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

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[1] Land use and physiographic variability influence stream low flows, yet their interactions and relative influence remain unresolved. Our objective was to assess the influence of land use and watershed geomorphic characteristics on low-flow variability in the southern Blue Ridge Mountains of North Carolina and Georgia. Ten minute interval discharge data for 35 streams (in watersheds from 3 to 146 km^2) were measured for two late summer low-flow seasons, coinciding with a severe drought period in the southeastern United States. Three low-flow metrics were calculated (1 and 7 day minimum flows and 1st percentile flow) for each low-flow season (5 August to 12 November 2007 and 1 August to 12 November 2008). A comprehensive suite of watershed characteristics, including factors of topography, channel network morphometry, soils, land use, and precipitation were used in multiple regression analysis of low-flow variability among the 35 watersheds. Additionally, low flows in groups of lower- and higher-forest cover watersheds were compared. Drainage density, areal coverage of colluvium, topographic variability (as slope standard deviation), and percent of the channel network as first order stream emerged as the most important variables for explaining low-flow variability. Watershed forest cover demonstrated a consistent, significant positive relationship with low flows, despite the higher evapotranspiration rates associated with forest compared with other land covers and despite the relatively small range of disturbance in this study area. This highlights the importance of infiltration and recharge under undisturbed land cover in sustaining low flows, and it bears noteworthy implications for environmental flows and water resource sustainability.

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1. Introduction

[2] Base flow is the portion of streamflow that enters stream channels via delayed pathways and sustains streamflow between precipitation events. Important sources of base flow include subsurface storage reservoirs, such as bedrock, weathered bedrock, colluvium, alluvium, and soil, as well as drainage from natural or artificial impoundments. Natural catchment physical characteristics, such as geology, geomorphology, and soils, exert important influence on base flow and serve as the template upon which other important factors, such as land use, are superimposed [*Johnson*, 1998; *Vivoni et al.*, 2008; *Bloomfield et al.*, 2009]. Base flow comprises a variable proportion of total streamflow throughout the year and is most important during dry seasons when precipitation is scarce and streamflow is predominantly sourced from delayed storage units. These dry season streamflows are referred to as "low flows" [*Smakhtin*, 2001] and are the focus of this study. As many regions are currently experiencing rapid land use change, concurrent with increased demands on public water supply, a better understanding of watershed function and low flows is critical to issues of contaminant dilution, aquatic habitat, and public water use [*Barnes and Kalita*, 1991; *Hornbeck et al.*, 1993; *Smakhtin*, 2001; *Konrad and Booth*, 2005]. Anthropogenic changes to the landscape may alter base flow timing and quantity. Aside from direct manipulations, such as impoundments and water withdrawals from streams and subsurface storage, human activity influences base flow by indirect mechanisms associated with changes in land use and land cover. Conversion of native vegetation to other vegetative covers or artificial surfaces can drastically alter evapotranspiration (ET) [*Liu et al.*, 2008]. Land use change also may alter surface permeability characteristics through soil compaction associated with human land use and addition of impervious surface to watersheds [*Rose and Peters*, 2001; *Gregory et al.*, 2006; *Price et al.*, 2010]. It is important to evaluate the relative influences of anthropogenic

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and geomorphic factors in order to fully understand how land use change affects base flows in regions of variable topography. Thus, the goal of the research presented here was to quantitatively explore the effects of land use, topography, and precipitation on low flows in 35 small-scale to mesoscale watersheds (3 – 146 km^2) in the southern Blue Ridge Mountains monitored over two low-flow seasons.

[3] There is a vast body of literature demonstrating reduced streamflow associated with greater watershed forest cover, with many studies specifically demonstrating lower base flow with higher watershed forest cover [*Harr et al.*, 1982; *Keppeler and Ziemer*, 1990; *Hicks et al.*, 1991; *Black et al.*, 1995; *Paco et al.*, 2009]. This negative relationship between watershed forest cover and base flow is attributed to greater interception and water use by mature trees compared with other land cover types [*Bosch and Hewlett*, 1982; *Calder*, 1990; *McCullough and Robinson*, 1993; *Johnson*, 1998; *Paco et al.*, 2009]. These results have occasionally been interpreted as a suggestion that watershed management approaches could include deforestation to increase water yield for public use [e.g., *Brooks et al.*, 1991; *Chang*, 2003]. However, much of this literature derives from experimental forestry, where soil disturbance is far less pronounced than occurs when forest is converted to more permanent land uses, such as pasture, residential development, etc. There is a sound theoretical basis and growing empirical evidence that long-term forest conversion reduces base flows, specifically low flows, because the intensive soil compaction and increases in impervious surface that accompany human land uses decrease infiltration rates and subsurface storage recharge [*Bruijnzeel*, 2004; *Gregory et al.*, 2006; *Chaves et al.*, 2008; *Germer et al.*, 2009; *Price et al.*, 2010; *Price*, 2011]. These changes in surface infiltration apparently outweigh the reductions in ET ascribed to removal of mature forest stands. Furthermore, the majority of experimental forestry studies have focused on very small systems (generally smaller than 1 km^2), and there is evidence that upscaling results from such studies to larger, more heterogeneous basins is problematic, presumably because regional recharge response is not captured in such small watersheds [*Blöschl*, 2001; *Sivapalan*, 2003; *Soulsby et al.*, 2004; *National Research Council*, 2008]. The few examples assessing base flow response at larger scales have demonstrated mixed results [*Wilk et al.*, 2001; *Costa et al.*, 2003], indicating a need for further investigation.

[4] Analysis of low-flow response to land use change is complicated by the breadth of other factors that influence infiltration and transmission rates from subsurface storage to the stream channel network. Within a context of consistent bedrock type, topography may exert substantial influence on base flow processes, particularly in areas of pronounced relief [*McGuire et al.*, 2005, *Vivoni et al.*, 2008; *Tetzlaff et al.*, 2009]. Spatial variability in ET and precipitation may result from differences in topographic characteristics, such as aspect and elevation among watersheds. Furthermore, topographic slope and channel network development influence transmission rates of water [*Vivoni et al.*, 2008; *Tetzlaff et al.*, 2009]. Climatic and topographic variability additionally influence the storage reservoir itself, through their effects on bedrock weathering and soil development. The effects of land use change on base flow timing and quantity may be mitigated or amplified by basin topography, and there may be situations in which topographic conditions exert such strong control on base flow that drastic changes in land use are required to induce detectible changes in low flows [*Konrad and Booth*, 2002].

[5] Previous studies have demonstrated that factors such as relief, slope, drainage density, and watershed shape, which all influence the ability of water to flow to the channel network and out of the watershed, significantly relate to stream low flow [*Farvolden*, 1963; *Thomas and Benson*, 1970; *Vogel and Kroll*, 1992; *Woods et al.*, 1997; *Marani et al.*, 2001; *Warner et al.*, 2003; *Cherkauer and Ansari*, 2005]. However, there remains little understanding about which metrics expressing basin topography and morphometry are most useful for explaining low-flow variability, and it remains unclear how variables of topography and land use interact to influence low flow [*Price*, 2011]. It is especially important to develop a better understanding of watershed processes and impacts on water quantity on headwater areas, especially in mountainous regions, because of the high proportion of water sourced from these areas [*Vivrioli and Weingartner*, 2004].

[6] There were two main objectives of this study, in which we monitored streamflow in 35 small to medium watersheds in the southern Blue Ridge Mountains for two annual low-flow seasons. The first objective was to relate the variation in low flows to land use characteristics, a thorough suite of topographic metrics, and rainfall measured over the study period. The second objective was to compare low flows among watersheds with higher and lower watershed forest cover. The suite of topographic metrics was developed from all metrics identified in the literature as factors affecting low flow. The independent variable list was reduced by simple correlation and principal components analysis, and backward stepwise regression and other statistical tests were used to identify dominant controls of low-flow discharge and the effect of basin forest cover on streamflows.

2. Study Area

[7] This study was conducted within the upper watersheds of the Tuckasegee, Nantahala, and Little Tennessee rivers, which together compose the majority of the Little Tennessee River system upstream of Lake Fontana, a Tennessee Valley Authority (TVA) reservoir (Figure 1). This study area contains the entirety of Macon County, North Carolina, and portions of Clay and Jackson counties, North Carolina, and Rabun County, Georgia. These watersheds are located within the Blue Ridge physiographic province. The regional geology is characterized by crystalline bedrock with minimal fracture flow [*Velbel*, 1985; *Santhi et al.*, 2008], and the hydraulic conductivities of all bedrock types are of similar magnitudes [*Daniel and Payne*, 1990; *Mesko et al.*, 1999]. A saprolite mantle 1 – 30 m thick drapes the ridges and slopes throughout the study area [*Hewlett*, 1961], and substantial deposits of colluvium are present on benches, coves, and foot slopes [*Southworth*, 2003; *Leigh and Webb*, 2006]. The saprolite-bedrock contact is believed to generally parallel surface topography and to serve as the predominant subsurface topographic control on hillslope hydrology [*Hatcher*, 1988]. The average depth to solid

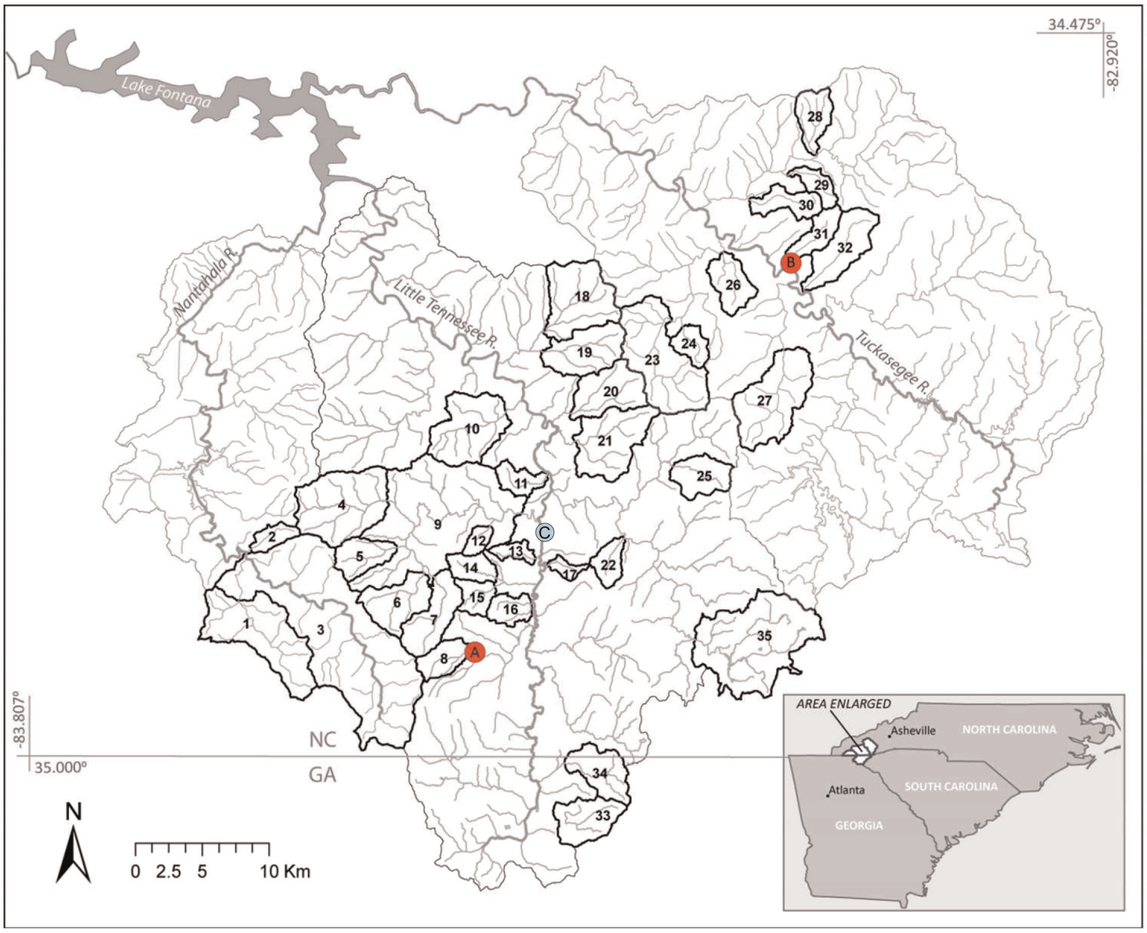

Figure 1. Study area and monitored watersheds. Watershed numbers correspond to site numbers in Table 1. Points A and B are the National Climate Data Center (NCDC) Coweeta and Cullowhee climate stations, for which long-term normals are presented in the text. Watersheds 3, 9, and 35 correspond to U.S. Geological Survey (USGS) gauges (Nanthala River near Rainbow Springs, Cartoogechaye Creek near Franklin, and Cullasaja River near Highlands, respectively). Point C represents the USGS gauge at the Little Tennessee near Prentiss, which is referenced in descriptions of regional conditions.

bedrock in the Coweeta Creek basin in the southern part of the study area is 6 m [*Swank and Douglass*, 1975].

[8] Precipitation in this region typically is quite high but spatially variable, with the general trend of highest precipitation toward the southern escarpment of the Blue Ridge and lower precipitation toward the northern part of the study area [*Konrad*, 1996]. The 30 year average precipitation at the Coweeta Experiment Station's low-elevation rain gauge (686 m above sea level (asl)) is 1826 mm, whereas 38 km to the northeast in Cullowhee, North Carolina (elevation of 668 m asl), the 30 year average is only 1313 mm (Figure 1). The 30 year average annual daily mean temperatures at these stations are quite similar: 19.8°C at Coweeta and 19.6°C at Cullowhee. The study period coincided with a severe drought affecting the southeastern United States. The average deficits from 30 year precipitation normals at the Coweeta and Cullowhee stations were 18% for 2007 and 19% for 2008 [*National Climatic Data Center* (*NCDC*), 2004]. This severe drought period, defined by a Palmer hydrologic drought index (PHDI) below −3, affected the southern Blue Ridge from July 2007 to January 2009 [*NCDC*, 1994, 2010]. Extreme drought conditions (PHDI < −4) affected the region between November 2007 and January 2008 and again in August 2008, coinciding with the lowest streamflows on long-term records across the region.

[9] In the absence of human impact, regional land cover would be nearly 100% forest [*Yarnell*, 1998; *Delcourt and Delcourt*, 2004]. Present-day land cover is predominantly forest, with nonforest land cover occurring primarily as pasture and low-density development. The region experienced intensive, widespread timber harvest and agriculture during the late nineteenth and early twentieth centuries, followed by forest regrowth on mountain slopes [*Davis*, 2000]. While the pulse of timber harvest affected large areas of the region in the early twentieth century, agriculture was limited to subsistence farming and impacted relatively small areas (<10%) [*Kirk*, 2009]. In most of the study area, agricultural land abandonment and vegetation regrowth have been common since the 1930s, but over recent decades, exurban population growth and associated expansion of residential and low- to medium-density urban land cover have affected substantial portions of the region [*Wear and Bolstad*, 1998;

Cho et al., 2003; *Gragson and Bolstad*, 2006]. The largest town in the study area is Franklin, with a 2006 population of 3618 [*U.S. Census Bureau*, 2007].

3. Methods

3.1. Site Selection and Instrumentation

[10] Over 100 watersheds were delineated upstream of public access points and characterized in terms of watershed forest cover, maximum elevation, minimum elevation, and aspect. A subset of 36 sites was selected for instrumentation with stage recorders. In an effort to represent the full range of regional watershed characteristics, the watersheds with the greatest and least total relief (the difference between the maximum and minimum watershed elevations) and the maximum and minimum watershed forest cover were included. For selection of intermediate sites, *k*-means cluster analysis was used to identify groups of similar watersheds on the basis of maximum elevation, aspect, and forest cover. Study sites were randomly selected from within each cluster, with number of sites selected proportional to cluster size. No nested watersheds were included in these 36 sites, which range from 2.68 to 34.10 km^2 in watershed area and 44.4%–99.9% watershed forest cover (Table 1 and Figure 1).

[11] The majority of these watersheds (35 of 36 sites) were instrumented with Odyssey capacitance water level recorders. This was achieved by suspending the recorder in 38 mm diameter PVC tubing in the stream bank connected to the stream thalweg with a lateral 25 mm diameter PVC pipe or by suspending the probe directly into the stream channel by attaching the PVC housing to a wooden bridge support. Because of shallow bedrock and a lack of a bridge attachment, one site (Fulcher Branch) was not suitable for Odyssey probe use. At this site, a HOBO pressure transducer was situated under a bedrock ledge within the streambed, with an additional transducer installed on the bank for barometric pressure adjustment. These instruments recorded the water level every 10 min, with the period of record spanning 5 August 2007 to late November 2008. Time and budget constraints limited us to this period for monitoring. As there is only a very small number of long-term regional gauge records available, it was determined that this period encompassing two low-flow seasons during an extreme drought could provide interesting and needed insights into watershed function and water quantity in this region [*Laaha and Blöschl*, 2005]. Additionally, three U.S. Geological Survey (USGS) gauged watersheds (Nantahala River at Rainbow Springs, Cartoogechaye Creek, and Cullasaja River near Highlands) and one watershed gauged as

Table 1. Watershed Land Use, Elevation, and Outlet Coordinates[a]

Watershed	Stream Name	Area (km^2)	Developed (%)	Forest/ Shrub (%)	Pasture/ Agriculture (%)	Maximum Elevation (m)	Relief (m)	Outlet Location		Rating Curve Fit R^2
								East (m)	North (m)	
1	Buck Creek	33.8	3.3	96.5	0.2	1535	555	260745	3886771	0.955
2	Roaring Fork	4.7	0.2	99.9	0.0	1590	634	261677	3890634	0.953
3	Nantahala River	134.9	2.1	97.5	0.2	1676	739	261272	3890251	N/A
4	Wayah Creek	30.6	2.9	96.7	0.3	1650	964	271826	3894252	0.964
5	Poplar Cove Creek	9.6	8.5	90.1	1.4	1416	743	272585	3890734	0.838
6	Allison Creek	15.2	6.1	90.4	3.4	1514	828	274599	3888836	0.953
7	Jones Creek	15.3	3.3	94.3	2.4	1533	840	275324	3888583	0.990
8	Shope Fork	7.8	1.6	98.4	0.0	1593	893	277914	3882718	0.968
9	Cartoogechaye Creek	145.5	8.0	85.9	5.9	1661	1041	281828	3893272	N/A
10	Iotla Creek	23.5	8.8	77.5	13.3	1157	550	280766	3900933	0.981
11	Crawford Branch	6.0	48.9	44.4	6.3	886	276	283780	3896278	0.966
12	Blaine Branch	3.3	8.4	82.3	9.1	968	341	279509	3892346	0.889
13	McDowell Branch	3.5	17.0	70.9	11.9	886	269	282953	3889889	0.950
14	North Fork Skeenah Creek	6.4	6.5	84.7	8.5	1081	447	280032	3888436	0.994
15	South Fork Skeenah Creek	6.0	5.7	90.5	3.8	1113	475	279908	3887811	0.995
16	Bates Branch	6.3	10.7	76.8	12.1	996	379	282651	3886531	0.973
17	Fulcher Branch	2.7	12.4	76.3	11.1	1170	551	283877	3889427	0.974
18	Cowee Creek	24.3	2.6	95.4	1.9	1510	871	283477	3906869	0.950
19	Caler Fork	17.4	4.4	93.4	1.9	1361	742	283436	3905393	0.807
20	Watauga Creek	16.7	13.0	82.4	4.3	1232	614	285452	3900783	0.997
21	Rabbit Creek	22.9	8.5	77.9	13.5	1345	730	285868	3898678	0.972
22	Nickajack Creek	6.1	3.6	95.0	0.5	1281	651	289564	3891416	0.985
23	Savannah Creek	34.1	5.7	93.7	0.6	1422	731	293127	3907672	0.992
24	Tathams Creek	5.9	1.1	98.6	0.3	1311	600	293990	3906751	0.949
25	Little Ellijay Creek	10.8	3.0	96.4	0.4	1464	785	293240	3896825	0.945
26	Little Savannah Creek	10.1	9.1	83.5	7.0	1048	432	296976	3912843	0.823
27	Cullowhee Creek	27.6	3.5	95.6	0.8	1459	797	301482	3905556	0.968
28	Buff Creek	9.3	2.7	96.1	1.0	1840	1152	303974	3920145	0.855
29	Blanton Branch	5.3	11.0	86.0	2.7	1147	488	301771	3918587	0.911
30	Cope Creek	8.5	15.4	80.3	4.0	1084	460	298901	3916772	0.829
31	Cane Creek	7.7	4.0	95.0	1.0	1238	613	302127	3912145	0.999
32	Wayehutta Creek	16.3	3.4	95.8	0.7	1469	840	303060	3909835	0.999
33	Darnell Creek	13.7	0.5	99.2	0.0	1405	742	284267	3871058	0.963
34	Mud Creek	13.1	23.4	75.1	0.9	1432	778	285112	3874639	0.999
35	Cullasaja River	48.2	26.7	71.6	1.0	1525	544	294849	3883827	N/A

[a]Coordinates are universal transverse Mercator (UTM) NAD83. N/A indicates USGS gauged streams. The rating curves are developed and updated by the USGS.

part of the U.S. Forest Service (USFS) Coweeta Hydrologic Laboratory network (Shope Fork) were included. Six of the smaller watersheds are nested within the USGS watersheds. The Coweeta laboratory maintains a trapezoidal weir on Shope Fork, with a pressure transducer used for continuous inflection point stage monitoring for Shope Fork. This site was additionally instrumented with an Odyssey capacitance water level recorder for accuracy assessment of the discharge calculation method by comparison with weir data. The USGS gauges record instantaneous stage data every 15 min.

3.2. Flow Measurement and Rating Curve Development

[12] For each of the watersheds instrumented with Odyssey and HOBO recorders, stage-discharge rating curves were developed. Several methods were tested, including second-order polynomial ordinary least squares regression and multisegmented power law curve fitting, but Bayesian power law curve fitting produced the best results and was applied to all sites [*Arnason*, 2005; *Moyeed and Clarke*, 2005; *Petersen-Øverleir and Reitan*, 2005; *Reitan and Petersen-Øverleir*, 2008, 2009; *McMillan et al.*, 2010].

[13] As illustrated by the representative examples shown in Figure 2, the other curve fitting methods tended to bias fitting of the high-flow points, leading to overestimates or underestimates of low flows. Particularly because this study emphasized low flows, the Bayesian multisegment method was selected on the basis of the visual evidence that low flows were best represented by this approach. The R^2 values for the fits were also higher for many of the streams with the Bayesian multisegment method than the ordinary least squares methods, but this was of secondary importance to the visual evidence that the Bayesian approach fit the data better than the other methods. Single-segment and multisegmented Bayesian rating curve fitting followed the methods outlined by *Reitan and Petersen-Øverleir* [2009], with the addition of a prior distribution, based on the knowledge that the zero plane is lower than the lowest stage in the time series, a mirrored and translated lognormal distribution for the zero plane specified by this maximal value, and a 95% credibility interval.

[14] Discharge was measured for rating curves using the midsection method [*Mosley and McKerchar*, 1993], with an acoustic Doppler velocity meter used for 60% water depth velocity measurement at no fewer than 13 points per cross section. This method of discharge measurement has been shown to have an error range of 3%–6% [*Sauer and Meyer*, 1992]. Discharge was measured at least 10 times for each stream during the study period. For measurement of high flows on the largest streams, it was necessary to use dye for

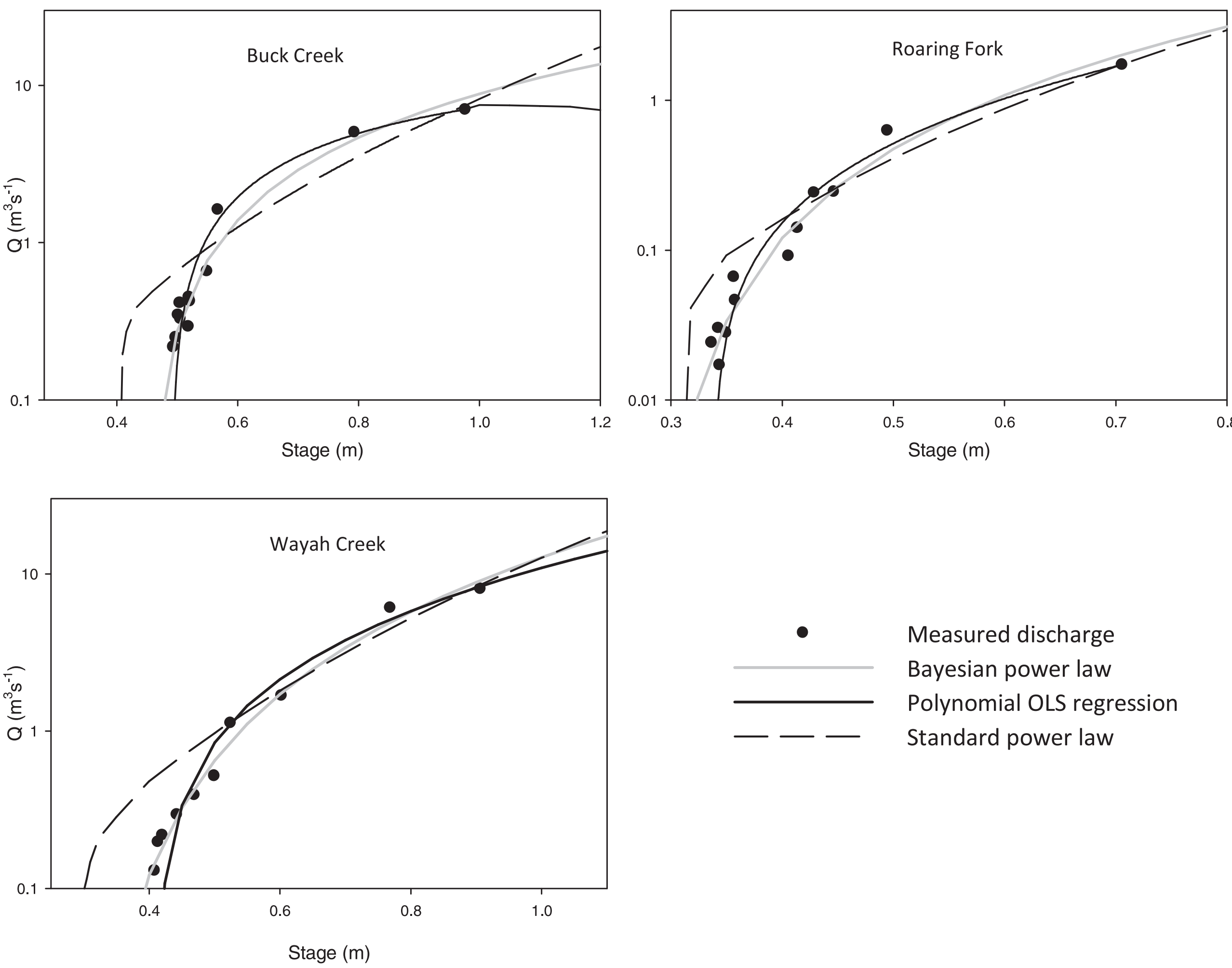

Figure 2. Representative examples of rating curves developed using different curve fitting methods.

velocity measurements within five sections of the channel, with channel area determined by probe stage and laser level channel survey. Additionally, bankfull discharge was modeled using Manning's equation. Channel dimension parameters for Manning's equation were calculated from cross-sectional and slope data from laser level channel survey, and Manning's *n* was calculated from the highest measured discharge value at each site. The corresponding bankfull stream stage was paired with the modeled bankfull discharge and included in rating curve development. Several sites had problems with the stage-discharge fit because of intermittent beaver dams, flood scour, etc., and were excluded from analyses. Ultimately, sites included in the analysis were limited to 35 watersheds, including the USGS and USFS sites.

3.3. Streamflow Analysis

[15] Streamflow records were subset into two time periods for statistical analysis of watershed influences on low flow: (1) low-flow season 2007, 5 August to 12 November (LF07), and (2) low-flow season 2008, 1 August to 12 November (LF08). The designation of "low-flow season" does not imply 100% base flow during the time period but, instead, designates the season generally containing the lowest flows of the year [*Smakhtin*, 2001]. Low-flow season was defined on the basis of regional long-term trends, data availability, and 2007–2008 conditions (Figure 3). Because installation of the stage-recording capacitance probes was not complete until early August 2007, the LF07 was assigned a slightly later start date of 5 August. Sites with missing data totaling 5% of a given low-flow season were not included in the analyses corresponding to that time period. Ten minute interval stage data were available for all Odyssey probe and HOBO transducer sites. The inflection point record of the USFS site at Shope Fork was converted to 10 min data by linear interpolation.

[16] In this study, three low-flow metrics were calculated for each stream: (1) the flow exceeded 99% of the time (Q_{99}), (2) minimum daily mean flow ($Q_{\min1}$), and (3) minimum 7 day mean flow ($Q_{\min7}$). In this study, Q_{99} was calculated from the 10 and 15 min gauge records, while $Q_{\min1}$ and $Q_{\min7}$ were calculated from daily mean flows (Q_{mean}). $Q_{\min1}$ represents the minimum daily flow value within the specific time period, and $Q_{\min7}$ was determined from the 7 day moving averages of daily mean flow. For comparison of flow magnitudes across stream systems of different scales, all metrics were standardized by dividing by watershed area. Hereafter, Q_{99}, $Q_{\min1}$, $Q_{\min7}$, and Q_{mean} represent the area-adjusted flows ($\mathrm{m^3 s^{-1}\ km^{-2}}$).

3.4. Watershed Precipitation Summary Data

[17] Daily precipitation data for the study period were obtained for 35 stations throughout the region from the

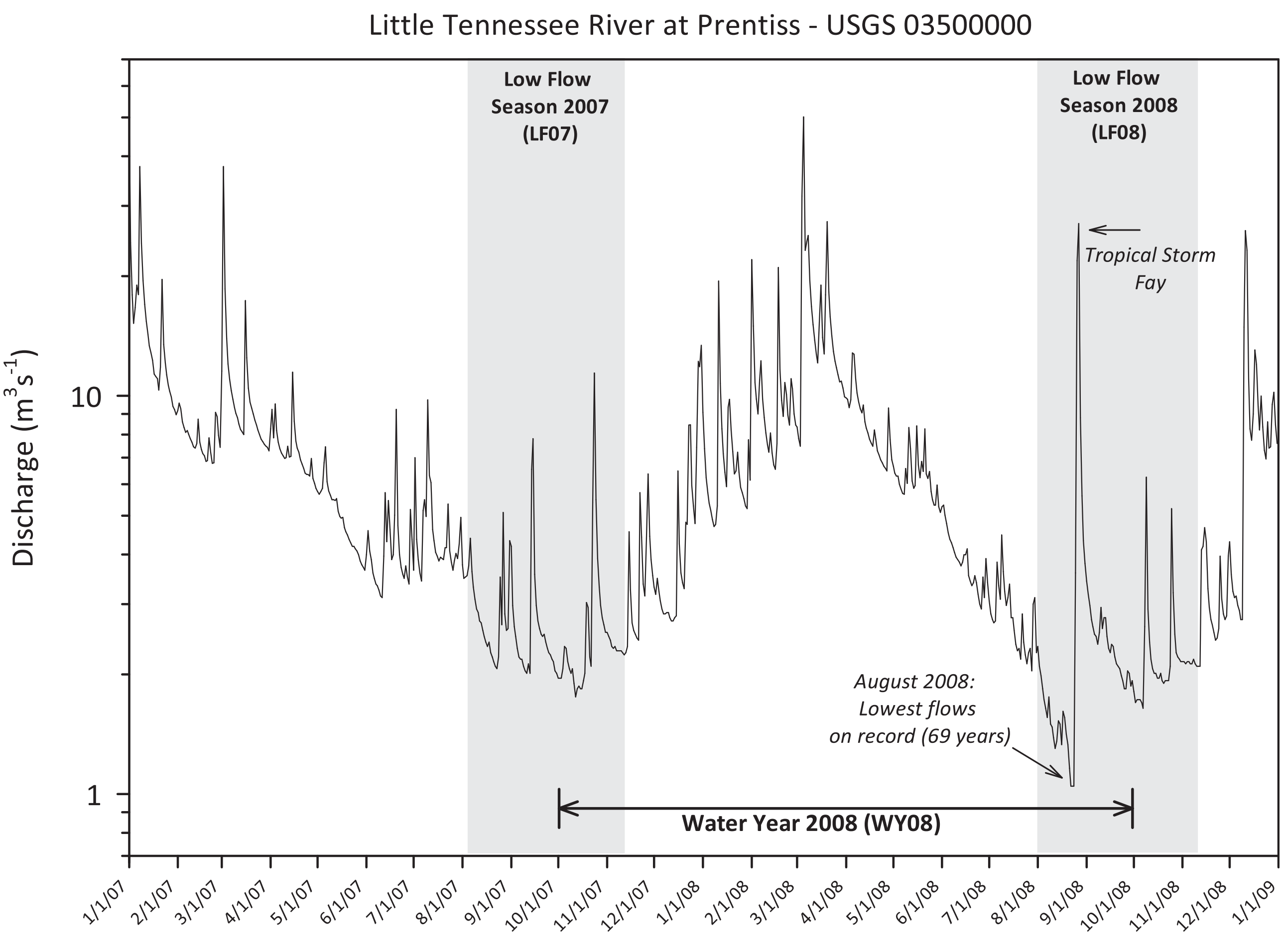

Figure 3. Regional hydrologic conditions during the study period, from USGS gauge 03500000 (Little Tennessee River at Prentiss).

Coweeta Hydrologic Laboratory, the NCDC, the State Climate Office of North Carolina, and the National Weather Service Integrated Flood Warning System (IFLOWS). Missing data values were filled using double-mass curve analysis combining precipitation totals from three neighboring stations [*Brutsaert*, 2005]. Precipitation data from 35 regional stations were converted to grid coverage using ordinary kriging [*Nour et al.*, 2006; *Attorre et al.*, 2007; *Carrera-Hernández and Gaskin*, 2007; *Zhang and Srinivasan*, 2009], and the mean precipitation depth of all pixels within a watershed was used to represent total precipitation during the periods of analysis.

3.5. Selection of Topographic and Landscape Variables for Analysis

[18] For final site characterization, watersheds were delineated and stream networks were defined using the Basin 1 extension in Arc View 3.3 (http://arcscripts.esri.com/details.asp?dbid=10668), and ArcGIS 9.2 was used for calculation of all other watershed characteristics. To define watershed land use, a classification of 2006 Landsat imagery following the National Land Cover Database (NLCD) classification scheme was obtained from the Coweeta Long Term Ecological Research (LTER) program. The NLCD categories were reclassified to five general land use categories: (1) forest and shrub, (2) developed, (3) pasture and agriculture, (4) barren, and (5) open water. Topographic and morphometric variables were selected from classic and recent literature on the basis of those which have a strong theoretical relationship to streamflow, have a legacy of inclusion in watershed characterization, and/or have previously been demonstrated to have statistically significant relationships to streamflow metrics (Table 2). Topographic and morphometric characteristics were calculated from lidar data (6.1 m pixels, ±25 cm vertical accuracy) for all sites in North Carolina (North Carolina Department of Transportation, elevation grids for Clay, Jackson, and Mason counties, http://www.ncdot.org/it/gis). For the two Georgia watersheds, a 10 m digital elevation model (DEM) was used. The Basin 1 extension for ArcView 3.2 was used to delineate the regional stream network, using an accumulation threshold of 18,050 m^2, which was shown to best match the ground-truthed stream network available for a small portion of the study area [*North Carolina Department of Environment and Natural Resources*, 2009]. Hypsometry was calculated using the CalHypso Extension for ArcGIS *Pérez-Peña et al.*, 2009]. Soil parameters were calculated from SSURGO soils data [*Natural Resources Conservation Service*, 2005, 2006, 2007, 2008]. Bedrock geology was classified by hydraulic conductivity, following the Blue Ridge regional scheme presented by *Mesko et al.* [1999], using digital 1:250,000 maps available for the North Carolina watersheds [*Robinson et al.*, 1992] and a digital 1:500,000 map available for the state of Georgia [*Georgia Geologic Survey*, 1999].

[19] Watershed characterization included calculation of 66 metrics of basin and channel network geomorphology, soils and bedrock, land use, and precipitation (Table 2). Simple correlation analysis was used to identify strongly correlated variables (operationally defined as $|R| > 0.8$) among the watershed characteristics and precipitation totals, of which only one was retained. Preference was given to variables with previously demonstrated or strong theoretical linkages to streamflow. Principal components analysis (PCA) was used to examine the data structure of the 43 remaining explanatory variables. The PCA rotated factor loadings were used to further reduce the data to 14 candidate variables for inclusion in multiple regression modeling. This method reduces redundancy and correlation among the independent variables and provides an objective means of variable selection [*Morris et al.*, 2009; *Singh et al.*, 2009].

3.6. Multiple Regression Modeling

[20] Separate analyses were performed for each of the three dependent variables (Q_{99}, Q_{min1}, and Q_{min7}). Each of the two periods (LF07 and LF08) were analyzed separately, resulting in a total of six models. From the reduced set of 14 independent variables, backward stepwise regression was used to identify the best models, as judged by values of the corrected Akaike information criterion (AICC). To achieve a normal distribution of the dependent variables, $\log_{10}$ transformations were applied to the metrics of low-flow magnitude (Q_{99}, Q_{min1}, and Q_{min7}). Regression assumptions of homoskedasticity and linear relationships were tested. Standard transformations ($\log_{10}$, square root, and reciprocal) were used to normalize independent variables that were non-normally distributed. All variables in percent format were transformed using the arcsin square root transformation. Determination of the best model was additionally based on overall goodness of fit, significance and direction of influence of independent variables, parsimony, and logic. Low-flow metrics were normalized by watershed area, having demonstrated bivariate correlations 0.87 and greater with watershed area.

3.7. Comparison of Low Flows Among More- and Less-Forested Watersheds

[21] Standard t tests were used to compare low flows of relatively higher- and lower-forest watersheds. Categories of higher and lower forest were determined by k-means cluster analysis. Simple correlation analyses were performed between watershed forest cover and all low-flow metrics. Significance was defined as $p \leq 0.05$ for all analyses. Four pairs of sites were identified in which topographic characteristics were very similar but watershed forest cover was different. These sites were used for pairwise comparison of low flow under different land use conditions while controlling for topographic variability.

4. Results

4.1. Rating Curves

[22] Bayesian power law curve fits were evaluated using R^2 values along with visual evaluation of credibility (Table 1). Four sites with intolerable point scatter and poorest fits were not included in further analyses. Results from discharge calculations using the velocity-area method and Bayesian rating curve development at Shope Fork were compared with measured discharge at the USFS weir, located approximately 50 m downstream from the capacitance probe gauging site. These results indicated an average 6.5% difference between the daily mean flows, which is just outside the 3%–6% error range presented by *Sauer and Meyer* [1992] and can be assumed to generally represent the magnitude of error across the sites. On a

Table 2. Explanation of Independent Variables Considered[a]

Metric	Abbreviation	Unit	Calculation Method	Reference	Exclusion	Transform
Basin topography						
Basin elevation, maximum	ElevMax	m	Elevation at highest point in basin	(http://arscripts.esri.com)	SC	-
Basin elevation, mean	ElevMean	m	Mean elevation of watershed DEM pixels	(http://arscripts.esri.com)	SC	-
Basin elevation, median	ElevMed	m	Median elevation of watershed DEM pixels		*	-
Basin elevation, minimum	ElevMin	m	Elevation at basin outlet	(http://arscripts.esri.com)	SC	X
Basin elevation, SD	ElevSD	m	SD of watershed DEM pixels	(http://arscripts.esri.com)	SC	-
Basin relative relief	RelRelief		Basin relief/basin perimeter	*Fitzpatrick et al.* [1998]	SC	-
Basin relief	TotRelief	m	Maximum elevation − minimum elevation	*Fitzpatrick et al.* [1998]	PCA	-
Hypsometric index 1	Hyp1		Percent change between 25th and 75th percentiles of curve	*Warner et al.* [2003]	*	$\log_{10}$
Hypsometric index 2	Hyp2	km^{-2}	Hypsometric index 1/area	*Warner et al.* [2003]	PCA	-
Hypsometric index 3	Hyp3		Hypsometric index 1/percent change between 50th and 75th percentiles of curve	*Warner et al.* [2003]	PCA	X
Hypsometric integral	HypInt		Integral of hypsometric curve	*McGuire et al.* [2005]	PCA	-
Hypsometric kurtosis	HypKurt		Kurtosis of hypsometric curve		PCA	-
Hypsometric skewness	HypSkew		Skewness of hypsometric curve		PCA	-
Topographic index, mean	TImean		Mean TI of pixels (ln(tan(slope))/dimension of accumulation area)	*McGuire et al.* [2005]	PCA	X
Topographic index, SD	TISD		SD of TI of pixels		PCA	X
Basin morphometry						
Basin area	Area	km^2	Area enclosed by drainage divide	*Fitzpatrick et al.* [1998]	*	$\log_{10}$
Basin circularity ratio	Circ		$4 \times \prod \times$ basin area/(basin perimeter)^2	*Apaydin et al.* [2006]	SC	-
Basin compactness ratio	Comp		Basin perimeter/2($\prod \times$ basin area)$^{0.5}$	*Apaydin et al.* [2006]	PCA	-
Basin elongation	Elong		2(basin area/$\prod$)$^{0.5}$/basin length	*Apaydin et al.* [2006]	*	-
Basin length	Length	km	Length from watershed outlet to drainage divide	*Fitzpatrick et al.* [1998]	SC	-
Basin length, equivalent	L_Equiv	km	(Basin perimeter + (basin perimeter^2 − 16 × basin area)$^{0.5}$)/4	(http://arscripts.esri.com)	SC	$\log_{10}$
Basin length, relative	L_Rel		Basin length/(basin area)$^{0.5}$	(http://arscripts.esri.com)	SC	$\log_{10}$
Basin perimeter	Perim	km	Length of basin boundary	*Warner et al.* [2003]	SC	$\log_{10}$
Basin relief ratio	RelRat		Basin relief/basin length×1000	*Fitzpatrick et al.* [1998]	SC	-
Basin ruggedness 1	Rugg1		Basin relief/(basin area)$^{0.5}$	*Apaydin et al.* [2006]	SC	-
Basin ruggedness 2	Rugg2		Basin relief × drainage density	*Melton* [1957]	SC	-
Basin shape	Form		Basin area/(basin length)^2	*Fitzpatrick et al.* [1998]	SC	-
Basin thickness	V/A	m	(Pixel area × sum of all pixel elevations)/basin area		SC	-
Aspect						
Aspect, east facing	EF		Fraction of pixels facing 45°–135°	*Warner et al.* [2003]	PCA	asr
Aspect, north facing	NF		Fraction of pixels facing 315°–45°	*Warner et al.* [2003]	PCA	asr
Aspect, south facing	SF		Fraction of pixels facing 135°–225°	*Warner et al.* [2003]	*	asr
Aspect, west facing	WF		Fraction of pixels facing 225°–315°	*Warner et al.* [2003]	SC	asr, exp
Cos(aspect)	cos(asp)		Mean cos(aspect) of watershed pixels	*Brenning and Trombotto* [2006]	PCA	-
Sin(aspect)	sin(asp)		Mean sin(aspect) of watershed pixels	*Brenning and Trombotto* [2006]	PCA	-
Basin slope						
Slope, 95th percentile	Slope 95th		95th percentile of pixel slope distribution		SC	-
Slope, basin area <2%	Slope<2		Fraction of pixels less than 2% slope	*Warner et al.* [2003]	*	$\log_{10}$
Slope, basin area <5%	Slope <5		Fraction of pixels less than 5% slope	*Warner et al.* [2003]	SC	$\log_{10}$
Slope, basin area <10%	Slope<10		Fraction of pixels less than 10% slope	*Warner et al.* [2003]	SC	$\log_{10}$
Slope, basin area <20%	Slope<20		Fraction of pixels less than 20% slope	*Warner et al.* [2003]	SC	$\log_{10}$
Slope, kurtosis	Slope Kurt		Kurtosis of pixel slope distribution		PCA	X
Slope, maximum	Slope Max		Maximum pixel slope	(http://arscripts.esri.com)	*	recip
Slope, mean	Slope Mean		Mean slope of watershed pixels	*McGuire et al.* [2005]	SC	-
Slope, median	Slope Med		Median slope of watershed pixels		SC	-
Slope, skewness	SlopeSkew		Skewness of pixel slope distribution		PCA	-
Slope, SD	SlopeSD		SD of watershed slope pixels		*	X
Channel network morphometry						
Bifurcation ratio (count)	BR		Average (number of stream segments order$_x$)/(number of stream segments order$_{x+1}$)	*Shehata and Al-Ruwaih* [2005]	*	-
Bifurcation ratio (length)	BR_L		Average (sum length order$_x$)/(sum length order$_{x+1}$) $\neq$ order$_{x_max}$		PCA	X
Tributary/trunk ratio	ChaTri		Total tributary length/trunk stream length	*Warner et al.* [2003]	SC	-
Drainage density	DD	km^{-1}	Total stream length/basin Area	*Fitzpatrick et al.* [1998]	*	-

Table 2. (continued)

Metric	Abbreviation	Unit	Calculation Method	Reference	Exclusion	Transform
Entire stream gradient	BasinSl		(Elevation at 85% length − elevation at 10% length)/(85% − 10% length)	*Fitzpatrick et al.* [1998]	PCA	$\log_{10}$
First-order stream fraction	%1st		First-order stream length/total stream length		*	-
Total stream length	Tot Length	km	Sum of segment lengths (using accumulation threshold of 18,050 m^2)	*Fitzpatrick et al.* [1998]	SC	$\log_{10}$
Soil and bedrock						
Soil, alluvium	Alluvium		Fraction of basin area mapped as alluvium parent material	*Tetzlaff and Soulsby* [2008]	*	Asr
Soil, colluvium	Colluvium		Fraction of basin area mapped as colluvium parent material	*Tetzlaff and Soulsby* [2008]	*	Asr
Soil, residuum	Residuum		Fraction of basin area mapped as residuum parent material	*White and Burbey* [2007]	PCA	asr, X
Soil, sand fraction	Sand		Area-weighted mean sand fraction of watershed soils	*Batelaan and DeSmedt* [2007]	PCA	asr,X
Soil, silt fraction	Silt		Area-weighted mean silt fraction of watershed soils	*Batelaan and DeSmedt* [2007]	PCA	asr, X
Soil, clay fraction	Clay		Area-weighted mean clay fraction of watershed soils	*Batelaan and DeSmedt* [2007]	*	asr,X
Bedrock, class 2 conductivity	Geol2		Fraction of watershed bedrock geology mapped as category 2		PCA	X
Land use						
Impervious surface area	Imperv		As fraction of watershed area, calculated from NLCD class		SC	
Developed	Dev		Fraction of watershed area in NLCD classes 21, 22, 23, and 24		SC	
Forest and shrub	For		Fraction of watershed area in NLCD classes 41, 42, 43, and 52		*	
Pasture and agriculture	Pas		Fraction of watershed area in NLCD classes 71, 81, and 82		SC	
Barren	Barren		Fraction of watershed area in NLCD class 31		PCA	
Wetland	Wetland		Fraction of watershed area in NLCD class 90		PCA	
Open water	Water		Fraction of watershed area in NLCD class 11		PCA	
Precipitation						
Antecedent precipitation LF07	A-PPTLF07	Mmol	Total precipitation over previous year (average depth)		*	
Antecedent precipitation LF08	A-PPTLF08	Mmol	Total precipitation over previous year (average depth)		*	
Accumulated precipitation LF07	PPTLF07	Mmol	Total precipitation during study period (average depth)		*	
Accumulated precipitation LF08	PPTLF08	Mmol	Total precipitation during study period (average depth)		*	

[a]The Exclusion column conveys the analysis that led to removal of the variable from further analysis. SC indicates simple correlation, PCA indicates principal components analysis, and an asterisk indicates a variable that was included in regression modeling. The Transform column presents the standard transform that was used to achieve a normal distribution of the variable. A dash indicates a variable that was normally distributed without transformation, a cross indicates that no standard transform normalized the variable, and asr indicates an arcsin square root transform was used (in cases of proportions). NLCD, National Land Cover Database; LF07, low-flow period in 2007; LF08, low-flow period in 2008.

percentage basis, differences were minor during low flows and most pronounced during high flows, in which the weir discharge was generally higher than the discharge calculated using the capacitance probe and natural cross section.

4.2. Precipitation Interpolation

[23] The 35 regional precipitation stations encompass an area of 6545 km^2, and station elevation ranged from 580 to 1663 m. Because of a prevalent south to north track of large tropical storms from the Atlantic Ocean and Gulf of Mexico, there was much greater rainfall in the southern part of the study area. Spatial variability of rainfall across the study region is pronounced and obscures the typical expectation of increasing precipitation with elevation. The correlations between total precipitation and elevation were significant but not strong (LF07: $R = 0.381$, $p = 0.024$; LF08: $R = 0.421$, $p = 0.012$), and similarly low correlations were evident for five individual storms that included nine additional precipitation stations. Significant spatial autocorrelation of precipitation was present for all time periods and confirmed kriging as an appropriate approach. The weak correlation between precipitation and elevation suggested that the use of cokriging to account for elevation in the interpolation was inappropriate for these data, and watershed precipitation totals using ordinary kriging resulted in a marginally stronger relationship to base flows than seen with cokriging. Ordinary kriging demonstrated significant precipitation variability across the study watersheds (Figure 4). Precipitation during the low-flow periods was more than double in some areas than in others, varying from as little as 128 mm to as much as 390 mm over the study area.

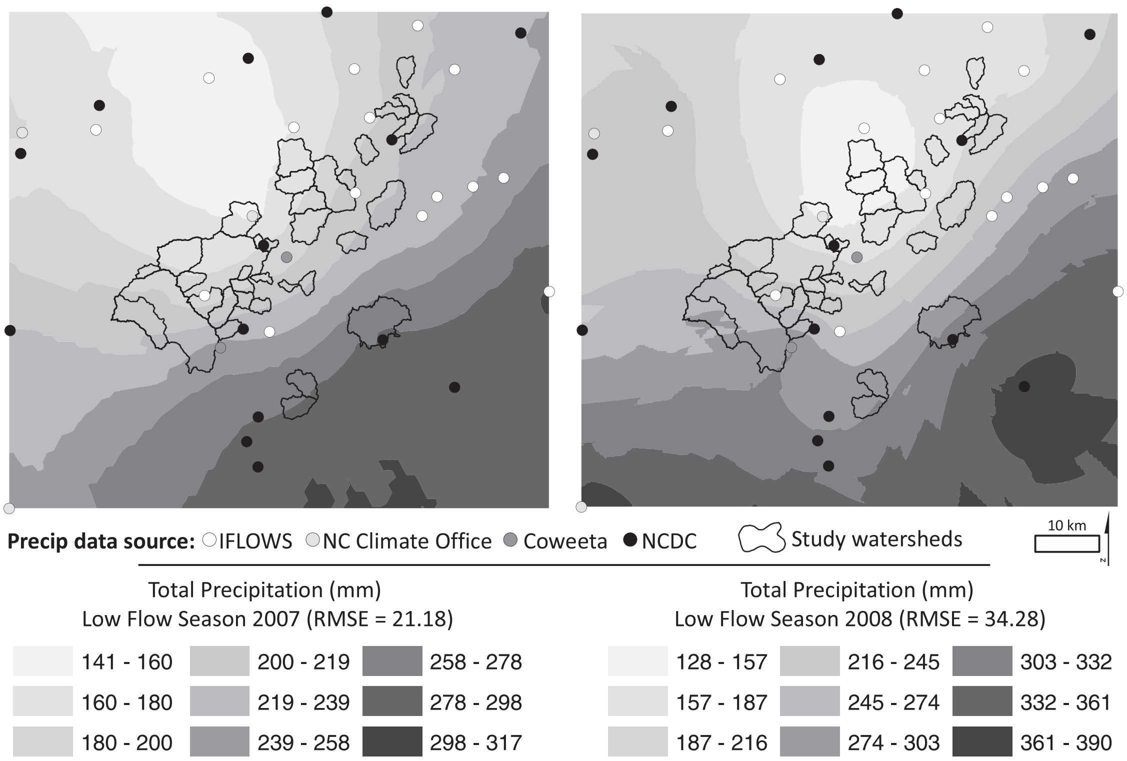

Figure 4. Precipitation interpolations (by ordinary kriging) for the two time periods evaluated in this study.

4.3. Multiple Regression Modeling of Low-Flow Metrics

[24] Watershed forest cover (forest) emerged as the key land use metric for inclusion in multiple regression. Two metrics of watershed elevation were included: median elevation and hypsometric index (Hyp1), a metric of watershed elevation distribution (Table 2). Elongation (Elong) and south facing slopes (SF; as fraction of the watershed hillslope pixels with aspect between 135° and 215°) were the sole variables included from each of the categories of basin morphometry and aspect. Within the study area, there is a very strong correlation between most land surface slope and land use (as low-slope land is more suitable for conversion to pasture or developed use than high-slope land). As a result, only the fraction of watershed area with slope lower than 2% rise (Slope<2) and slope standard deviation (SlopeSD, a metric of complexity of watershed slope and topography) were included from the suite of slope metrics originally characterized. Several channel network morphometric variables were included in the multiple regression modeling: drainage density (DD), percent of stream length that is first-order stream (%1st), and bifurcation ratio (BR), all of which express various aspects of channel distribution and potentially relate to the ability of the watershed to remove water from subsurface storage. The areal percentage of two soil parent materials (alluvium and colluvium) and the area-weighted average of the clay fraction of soil texture were selected. Correlation analyses of low flows were performed with 1 year antecedent precipitation, 6 month antecedent precipitation, and the accumulated precipitation during the study periods. Accumulated precipitation (PPT) showed a much stronger correlation to the low flows than antecedent precipitation, and PPT from LF07 and LF08 were included in the regression analyses for the corresponding time period. More detailed information for these variables is presented in Table 2.

[25] Area-adjusted low flows varied considerably across sites, spanning an order of magnitude for all metrics (Figure 5). Models were created independently for each low-flow season and for each of the three low-flow metrics, yielding a total of six models. While parameters of precipitation, geomorphology, and land use were able to be combined to create statistically significant models for all low-flow metrics, all models left significant variability unexplained. The weakest model, developed for $Q_{\min 1}$ LF08, only produced an R^2 of 0.15 ($p = 0.029$), while the strongest model, developed for Q_{99} LF07, produced an R^2 of 0.65 ($p < 0.001$).

[26] Regression modeling demonstrated a predominant influence of geomorphic parameters on stream low flows in this study area (Table 3). DD was selected in almost all of the models (five of six), and colluvium, SlopeSD, and %1st were selected in at least half of the models. The models indicate that greater DD, indicating greater fluvial dissection and connectivity of subsurface storage to the channel network, is associated with reduced low flows. The variable %1st also demonstrated a negative relationship with base flow. Colluvium, SlopeSD, BR, Slope<2, and PPT all showed a positive relationships to low flow. Elev, Elong, Hyp1, SF, alluvium, clay, and forest were not included in any of the best models. The LF07 models were generally much stronger than the LF08 models, often accounting for twice the variability. DD, SlopeSD, Colluvium, and %1st were important explanatory variables for the LF07 period. In LF08, PPT and DD were

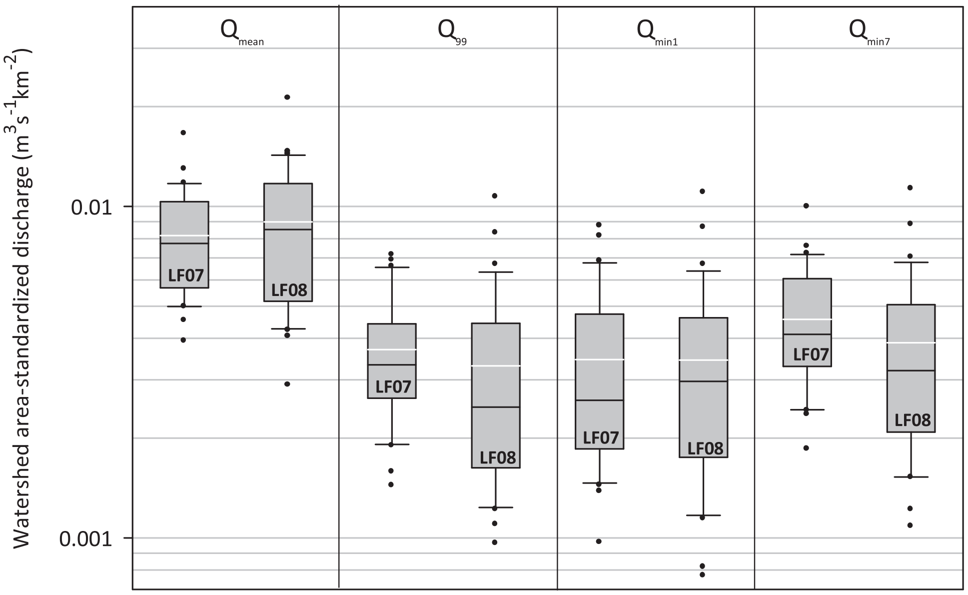

Figure 5. Variability of area-standardized flows across all sites. The upper and lower limits of the boxes represent the interquartile range, with the black line representing the median value and the white line representing the mean. Whiskers represent one standard deviation, and dots represent all outliers. Low-flow metric abbreviations are explained in the text.

the most important variables. Despite the fact that these flows were area standardized, supplemental analyses were performed in which watershed area was incorporated in order to determine whether accounting for variation in watershed area (and associated variation in transit times) improved the modeling results. Including area as a candidate variable did not change the best models for any variable

4.4. Difference of Means Tests and Watershed Pair Comparisons of Forest Cover Influence

[27] The results of the *k*-means cluster analysis established two distinct groups of watersheds on the basis of forest cover ($F = 60.20$, $p < 0.001$). The lower-forest group included 15 sites and ranged from 44.4% to 86.0% forest cover, with a center (mean) of 75%, and the higher-forest group included 20 sites and ranged from 90.1% to 99.9% forest cover, with a center of 94%. Standard *t* tests were performed to compare the mean low flow of lower- and higher-forest watersheds, with separate analyses performed for each low-flow metric (Figure 6). Results showed that the mean low flow of higher-forest watersheds was greater than that of the lower-forest watersheds across all low-flow metrics and all time periods. These differences were statistically significant for all of the flow magnitude

Table 3. Best Multiple Regression Models for Each Low-Flow Metric Selected by AICc[a]

Dependent Variable	R^2	Adjusted R^2	AIC	AICc	F (p)	Independent Variable	t (p)
				Low Flow 2007			
Q_{99}	0.65	0.56	−83.1	−76.2	7.09 (<0.001)	DD	−2.94 (0.007)
						SlopeSD	2.45 (0.022)
						Colluvium	2.12 (0.045)
						BR	1.92 (0.068)
						%1st	−1.84 (0.078)
						Slope<2	−1.79 (0.087)
Q_{min1}	0.54	0.46	−77.7	−74.0	7.24 (<0.001)	SlopeSD	2.79 (0.010)
						DD	−2.71 (0.012)
						Colluvium	2.31 (0.029)
						%1st	−2.25 (0.034)
Q_{min7}	0.54	0.47	−83.6	−80.0	7.46(<0.001)	SlopeSD	2.92 (0.007)
						DD	−2.61 (0.015)
						Colluvium	2.25 (0.021)
						%1st	−1.99 (0.057)
				Low Flow 2008			
Q_{99}	0.36	0.32	−56	−54.5	8.27 (0.001)	PPT08	3.35 (0.002)
						Slope<2	−2.35 (0.026)
Q_{min1}	0.15	0.12	−27.1	−26.3	5.27 (0.029)	DD	−2.30 (0.029)
Q_{min7}	0.36	0.29	−58.1	−55.8	5.19 (0.006)	DD	−2.64 (0.014)
						Colluvium	1.90 (0.067)
						PPT08	1.74 (0.093)

[a]AIC, Akaike information criterion; AICC, corrected Akaike information criterion.

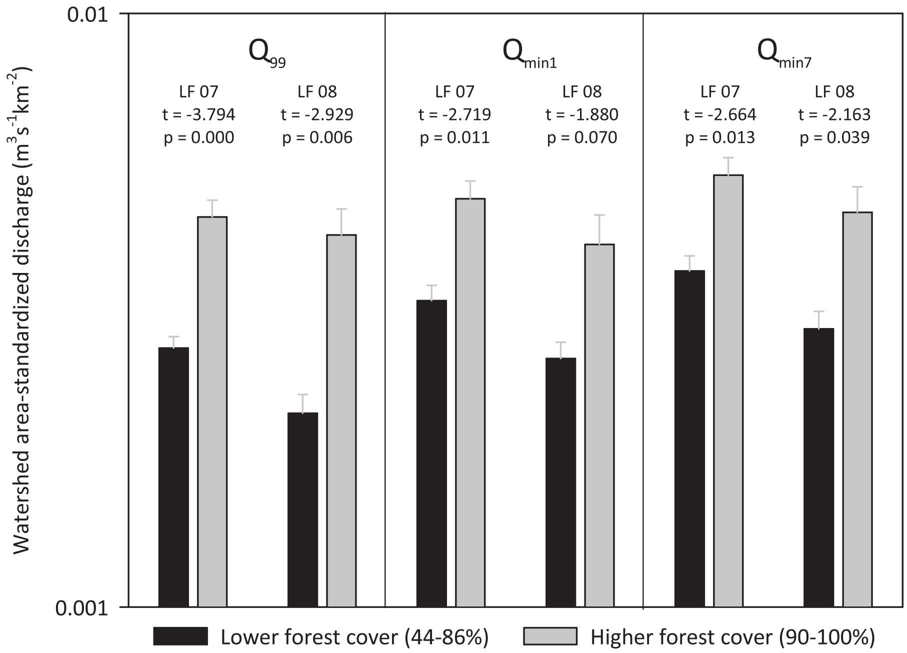

Figure 6. Difference of mean flow between lower- and higher-forest-cover watersheds. The *t* and *p* values presented reflect the results of standard *t* tests. Lower- and higher-forest-cover groups were determined using *k*-means cluster analysis. Low-flow metric and time period abbreviations are explained in the text.

metrics and time periods, except for $Q_{\min1}$ in the LF08 period.

[28] Comparison of the four pairs of topographically similar watersheds also indicated consistently higher low flow in the higher-forested pair member, among all of the flow magnitude metrics (Table 4). Values of Q_{99}, $Q_{\min1}$, and $Q_{\min7}$ range from 7% to 132% higher in the higher-forest watershed. Among the four pairs, the difference in forest cover ranged from 6% to 24%. These results indicate that greater reductions in forest cover are associated with more pronounced decreases in low flow. Simple correlation analysis indicated consistently greater low flow with higher forest cover and reduced low flow with greater nonforest land use, especially pasture (Table 5).

5. Discussion

[29] The expected results for this study were that a combination of precipitation, land use, and geomorphic variables would emerge as significant explanatory variables for stream low flows in the southern Blue Ridge Mountains. Land use was less influential in the regression modeling than expected. This study area is characterized by relatively low human impact, and the range of watershed land use among sites included in this study is relatively narrow. Overall, forest cover ranges from 44.4% to 99.9% among the sites, but only one watershed has less than 70% forest cover. Despite this relatively small range of conditions and relatively low level of watershed disturbance, forest cover demonstrated a consistently positive relationship with all low-flow metrics (Table 5), showed statistically significant positive correlations with the majority of low-flow metrics, and showed statistically significant differences between more- and less-forested watersheds. While the influence of land use is clearly present on stream low flows, the results of this study indicate the geomorphic influences in this highly variable topographic setting outweigh the influence of land use at the current levels of development.

[30] Overall, the variables that demonstrated the most consistent influence among these low-flow metrics were DD, SlopeSD, colluvium, and %1st, and these four variables were included in all of the models for the LF07 period. PPT and DD were the most important variables during the LF08 period. As one would expect, the relationships are positive between precipitation and the metrics of low-flow magnitude (Q_{99}, $Q_{\min1}$, and $Q_{\min7}$). DD, or the length of stream channel per unit watershed area, emerged as the single most important variable, and it showed a negative relationship to all low-flow metrics. It is quite logical and theoretically viable that greater fluvial dissection and, thus, greater connectivity between subsurface storage and the channel network would have a negative relationship with minimum flows [*Smakhtin*, 2001]. The results of several other studies corroborate the negative relationship between drainage density and low flow [*Gregory and Walling*, 1968; *Warner et al.*, 2003]. Greater contact area between stored water and stream channels facilitates removal of water, thus leaving less water in subsurface storage when systems are stressed during warmer and drier times of year. Additionally, the negative relationship between drainage density and low flow is at least partially due to negative correlations between subsurface characteristics and drainage density. For example, drainage density is theoretically greater in watersheds with more shallow confining layers, in which channel development occurs more readily because of a lack of subsurface storage capacity. Thus, it is possible

Table 4. Comparison of Paired Watershed Flows[a]

Flow Metric	Time Period	Site 12	Site 17	Difference of Sites 12 and 17 (%)	Site 24	Site 29	Difference of Sites 24 and 29 (%)	Site 19	Site 21	Difference of Sites 19 and 21 (%)	Site 33	Site 34	Difference of Sites 33 and 34 (%)
Mean	LF07	NA	NA	NA	NA	NA	NA	NA	NA	NA	9.22E-03	7.74E-03	+19
	LF08	1.17E-02	1.21E-02	−3	4.58E-03	5.26E-03	−13	6.44E-03	5.15E-03	+25	1.17E-02	7.38E-03	+59
Q_{99}	LF07	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.91E-03	3.31E-03	+18
	LF08	2.79E-03	2.06E-03	+36	1.79E-03	1.22E-03	+47	3.28E-03	1.41E-03	+132	4.17E-03	2.38E-03	+78
Q_{min1}	LF07	NA	NA	NA	NA	NA	NA	NA	NA	NA	4.05E-03	3.57E-03	+13
	LF08	3.07E-03	2.46E-03	+25	1.82E-03	1.45E-03	+26	3.46E-03	1.94E-03	+78	4.59E-03	2.60E-03	+76
Q_{min7}	LF07	NA	NA	NA	NA	NA	NA	NA	NA	NA	4.38E-03	3.92E-03	+12
	LF08	3.70E-03	2.61E-03	+41	0.00,213	0.001548	+38	3.63E-03	2.08E-03	+74	5.08E-03	2.96E-03	+72
Watershed forest (%)		82.3	76.3	(6.0)	98.6	86.0	(12.6)	93.4	77.9	(15.5)	99.2	75.1	(24.1)

[a]Each pair is comprised of topographically similar, proximal watersheds, whose forest cover differs. These pairs demonstrate that greater reductions in watershed forest cover are associated with greater reductions in stream base flows. All flows are expressed as watershed area-standardized discharge ($m^3 s^{-1} km^{-2}$). Differences in flow are calculated as percent of the flow of the lower-forest watershed; watershed forest cover differences (in parentheses) are simple magnitude differences.

that drainage density relates negatively to base flow during droughts not only because it facilitates removal of water in subsurface storage but also because it is a direct reflection of the subsurface storage conditions [*Luo and Stepinski*, 2008].

[31] Topographic complexity (SlopeSD) showed a consistently positive relationship to the low-flow metrics. Topographic complexity implies a variety of potential storage units and can be understood through the extreme cases of topographic uniformity. A uniformly steep watershed would favor rapid transfer of water out of the watershed, while a uniformly flat watershed may not contain sufficient subsurface storage volume to sustain high base flows. Furthermore, low-slope areas favor infiltration and increase the likelihood of down-valley movement of water through the alluvial aquifer, below and alongside the stream network itself. High topographic variability reflects the intermediate condition, in which watersheds contain a range of slopes. This variability results from a mixture of hillslope and fluvial deposits, such as colluvium and alluvium, favoring greater storage of subsurface watersheds. This is substantiated by the fact that the amount of watershed colluvium also emerged as an important explanatory variable. This corroborates recent work in Scotland, in which groundwater storage at lower slopes in mountainous headwaters (where colluvium accumulates) was shown to be a major source of base flow [*Tetzlaff and Soulsby*, 2008], as well as a recent study indicating substantial colluvial water storage in the Cascades [*Schulz et al.*, 2008].

[32] There were systematic differences in the models selected for the LF07 and LF08 time periods. The LF07 models consistently included DD, SlopeSD, colluvium, and %1st as important variables, whereas no model for LF07 low-flow magnitude contains PPT. LF08 models consistently contained PPT and DD as explanatory variables. Interestingly, LF07 consistently produced stronger multiple regression models than LF08. The most satisfactory explanation for this difference is the pronounced drought that affected the region during 2007–2008, along with a very large tropical storm that occurred during LF08. While the LF07 period is classified as "severe drought" in the region [*NCDC*, 2010], the persistence of the drought into the next summer resulted in "extreme drought" conditions and record low flows during LF08 (Figure 7). As the drought had only recently begun in August of 2007, the LF07 period is more representative of typical low-flow periods in this region than LF08, during which the systems were under greater stress from the prolonged drought. Low flows during these anomalously intense conditions likely reflect the availability of long residence time storage among the watersheds. Introducing further complexity to the LF08 time period, the remnants of a large Gulf of Mexico storm system (Tropical Storm Fay) passed directly over the study area on 28–29 August 2008, with storm totals in excess of 250 mm in parts of the study area. This storm generated overbank floods throughout the region, but precipitation totals were highly variable among the watersheds. As a result, the coefficient of variation (CV) of precipitation was nearly twice as high for the LF08 period than for LF07 (0.209 versus 0.131). Base flow is a product of both recharge quantity and groundwater flow paths, which are likely shallow and short in this crystalline terrain. Distinct

Table 5. Correlations Between Land Use and Low-Flow Metrics[a]

Low Flow Metric	Time Period	Forest R (p)	Developed R (p)	Pasture R (p)	Impervious R (p)	n
Q_{99}	LF07	0.529 (0.003)	−0.455 (0.011)	−0.496 (0.005)	−0.448 (0.013)	30
Q_{99}	LF08	0.426 (0.015)	−0.355 (0.046)	−0.472 (0.006)	−0.413 (0.019)	32
$Q_{\min 1}$	LF07	0.379 (0.039)	−0.320 (0.085)	−0.358 (0.052)	−0.308 (0.098)	30
$Q_{\min 1}$	LF08	0.237 (0.192)	−0.159 (0.385)	−0.370 (0.037)	−0.254 (0.160)	32
$Q_{\min 7}$	LF07	0.381 (0.038)	−0.323 (0.082)	−0.339 (0.067)	−0.294 (0.115)	30
$Q_{\min 7}$	LF08	0.339 (0.058)	−0.269 (0.137)	−0.413 (0.019)	−0.335 (0.061)	32

[a]All flow metrics are expressed as watershed area-standardized discharge ($m^3 s^{-1} km^{-2}$).

base flow metrics, such as recession characteristics, long-term average base flows, and extreme minimum flows, are controlled to different degrees by recharge quantity versus groundwater flow, and these distinctions explain the inconsistency in explanatory variables selected by the models for the different dependent variables.

[33] Watershed responses to the intense drought, punctuated by an intense storm event, were highly variable. For some watersheds, the late August 2008 period immediately prior to Tropical Storm Fay were no lower than LF07 minimum flows, whereas others demonstrate reductions from LF07 levels greater than an order of magnitude. While direct water withdrawals during this period of water scarcity may have introduced variability, it is also clear that some watersheds have apparently greater drought resilience, which is likely due to greater long-term storage capacity in the watersheds. The watersheds also accumulated highly variable amounts of recharge from Tropical Storm Fay and a smaller storm that occurred immediately afterward (a remnant of Hurricane Gustav). Many sites demonstrated low flows that were twice as high following the storm series. In contrast, several sites immediately receded to levels even lower than flows prior to Tropical Storm Fay (Figure 8). Spatial variability of rainfall during the storm and widely varying infiltration and retention characteristics among the watersheds explain the wide range of shallow subsurface recharge as a result of these storms. Pronounced differences in system responses to both the intense drought and the very large storm event introduced variability that is likely far greater than in a typical year, and this may partially explain the relatively weak statistical modeling results for the LF08 time period.

[34] General understanding of watershed function holds that factors of land use, climate, and geomorphology/geology are the important controls on low-flow discharge. However, the models generated from this analysis accounted for only 15%−65% of the variability among the sites, with half of the models explaining less than 50% of low-flow variability. These results are similar to other studies attempting to statistically model low flow [e.g., *Thomas and Benson*,1970; *Gustard et al.*, 1989; *Kent*, 1999; *Neff et al.*, 2005]. While there are studies presenting low-flow modeling results with very high R^2 values using geomorphic, land use, and climate parameters [e.g. *Vogel and Kroll*, 1992; *Nathan et al.*, 1996; *Zhu and Day*, 2005], these studies have modeled unstandardized low flows, using watershed area as

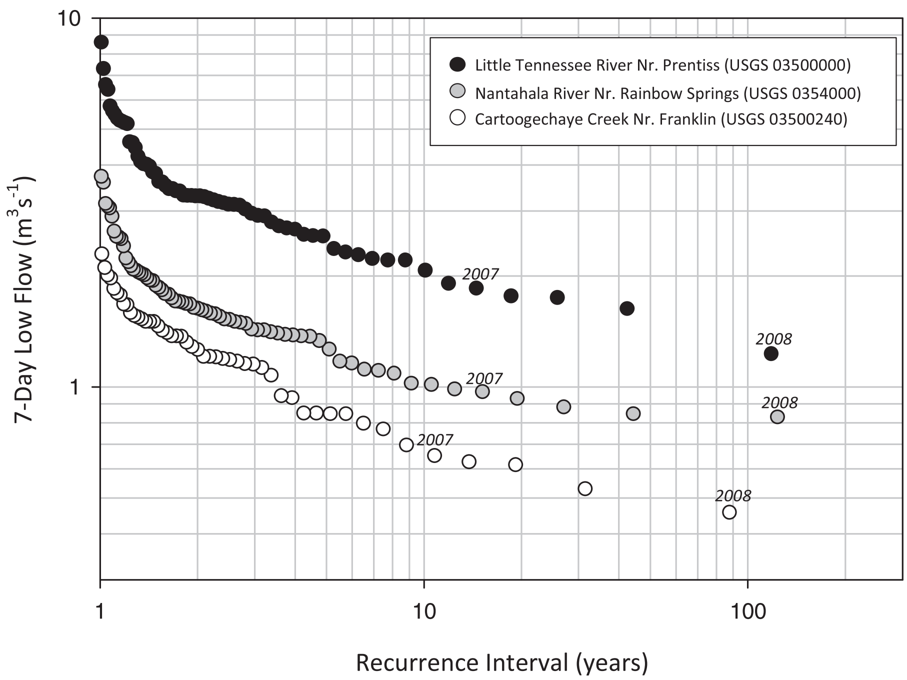

Figure 7. Seven day low-flow recurrence curves constructed from three long-term USGS gauges in the study area (Little Tennessee River near Prentiss has a 66 year record, Nantahala River near Rainbow Springs has a 69 year record, and Cartoogechaye Creek near Franklin has a 49 year record).

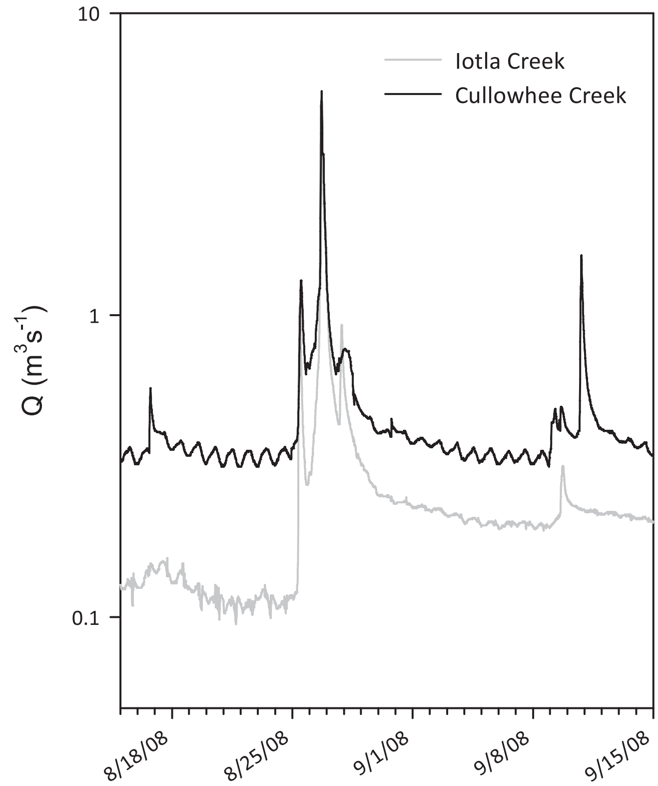

Figure 8. Example of varied recharge response to Tropical Storm Fay.

an independent variable. However, area is responsible for such a large amount of low-flow variability that area-standardized low flows were used in this study in order to allow for further insights into watershed function, which are important for sharpening our understanding of complexity and organizing principles in watershed science [*McDonnell et al.*, 2007]. For example, low-flow models with area as the sole independent variable produced R^2 values ranging from 0.948 to 0.981 for Pennsylvania streams, leaving very little variability to explore the influences of other watershed characteristics [*Zhu and Day*, 2005]. Among the watersheds in this study, multivariate models including area as an independent variable produced R^2 values ranging from 0.84 to 0.96 across all metrics of low-flow magnitudes.

[35] It was surprising that no significant relationship emerged between elevation and precipitation in this study area. The relationship between elevation and precipitation is clouded in this study area because of the importance of Gulf of Mexico and western Atlantic storm systems moving into the region from the south. While the highest elevations are in the northern part of the study area, along the Plott-Balsam Range and toward the Great Smoky Mountains National Park, the highest rainfall totals occur in association with the Blue Ridge Escarpment in the southern part of the study area [*Konrad*, 1995, 1996]. It is likely that orographic effects are evident at the scale of individual mountains during individual storm events but that this relationship does not scale up to demonstrate a regional trend because of the greater importance of the predominant south–north track of major storm events. This interpretation is supported by the findings of an analysis of topographic setting and precipitation patterns from long-term records among 44 climate stations in the southern Blue Ridge [*Konrad*, 1996]. The results of this study showed that elevation was found to correlate significantly with light precipitation events but not heavy events. Heavy events, which contribute the bulk of precipitation to the region, were best explained by (1) southern exposure and (2) distance from the Gulf of Mexico.

[36] The variability left unexplained by the multiple regression models (Table 3) can be accounted for by (1) data uncertainty, (2) inability to directly measure dynamic subsurface storage, (3) the short time period of monitoring and the lack of information on changes in storage during the study period, and (4) the inability to directly monitor water importation or withdrawal. There may be error resulting from the stage-discharge method in natural channels, and comparison of this method against discharge calculated from a trapezoidal weir demonstrated a 6.5% difference for daily flows. The spatial interpolation of point precipitation totals is notably uncertain (Figure 4). Analysis of historical land use change has shown that some areas that are currently forest were previously in agricultural use. However, even at its peak, agricultural land use did not exceed 10% of the watershed area in the Little Tennessee River basin; it was predominantly small-scale subsistence agriculture (as opposed to large-scale commercial operations), and most of this agricultural land had been abandoned by the 1930s [*Kirk*, 2009]. Given the scale of operations and the more than 70 years for soil recovery from this land use, legacy effects of past land use are of little concern [*Richter and Markewitz*, 2001]. The most important reason that these watershed characteristics fail to account for greater low-flow variability is that the independent variables themselves are only correlates to the actual hydrologic parameters of

interest. The key hydrologic variables of ET and subsurface storage are only crudely approximated by watershed characteristics. Factors of land use, aspect, and elevation relate to ET but do not directly quantify it. Factors of geomorphology relate to subsurface storage capacity, and factors of soil texture and land use relate to infiltration and recharge, but subsurface storage volumes and aquifer properties are not directly represented. It is also possible that low-flow variability is best explained by nonlinear combinations of the variables included in these analyses, which would not have been discovered in this multiple linear regression approach. Given these limitations and more, explaining 15%–65% of low-flow variability with a small set of surficial watershed characteristics seems appropriate.

6. Summary and Conclusions

[37] The streamflow from 35 watersheds ranging in size from 3 to 146 km^2 in the southern Blue Ridge of North Carolina was monitored for 1.5 years, encompassing two low-flow seasons. The watershed and channel network morphometry, soil characteristics, land use, and precipitation were characterized for the 35 watersheds and related to unit area low-flow metrics. The results of this study indicate that low flows in the southern Blue Ridge are affected most strongly by factors of geomorphology, particularly drainage density, topographic variability (as the standard deviation of watershed pixel slopes), amount of watershed colluvium, and percentage of the stream network that is first order. While apparently less influential than watershed geomorphology in this region, watershed forest cover demonstrated a consistent, positive relationship with low flow. This is especially noteworthy given the relatively low levels of development in the study area. Three low-flow metrics were considered in this study: the flow exceeded 99% of the time (Q_{99}) and the 1 and 7 day minimum flows ($Q_{\min1}$ and $Q_{\min7}$). All metrics were standardized by watershed area, which demonstrated very strong correlations to metrics of low-flow magnitude. Multiple regression modeling of various landscape factors of topography, land use, and precipitation was used to explain unit area low-flow variability during two time periods: (1) low-flow season 2007 (LF07, 5 August to 12 November) and (2) low-flow season 2008 (LF08, 1 August to 12 November). Regression models were stronger for LF07 than LF08. This is attributed to a pronounced drought that caused severe low flows that were the lowest on regional record in August 2008. Moreover, Tropical Storm Fay occurred early in the LF08 period and apparently induced considerable regional variability in recharge. Flows during LF07 are more representative of "typical" drought conditions and may better reflect watershed function.

[38] The models for all metrics and time periods left considerable variability unexplained. While the model strength is not unusually low for this type of study, the results raise questions about the sources of the remaining variability. The substantial variability left unexplained by the regression models is attributed to the fact that the variables included only *relate* to the gains and losses of water from the system, as opposed to directly quantifying them. The region is characterized by fairly low variability in land cover, which is likely the reason that forest cover failed to demonstrate a more consistent role in explaining low-flow variability in the multiple regression analyses. The results from *t* tests comparing means of lower- and higher-forest-cover watersheds, paired comparisons of topographically similar watersheds with varied forest cover, and simple correlations between land use and low-flow metrics all confirm that higher forest cover is associated with higher low flow among these watersheds. The results of this study counter the theory that forest cover reduces base flows in all circumstances and corroborate recent studies showing that the effects of soil disturbance and impervious surface additions associated with nonforest land use override the evapotranspirative losses in forests. These results also suggest that as development continues in this region, further land use change will be associated with reductions in low flow. This carries negative implications that water availability for public use and issues of environmental flows will be reduced as forest is converted to nonforest land use in this developing region, and this is of great concern because of the high number of endangered aquatic species endemic to the southern Blue Ridge [*Mayden*, 1987; *Warren et al.*, 2000; *Sutherland et al.*, 2002].

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