Hydraulic Geometry Relationships for Rural North Carolina Coastal Plain Streams

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ABSTRACT: Hydraulic geometry relationships, or regional curves, relate bankfull stream channel dimensions to watershed drainage area. Hydraulic geometry relationships for streams throughout North Carolina vary with hydrology, soils, and extent of development within a watershed. This coastal curve shows the bankfull features of streams in the rural areas throughout the North Carolina Coastal Plain. Sixteen streams were surveyed in watersheds that had less than ten-percent impervious cover. Any disturbance to the stream channels had occurred long enough ago for the streams to redevelop bankfull features and had no major impoundments. The drainage areas for the streams ranged from 0.2 to 161 square miles. Cross-sectional and longitudinal surveys were conducted to determine the channel dimension, pattern and profile of each stream and power functions were fitted to the data. NC State University and the Natural Resource Conservation Service collected the study data. Regional curves are useful tools for applying natural channel design. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions.

KEY TERMS: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses

INTRODUCTION

Decades of ditching, draining, farming and development have degraded large numbers of streams throughout the coastal area of North Carolina. Watershed hydromodification, channelization, loss of riparian vegetation, floodplain restrictions and changes in hydrology have altered the dimension, pattern, and profile, and thereby the function, and habitat of many coastal streams. Restoration of streams is a priority focus for many federal, state and local government agencies and nonprofit groups. Many restoration practitioners

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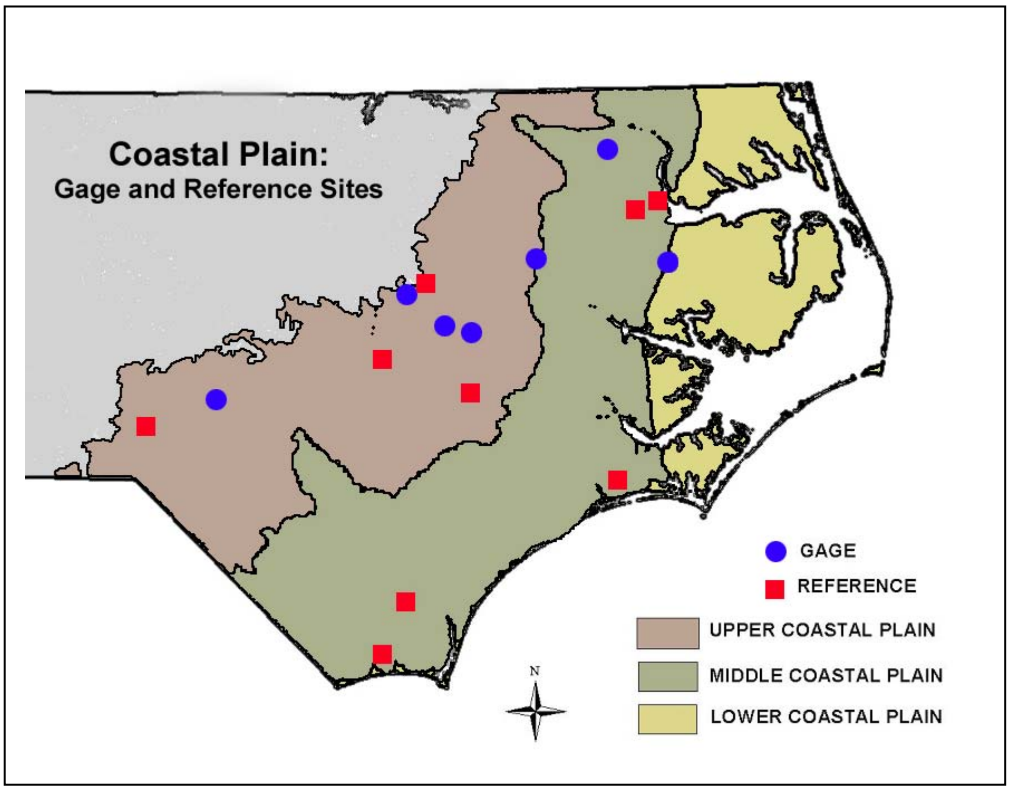
strive to restore stability to disturbed streams by rebuilding natural stream characteristics, including a properly sized bankfull channel, adequate floodplain width, meanders, riffles and pools. Stability is achieved when the stream has developed a stable dimension, pattern and profile such that, over time, channel features are maintained and the stream system neither aggrades nor degrades (Rosgen, 1996). This restoration approach relies on the accurate identification of the bankfull channel dimension and discharge. Hydraulic geometry relationships that relate bankfull stream channel dimensions and discharge to watershed drainage area are therefore useful tools for stream restoration design. Dunne and Leopold (1978) first developed hydraulic geometry relationships for the bankfull stage, also called regional curves.

Hydraulic geometry relationships for streams vary with hydrology, soils, and extent of development within a watershed; therefore, it is necessary to develop curves for various levels of development in each hydrophysiographic region. There are three primary physiographic regions in North Carolina including the Mountains, Piedmont, and Coastal Plain. The Coastal Plain is characterized by flat land to gently rolling hills and valleys. Elevations range from sea level near the coast to about 600 feet in the Sand Hills of the southern inner Coastal Plain. The Coastal Plain is the largest geologic belt in the state covering 45 percent of the land area and consisting of a wedge of mostly marine sedimentary rocks that gradually thickens to the east. The most common sediment types are sand and clay, although a significant amount of limestone occurs in the southern part of the Coastal Plain. Rainfall is highly variable in the Coastal Plain, averaging between 45 and 60 inches per year depending on location. Hydraulic geometry data have already been developed for rural (Harman et al., 1999) and urban (Doll et al, 2002) Piedmont North Carolina streams and for the Mountains (Harman et al., 2000). This study focuses on identifying bankfull dimension and discharge of rural streams in the Coastal Plain region.

Sixteen streams were surveyed in North Carolina Coastal Plain with watersheds that had less than ten-percent impervious cover, including seven USGS gaged streams and nine reference quality stream reaches. Despite any past disturbance, modifications to the streams included in the study had occurred long enough ago for the streams to redevelop bankfull features and had no major impoundments. The USGS gaged streams included in the study were in the process of recovering from past disturbances, primarily channelization. The reaches selected for survey were, however, stable. The reference reach channels selected appeared to have experienced much less modification if any compared to the USGS gaged streams. These reaches were very stable meandering streams with high quality habitat features, including properly located riffles and pools and large woody debris.

The drainage areas for the streams ranged from 0.2 to 161 square miles. The study includes data collected by NC State University, and by the Natural Resource Conservation Service. The locations of the survey sites are displayed on the map in Figure 1.

Figure 1. Survey Sites in North Carolina



MATERIALS AND METHODS

U.S. Geological Survey (USGS) gaged Coastal Plain streams were identified. Of the gaged streams, only those that met the study criteria were surveyed. The study site criteria included: Coastal Plain streams with less than ten-percent impervious surface in their drainage area (Schueler, 1995), no major impoundments, exhibiting bankfull indicators and having a stable riffle or run cross-section. In addition, reference quality streams were identified through map analysis, local agency contacts and field reconnaissance. A reference reach is a stable river segment that represents a stable channel within a particular valley morphology (Rosgen, 1998). The reference streams were not necessarily pristine, however, they were in stable watersheds; did not exhibit any signs of incision or head-cutting; had well-vegetated, gently sloping streambanks and well-defined properly located bed features, including riffles and pools. Only those channels with bankfull stage located at the top of bank were selected as reference reaches.

A consistent bankfull indicator was identified along each stream survey reach. Bankfull stage in general corresponds to the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel-forming flow, maintaining channel dimension and transporting the bulk of sediment over time (Leopold, 1994). Field indicators of bankfull stage include the back of point bars, significant breaks in slope along the streambank (cross-sectional perspective), changes in vegetation, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for North Carolina streams are the highest scour line and the back of the point bar. The top of the bank or the lowest scour or bench is rarely an indicator of bankfull (Harman et al., 1999). Bankfull is generally not the top of bank as most streams in North Carolina have suffered past disturbance. However, bankfull was located at the top of bank for all of the nine reference reach streams included in the study.

Cross-sectional and longitudinal surveys were conducted to determine the channel dimension, pattern and profile for each stream. Cross-sections were surveyed at a representative stable riffle or run that was not suffering from severe active erosion. Morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994; U.S. Geological Survey, 1969). Bankfull hydraulic geometry was calculated from the survey data at each riffle cross-section.

For each reach, a longitudinal survey was completed over a stream length equal to at least 20 bankfull widths (Leopold, 1994). Longitudinal stations were established at each bed feature (heads of riffles and pools, maximum pool depth, scour holes, etc.). The following channel features were surveyed at each station: thalweg, water surface, low bench or scour, bankfull stage, and top of bank. The slope of a line fitted through the bankfull stage indicators was compared to a line of best fit through the water surface points. Leopold (1994) used this technique to verify the feature as bankfull if the two lines were parallel and consistent over a long reach. At gaged stream sites, the longitudinal survey was carried through the gage plate to obtain the bankfull stage. The stream was classified using the Rosgen method (1994).

For gaged streams, the bankfull discharge and return period were determined using the USGS stage-discharge rating table and flood-frequency analysis, respectively. At least ten years of USGS gage discharge data, including annual peak flows, were necessary to develop flood frequency relationships. Log-Pearson Type III distributions were used to analyze the annual peak discharge data (U.S. Geological Survey, 1982). The generalized skew coefficient presented in the USGS Bulletin 17B was used for the flood frequency analysis (U.S. Geological Survey, 1982). The annual exceedence probability was calculated as the inverse of the recurrence interval. Exceedence probabilities were plotted as functions of corresponding calculated discharge measurements. From these flood frequency relationships a specific discharge can then be related to a return interval.

For non-gaged reference reach streams, bankfull discharge was calculated using Manning's equation (Chow, 1959). Cross-sectional area and hydraulic radius were calculated using the cross-section survey data and a roughness coefficient was estimated using a method published by USGS (Arcement and Schneider, 1989). For this method, a base roughness coefficient value is selected according to bed material size. The base value is then adjusted according to five factors, including: degree of channel irregularity (i.e. bed and banks), variation in channel cross-section size and shape, obstructions, vegetation and degree of meandering.

1996 landcover data, obtained from North Carolina Center for Geographic Information and Analysis (CGIA), was used to evaluate the land cover of each stream's watershed. The CGIA land cover data are classified into seven major categories, which are further broken down into sub-categories. The seven major categories include: developed, cultivated, herbaceous cover and shrubland, forest, waterbodies, barren land, and indeterminate landcover. The classification method used was "The Comprehensive Statewide Landcover Mapping Classification System" (CGIA, 1994). The landcover data was clipped by the boundary for each study watershed. The resulting land cover breakdown by percentage for each of the study watersheds is provided in Table 1.

For each stream, the bankfull cross-sectional area, discharge, width, and depth were plotted versus drainage area. These relationships were found to be linear on a log scale, e.g., a power function was utilized. Confidence intervals (95%) on the individual observations and the regression relationships were also calculated.

RESULTS AND DISCUSSION

Table 2 summarizes field measurements and hydraulic geometry data for the Coastal Plain streams. The relationships for bankfull discharge, cross-sectional area, width, and mean depth as functions of watershed area for the streams are shown in Figure 2. The resulting 95% confidence intervals for both the individual observations and the regression relationship are also shown on Figure 2. The relationships shown in Figure 2 represent seven USGS gage stations and nine un-gaged reference reaches ranging in watershed area from 0.2 to 161 square miles. The power functions regression equations and corresponding coefficients of determination for the Coastal Plain curves are:

$$A_{bkf} = 14.52\ A_w^{0.66} \qquad r^2=0.88 \qquad (1)$$

$$Q_{bkf} = 16.56\ A_w^{0.72} \qquad r^2=0.90 \qquad (2)$$

$$W_{bkf} = 10.97\ A_w^{0.36} \qquad r^2=0.87. \qquad (3)$$

$$D_{bkf} = 1.29\ A_{w.}^{0.30} \qquad r^2=0.74 \qquad (4)$$

where, Q_{bkf} = bankfull discharge in cubic feet per second (cfs), A_w = watershed drainage area in square miles (sq. m.), A_{bkf} = bankfull cross sectional area in square feet (sq. ft.), W_{bkf} = bankfull width in feet (ft), and D_{bkf} = bankfull mean depth in feet (ft). The regression analyses documented a statistically significant exponent, verifying that as watershed area increases the cross-sectional area, discharge, width, and depth of the bankfull channel also increase. The high coefficients of determination indicate these power functions explain a high percentage of the variability of the four hydraulic geometric variables. Additional sources of variability include natural variations in average annual runoff, stream type (Rosgen, 1994), land use, and stream hydrology (Leopold and Maddock, 1953, Leopold, 1994). The bankfull return interval ranged from 1.0 to 1.25 for the gaged stream stations, with the average and the median return interval at 1.12 and 1.2, respectively. Dunne and Leopold (1978) reported a bankfull return interval of 1.5 years from a national study. Rural Piedmont streams in North Carolina produced and average bankfull return interval of 1.4 (Harman et al., 1999) and Urban Piedmont streams produced an return interval of 1.3 (Doll et al. 2002). Return intervals for the North Carolina seven gaged Coastal Plain streams were slightly lower than the return intervals reported by previous studies of other North Carolina hydrophysiographic regions.

CONCLUSION

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the Coastal Plain region of North Carolina.

Figure 2: Hydraulic geometry relationships of (a) bankfull cross-sectional area, (b) discharge, (c) width, and (d) depth compared to watershed area for streams in the Coastal Plain region of North Carolina

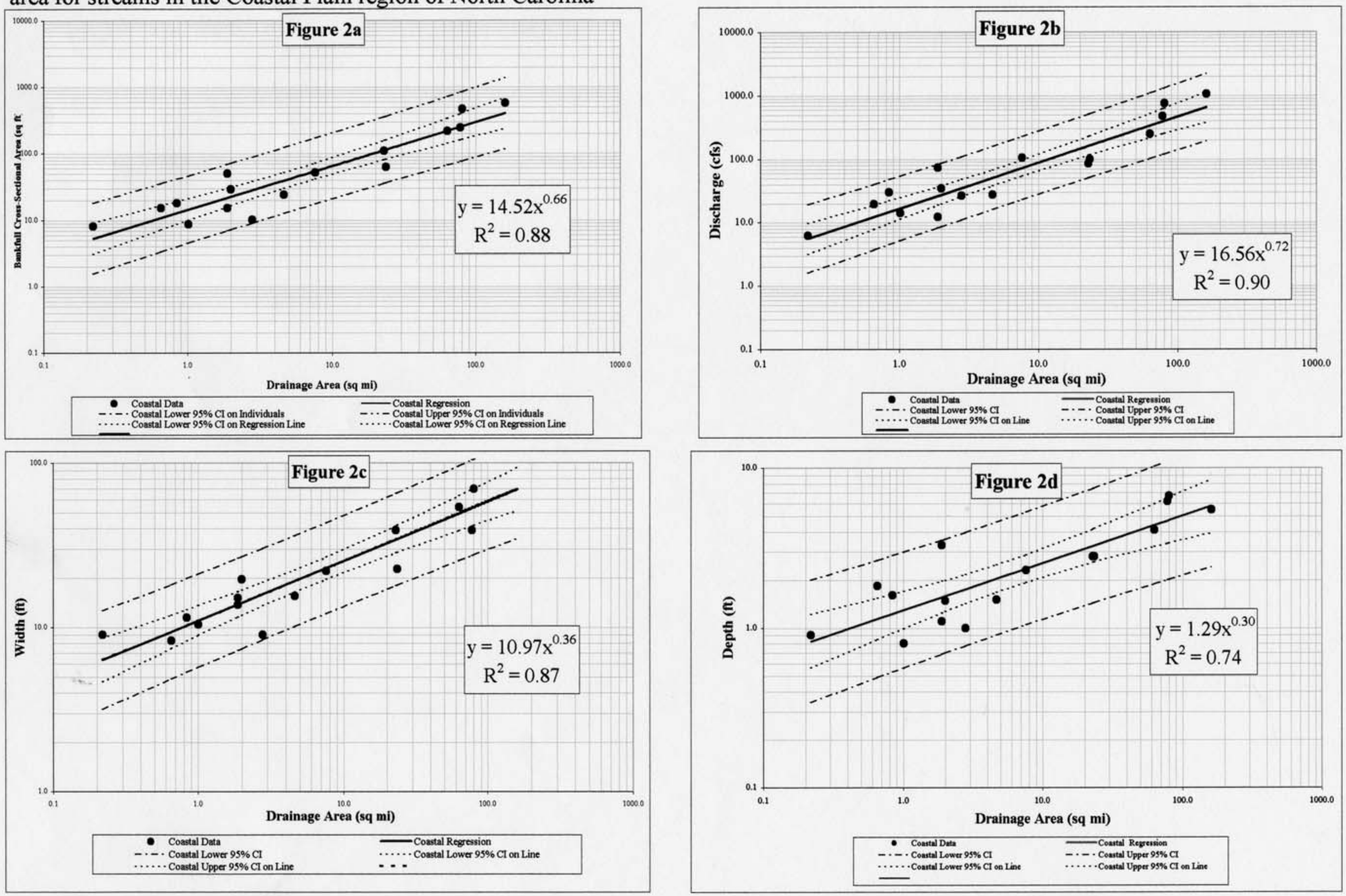


Table 1: Landcover Percentages for Coastal Plain Stream Drainage Areas

Stream Name	Developed	Cultivated	Herbaceous Cover & Shrublands	Forrest Land	Water Bodies	Barren Land	Indeterminate Landcover
UT of Salmon Creek #1	0.00%	26.55%	0.31%	73.14%	0.00%	0.00%	0.00%
Lee Swamp	0.00%	50.24%	16.06%	33.08%	0.62%	0.00%	0.00%
Panther Creek	0.00%	61.91%	14.42%	22.47%	1.21%	0.00%	0.00%
Johannah Creek	0.00%	38.57%	10.65%	50.78%	0.00%	0.00%	0.00%
Pettiford Creek	0.75%	47.92%	6.09%	44.70%	0.53%	0.00%	0.00%
Moccasin Run	0.00%	0.00%	2.79%	97.21%	0.00%	0.00%	0.00%
Little Doe Creek	3.25%	21.12%	19.90%	55.72%	0.00%	0.00%	0.00%
UT of Salmon Creek #2	0.00%	8.56%	16.29%	75.15%	0.00%	0.00%	0.00%
Batarora Creek	0.00%	1.58%	4.73%	93.62%	0.08%	0.00%	0.00%
Flat Creek	0.46%	0.00%	16.17%	78.36%	0.00%	5.01%	0.00%
Van Swamp	0.27%	75.17%	4.37%	20.17%	0.02%	0.00%	0.00%
Hitchcock Creek	0.30%	6.64%	10.39%	81.94%	0.61%	0.13%	0.00%
Ahoskie	1.03%	24.99%	15.17%	58.61%	0.20%	0.00%	0.00%
Conetoe Creek	0.70%	40.50%	18.60%	40.16%	0.04%	0.00%	0.00%
Nahunta Creek	0.20%	55.43%	12.82%	31.25%	0.28%	0.00%	0.00%
Contentnea Creek	1.47%	25.87%	21.53%	49.45%	1.68%	0.00%	0.00%

Table 2. Hydraulic geometry and survey summary for Coastal Plain stream reaches.

Stream Name	**Gage Number**	**Drainage Area** (sq mi)	**Bkfl Cross-Sectional Area** (sq ft)	**Discharge** (cfs)	**Width** (ft)	**Depth** (ft)	**Return Interval**	**Stream Type (Rosgen)**	**County**	**Data Collected By**	**Slope %**
UT of Salmon Creek #1	reference reach	0.22	8.1	6.3	9.0	0.9		E	Bertie	NCSU	0.08
Lee Swamp	reference reach	0.66	15.2	19.4	8.3	1.8		E5	Wilson	NCSU	0.284
Panther Creek	reference reach	0.84	17.9	29.9	11.5	1.6		E5	Lenior	NCSU	0.314
Johannah Creek	reference reach	1.0	8.6	14.2	10.4	0.8		C5	Johnston	NCSU	0.482
Pettiford Creek	reference reach	1.9	15.1	12.3	13.7	1.1		E5	Carteret	NCSU	0.125
Moccasin Run	0209096970	1.9	49.7	72.9	15.1	3.3	1.02	E6	Wayne	NCSU	0.038
Little Doe Creek	reference reach	2.0	29.0	34.5	19.6	1.5		C5	Brunswick	NCSU	0.159
UT of Salmon Creek #2	reference reach	2.8	10.1	26.6	9.0	1.0		E5	Bertie	NCSU	0.585
Batarora Creek	reference reach	4.7	23.9	27.4	15.5	1.5		E5	Brunswick	NCSU	0.181
Flat Creek	02102908	7.6	51.4	105	22.0	2.3	1.25	E	Hoke	NCSU	0.735
Van Swamp	02084557	23.0	109.6	85	39.0	2.8	1	F	Washington	NCSU	0.150
Hitchcock Creek	reference reach	23.6	62.7	100	22.7	2.8		E5	Richmond	NCSU	0.280
Ahoskie	2053500	63.3	218.3	245	53.8	4.1	1	F6	Hertford	NCSU	0.005
Conetoe Creek	02083800	78.1	243.0	472	39.0	6.2	1.2	E	Pitt	NRCS	0.067
Nahunta Creek	2091000	80.4	468.6	746	69.5	6.7	1.2	E5	Greene	NCSU	0.1
Contentnea Creek	2090380	161.0	569.0	1052	103.0	5.5	1.2	C	Wilson	NRCS	

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