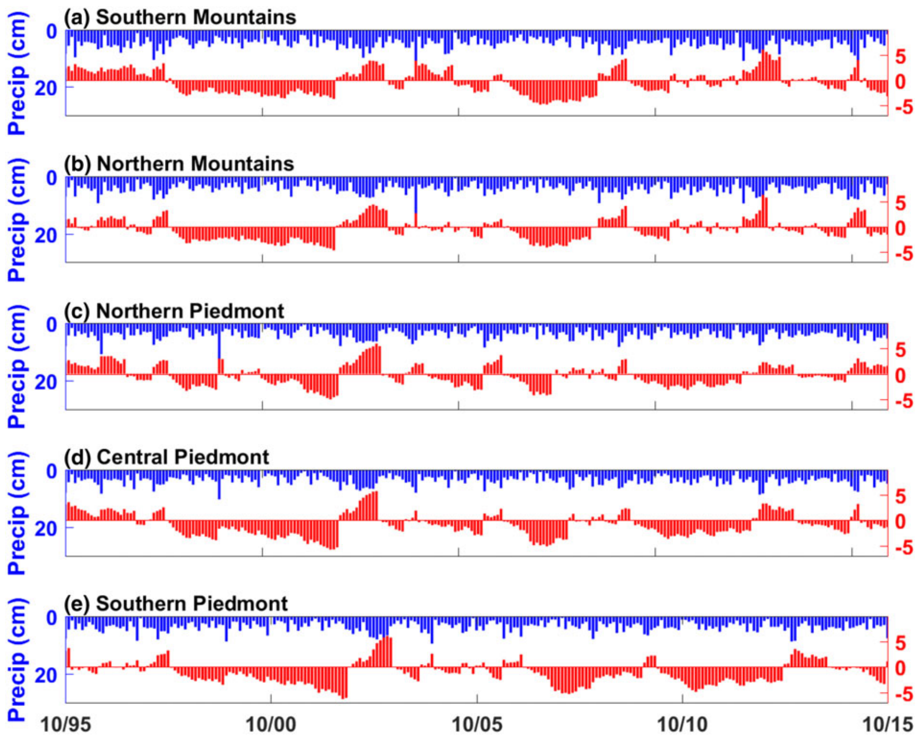

FIGURE 4 Monthly precipitation (blue) and Palmer Drought Severity Index (PDI) values (red) across the five subregions in the mountains (a,b) and Piedmont (c,e) regions. Positive PDI values represent above average moisture conditions and negative PDI values represent below average moisture conditions

TABLE 2 Slope and r^2 values from linear regressions between landscape metrics and mean annual baseflow index over 20 years

	All sites		Piedmont		Mountains	
Landscape metric (units)	Slope of fit	r^2	Slope of fit	r^2	Slope of fit	r^2
Mean watershed slope (%)	0.01	***0.30***	0.03	***0.50***	−0.01	0.20
Developed land (%)	−0.01	0.05	−0.01	0.01	0.01	0.02
Forested land (%)	0.01	0.25	0.00	0.05	−0.00	0.09
Agricultural land (%)	−0.01	0.23	−0.00	0.04	0.01	0.09
Water bodies (%)	−0.04	0.06	−0.01	0.01	−0.04	0.08
Watershed area (km^2)	0.00	0.06	0.00	0.11	0.00	0.05
Mean annual precipitation (mm)	0.00	0.23	0.02	***0.43***	0.00	0.00
Maximum temperature (degrees F)	−0.03	0.19	−0.09	0.21	0.02	0.19
Potential evapotranspiration (mm)	−0.00	0.24	−0.00	0.27	0.00	0.15
Stream density (km/km^2)	0.20	0.03	0.16	0.02	−0.02	0.00
Topographic wetness index ln(m)	−0.08	***0.34***	−0.15	***0.41***	0.06	***0.30***
Mean annual run-off (mm)	0.00	***0.34***	0.00	***0.43***	0.00	0.00
Percentage of 1st order streams (%)	0.01	0.12	0.01	0.05	−0.00	0.04
Dam density ($\#/km^2$)	−0.01	0.01	−0.00	0.01	0.01	0.08
Percent deciduous trees (%)	0.00	0.28	0.00	0.08	−0.00	0.09
Percent coniferous trees (%)	−0.01	0.09	−0.00	0.01	0.00	0.00
Mean soil permeability (mm/day)	0.09	0.28	0.08	0.15	−0.05	0.11
Mean depth to bedrock (inches)	−0.01	0.13	−0.00	0.01	−0.00	0.02
Percent clay in soil (%)	−0.01	***0.32***	−0.02	0.16	0.01	0.13
Percent silt in soil (%)	−0.00	0.01	−0.01	0.20	−0.00	0.00
Percent sand in soil (%)	0.01	***0.37***	0.01	0.27	−0.01	0.14

Note. r^2 values above 0.30 (good fits) are bold italicized.

incorporated into the R package EcoHydRology with the recommended filter parameter of 0.925. From this, we calculated a baseflow index (BFI) at seasonal and annual time scales as total baseflow divided by total run-off across the designated time interval. We calculated annual values if more than 350 days of data were available. For each site, we calculated an annual percent difference from mean annual baseflow as the current year baseflow amount divided by the mean annual baseflow across the entire study period. We separated seasonal time scales by growing and dormant seasons, where the growing season extended from April 1 to October 31. The dormant season extended from November 1 to March 31. Other studies conducted in Appalachian watersheds have used mid-October and mid-April periods as transitions between seasons (Jones & Post, 2004; Vose & Swank, 1994), but the timing of leaf-on and leaf-off has also been shown to vary by several weeks across elevation gradients in the Appalachian Mountains (Hwang, Song, Vose, & Band, 2011). Further, the growing season is slightly longer in Piedmont landscapes (Novick et al., 2015). Given these apparent regional and elevational influences on leaf-on and leaf-off periods, we chose to use the same interval across all sites to ensure a consistent comparison. As a consequence, there may be slight seasonal effects as the actual growing season may be slightly shorter than the chosen period.

We conducted a series of linear regressions between mean annual BFI and 21 geospatial landscape characteristics (Table 2; polyfit and polyval functions in MATLAB 2016b) to isolate critical zone characteristics that were correlated to BFI. We calculated a series of Pearson correlation coefficients (corrcoeff function in MATLAB 2016b, significance threshold: $p < .05$) between dormant and growing season BFI and total precipitation to investigate seasonality in rainfall–run-off responses. We also calculated Pearson correlation coefficients between annual BFI and annual precipitation. We conducted these analyses separately for Mountain watersheds and for Piedmont watersheds.

4 | RESULTS

4.1 | Daily, seasonal, and annual run-off and baseflow characteristics across physiographic provinces

4.1.1 | Daily

Minimum and mean daily average run-off (daily run-off values downloaded from USGS website as daily average) were statistically different as tested by a Wilcoxon rank sum test ($p < .05$) across Piedmont and Appalachian Mountain watersheds (Figure 5). Mountain watersheds had significantly higher minimum and mean daily run-off values than Piedmont watersheds ($p < .05$). Minimum daily run-off in the Piedmont watersheds responded minimally to increases in precipitation (slope = 9.6×10^{-5}, $p = .056$; Figure 6), whereas Appalachian Mountain watersheds had a stronger positive relationship (slope = 4.5×10^{-4}, $p = 6.1 \times 10^{-5}$; Figure 6). Maximum daily run-off values were not significantly different across provinces (Wilcoxon rank sum test, $p = .5$).

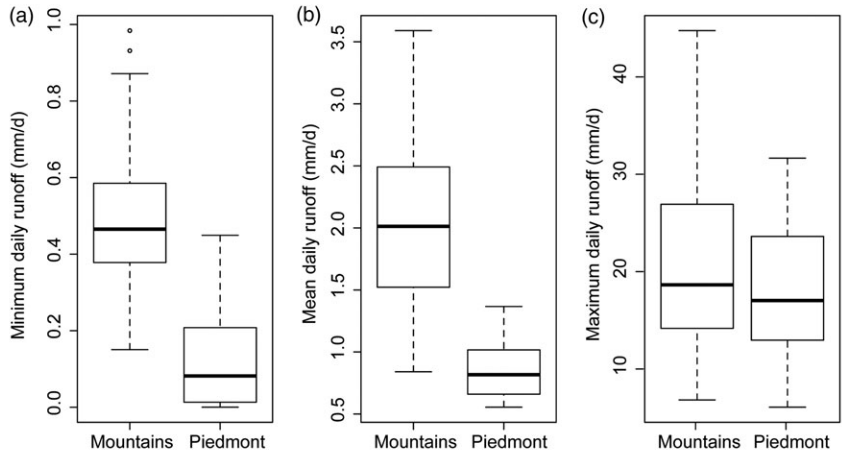

FIGURE 5 Annual minimum (a), mean (b), and maximum (c) daily average run-off for mountain and Piedmont watersheds. Circles represent outliers and whiskers represent 10th and 90th percentile. Box represents 25th, median, and 75th percentiles

4.1.2 | Seasonal

The mean BFI value for Piedmont watersheds was 0.40 (standard deviation [*SD*] = 0.18) during the growing season and 0.46 (*SD* = 0.18) during the dormant season. A Wilcoxon rank sum test revealed mean BFIs were statistically different across dormant and growing seasons in the Piedmont watersheds ($p < .05$). The mean BFI value for Appalachian Mountain watersheds was 0.59 (*SD* = .09) during the growing season and 0.58 (*SD* = 0.09) during the dormant season. A Wilcoxon rank sum test revealed mean BFIs were also statistically different across dormant and growing seasons in the Appalachian Mountain watersheds ($p < .05$).

Pearson correlation coefficients between seasonal precipitation and seasonal BFIs highlighted distinct seasonal differences in rainfall–run-off relationships between Piedmont and Mountain watersheds. Pearson correlation coefficients were −0.32 and −0.34 ($p < .05$) for dormant and growing seasons in the Appalachian Mountains, respectively. Pearson correlation coefficients were −0.17 and −.15 ($p < .05$) for dormant and growing seasons in the Piedmont region, respectively.

4.1.3 | Annual

Mean annual BFI was 0.60 (*SD* = 0.08) for Mountain watersheds and 0.43 (*SD* = 0.18) for Piedmont watersheds. Although the Piedmont watersheds displayed systematically lower BFIs (Figures 7 and 8), watersheds were more variable site-to-site and year-to-year (Figure 9). Across the Appalachian Mountain watersheds, BFI ranged from 0.30 to 0.77. Percent difference from mean annual baseflow ranged from −55% to 105%. Across the Piedmont watersheds, BFI ranged from 0.05 to 0.92. Percent difference from mean annual baseflow ranged from −100% to 200%. In 16 of the 20 water years in this study, Piedmont watersheds had greater percent differences from mean annual baseflow than Mountain watersheds (Figure 9). These differences from mean annual baseflow were positively correlated to increases in precipitation (Figure 6b).

The influence of year-to-year precipitation variability on BFI can be observed most directly from water year 2002 (WY02) to WY03 in Figures 7, 8, and 9. Water year 2002 had the lowest recorded precipitation across the study period for both the Mountain and Piedmont provinces. Similarly, the percent difference from mean annual baseflow

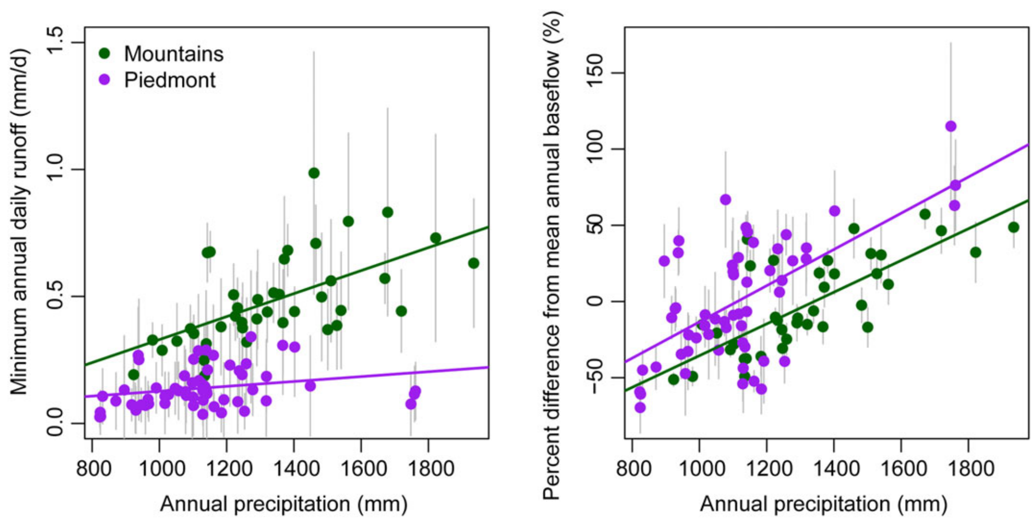

FIGURE 6 Left: Minimum annual daily run-off versus mean annual precipitation. Fitted slopes (lines on plot) are 4.5×10^{-4} ($r^2 = 0.35$, $p = .00$) for Mountain (green) and 9.6×10^{-5} ($r^2 = 0.05$, $p = .056$) for Piedmont (purple) watersheds. Right: Annual percent difference from mean annual baseflow for each site across entire study period versus mean annual precipitation across region. Fitted slopes (lines on plot) are 0.10 ($r^2 = 0.62$, $p = .00$) for Mountain (green) and 0.12 ($r^2 = 0.37$, $p = .00$) for Piedmont (purple) watersheds. Circles and whiskers represent mean and standard deviation across watersheds

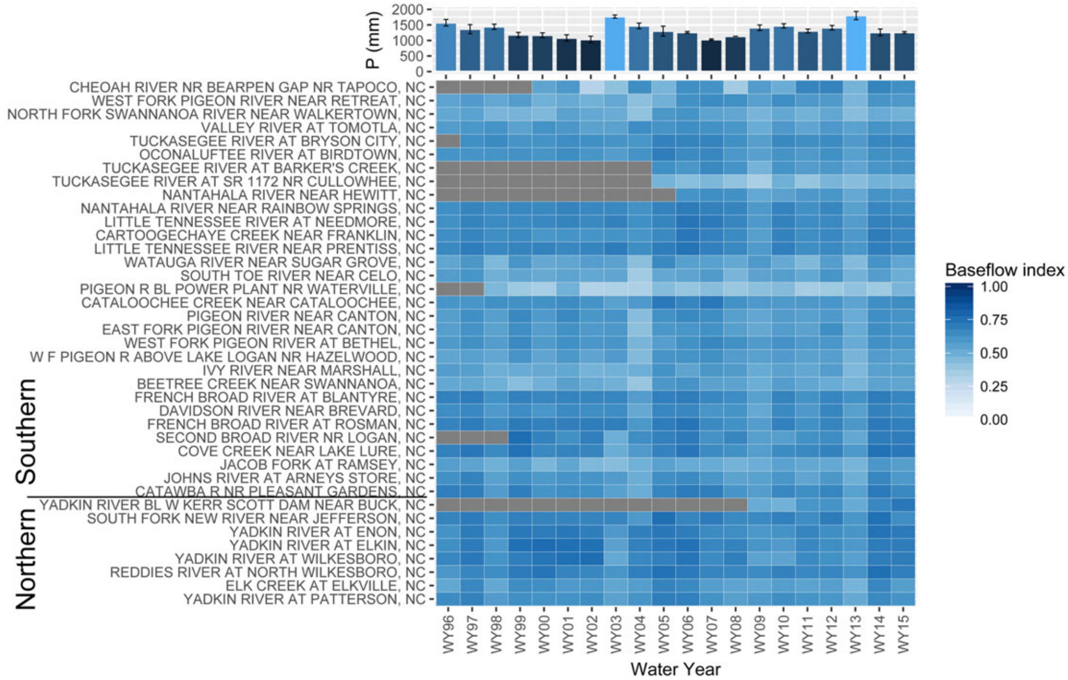

FIGURE 7 Annual baseflow indices for the 39 Appalachian Mountain watersheds. Grey boxes represent missing data

for Piedmont watersheds was the most negative (Figure 9). The Mountain watersheds, however, showed similar differences to the prior dry year. In WY03, both the Piedmont and Mountain watersheds received the highest recorded precipitation for the period examined. The Piedmont watersheds correspondingly had the highest percent difference from mean annual baseflow (~80% difference). While the baseflow of the Mountain watersheds also responded, the magnitude of the difference was much smaller (~30%). Percent difference from mean annual baseflow in the Mountain watersheds was not the highest for this observed water year, despite the high precipitation input.

4.2 | Linear regressions between climate, critical zone characteristics, and BFI

A series of linear regressions were conducted between 21 landscape and climate characteristics and mean annual BFI for three groups: Piedmont watersheds, Appalachian Mountain watersheds, and all watersheds together (Table 2). Watershed area, average annual precipitation amounts, and average annual run-off amounts had positive explanatory power across the three groups. Across all watersheds, explanatory parameters with intermediate strength relationships

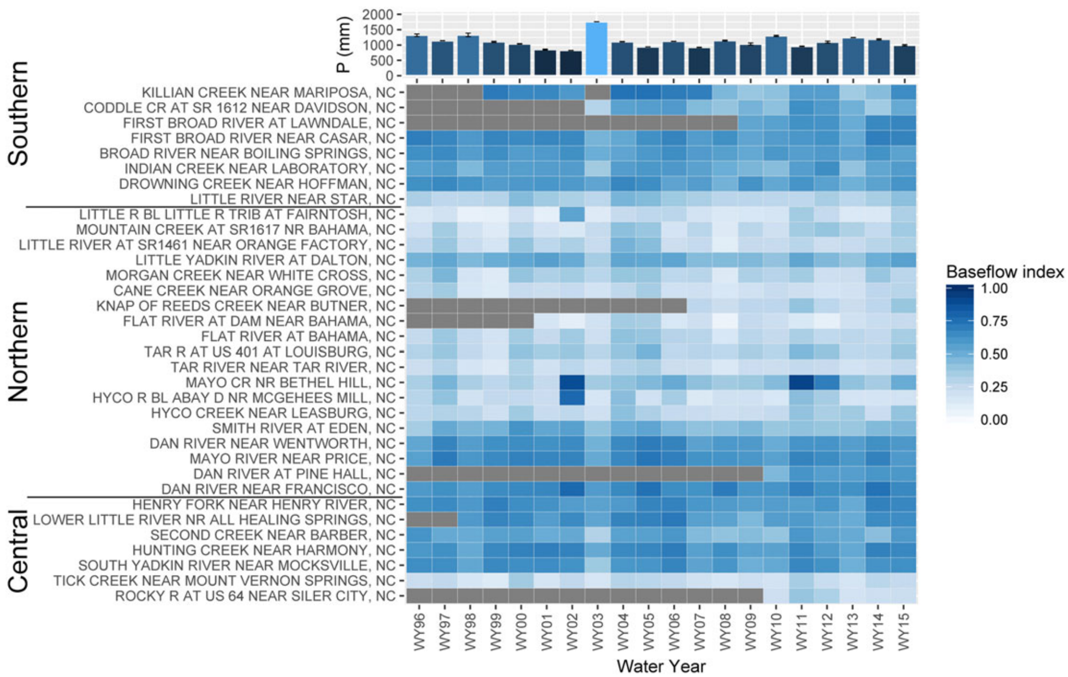

FIGURE 8 Annual baseflow indices for the 34 Piedmont watersheds. Grey boxes represent missing data

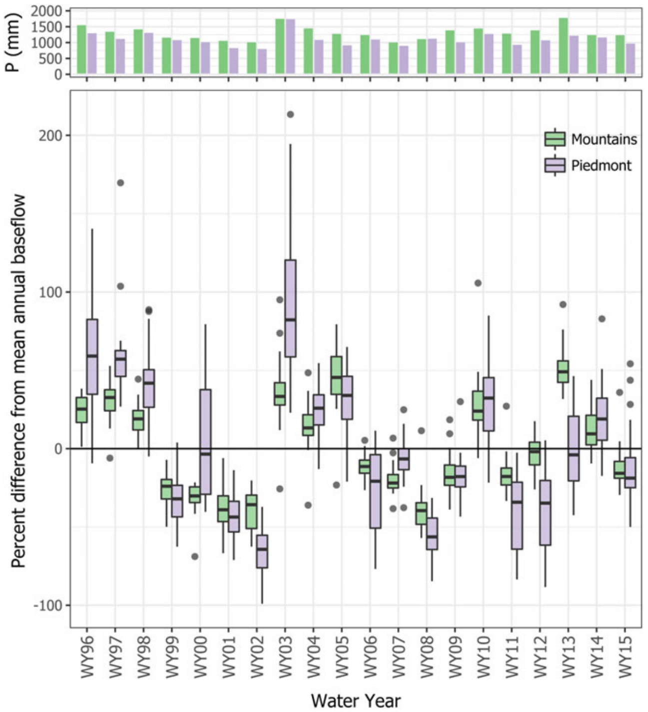

FIGURE 9 Top: Annual precipitation totals for Mountain region (green) and Piedmont region (purple). Bottom: Annual percent difference from mean annual baseflow across the entire study period for each Mountain and Piedmont watershed. Circles represent outliers and whiskers represent 10th and 90th percentile. Box represents 25th, median, and 75th percentiles

(defined as $0.3 < r^2 < 0.5$) were slope (0.30), topographic wetness index (0.34), average annual run-off (0.34), clay content in soil (0.32), and sand content in soil (0.38). Water bodies extent, depth to competent rock, and silt content in soil consistently had negative explanatory power across the three groups. All other landscape metrics in the linear regressions had complex and inconsistent directional (positive or negative) influences depending on if the analysis included all sites or just Piedmont or Appalachian Mountain watersheds (Table 2). The direction of influence for each landscape metric was the same between Piedmont watersheds and all watersheds groups.

5 | DISCUSSION

5.1 | Potential critical zone controls on regional scale run-off across two physiographic provinces with contrasting geomorphologies

In this study, we investigated regional scale run-off regimes in 73 watersheds across two physiographic provinces, the Appalachian Mountain and Piedmont provinces of North Carolina, United States (Figure 1). Our results indicated that daily and annual run-off and annual BFIs were systematically higher in Appalachian Mountain watersheds and lower in Piedmont watersheds. Our results also showed that while minimum annual daily run-off values were less responsive to precipitation, annual BFIs were much more responsive to year-to-year variability in precipitation across Piedmont watersheds. Here, we address three potential hypotheses to explain these run-off differences in the context of the critical zone as a passive regulator of flow, and discuss necessary next steps, current knowledge gaps, and study limitations.

> **Hypothesis 1.** *Variations in climate, weather, and evapotranspiration across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

Annual run-off has been shown to be strongly influenced by climate (Jones et al., 2012), evapotranspiration (Nippgen et al., 2016), and smaller scale weather patterns and storm characteristics (Gaál et al., 2012). The temperate Appalachian Mountains typically receive more annual precipitation and have less annual potential evapotranspiration than the subtropical humid Piedmont Region in North Carolina, United States (Table 1; Figure 2). Given the spatial extent of these provinces (Figure 1), weather patterns may also vary across the two regions. In this section, we discuss how spatial differences in hydroclimatic and vegetative forcings may affect run-off regimes. We suggest climate, weather, and evapotranspiration may not be the dominant driver of regional discrepancies in baseflow regimes, but that more work is needed to address current knowledge and methodological gaps.

Expected and calculated mean annual run-off coefficients were systematically higher (0.4–0.55) in the Appalachian Mountains and lower (0.25–0.33) in the Piedmont provinces (Table 1). Given the large range in expected run-off coefficients, it is difficult to interpret a comparison between expected and calculated run-off coefficients (Table 1). Any perceived differences or similarities may be due to methods for calculating potential evapotranspiration in the dataset used in this study (Lu, Sun, Mcnulty, & Amatya, 2005) or in discrepancies between potential and actual evapotranspiration (Emanuel, Odorico, & Epstein, 2007; Stoy et al., 2006), though these systems are classified as energy limited, and thus discrepancies are expected to be minor. To address evapotranspiration as a control, the incorporation of actual evapotranspiration information is an important next research step. Differences between expected and calculated run-off coefficients may also be due to spatial variability in precipitation not captured by the subregion scale precipitation data used in this study. To address potential uncertainty from this precipitation dataset, a more detailed analysis of fine-scale spatial precipitation is a necessary next research step.

Although annual precipitation magnitudes were higher in the Appalachian Mountains (Table 1), both provinces had minimal seasonality in monthly precipitation. Additionally, the general trends in the monthly PDI were similar between provinces and subregions (Figure 4). Finally, the direction of the year-to-year percent differences from the mean annual baseflow for watersheds in both provinces were consistent (Figure 9). Together, this suggests that regional scale weather differences are masked by interregional climate regimes or are not large enough to explain differences in run-off regimes across provinces.

To investigate the potential role of evapotranspiration on run-off regimes, we compared BFI values during dormant and growing seasons. Both Piedmont and Appalachian Mountain provinces had strong seasonality in evapotranspiration rates, as both have long, warm growing seasons and are dominated by deciduous trees (see Supporting Information on percentage tree cover in watersheds analysed in this study). Given these distinct leaf-on/leaf-off periods (Hwang et al., 2011; Oishi, Oren, & Stoy, 2008), the majority of evapotranspiration losses occur during the growing season in these systems. Our results showed that mean BFIs were similar across seasons for the Appalachian Mountain watersheds (mean BFIs were 0.58 and 0.59 for dormant and growing seasons, respectively). Mean BFI was higher in the dormant season in the Piedmont watersheds (mean BFIs were 0.46 and 0.40 for dormant and growing seasons, respectively).

Similar mean BFIs across seasons in the Mountain watersheds suggest that the dominant hydrological processes leading to baseflow contributions are similar across seasons. This may also suggest that there is ample water stored in the subsurface critical zone of the Appalachian Mountains that increased evapotranspiration does not affect overarching seasonal BFI values. A lower BFI in the growing season in Piedmont watersheds may be driven by an increase in evapotranspirative demands on water sources that contribute predominantly to baseflow. It may also be due to less water stored in the subsurface critical zones of Piedmont landscapes, which can decrease the ability of a watershed to buffer against higher evapotranspiration rates in the summer. Alternatively, the lower BFI in the growing season of Piedmont watersheds may be driven by increased stormflow during summer months, which could be driven by high intensity convective precipitation events that dominant in summer time. However, these convective events are characteristic across both regions.

Although minor seasonal differences in BFI values within physiographic provinces may potentially be influenced by differences in evapotranspiration, any regional differences in evapotranspiration are not enough to explain the substantial differences in annual BFIs between provinces (Figures 7 and 8). Further, year-to-year percent differences from mean annual baseflow have similar directionality across both provinces (Figure 9), which suggests any variability in spatial weather patterns between provinces were subsumed by similarities in larger, interregional weather and climate characteristics. Although differences in annual precipitation between the regions can affect total run-off values, climate, weather, and evapotranspiration alone do not explain why more run-off was partitioned as baseflow in Appalachian Mountain than Piedmont watersheds.

Hypothesis 2. *Variations in subsurface critical zone depth across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

Watersheds have the ability to store and retain water in their subsurface and transmit it to the stream channel on a variety of time scales (Hewlett & Hibbert, 1963; McNamara et al., 2011). Subsurface storage capacity in the unsaturated and saturated zones is typically thought to be influenced by the volume of the subsurface critical zone (determined by depth to competent bedrock) and the physical characteristics of that material, such as transmissivity, porosity, and texture (McNamara et al., 2011). Surface topography is a primary control on the movement of water stored in watersheds (Jencso & McGlynn, 2011), as it directly influences hydraulic gradients. In this context, deeper soils in low relief landscapes, such as the Piedmont province, would be expected to have higher storage capacities and subsurface water residence times than steeper watersheds with thinner soils, such as the Appalachian Mountains. That said, little is known about the role of subsurface critical zone depth on watershed storage in varied geomorphic landscapes (McNamara et al., 2011) and its influence on run-off characteristics, such as baseflow (Price, 2011) or interwatershed transfer of groundwater (e.g., Genereux & Jordan, 2006). Here, we discuss three distinct processes influenced by subsurface critical zone depth in the context of our results: (a) subsurface critical zone depth - potential water storage relationships, (b) the partitioning of subsurface versus surface flow at the watershed outlet, and (c) the balance of elevation head and pressure head within groundwater hydraulic gradients driving baseflow generation. Based on our results, we suggest that subsurface critical zone depth may not be a dominant control on differences in run-off or baseflow/stormflow partitioning across these provinces, but may help explain the presence/absence of seasonal variations in partitioning.

Our results showed that Piedmont watersheds had systematically lower annual BFI values, but that annual BFIs were more responsive to year-to-year variability in precipitation inputs (Figures 8 and 9). Annual daily minimum run-off values were significantly lower in the Piedmont watersheds (Figure 5) and did not respond as much to increases in annual precipitation inputs as Appalachian watersheds (Figure 6). These results suggest that there may be much less subsurface water storage or that subsurface water storage is not well connected to surface waters in Piedmont watersheds. Low storage may decrease the capacity of these Piedmont watersheds to buffer against dry years or seasons.

In contrast, our results showed lower percent differences from mean baseflow year-to-year in the Appalachian Mountain watersheds (Figure 9) and similar BFI values across dormant and growing seasons. Our results also showed that annual daily minimum run-off values responded positively to increases in annual precipitation inputs (Figure 6). These results suggest Appalachian watersheds may be able to buffer against variability in annual precipitation inputs by storing more water and releasing it much slower than Piedmont watersheds.

Water fluxes out of watersheds can occur on the land surface (e.g., evapotranspiration and streamflow) as well as below the land surface (e.g., interwatershed transfer of groundwater). Typically, in water budget calculations conducted in small watershed studies, any flow leaving the watershed outlet is funnelled through a flume or weir. In larger, regional scale watersheds, the ability to funnel flow exiting a watershed outlet is more difficult. Further, in landscapes with deep, highly weathered subsurface critical zones, interwatershed transfer of groundwater has been shown to be a substantial output in watershed budgets (Genereux & Jordan, 2006). Therefore, the run-off coefficients calculated at regional watershed scales may not capture the entirety of flow leaving the system. As a result, any discrepancies in expected versus calculated run-off coefficients may be due in part to unaccounted subsurface flow (Table 1). More work is needed to understand the role of the subsurface critical zone depth on relaying deeper groundwater flowpaths between watersheds.

Higher BFIs in dormant versus growing seasons in the Piedmont watersheds may be partly explained by the key correlation between soil depth and landscape slope in these landscapes (Figure 3c,d,g,h; McKenzie & Ryan, 1999). The hydraulic gradient of groundwater contributing to run-off is influenced by both elevation (landscape slope) and pressure (a function of water storage) heads. In the Mountains, slopes are steeper and thus hydraulic gradients of groundwater may be derived predominantly from elevation head differences. Because hydraulic gradients are predominantly geomorphically dependent, they are relatively insensitive to seasonality in water storage in hillslopes draining to rivers. This may explain the lack of seasonal differences in BFI in the Mountains. In contrast, the Piedmont province is characterized by gentle slopes and relatively deep soil and regolith. As a result, hydraulic gradients may be driven less by topography and more by water storage (pressure head), which is greatly influenced by seasonal evapotranspiration and the associated seasonal rise and fall of water tables. This may explain the seasonal differences in BFI in the Piedmont.

From the above outlined pieces of evidence, we suggest that critical zone depth differences across the Appalachian Mountains to Piedmont provinces may contribute to the observed seasonal differences in baseflow dynamics across these watersheds. However, critical zone depth alone does not appear to account for the overarching differences in baseflow/run-off partitioning observed over the study period. More research is needed to fully understand both the potential versus actual storage of water in the subsurface as well as the interactions between slope and soil depth on run-off dynamics in these two regions.

> **Hypothesis 3.** *Variations in subsurface critical zone stratigraphy across physiographic provinces drive differences in runoff regimes and baseflow/stormflow partitioning.*

Subsurface critical zone stratigraphy can have a strong influence on the partitioning of infiltrated water across watersheds. Confining layers in the subsurface can reroute percolating water laterally (Hutchinson & Moore, 2000). These confining layers can occur at a variety of depths. Deeper confining layers can include the soil-bedrock interface (Tromp-Van Meerveld & McDonnell, 2006), till layer (Gannon, Bailey, & McGuire, 2014), B/C soil horizon interface (Weyman, 1973), and shallow layers including the A/B (Zimmer & McGlynn, 2017) and O/A soil horizon interfaces (Betson & Marius, 1969). The physical and hydrological characteristics of the subsurface critical zone above an impeding layer can dictate the transmission rates of lateral subsurface flow and can partition such water into either rapid stormflow or slower run-off contributions. Substantial research has gone into characterizing and understanding the role of soil stratigraphy and impeding layers in run-off generation processes, specifically in small catchments (Ameli, McDonnell, & Bishop, 2016; Du et al., 2016). Little work has addressed how the specific depth to the dominant impeding layer, in relation to total potential subsurface storage, dictates how the subsurface critical zone passively regulates the distribution of baseflow/stormflow contributions across landscapes. In this section, we will discuss how the depth to impeding layers across the Piedmont to Appalachian Mountains can influence differences in run-off and baseflow regimes across these provinces. Our results suggest that soil stratigraphy may play an important role in baseflow dynamics.

Perched water tables on shallow subsurface impeding layers have been observed across the Southeastern United States. Wilson, Jardine, Luxmoore, and Jones (1990) reported perched water tables observed at 1.0–2.5 m depths in the Oak Ridge Reservation within the eastern Tennessee Valley and Ridge physiographic region. Depths for water table development and subsequent lateral subsurface flow were shown to be between 1.2–3.5 m at the Coweeta Hydrologic Lab in the southern Appalachian Mountains of North Carolina (Hales, Ford, Hwang, Vose, & Band, 2009; Nippgen et al., 2016). Perched water tables in Piedmont watersheds have been reported to occur at the A/Bt soil horizon interface (~0.25 m) as well as at the Bt/C soil horizon interface (~1 m depth; Zimmer & McGlynn, 2017). Beyond these regions, a trench study in the Upper Coastal Plain of South Carolina reported argillic soil horizons between ~0.80–1.5 m depths (Du et al., 2016). Further, the soils of the Southeastern United States have been dramatically altered from intensive human land use practices, mainly tobacco and cotton farming, across much of the 18th through 20th centuries (Richter et al., 1999). This has led to soil erosion of up to 10 m (Trimble et al., 1987). The Piedmont lost more topsoil than the Appalachian Mountain region, predominantly because it had more viable land for farming. This may have decreased the impeding layer depth across the Piedmont, which may have further reduced the shallow storage zone in the subsurface critical zone.

Previous research has shown that at the event scale, low relief headwater catchments in the Piedmont region produce larger and flashier run-off responses in comparison to steeper Appalachian headwater catchments (e.g., Burns et al., 2001; Nippgen et al., 2016; Scanlon et al., 2000; Zimmer & McGlynn, 2017). Rose and Peters (2001) showed higher peakflows in regional Piedmont watersheds as well. They attributed these higher flows to impervious surfaces, even in their unaltered, control watersheds. In our study, we analysed watersheds with <10% land development and found that maximum average daily run-off values were not statistically different between Piedmont and Appalachian watersheds, though minimum and mean average daily flows were much higher (>2×) in the Appalachian watersheds (Figure 5). Given the reported flashiness of Piedmont streams and the fact that the USGS data used in this study were average daily run-off values, it is possible that the maximum average daily run-off values do not fully capture the rapid, brief stormflow peaks that can occur on subdaily time scales. This suggests that at a regional scale, Piedmont watersheds may be much flashier, which is in agreement with hydrograph recession analysis results in Rose and Peters (2001). BFI values in the two regions may thus be even more different than the average daily data suggest.

We hypothesize that the ubiquitous, shallow impeding layers in the subsurface critical zone of Piedmont watersheds drive rapid lateral stormflow and reduce the percolation of water to deeper storage zones. This passive regulation of water across the critical zone reduces the ability for Piedmont watersheds to buffer against variability in annual precipitation inputs and seasonal evapotranspiration. The Appalachian Mountains have more discontinuities in the shallow impeding layer in the subsurface critical zone (Buol & Weed, 1991), which allows for more percolation of water into subsurface storage zones, which can then be released more slowly as baseflow. More work is needed to fully understand the magnitude of this partitioning of water into shallow and deep portions of the subsurface critical zone as well as the residence time of water within these zones.

5.2 | Study uncertainty and next steps

In a review on run-off regimes in humid Southeastern watersheds, Price et al. (2011) highlighted the need for more research on the feedbacks between topography and soils on run-off, given the complex co-evolution of these characteristics. In our study, we conducted individual linear regressions between a suite of 21 landscape metrics and mean annual BFI across all watersheds as well as just within Piedmont and just within Appalachian watersheds (Table 2). We found that only watershed area, average annual precipitation amounts, and average annual run-off amounts consistently had positive explanatory power. These relationships intuitively make sense as greater watershed area, more annual precipitation, and more annual run-off are expected to contribute to increased baseflow magnitudes. We also found that percent water body of total area, depth to competent rock, and silt content in soil consistently had negative explanatory power (Table 2). The negative relationship with water bodies is also intuitive, as lakes, reservoirs, and other water bodies can restrict the flow of water through networks and can thus alter baseflow. A negative, if not near-zero, relationship between depth to bedrock and baseflow is in line with run-off patterns seen in the Piedmont, but is counter-intuitive as a larger subsurface volume would often be expected to increase storage potential. It is clear more work is needed to understand how soil depth and the lithologies of these landscapes affect the storage and release of water. As depth to impeding layer(s) was not a landscape metric available in the dataset we used, we believe a more in-depth landscape analysis is needed. All other landscape metrics in the linear regressions had complex and inconsistent directional relationships depending on if the analysis included all sites or just Piedmont or Appalachian Mountain watersheds (Table 2). For example, clay content had negative and positive relationships with baseflow in the Piedmont and Appalachian Mountains, respectively. In the Piedmont, the presence of clay may act as a barrier for percolation of water into deeper groundwater stores, whereas in the Appalachian Mountains clay may provide increased storage capacity as impeding layers are relatively discontinuous.

The interaction of variables inherently complicates the interpretation of univariate analyses and most likely produced some of the inconsistent directional relationships in Table 2. For example, slope had a positive relationship with baseflow in the Piedmont watersheds but had a negative relationship with baseflow in the Appalachian Mountains (Table 2). This may be driven by the inverse relationship between slope and soil depth from the Appalachian Mountains to the Piedmont. Additional steps are needed to further this and other landscape–run-off analyses (e.g., Price et al., 2011) through multivariate investigations of the specific surface and subsurface critical zone characteristics that may drive hydrological processes in these landscapes.

Although more work is needed to disentangle how specific surface and subsurface critical zone characteristics passively regulate run-off, we provided evidence for several key critical zone characteristics that may play an important role in the regulation of run-off regimes in the Appalachian and Piedmont provinces. Steps to understand how land-use and hydroclimatic variability can influence the role specific critical zone characteristics have on run-off regimes are also necessary. Further, while USGS stream gaging stations used in this study are distributed within, as well as between, the Appalachian and Piedmont regions, we treat these systems as two distinct landscape features. In reality, landscapes are gradients of complex interrelated and co-evolved critical zone characteristics and more work is needed to further understand the thresholds, feedbacks, and relationships between the dominant run-off drivers across geomorphic gradients.

6 | IMPLICATIONS

Our results suggest that Piedmont watersheds are highly responsive to variability in precipitation inputs on daily to annual timescales. Our results also showed that the buffer capacity of Piedmont watersheds against precipitation extremes (e.g., drought or excess wetness) may be lower than those in the Mountains. With expected increased and prolonged droughts and higher intensity precipitation events (IPCC, 2013), the percolation of precipitation into the subsurface is crucial for sustaining water resources for a growing population in the Southeastern United States (Terando et al., 2014) and for mitigating flood risk. However, our results suggest Piedmont watersheds are less drought and flood resilient to future fluctuations in hydroclimatic forcings. Linkages between process-based understanding at the watershed-scale and run-off characterization at the regional scale may provide additional information for predicting how regional run-off may respond in a changing world.

Rose and Peters (2001) showed that urbanization greatly affects run-off magnitudes by increasing rapid run-off during precipitation events. As Piedmont regions are already prone toward large fluctuations in daily to annual run-off, it is imperative practitioners and researchers manage land-use/land-cover to enhance, not restrict the infiltration capacity of water into the terrestrial environment. For example, Price et al. (2011) showed that landscape metrics related to infiltration increased low flows during drought years. Thus, if landscapes are managed incorrectly, we may see exacerbated hydrological effects (e.g., reduced flow stability and reduced drought resilience) of reduced infiltration capacity in these landscapes. Our results have showcased that across the critical zone continuum, there are complex relationships and controls on run-off that are often landscape-specific. It is imperative to take into account the evolution of the landscape through geologic and human-use time scales and recognize that the biophysical factors across critical zones play complex, important, and highly interconnected roles in the distribution of water in our landscapes.

7 | CONCLUSIONS

Our objectives in this study were to investigate how hydroclimatic forcings coupled with biophysical differences across critical zones passively regulate regional scale run-off regimes in two distinct physiographic provinces (the Appalachian and Piedmont regions of North Carolina, United States). To do this, we presented a catchment-scale conceptual model of how critical zone characteristics influence run-off generation in these two physiographic provinces as informed from a literature review of the rich history of process-based headwater catchment hydrology work conducted in the Southeastern United States (see Section 2; Figure 2). We then investigated and interpreted 20 years of daily run-off from 73 regional watershed-scale USGS stream gaging sites across North Carolina, United States (Figure 1; Table 1). These watersheds represented minimal land use development (<10% developed) and a gradient of catchment and critical zone characteristics, including a range of watershed sizes, topography, vegetation, and subsurface characteristics (see Supporting Information). From this, we proposed and discussed a set of hypotheses for how the critical zone may produce the reported regional scale run-off regime differences across these two physiographic provinces.

Our results suggest differences in subsurface critical zone characteristics may outweigh topographic and climatic differences across physiographic provinces in controlling the redistribution of precipitation across watersheds. Our work indicates that Piedmont watersheds may be less resilient to prolonged or more frequent drought conditions and may respond to increased precipitation intensities with increased stormflow magnitudes instead of increased recharge. Appalachian Mountain watersheds may be more resilient to future prolonged or more frequent droughts and may buffer downstream flow from increased precipitation magnitudes. Together, this work brings together a process-based understanding at the small scale with regional scale run-off observations to decipher how the balance between subsurface and surface critical zone characteristics can control hydrological processes. This work addressed how spatial differences in the evolution of the below ground Earth system passively affects the distribution of water across landscapes at the watershed scale and can have societal implications for the management of water resources.

ACKNOWLEDGMENTS

We thank Scott Bailey, Ryan Emanuel, and Matt Miller for helpful suggestions and comments that greatly improved this manuscript. Run-off data were downloaded from the USGS stream gaging station database (https://waterdata.usgs.gov/nwis/rt), precipitation data were downloaded from NOAA Climate Division database (http://www.ncdc.noaa.gov/cag), and geospatial landscape information was downloaded from the USGS GAGES II database (https://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml).

ORCID

Margaret A. Zimmer http://orcid.org/0000-0001-8287-1923
John P. Gannon http://orcid.org/0000-0002-4595-3214

REFERENCES

Ameli, A. A., McDonnell, J. J., & Bishop, K. (2016). The exponential decline in saturated hydraulic conductivity with depth: A novel method for exploring its effect on water flow paths and transit time distribution. *Hydrological Processes*, *30*(14), 2438–2450. https://doi.org/10.1002/hyp.10777

Betson, R., & Marius, J. (1969). Source areas of storm runoff. *Water Resources Research*, *5*(3), 574–582. https://doi.org/10.1029/WR005i003p00574

Botter, G., Basso, S., Rodriguez-Iturbe, I., & Rinaldo, A. (2013). Resilience of river flow regimes. *Proceedings of the National Academy of Sciences*, *110*(32), 12925–12930. https://doi.org/10.1073/pnas.1311920110

Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., & Roy, A. G. (2013). Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth-Science Reviews*, *119*, 17–34. https://doi.org/10.1016/j.earscirev.2013.02.001

Brammer, D. D., & McDonnell, J. J. (1996). An evolving perceptual model of hillslope flow at the Maimai catchment. *Advances in hillslope processes*, *1*, 35–60.

Brantley, S. L., Goldhaber, M. B., & Vala, R. K. (2007). Crossing disciplines and scales to understand the critical zone. *Elements*, *3*(5), 307–314. https://doi.org/10.2113/gselements.3.5.307

Buol, S. W., & Weed, S. B. (1991). Saprolite-soil transformations in the Piedmont and Mountains of North Carolina. *Geoderma*, *51*(1–4), 15–28. https://doi.org/10.1016/0016-7061(91)90064-Z

Burns, D. A., McDonnell, J. J., Hooper, R. P., Peters, N. E., Freer, J. E., Kendall, C., & Beven, K. (2001). Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain research watershed (Georgia, USA). *Hydrological Processes*, *15*(10), 1903–1924. https://doi.org/10.1002/hyp.246

Carmona, A. M., Sivapalan, M., Yaeger, M. A., & Poveda, G. (2014). Regional patterns of interannual variability of catchment water balances across the continental U.S.: A Budyko framework. *Water Resources Research*, *50*(12), 9177–9193. https://doi.org/10.1002/2014WR016013

Daniels, W. L., Everett, C. J., & Zelazny, L. W. (1987). Virgin hard-wood forest soils of the southern Appalachian Mountains: I. Soil morphology and geomorphology. *Soil Science Society of America Journal*, *51*, 722–729. https://doi.org/10.2136/sssaj1987.03615995005100030029x

Detty, J. M., & McGuire, K. J. (2010). Topographic controls on shallow groundwater dynamics: Implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes*, *24*(16), 2222–2236. https://doi.org/10.1002/hyp.7656

Di Luzio, M., Johnson, G. L., Daly, C., Eischeid, J. K., & Arnold, J. G. (2008). Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States. *Journal of Applied Meteorology and Climatology*, *47*(2), 475–497. https://doi.org/10.1175/2007JAMC1356.1

Du, E., Rhett Jackson, C., Klaus, J., McDonnell, J. J., Griffiths, N. A., Williamson, M. F., … Bitew, M. (2016). Interflow dynamics on a low relief forested hillslope: Lots of fill, little spill. *Journal of Hydrology*, *534*, 648–658. https://doi.org/10.1016/j.jhydrol.2016.01.039

Emanuel, R. E., Odorico, P. D., & Epstein, H. E. (2007). A dynamic soil water threshold for vegetation water stress derived from stomatal conductance models. *Water Resources Research*, *43*(3), 1–13. https://doi.org/10.1029/2005WR004831

Falcone, J. (2011). *GAGES-II: Geospatial attributes of gages for evaluating streamflow*. Reston, Virginia: US Geological Survey.

Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., & Blöschl, G. (2012). Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology. *Water Resources Research*, *48*(4), 1–21. https://doi.org/10.1029/2011WR011509

Gannon, J. P., Bailey, S. W., & Mcguire, K. J. (2014). Organizing groundwater regimes and response thresholds by soils: A framework for understanding runoff generation in a headwater catchment. *Water Resources Research*, *50*, 8403–8419. https://doi.org/10.1002/2014WR015498%20Key

Genereux, D. P., & Jordan, M. (2006). Interbasin groundwater flow and groundwater interaction with surface water in a lowland rainforest, Costa Rica: A review. *Journal of Hydrology*, *320*(3–4), 385–399. https://doi.org/10.1016/j.jhydrol.2005.07.023

Hales, T. C., Ford, C. R., Hwang, T., Vose, J. M., & Band, L. E. (2009). Topographic and ecologic controls on root reinforcement. *Journal of Geophysical Research - Solid Earth*, *114*(3), 1–17. https://doi.org/10.1029/2008JF001168

Hamon, W. R. (1961). Estimating potential evapotranspiration. *American Society of Civil Engineers, Journal of the Hydraulics Division*, *87*(HY3), 107–120.

Hewlett, J. D., & Hibbert, A. R. (1963). Moisture and energy conditions within a sloping soil mass during drainage. *Journal of Geophysical Research*, *68*(4), 1081–1087. https://doi.org/10.1029/JZ068i004p01081

Hewlett, J. D., & Hibbert, A. R. (1967). Factors affecting the response of small watershed to precipitation in humid areas. *Forest Hydrology*, *33*, 275–279. https://doi.org/10.1177/0309133309338118

Hirsch, R. M., & De Cicco, L. (2015). User guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R packages for hydrologic data (no. 4-A10).

Hooper, R. P., Christophersen, N., & Peters, N. E. (1990). Modelling streamwater chemistry as a mixture of soilwater end-members—An application to the Panola Mountain catchment, Georgia, U.S.A. *Journal of Hydrology*, *116*(1–4), 321–343. https://doi.org/10.1016/0022-1694(90)90131-G

Hutchinson, D. G., & Moore, R. D. (2000). Throughflow variability on a forested hillslope underlain by compacted glacial till. *Hydrological Processes*, *14*(10), 1751–1766. https://doi.org/10.1002/1099-1085(200007)14:10%3C1751::AID-HYP68%3E3.0.CO;2-U

Hwang, T., Song, C., Vose, J. M., & Band, L. E. (2011). Topography-mediated controls on local vegetation phenology estimated from MODIS vegetation index. *Landscape Ecology*, *26*(4), 541–556. https://doi.org/10.1007/s10980-011-9580-8

IPCC (2013). Climate Change 2013: The Physical Science Basis. In D. Qin TF (Ed.), *Contributions of working group I to the fifth assessment report of the inter-governmental panel on climate change*. Cambridge, U.K.: Cambridge University. 1535. https://doi.org/10.1017/CBO9781107415324

Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, *47*, W11527. https://doi.org/10.1029/2011WR010666

Jones, J. A., Creed, I. F., Hatcher, K. L., Warren, R. J., Adams, M. B., Benson, M. H., … Williams, M. W. (2012). Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. *Bioscience*, *62*(4), 390–404. https://doi.org/10.1525/bio.2012.62.4.10

Jones, J. A., & Post, D. A. (2004). Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research*, *40*(5), 1–19. https://doi.org/10.1029/2003WR002952

Lu, J., Sun, G., Mcnulty, S. G., & Amatya, D. M. (2005). A comparison of six potential evapotranspiration methods for regional use in the Southeastern United States. *Journal of the American Water Resources Association*, *41*(3), 621–633.

McKenzie, N. J., & Ryan, P. J. (1999). Spatial prediction of soil properties using environmental correlation.

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., … Hooper, R. (2011). Storage as a metric of catchment comparison. *Hydrological Processes*, *25*(21), 3364–3371. https://doi.org/10.1002/hyp.8113

Nathan, R. J., & McMahon, T. A. (1990). Evaluation of automated techniques for base flow and recession analyses. *Water Resources Research*, *26*(7), 1465–1473. https://doi.org/10.1029/WR026i007p01465

Nippgen, F., Mcglynn, B. L., Emanuel, R. E., & Vose, J. M. (2016). Watershed memory at the Coweeta Hydrologic Laboratory: The effect of past precipitation and storage on hydrologic response. *Water Resources Research*, *52*, 7548–7555. https://doi.org/10.1002/2015WR018196

NOAA. (2017). NOAA national centers for environmental information, climate at a glance: U.S. time series. *October 2017*. https://www.ncdc.noaa.gov/cag/

North Carolina Geological Survey. (1985). Geologic map of North Carolina: North Carolina Geological Survey, General Geologic Map: scale 1:500000

Novick, K. A., Oishi, A. C., Ward, E. J., Siqueira, M. B. S., Juang, J. Y., & Stoy, P. C. (2015). On the difference in the net ecosystem exchange of CO2 between deciduous and evergreen forests in the southeastern United States. *Global Change Biology*, *21*(2), 827–842. https://doi.org/10.1111/gcb.12723

Oishi, A. C., Oren, R., & Stoy, P. C. (2008). Estimating components of forest evapotranspiration: A footprint approach for scaling sap flux measurements. *Agricultural and Forest Meteorology*, *148*(11), 1719–1732. https://doi.org/10.1016/j.agrformet.2008.06.013

Palmer, W. C. (1965). *Meteorological drought*. Washington, DC: US Department of Commerce, Weather Bureau.

Pierce, R. S., Hornbeck, J. W., Likens, G. E., & Borman, F. H. (1970). Effect of elimination of vegetation on stream water quantity and quality. *International Association of Hydrological Sciences*, *96*, 311–328.

Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. *Progress in Physical Geography*, *35*(4), 465–492. https://doi.org/10.1177/0309133311402714

Price, K., Jackson, C. R., Parker, A. J., Reitan, T., Dowd, J., & Cyterski, M. (2011). Effects of watershed land use and geomorphology on stream low flows during severe drought conditions in the southern Blue Ridge Mountains, Georgia and North Carolina, United States. *Water Resources Research*, *47*(2). https://doi.org/10.1029/2010WR009340

Rempe, D. M., & Dietrich, W. E. (2014). A bottom-up control on fresh-bedrock topography under landscapes. *Proceedings of the National Academy of Sciences*, *111*(18), 6576–6581. https://doi.org/10.1073/pnas.1404763111

Richter, D. D., Markewitz, D., Trumbore, S. E., & Wells, C. G. (1999). Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature*, *400*(6739), 56–58. https://doi.org/10.1038/21867

Rose, S., & Peters, N. E. (2001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): A comparative hydrological approach. *Hydrological Processes*, *15*(8), 1441–1457. https://doi.org/10.1002/hyp.218

Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., & Carrillo, G. (2011). Catchment classification: Empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences*, *15*(9), 2895–2911. https://doi.org/10.5194/hess-15-2895-2011

Sawicz, K. A., Kelleher, C., Wagener, T., Troch, P., Sivapalan, M., & Carrillo, G. (2014). Characterizing hydrologic change through catchment classification. *Hydrology and Earth System Sciences*, *18*(1), 273–285. https://doi.org/10.5194/hess-18-273-2014

Scanlon, T. M., Raffensperger, J. P., Hornberger, G. M., & Clapp, R. B. (2000). Shallow subsurface storm flow in a forested headwater catchment: Observations and modeling using a modified TOPMODEL. *Water Resources Research*, *36*(9), 2575–2586. https://doi.org/10.1029/2000WR900125

St. Clair, J., Moon, S., Holbrook, W. S., Perron, J. T., Riebe, C. S., Martel, S. J., … Richter, D. D. (2015). Geophysical imaging reveals topographic stress control of bedrock weathering. *Science*, *350*(6260), 534–538. https://doi.org/10.1126/science.aab2210

Stoy, P. C., Katul, G. G., Siqueira, M. B. S., Juang, J.-Y., Novick, K. A., McCarthy, H. R., … Oren, R. (2006). Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. *Global Change Biology*, *12*, 2115–2135. https://doi.org/10.1111/j.1365-2486.2006.01244.x

Terando, A. J., Costanza, J., Belyea, C., Dunn, R. R., McKerrow, A., & Collazo, J. A. (2014). The southern megalopolis: Using the past to predict the future of urban sprawl in the Southeast U.S. *PLoS One*, *9*(7), e102261. https://doi.org/10.1371/journal.pone.0102261

Trancoso, R., Larsen, J. R., McAlpine, C., McVicar, T. R., & Phinn, S. (2016). Linking the Budyko framework and the Dunne diagram. *Journal of Hydrology*, *535*, 581–597. https://doi.org/10.1016/j.jhydrol.2016.02.017

Trancoso, R., Phinn, S., McVicar, T. R., Larsen, J. R., & McAlpine, C. A. (2017). Regional variation in streamflow drivers across a continental climatic gradient. *Ecohydrology*, *10*(3). https://doi.org/10.1002/eco.1816

Trimble, S. W., Weirich, F. H., & Hoag, B. L. (1987). Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. *Water Resources Research*, *23*(3), 425–437. https://doi.org/10.1029/WR023i003p00425

Troch, P. A., Lahmers, T., Meira, A., Mukherjee, R., Pedersen, J. W., Roy, T., & Valdes-Pineda, R. (2017). Catchment coevolution: A useful framework for improving predictions of hydrological change? *Water Resources Research*, *51*, 237–256. https://doi.org/10.1002/2015WR017032

Tromp-Van Meerveld, H. J., & McDonnell, J. J. (2006). Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, *42*(2), 1–11. https://doi.org/10.1029/2004WR003800

Vose, J. M., & Swank, W. T. (1994). Effects of long-term drought on the hydrology and growth of a white pine plantation in the southern Appalachians. *Forest Ecology and Management*, *64*(1), 25–39. https://doi.org/10.1016/0378-1127(94)90124-4

Weyman, D. R. (1973). Measurements of the downslope flow of water in a soil. *Journal of Hydrology*, *20*, 267–288. https://doi.org/10.1016/0022-1694(73)90065-6

Wilson, G. V., Jardine, P. M., Luxmoore, R. J., & Jones, J. R. (1990). Hydrology of a forested hillslope during storm events. *Geoderma*, *46*, 119–138.

Zimmer, M. A., & McGlynn, B. L. (2017). Ephemeral and intermittent runoff generation processes in a low relief, highly weathered catchment. *Water Resources Research*, *53*, 1–23. https://doi.org/10.1002/2016WR019742

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Zimmer MA, Gannon JP. Run-off processes from mountains to foothills: The role of soil stratigraphy and structure in influencing run-off characteristics across high to low relief landscapes. *Hydrological Processes*. 2018;1–15. https://doi.org/10.1002/hyp.11488