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Long-term Channel Geometry Adjustments for Reference Streams in the North Carolina Piedmont

Jonathan L. Page[1], Barbara A. Doll[1,2], J. Jack Kurki-Fox[1], Sara Donatich[1], Cameron Jernigan[1]

[1]Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina, USA

[2]North Carolina Sea Grant, Raleigh, North Carolina, USA

Correspondence
Barbara A. Doll
North Carolina State University
Department of Biological and Agricultural Engineering
Campus Box 7625
Raleigh, NC 27695-7625, USA
Email: bdoll@ncsu.edu

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The evaluation of reference streams can inform stream restoration designs, ecological function targets, hydraulic and sediment transport regimes, and project success criteria. Reference streams are often assumed to be in a state of quasi-equilibrium, with a hydraulic geometry representing a long-term average of a channel's form that has developed under relatively constant morphological boundary conditions. However, more rapid changes in boundary conditions, such as water or sediment discharge, bed material size, or streambank vegetation, can result in accelerated changes to channel morphology and the development of new hydraulic geometry relationships (Davidson and Hey 2011). The goal of this study was to evaluate the morphologic equilibrium of reference streams by quantifying their long-term adjustments in riffle cross-section dimensions (i.e., width, mean depth, and cross-sectional area) and discharge. Eighteen reference streams in the Piedmont of North Carolina, United States, originally assessed in 2007, were resurveyed in 2017 and 2018 (hereinafter referred to as 2018). The adjustment in riffle channel geometry was quantified and evaluated by analyzing existing boundary conditions and changes in watershed land cover and precipitation patterns. Hydraulic geometry relationships (i.e., geometry parameters and discharge versus drainage area) from 2007 and 2018 were nearly identical and no statistically significant differences were detected in bankfull discharge, cross-sectional area, width, or mean depth. Inspection of individual sites revealed bankfull cross-sectional area adjusted by 0% to 19% at most sites, however 4 urbanizing sites adjusted by more than 25%. The adjustments in discharge and area from 2007 to 2018 were significantly correlated with impervious cover, indicating channel geometry adjustments are likely the result of changes in discharge that occur as a result of changes in watershed conditions and land cover. Changes in precipitation did not appear to be drivers of adjustment, as patterns were similar during the 10.5-year period preceding each field survey in 2007 and 2018. These data were used to update the regional curve relationships, and other summary morphological data compiled can be used to help guide future stream restoration designs. The geometry adjustments and percent erosion reported for the more stable reference streams can serve as a gauge for evaluating the degree of change in channel geometry measured at both degraded and restored streams.

Keywords Quasi-equilibrium; Regional curves; Stream morphology; Stream restoration

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Study/project photographs Left: UT Varnals Creek (UTVC) (2018). Right: UT Billy's Creek (UTBC) (2018). (Photographs by Barbara Doll.)

1. Introduction

Many streams and rivers in the Southeast United States have been dammed, straightened, and leveed to develop water resources, reduce flood risk, improve drainage, increase arable land area, and generate power (Wohl 2019). They have also been impacted by land cover and upland changes in their basins, which modify the frequency, magnitude, and duration of water and sediment discharge (Carlisle et al. 2019). This can lead to sudden degradation of the stream ecosystem through erosion and deposition on reach- and basin-wide scales, and triggers channel evolution processes that eventually lead to the development of a new, quasi-equilibrium condition (Cluer and Thorne 2014; Simon 1989). Critical functions of the stream ecosystem are lost through the adjustment process (Booth and Fischenich 2015; Colosimo and Wilcock 2007; Kroes et al. 2022) and some functions eventually recover with quasi-equilibrium.

Widespread efforts over the last 20 – 30 years to reverse this ecosystem degradation have led to a multibillion-dollar stream restoration industry (Alexander and Allan 2006; BenDor et al. 2015; Bernhardt et al. 2005). During this time, the term "stream restoration" has been used to describe many different manipulations of channels and riparian areas. We define stream restoration as the return of a degraded stream system to a higher potential level of hydrologic, hydraulic, geomorphic, physicochemical, and biological function, achieved through active rehabilitation or reconstruction of a stream channel and floodplain (Fischenich 2006; Harman et al. 2012). Stream restoration should place the system on a trajectory toward long-term recovery and function. Identifying appropriate reference conditions for design and criteria for measuring success are critical components of stream restoration projects. Reference conditions provide a basis for analog, empirical, and analytical approaches to stream restoration design (Hey 2006; Hey and Thorne 1986; Julien and Wargadalam 1995; Rosgen 1997; Shields Jr et al. 2003). Ecological targets, hydraulic and sediment transport regimes, stream morphology parameters, and project success criteria can be informed by investigation of reference streams.

The Piedmont ecoregion of the Mid-Atlantic and Southeast United States has been heavily impacted by historic soil erosion and aggradation in valley bottoms caused by land clearing for agriculture, poor soil conservation practices, and mill pond construction in the years following European settlement (Merritts et al. 2011; Trimble 2008; Walter and Merritts 2008). These earlier human activities and legacy effects continue to influence the process and form of Piedmont landscapes today. Locating and verifying reference-quality streams in the North Carolina Piedmont, United States, can be challenging due to the historic aggradation of sediment in valley bottoms and by more recent channel incision that occurred as watersheds were disturbed by the conversion of forests to agricultural lands and growth of urban areas. To obtain appropriate reference conditions in the Piedmont today, streams that have evolved to quasi-equilibrium conditions in a post-European-settlement era must be evaluated and documented.

The quasi-equilibrium condition builds upon the concept of the equilibrium channel (Strahler 1957), which can transport water and sediment without excessive erosion or deposition; the size and shape of the cross-section adjust gradually over time in response to changes in water discharge (Q_w), sediment discharge (Q_s), median grain size (D_{50}), or channel slope (S_o). Reference

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streams are stable reaches (Rosgen 1998) with hydraulic geometry that represent a long-term average of a channel's form that has developed under relatively constant boundary conditions including Q_w, Q_s, bed material size, bank material characteristics, S_o, and bank vegetation (Hey and Thorne 1986). However, a change in boundary conditions can affect the Q_w or Q_s and alter the channel geometry over a period of time as the channel adjusts to a new regime condition such that it transports the sediment and water without excessive scour or deposition. This subtle channel geometry adjustment is termed "dynamic equilibrium" or "quasi-equilibrium," whereas dramatic adjustments indicate "disequilibrium" as the system responds to changes in boundary conditions (Julien 2002; Leopold 1994; Wolman and Miller 1960). Changes in boundary conditions and associated adjustments in channel morphology are frequently driven by changes in the watershed (e.g., deforestation, urbanization) (Ashmore et al. 2023; Bevan et al. 2018; Chin 2006; Hammer 1972; Papangelakis et al. 2019; Taniguchi and Biggs 2015). Other factors can alter Q_w or Q_s and affect channel morphology independently of changes in watershed conditions (e.g., changes in climate and precipitation [East and Sankey 2020]); changes in streambank vegetation; channel incision, head cutting, and associated streambank erosion (Simon and Rinaldi 2006); impoundments (Gordon and Meentemeyer 2006; Grant et al. 2003); dam removal (Neave et al. 2009); and landslides (Benda et al. 2005). The presence or absence in a watershed of predators that regulate grazing on riparian corridors has been shown to substantially affect stream channel morphology and geometry (Beschta and Ripple 2006; 2008; 2012).

Highlight

Reference stream channel cross-sectional area adjusted by 0% to 17% in watersheds with relatively stable watershed conditions, while stream channel geometry for developed or rapidly developing watersheds (changing boundary conditions) adjusted by 19% to 39% over the same 10.5-year period.

The goals of this study were (1) to quantify the magnitude of adjustment for streams that were previously identified as reference condition in the North Carolina Piedmont; (2) to evaluate the influence of boundary conditions (Q_w and Q_s) on the morphological form and rate of channel adjustment on these reference-quality streams; (3) to verify quasi-equilibrium conditions; and (4) to update existing regional curve relationships for the ecoregion. We tested our hypothesis that existing boundary conditions and changes in watershed land cover and precipitation would influence the rate of adjustment in channel geometry. Temporal variation in watershed land use and precipitation were used as proxies for changes in Q_w and Q_s.

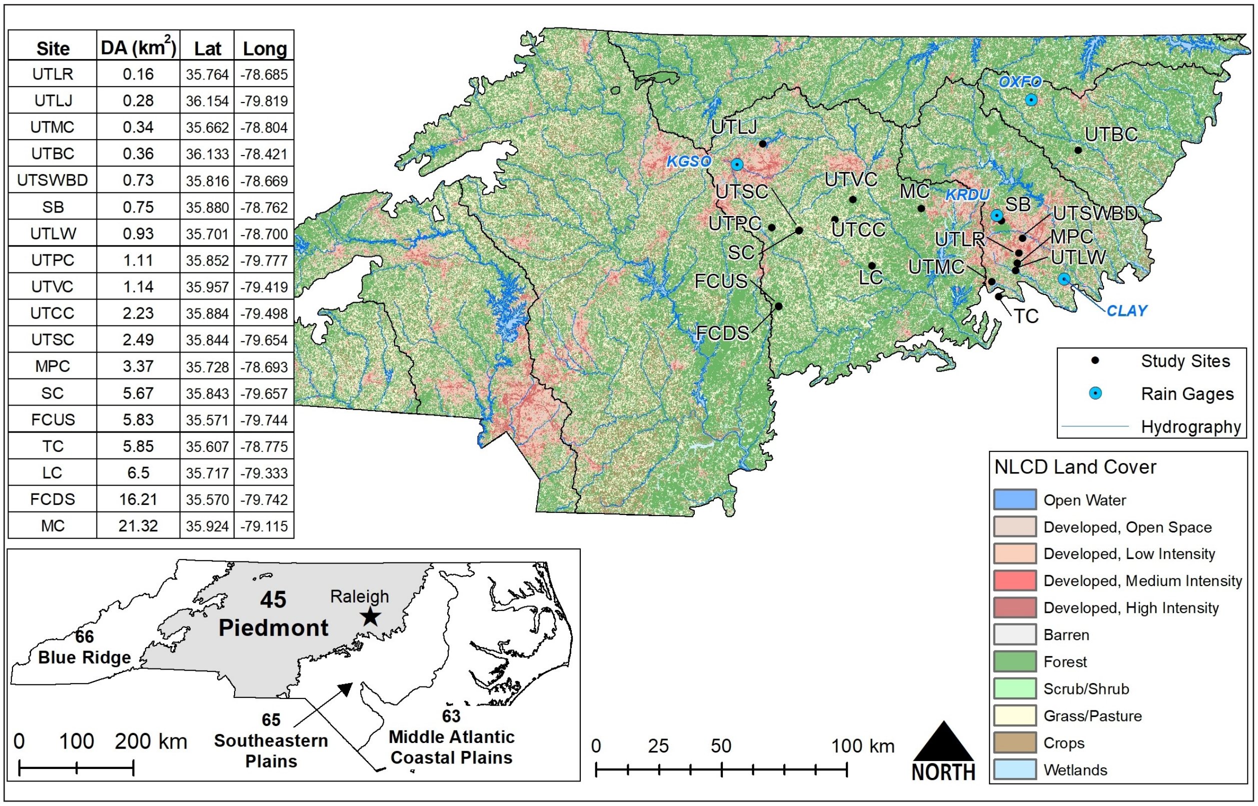
2. Materials and Methods

2.1 Study Stream Sites

Eighteen non-randomly selected streams that were previously identified as reference streams and surveyed by Lowther (2008) in the summer of 2007 were used for this study (Fig. 1). Selection criteria identified by Lowther (2008) included physical access, minimal streambank erosion, presence of an established woody riparian buffer, diverse bedforms (e.g., riffle, pool), and a well-connected floodplain (i.e., little to no incision). Reference conditions were not validated in 2018, but changes in channel geometry and presence of streambank erosion were quantified. The streams are in the EPA Level III – 45 Piedmont ecoregion and located within the central and eastern Piedmont of North Carolina. All but one site were recorded by the North Carolina Division of Mitigation Services (NC DMS) as reference streams and previously used by restoration practitioners for analog restoration design, in which geometry measures from the reference channel were scaled and applied to a design stream (Hey 2006). Drainage Areas (DA) ranged in size from 0.16 km^2 to 21.32 km^2 and stream order ranged from one to 3 using the high resolution National Hydrography Dataset (Moore et al. 2019). All streams were characterized as perennial systems except for UTLR, which was intermittent.

2.2 Precipitation

Hourly rainfall data were obtained from the North Carolina State Climate Office (NCSCO) for 4 weather stations with precipitation records to January 1, 1997, or earlier: Central Crops Research Station – Clayton (CLAY), Piedmont Triad International Airport – Greensboro (KGSO), Raleigh-Durham International Airport (KRDU), and Oxford Tobacco Research Station (OXFO). The hourly rainfall data were parsed into individual events using a 6-hour antecedent dry period (Driscoll et al. 1989) and a minimum precipitation total of 2.5 cm, as this was used as a threshold for storms likely to generate geomorphically significant instream flows. The Mann-Kendall test was used to test for statistically significant increasing or decreasing trends in the event-based precipitation patterns.



Site	DA (km^2)	Lat	Long
UTLR	0.16	35.764	-78.685
UTLJ	0.28	36.154	-79.819
UTMC	0.34	35.662	-78.804
UTBC	0.36	36.133	-78.421
UTSWBD	0.73	35.816	-78.669
SB	0.75	35.880	-78.762
UTLW	0.93	35.701	-78.700
UTPC	1.11	35.852	-79.777
UTVC	1.14	35.957	-79.419
UTCC	2.23	35.884	-79.498
UTSC	2.49	35.844	-79.654
MPC	3.37	35.728	-78.693
SC	5.67	35.843	-79.657
FCUS	5.83	35.571	-79.744
TC	5.85	35.607	-78.775
LC	6.5	35.717	-79.333
FCDS	16.21	35.570	-79.742
MC	21.32	35.924	-79.115

Fig. 1 Study sites within the Piedmont – EPA Level III Ecoregion 45 (US EPA 2018). Land cover data is from the National Land Cover Database (MRLC 2019) and hydrography is from the North Carolina Major Hydrography Layer (NC CGIA 2021).

2.3 Watershed and Land Cover Conditions

Watershed and land cover conditions were documented using Curve Number (CN), Impervious Cover (IC), Change in Impervious Cover (ΔIC), and Developed Cover (DC). National Land Cover Datasets (NLCD) for 2006 and 2016 (MRLC 2019) were obtained and processed to determine IC and DC for the study watersheds using ArcMap 10.7.1 (ESRI 2018). IC represents urban impervious surfaces as a percentage of developed surface, and DC included all areas classified as either developed open space or low-, medium-, or high-density developed. The NLCD datasets were then overlaid with the Soil Survey Geographic Database (SSURGO) containing Hydrologic Soil Group (HSG) data (NRCS-USDA 2018) to calculate CN. CN, IC, and DC values from 2006 and 2016 were then paired with the field-collected data from 2007 and 2018, respectively.

2.4 Field Data Collection Methods

A robotic total station (Topcon, Tokyo, Japan) was used to survey the channel cross sections and longitudinal profiles previously surveyed by Lowther (2008). Surveyed reach lengths ranged from 100 m to 350 m. Because the original survey pins could not be located, a map of the site prepared by Lowther (2008) was used to identify the same riffle cross section that was previously surveyed. The survey data was processed in AutoCAD Civil3D (Autodesk 2018) and RIVERMorph 5.2.0 software (RIVERMorph 2019). The longitudinal surveys were used to calculate channel water surface slope (S_{wse}). For each riffle cross section, bankfull area (A_{bkf}), bankfull width (W_{bkf}), bankfull mean depth (D_{bkf}), width to depth ratio (WD), entrenchment ratio (ER) and bank height ratio (BHR) were calculated following guidelines reported by Doll et al. (2003). Bankfull discharge (Q_{bkf}) and velocity (V_{bkf}) were calculated using Manning's equation (Chow 1959). Manning's roughness was estimated using methods developed by the US Geological Survey for natural channels and floodplains (Arcement and Schneider 1989). The median grain size (D_{50}) was determined from a modified Wolman pebble count (Rosgen 1996; Wolman 1954). The critical shear stress (τ_c) (Leopold 1994) and the dimensionless critical shear stress (τ_c*) (Shields 1936) were calculated for each stream using the hydraulic radius (R_h) for the A_{bkf}, S_{wse}, and D_{50}. The percent of streambank erosion (Erosion) was quantified by calculating the ratio of the length of bank with the presence of erosion to the total bank length

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of the study reach. A streambank was classified as eroding if the vegetation and/or roots were sparse or absent and the bank showed visible signs of scour, unstable undercutting, or mass wasting.

The net (Δ) adjustments in riffle channel geometry (A_{bkf}, W_{bkf}, and D_{bkf}) and discharge (Q_{bkf}) were calculated following the example equation 1 for A_{bkf}:

$$\Delta A_{bkf} = \frac{A_{bkf}^{2018} - A_{bkf}^{2007}}{A_{bkf}^{2007}} \times 100\% \qquad (1)$$

2.5 Hydraulic Geometry Regression Curves

Bankfull channel geometry measures and discharge (A_{bkf}, W_{bkf}, D_{bkf}, Q_{bkf}) were plotted against DA on a log-log scale and regression lines were fit for each survey period (see Section 2.6, Statistical Methods). In addition, the data collected during the 2018 survey were combined with the rural reference sites from Doll et al. (2002) to update the regional hydraulic geometry relationships for the North Carolina Piedmont.

2.6 Statistical Methods

All statistical analyses were conducted using R (R Core Team 2018) and the statistical significance level, α, was set at 0.05 unless otherwise noted. For all linear regression analysis, the data were assumed to be independent and that the residuals follow a normal distribution. Analysis of Variance (ANOVA) with Type III sum of squares was used to test for significance of linear regressions. Analysis of Covariance (ANCOVA) was used to evaluate if there were statistical differences in the hydraulic geometry relationships (A_{bkf}, W_{bkf}, D_{bkf}, and Q_{bkf} versus DA) between the 2007 and 2018 surveys (i.e., differences in the slopes of the regression lines) following methods described in Doll et al. (2002). If there were no differences in slopes, a pooled slope was assumed and different intercepts were calculated. If the slopes were statistically different, each curve was allowed to have different slopes and intercepts (Doll et al. 2002).

Correlation matrices were produced to compare each riffle channel geometry parameter (Q_{bkf}, A_{bkf}, W_{bkf}, and D_{bkf}) with potential explanatory variables including CN, IC, ΔIC, WD, ER, BHR, S_{wse}, τ_c*, D_{50}, and Erosion. Velocity and τ_c were dropped from the analyses because they were highly correlated with S_{wse}. Due to the small sample size, lack of sediment supply data, and noise created by using the net channel geometry adjustments, the absolute value of the observed channel geometry adjustment ($|\Delta\ Q_{bkf}|$, $|\Delta\ A_{bkf}|$, $|\Delta\ W_{bkf}|$, $|\Delta\ D_{bkf}|$) was used as the response variable to construct the final correlation matrices; the goal was to evaluate the overall degree of change, as large change, whether negative or positive, can indicate instability.

Cluster analysis was conducted on absolute adjustment in A_{bkf}, CN, IC, DC, WD, ER, S_{wse}, D_{50}, τ_c*, and Erosion. The “k-means” clustering approach, with the Hartigan-Wong algorithm and scaled Euclidean distance calculations, was used with 2, 3, 4, and 5 centroids (K). The “Elbow Method” was used to determine the optimal number of clusters for analysis. The cluster analysis results were used to separate the sites into groups and the groups were evaluated to consider quasi-equilibrium and disequilibrium conditions.

3. Results

3.1 Watershed and Land Cover Conditions

Watershed and land cover conditions were fairly static from 2007 to 2018 relative to the mean and median of the dataset (Table 1). Median CN, IC, and DC changed by 1% or less. However, there were several sites that did experience larger changes in IC including UTMC (10.3% to 15.4%), UTSWBD (9.6% to 11.6%), MPC (5.2% to 6.5%), and TC (16.9% to 19.6%). DC in the UTMC, MC, and TC watersheds also increased

Table 1 Summary of watershed and land cover conditions of study sites

	Curve Number (CN)				Impervious Cover (IC)				Developed Cover (DC)			
	2006	2016	Δ CN	Δ %	2006	2016	Δ IC	Δ %	2006	2016	Δ DC	Δ %
Mean	65.4	65.7	0.2	0.4%	4.3%	4.9%	0.6%	6.9%	23.2%	24.5%	1.3%	3.8%
Median	65.6	65.6	0.1	0.1%	0.6%	0.6%	0.0%	1.0%	5.7%	5.9%	0.0%	0.0%
Min	51.9	51.8	-0.1	0.2%	0.1%	0.1%	0.0%	0.0%	1.0%	1.0%	0.0%	-0.4%
Max	77.2	77.8	1.5	1.9%	16.9%	19.6%	5.1%	50.1%	98.0%	98.0%	14.4%	34.9%

Note: The surveys were conducted in 2007 and 2018. The NLCD land cover data used for the analysis were from 2006 and 2016, the datasets closest to the survey periods.

by 34.9%, 11.5%, and 12.5%, respectively. (Watershed changes are depicted in Fig. S.1 Supplementary Material.) UTMC, UTSWBD, MPC, and TC are all located within Wake County, North Carolina, United States, which has experienced dramatic population growth and subsequent increases in development and road construction since 2000. Very small or negative changes (e.g., -0.4%, 0.2%) likely indicate uncertainty in the land cover spatial datasets.

3.2 Precipitation

Precipitation data from the CLAY, KGSO, KRDU, and OXFO stations indicate similar climate conditions for the 10.5 years prior to the 2007 survey (January 1, 1997 to June 30, 2007) and the 10.5 years following the 2007 survey (June 30, 2007 to January 1, 2018). The full dataset from 1997 to 2017 includes multiple tropical systems that impacted the study watersheds (Hurricane Floyd – 1999, Tropical Storm Alberto – 2006, Tropical Storm Hanna – 2008, Tropical Storm Fay – 2008, Hurricane Matthew – 2016) and drought conditions that persisted from 2007 to 2008. No statistically significant trends (increasing or decreasing) were detected in the dataset based on Mann-Kendall trend analyses, and the mean annual events were within +/-2.5 mm for each station (Table 2, Fig. S.2 Supplementary Material).

Exceedance probability plots were also created for each station and survey period. Precipitation of 2.5 cm was used as the threshold event to compare exceedance probabilities and number of events likely generating geomorphically significant instream flows (Table S.1 Supplementary Material). Exceedance probabilities increased very slightly from the 2007 to 2018 survey period at the CLAY, KGSO, and OXFO stations. There was a minor increase in the number of events >2.5 cm, with the greatest increase at OXFO (109 to 148). Overall, climate conditions based on precipitation analyses were relatively similar for the 2007 and 2018 survey periods.

3.3 Stream Channel Geometry Adjustments

Only 6 study sites adjusted by less than 20% for all 4 channel parameters: Q_{bkf}, A_{bkf}, W_{bkf}, and D_{bkf}. Adjustments in Q_{bkf} were greatest, with half the sites exhibiting changes from 20% up to 65% (Table 3). Q_{bkf} adjustments likely were greatest as Q_{bkf} responds to changes in both channel area (A_{bkf}) and channel shape (i.e., changes to wetted perimeter in R_h). Despite fairly large adjustments in W_{bkf} and D_{bkf}, only 5 streams exhibited changes in A_{bkf} of 19% or more, including UTLJ, UTMC, UTSWBD, MPC, and TC. Of the remaining 13 sites where A_{bkf} changed by 17% or less, a decrease in A_{bkf} was observed at 7 sites while an increase or no change in A_{bkf} was observed at 6 sites. For the 5 sites where A_{bkf} adjusted by more than 17% (19% – 39%), all were characterized by channel incision and 4 were characterized by widening.

3.4 Variable Correlation

$|\Delta Q_{bkf}|$ and $|\Delta A_{bkf}|$ were both significantly correlated with IC and ΔIC (Fig. 2). This strong positive correlation indicates that as existing IC and ΔIC cover increases, the observed adjustments in channel geometry also increase. $|\Delta W_{bkf}|$ was not correlated with IC or ΔIC, however it was positively and significantly correlated with BHR. This means that as BHR increases (i.e., the stream becomes more incised and less connected to its floodplain), ΔW_{bkf} also tends to increase. $|\Delta D_{bkf}|$ was significantly correlated with ΔIC. This analysis links watershed and land cover conditions, specifically IC, to observed adjustments Q_{bkf} and A_{bkf}. Observed adjustments in W_{bkf} were linked to channel incision and

Table 2 Precipitation summary for CLAY, KGSO, KRDU, and OXFO

Station	Survey	Mean Annual Event (mm)			Max Annual Event (mm)			Total Annual Precipitation (mm)			Mann-Kendall Test	
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	t	p
CLAY	2007	14.0	16.3	21.6	48.0	82.0	182.9	624.8	939.8	1237.0	0.006	0.72
	2018	13.2	17.3	22.9	44.5	111.8	181.4	505.5	1173.5	1983.7		
KGSO	2007	12.4	16.0	18.8	41.1	78.0	134.6	810.3	993.1	1493.5	0.004	0.81
	2018	11.2	16.8	19.1	43.2	99.6	149.6	810.3	1010.9	1237.0		
KRDU	2007	14.0	17.8	26.2	50.3	101.3	189.2	848.4	1071.9	1300.5	0.019	0.30
	2018	13.2	17.3	20.6	56.6	110.5	189.2	919.5	1135.4	1346.2		
OXFO	2007	12.4	15.5	19.8	51.1	73.4	113.5	622.3	896.6	1318.3	0.027	0.15
	2018	15.5	17.8	20.1	68.1	113.0	163.3	944.9	1219.2	1562.1		

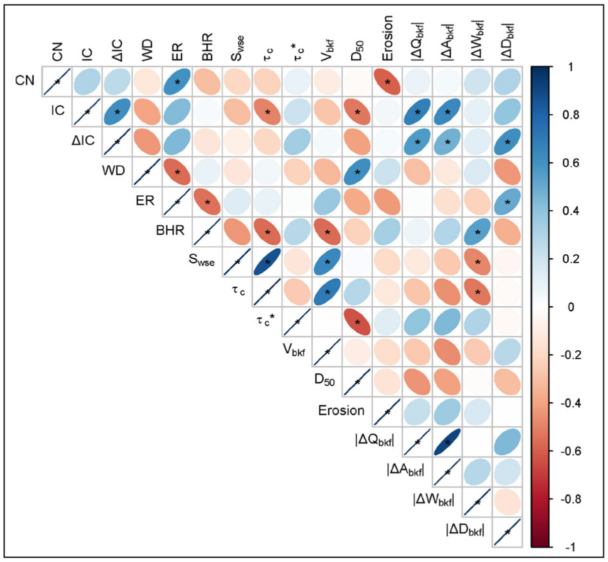

Fig. 2 Correlation matrices for $|\Delta Q_{bkf}|$, $|\Delta A_{bkf}|$, $|\Delta W_{bkf}|$, and $|\Delta D_{bkf}|$. * indicates the correlation is significant (Pearson Correlation, α = 0.05).

floodplain connection. Hydraulic factors like S_{wse} and τ_c were significantly correlated only with $|\Delta W_{bkf}|$.

Cluster analysis was conducted to further evaluate the findings and linkages observed in the correlation matrices where IC and ΔIC were identified as key explanatory variables for ΔA_{bkf}. The purpose of this cluster analysis was to identify characteristics of quasi-equilibrium streams and compare them to streams experiencing disequilibrium. Using K-means, the optimal number of clusters was K = 2, which is not uncommon for a dataset with a small sample size (Wossink and Hunt 2003) (Fig. 3). There were 13 sites in Cluster 1 and 5 sites in Cluster 2. The clusters are summarized with watershed, hydraulic and adjustment factors in Table 4.

Table 3 Summary of the net changes in channel geometry from channel cross-section surveys conducted in 2007 and 2018 for 18 reference streams in the North Carolina Piedmont

Stream	ΔQ_{bkf}	ΔA_{bkf}	ΔW_{bkf}	ΔD_{bkf}
UTLR	-17%	-9%	1%	-10%
UTLJ	44%	35%	29%	5%
UTMC	36%	19%	-17%	41%
UTBC	15%	8%	-10%	22%
UTSWBD	65%	39%	5%	31%
SB	3%	1%	-10%	11%
UTLW	-21%	-14%	1%	-14%
UTPC	-23%	-17%	-12%	-6%
UTVC	-8%	-4%	-1%	-5%
UTCC	-25%	-14%	8%	-19%
UTSC	6%	14%	31%	-13%
MPC	37%	31%	26%	3%
SC	-17%	-13%	-5%	-8%
FCUS	27%	12%	-10%	23%
TC	40%	26%	3%	21%
LC	-5%	0%	14%	-12%
FCDS	-11%	-11%	-10%	-2%
MC	6%	11%	23%	-11%

3.5 Regression Equations and Regional Hydraulic Geometry Relationships

Linear regression and ANCOVA were used to evaluate changes in the hydraulic geometry regional curve relationships developed from the 2007 and 2018 surveys (Fig. 4 and Table 5). There were no statistically significant differences in the slopes or intercepts of the regression lines (Table 5). The linear relationships for the 2 surveys were nearly identical as evidenced by the 2 regression lines overlapping in Figure 4. This comparison suggests there were not statistically significant or substantial changes in hydraulic geometry relationships from the 2007 to 2018 survey, however examination of individual sites in a tabulated format does reveal some level of change for all sites, with multiple sites experiencing particularly large adjustments. Twelve of the quasi-equilibrium Cluster 1 study sites were used to revise the North Carolina Piedmont Regional Curve described by Doll et al. (2002). Site SB was not included in the revised regional curve because it was also part of the Doll et al. (2002) dataset. Revised curves are shown in Figure 4 (equations are provided in Table 6; revised curves in English units are shown in Fig. S.3 Supplementary Material). Statistically significant linear relationships existed for all the existing and revised regional curves with high R^2 values (>0.85).

4. Discussion

4.1 Stream Channel Geometry Adjustments

Cluster analysis revealed 2 distinct clusters of streams. Cluster 2 streams (n=5) may be in a state of disequilibrium, as it appears that their channel geometry is responding to changes in boundary conditions. In contrast, Cluster 1 streams (n=13) are more likely in a quasi-equilibrium condition, as they exhibit more constant boundary conditions and relatively less change in channel geometry. On average, IC in the Cluster 2 watersheds was 14% and increased by 22% from 2006 to 2016, which is considerably greater than Cluster 1 watersheds, where mean IC was 1% and changed by only 1%. Mean $|\Delta A_{bkf}|$ for Cluster 2 was 30% compared to 10% for Cluster 1 streams. Cluster 2 watersheds generally had more disturbance due to IC and increases in IC than Cluster 1 watersheds, which resulted in greater impacts to ΔA_{bkf}. Therefore,

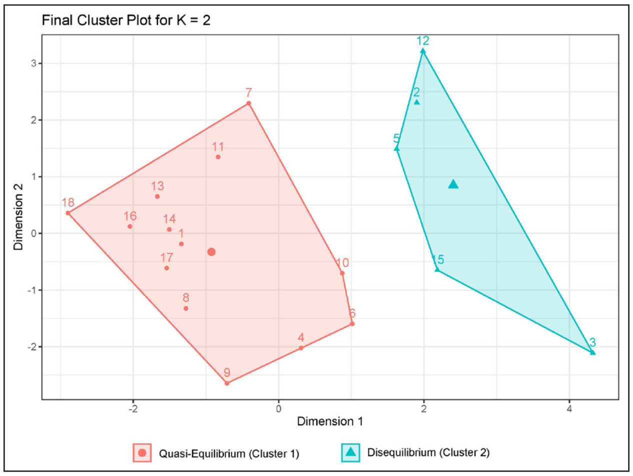

Fig. 3 Cluster Analysis using $|\Delta A_{bkf}|$.

both existing and changing watershed conditions likely have a strong influence on channel adjustment magnitudes and rates.

All 5 sites in Cluster 2 experienced increases in channel size, suggesting degradation and erosional processes led to disequilibrium within these systems as they responded to land cover changes in their watersheds. Increases in IC were found to significantly increase stream riffle cross-sectional areas when comparing bankfull hydraulic geometry of urban streams to that of streams in rural watersheds (Hammer 1972; Doll et al. 2002; Hawley et al. 2013; O'Driscoll et al. 2009; Taniguchi and Biggs 2015). Increased IC typically leads to an increase of water discharged to a stream, which results in a new boundary condition for Q_w. IC can also impact Q_s by decreasing upland sources of sediment supply but potentially increasing stream channel and bank derived sediment supply. ΔW_{bkf} was significantly correlated with increasing BHR, which follows Simon and Rinaldi's (2006) channel evolution model of degradation and widening in response to disturbance. Despite fairly substantial (>20%) measured adjustments in W_{bkf} for several of the channels included in this study, the

Table 4 Tabulated summary of cluster analysis variables

	Site	ID	DA (km^2)	CN	IC	Δ IC	S_{WSE} (m/m)	τ_c*	D_{50} (mm)	WD	ER	BHR	% Eros.	$\lvert \Delta A_{bkf} \rvert$
Cluster 1 Streams	1	UTLR	0.16	53	1%	3%	0.0230	0.26	14	12.4	2.9	1.17	12%	9%
	4	UTBC	0.36	67	1%	0%	0.0140	0.22	14	5.5	11.7	1.00	3%	8%
	6	SB	0.75	66	9%	2%	0.0080	0.29	7	6.4	14.6	1.00	11%	1%
	7	UTLW	0.93	52	4%	2%	0.0076	0.25	7	7.7	2.1	1.63	36%	14%
	8	UTPC	1.11	70	1%	0%	0.0138	0.03	68	9.8	3.4	1.00	6%	17%
	9	UTVC	1.14	72	0%	0%	0.0180	0.1	39	11.4	13	1.00	4%	4%
	10	UTCC	2.23	77	1%	0%	0.0080	1.03	2	12.1	7.7	1.00	7%	14%
	11	UTSC	2.49	66	0%	0%	0.0050	0.06	19	12.3	3.9	1.87	24%	14%
	13	SC	5.67	64	0%	0%	0.0060	0.04	39	15.7	1.7	1.65	9%	13%
	14	FCUS	5.83	63	0%	0%	0.0050	0.03	55	10.7	1.9	1.42	7%	12%
	16	LC	6.50	63	1%	0%	0.0092	0.05	55	13.7	3.4	1.60	17%	0%
	17	FCDS	16.21	63	1%	4%	0.0082	0.05	55	12.5	2.1	1.00	6%	11%
	18	MC	21.32	66	0%	0%	0.0070	0.03	77	21.9	2	1.00	26%	11%
Cluster 2 Streams	2	UTLJ	0.28	70	17%	2%	0.0050	0.63	1	10.3	2.26	2.16	11%	35%
	3	UTMC	0.34	78	15%	50%	0.0090	0.43	4	4.1	16.8	1.00	3%	19%
	5	UTSWBD	0.73	61	12%	20%	0.0130	0.31	10	9.6	5.5	1.00	35%	39%
	12	MPC	3.37	60	6%	24%	0.0060	1.40	1	10.4	2.58	1.86	26%	31%
	15	TC	5.85	72	20%	16%	0.0037	0.04	19	11.6	12.8	1.00	11%	26%
Summary							**Cluster 1 Summary**							
	Minimum		0.16	52	0%	0%	0.0050	0.03	2	5.5	1.7	1.00	3%	0%
	Mean		4.98	65	1%	1%	0.0102	0.19	35	11.7	5.4	1.26	13%	10%
	Maximum		21.3	77	9%	4%	0.0230	1.03	77	21.9	14.6	1.87	36%	17%
							Cluster 2 Summary							
	Minimum		0.28	60	5%	2%	0.0037	0.04	1	4.1	2.3	1.00	3%	19%
	Mean		2.11	68	14%	22%	0.0073	0.54	7	9.2	8.0	1.40	17%	30%
	Maximum		5.85	78	20%	50%	0.0130	1.40	19	11.6	16.8	2.16	35%	39%

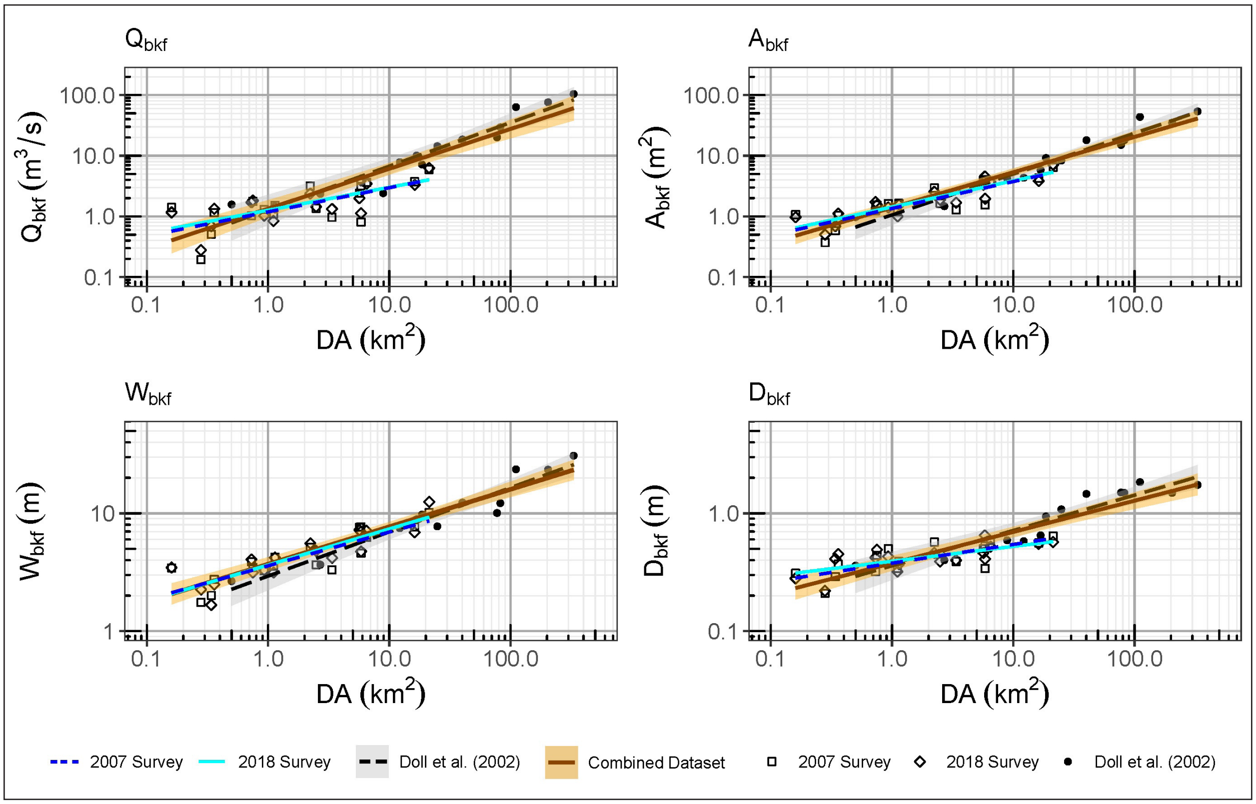

Fig. 4 Comparisons of hydraulic channel geometry for 2007 and 2018 surveys of 18 study streams and rural regional curve relationships from Doll et al. (2002) and the combined dataset (adding 12 new quasi-equilibrium channels). The shaded areas represent 95% confidence bounds.

changes are relatively small when compared to width variation measured between forested and non-forested stream channels (Allmendinger et al. 2005; Hession et al. 2003; Hey and Thorne 1986; Jackson et al. 2015). All streams included in this study had a woody riparian buffer. The adjustments in A_{bkf} for the Cluster 2 streams are also relatively small when compared to the A_{bkf} enlargement observed for developed versus rural streams in the Piedmont region (Doll et al. 2002). These streams may continue adjusting to these relatively recent changes in IC, as channel evolution processes could take place over decades or longer. In contrast, Faustini et al. (2009) recorded negligible differences in W_{bkf} between the least and most disturbed streams in the Southern Appalachians region of the United States.

Using the adjustment ranges for these 2 separate clusters of streams may be useful for comparing measured adjustments for restored streams in order to provide insight regarding quasi-equilibrium conditions, where projects with riffle cross-sectional area adjustments less than 20% could potentially be in an equilibrium condition and streams with larger adjustments likely are not. For example, Miller and Kochel (2010) evaluated dimensional adjustment at 26 reconfigured channels in the Piedmont and mountains of North Carolina. A_{bkf} changed by 20% or more at 60% of the sites and by greater than 35% at several of the sites. Large adjustments were associated with high sediment transport capacity, large sediment supply and/or easily eroded bank materials. Excess shear stress tended to increase the magnitude of adjustment whether or not the channel enlarged or contracted. Hydraulic factors like S_{wse} and τ_c were also significantly correlated with changes in W_{bkf} for our reference streams. Based on the findings of this study, the projects Miller and Kochel (2010) studied that experienced larger adjustments (>20%) likely were subjected to changing boundary conditions (e.g., Q_w, Q_s), which stream restoration projects typically do not address. Kondolf et al. (2001) and Nagle (2007) have also equated large post-restoration adjustments to instability.

4.2 Regional Hydraulic Geometry Relationships

The North Carolina Piedmont rural regional curve (Doll et al. 2002) was updated using 12 of the quasi-equilibrium Cluster 1 study sites. The dataset from Doll et al. (2002) contained only one site with DA <2.6 km^2,

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Table 5 Summary of statistical comparison between 2007 and 2018 hydraulic geometry curves

Parameter	Dataset	Equation	R^2	ANCOVA	
				Slope p-value	Intercept p-value
Q_{bkf}	2007 Survey	$Q_{bkf} = 1.185\ DA^{0.398}$	0.68	0.88	0.75
	2018 Survey	$Q_{bkf} = 1.262\ DA^{0.378}$	0.70		
A_{bkf}	2007 Survey	$A_{bkf} = 1.351\ DA^{0.443}$	0.81	0.90	0.67
	2018 Survey	$A_{bkf} = 1.427\ DA^{0.432}$	0.82		
W_{bkf}	2007 Survey	$W_{bkf} = 3.583\ DA^{0.287}$	0.80	0.75	0.86
	2018 Survey	$W_{bkf} = 3.640\ DA^{0.306}$	0.80		
D_{bkf}	2007 Survey	$D_{bkf} = 0.378\ DA^{0.158}$	0.60	0.50	0.61
	2018 Survey	$D_{bkf} = 0.392\ DA^{0.126}$	0.50		

which likely is because USGS-gauged sites were the focus of the study and data collection. In addition, the number of sites used to fit the regression relationships was nearly doubled (13 to 25). While the revised regression relationships mostly fall within the range of uncertainty (i.e., confidence intervals) (Fig. 4), the increase intercept values indicate that the Doll et al. (2002) curve likely underpredicted Q_{bkf}, A_{bkf}, W_{bkf}, and D_{bkf} for streams with DA <2.6 km^2 (see regression equations in Table 6). For example, predicted A_{bkf} and W_{bkf} using Doll et al. (2002) with DA = 1.3 km^2 was 1.28 m^2 and 3.45 m compared to the combined dataset, where predicted A_{bkf} and W_{bkf} were 1.63 m^2 and 4.02 m, respectively. These updated reference channel dimensions for smaller watersheds are important to practitioners for future restoration efforts because a review of NC DMS project documents indicated that approximately 60% of the streams restored for compensatory mitigation in the Piedmont of North Carolina have DAs <2.6 km^2 (Doll and Kurki-Fox 2022).

The largest channel geometry adjustments were observed in the watersheds with the most existing development and largest increases in IC over the monitoring period. This finding supports previous work indicating substantial enlargement in channels with urbanized watersheds (Doll et al. 2002; Hammer 1972; Hawley et al. 2013; O'Driscoll et al. 2009; Taniguchi and Biggs 2015). While Booth and Henshaw (2001) confirmed that urbanization does affect channel change, there are other factors that influence the rate of change. Regional curves are useful empirical tools for determining departure from reference conditions or the degree of degradation that has occurred at a site for a given hydrophysiographic region. These relationships can also be referenced when selecting channel dimensions for stream restoration designs but should never be used as the primary method. Channel designs should incorporate empirical, analytical, and process-based methodologies to iterate toward the optimal channel design size and configuration.

Table 6 Summary of original and updated hydraulic geometry curves for the North Carolina Piedmont

Dataset	Q_{bkf}	A_{bkf}	W_{bkf}	D_{bkf}
Doll et al. (2002)	$1.32\ DA^{0.71}$ $R^2 = 0.87$	$1.08\ DA^{0.67}$ $R^2 = 0.95$	$3.14\ DA^{0.36}$ $R^2 = 0.91$	$0.38\ DA^{0.29}$ $R^2 = 0.86$
Combined	$1.342\ DA^{0.657}$ $R^2 = 0.87$	$1.397\ DA^{0.582}$ $R^2 = 0.93$	$3.702\ DA^{0.317}$ $R^2 = 0.90$	$0.377\ DA^{0.266}$ $R^2 = 0.84$

Note: All regression relationships are statistically significant by ANOVA.

5. Conclusion

This study measured and quantified the changes in channel geometry and discharge for 18 streams in the North Carolina Piedmont that occurred over a 10.5-year period (2007 – 2018). Inspection of individual sites revealed A_{bkf} adjusted by 0% to 19% at many sites, however several urbanizing sites adjusted by more than 25%. Δ Q_{bkf} and Δ A_{bkf} were significantly correlated with IC and increasing IC, indicating channel geometry adjustments are likely as Q_w and Q_s change in response to changes in watershed condition and land cover. Analysis of event-based precipitation data from 1997 to 2018 indicated there were no statistically significant trends in rainfall. Δ W_{bkf} was significantly correlated with increasing BHR, which follows Simon and Rinaldi's (2006) channel evolution model of degradation and widening in response to watershed disturbance.

Two distinct clusters of streams were identified. Cluster 1 (n=13) streams exhibited subtle changes in channel geometry and relatively constant boundary conditions suggesting they are likely in a quasi-equilibrium condition. Cluster 2 (n=5) streams experienced greater changes in watershed land cover, were more incised, were less connected to their floodplain, exhibited more streambank erosion, and experienced larger adjustments in channel geometry. The Cluster 2 streams are likely in a state of disequilibrium as their channel geometry responds to changing boundary conditions.

Hydraulic geometry relationships from 2007 and 2018 were nearly identical and no statistically significant differences were detected. Twelve equilibrium streams from this study, including 7 sites with DA <2.6 km^2, were used to revise hydraulic geometry relationships developed by Doll et al. (2002), which included only one site with DA <2.6 km^2. This improves comparisons of bankfull channel geometry and discharge to drainage area for smaller streams in ungaged watersheds, which is critical given 70% – 80% of the total channel length in a river network is comprised of first- and second-order streams (Wohl 2017). Improvement to these empirical relationships is important as they are commonly used for restoration design and assessment efforts. Many impacts occur on smaller headwater streams (Wohl 2006) and as a result, restoration activities have commonly focused in smaller catchments. Over 62% of the 109 stream reaches restored for mitigation purposes by the NC Division of Mitigation Services in the North Carolina Piedmont were found to drain watersheds less than 2.6 km^2 (Doll and Kurki-Fox 2022).

The geometry adjustments and percent erosion reported for the more stable reference streams in this study can serve as a gauge for evaluating the degree of change in channel geometry measured at both degraded and restored streams. Because reference streams are used for restoration designs, ecological function targets, and project success criteria, the channel adjustments reported here could be used to help develop numerical success criteria. In addition, channel adjustment ranges recorded by this effort should be considered in future stream restoration designs. Early natural channel design restoration projects relied heavily on numerous boulder structures to protect the bed and banks of streams (Miller and Kochel 2008, 2010; Puckett 2008). In contrast, many newer projects have shifted to more vegetated solutions, such as brush toe and vegetated geogrids in place of boulder armoring (Allen and Fischenich 2001; Neuhaus and Mende 2021; Shields Jr et al. 2004; Zhang et al. 2018). Continued work is needed to develop and evolve approaches that will help to ensure ecological stability (Webster et al. 1983) and function of restored streams while also allowing for adjustments in channel geometry that are characteristic of reference streams. In urban areas, however, where protecting infrastructure supersedes channel migration and adjustments, extensive grade control, and bank protection will remain critical components of channel stability. In these situations, careful consideration of the initial channel geometry and detailed hydraulic analysis are necessary to ensure the channel is designed to provide long-term stability and resilience to a wide range of flow events.

Supplementary Material

The online version of this article contains a link to supplementary material that includes: Fig S.1 Summary of Watershed and Landuse Conditions; Fig. S.2 Precipitation Event Summary for Stations CLAY, KGSO, KRDU, and OXFO from January 1, 1997 to January 1, 2018; Fig. S.3 Revised North Carolina Piedmont Regional Curves Including 12 Additional Reference Reach Streams in English Units; Table S.1 Summary of Exceedance Probability and Rainfall Events >2.5 cm.

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Conceptualization: JP, BD; data curation: JP, BD, SD, CJ; methodology: JP, BD; formal analysis: JP, JKF; funding acquisition: JP, BD; investigation: JP, BD; project administration: BD; writing original draft: JP; review/editing original draft: JKF, BD. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data Availability Statement

Data from this study can be provided upon email request to the primary corresponding author.

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ORCID iDs

Jonathan L. Page
https://orcid.org/0009-0002-2736-8684

Barbara A. Doll
https://orcid.org/0000-0001-5969-3436

J. Jack Kurki-Fox
https://orcid.org/0000-0002-3969-7955

Sara Donatich
https://orcid.org/0000-0002-8048-2411

Cameron Jernigan
https://orcid.org/0009-0005-5205-5825

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