Stream Geomorphology Data Collection and Analysis

South Carolina Ecoregions 66, 45, 65, 63

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EXECUTIVE SUMMARY

This report includes reference stream morphology and large woody debris data collected throughout South Carolina during 2019 and 2020. Hydraulic geometry data are presented as regional curves for Ecoregions 66, 45, 65, and 63 to support stream assessment and restoration planning. Morphology relationships describe bankfull channel dimensions, pattern, and profile measurements in relation to channel-forming discharge and watershed drainage area. Large woody debris (LWD) data collected at reference streams serve as an indicator of natural stream conditions in forested valleys. These databases and relationships are valuable for assessing disturbed streams to evaluate degree of departure from equilibrium, selecting and planning restoration projects to improve natural stream functions, and monitoring changes in stream conditions in undisturbed and restored stream systems. These databases should be supplemented with additional information collected during site assessment and restoration planning to improve understanding of local stream conditions throughout South Carolina.

The morphology data collection included 50 streams ranging in width from 5 to 80 feet with watershed drainage areas ranging from 0.06 to 94.7 square miles. Where available, United States Geological Survey (USGS) gage station sites were surveyed to relate stream morphology data to a long-term hydrologic record. Bankfull stage indicators at a USGS gage provided the opportunity to quantify the channel-forming discharge and exceedance probability of a bankfull flow event. For reference streams without gages, natural equilibrium stream segments with clearly identifiable incipient-floodplain bankfull stage indicators were surveyed to determine morphology parameters. These ungaged reference streams were mostly located in forested, protected lands such as State Parks, State Forests, National Forests, and National Wildlife Refuges. Some reference stream locations coincided with monitoring sites used by the South Carolina Department of Natural Resources (SCDNR). In each ecoregion, several other streams were visited to evaluate their potential for inclusion in this study but were rejected due to local instability or other factors affecting their geomorphic conditions.

Results of this study should be considered an initial database of reference stream morphology. Additional stream data should be added as more reference streams are identified and measured during assessment and design projects. Stream assessment and restoration practitioners should carefully consider the natural variability demonstrated in these data. Designers should not use this information as the sole basis for planning restoration projects, but should evaluate evidence from hydrologic and hydraulic monitoring and modeling, nearby reference stream morphology, and existing stream conditions in order to determine appropriate restoration design parameters. Long-term monitoring data for restoration projects should be evaluated to understand natural channel evolution toward geomorphic equilibrium.

Ecoregion 66 (Blue Ridge)

Stream morphology data were collected at 6 reference and gaged streams in the Blue Ridge Ecoregion of South Carolina (EPA Level III Ecoregion 66), with drainage areas ranging from 0.11 to 20.8 square miles. One of these streams is at a USGS gage station. The study includes 5 B and 1 E Rosgen type streams based on the measured entrenchment ratios, width/depth ratios, and slopes. The entrenchment ratios range from 1.8 to 3.6. Width/depth ratios are highly variable, and generally range between 8 and 16. Reach channel slopes range from 0.0066 to 0.0555 ft/ft. The median streambed particle size (D_{50}) is classified as gravel at 4 sites and cobble at 2 sites.

The South Carolina stream parameters generally fit within the variability measured within this ecoregion in North Carolina and Tennessee. Overall, the South Carolina stream information matches well with North Carolina and Tennessee data, suggesting that the composite South Carolina + North Carolina + Tennessee regional curves are appropriate for use in Ecoregion 66 in South Carolina.

The regression hydraulic geometry regional curve relationships for South Carolina + North Carolina + Tennessee are summarized below, with watershed drainage area (DA) in square miles, channel bankfull area (A_{bkf}) in square feet, channel bankfull width (W_{bkf}) and mean depth (d_{bkf}) in feet, and bankfull discharge (Q_{bkf}) in cubic feet per second.

$A_{bkf} = 20.1\ DA^{0.694}$ $\quad R^2 = 0.972$

$W_{bkf} = 17.7\ DA^{0.400}$ $\quad R^2 = 0.948$

$d_{bkf} = 1.13\ DA^{0.296}$ $\quad R^2 = 0.922$

$Q_{bkf} = 93.4\ DA^{0.771}$ $\quad R^2 = 0.940$

Stream bedform profile data were collected for the 5 reference streams with discernable riffle-pool sequences. Median riffle and pool length ratios range from 1.4 to 3.3 for riffles and 1.2 to 2.0 for pools. Median pool spacing ratios range from 2.4 to 3.5. Median riffle slope ratios range from 1.0 to 1.7. Median step height ratios for the two reference streams with discernable steps range from 0.06 to 0.10. These profile parameter ratios are similar to those measured in reference streams within Ecoregion 66 in North Carolina and Tennessee.

Stream pattern data were collected for the 2 meandering reference streams with discernable planform parameters. Median meander wavelength ratios for this small sample size range from 4.7 to 6.3, belt width ratios are 2.6, and radius of curvature ratios are 2.1. These pattern parameter ratios are similar to those observed in reference streams within Ecoregion 66 in North Carolina and Tennessee.

Ecoregion 45 (Piedmont)

Stream morphology data were collected at 14 reference and gaged streams in the Piedmont Ecoregion of South Carolina (EPA Level III Ecoregion 45), with drainage areas ranging from 0.06 to 94.7 square miles. Seven of these streams are at USGS gage stations. The study includes 1 B, 4 C, and 9 E Rosgen type streams based on the measured entrenchment ratios, width/depth ratios, and slopes. The entrenchment ratios range from 1.4 for the narrow-valley B stream to >10.0 for some of the alluvial C and E streams. Width/depth ratios generally range from 9 to 14, with a few exceptions. Reach channel slopes range from 0.0005 ft/ft for the largest river to 0.0143 ft/ft for one of the smaller streams. The median streambed particle size (D_{50}) is classified as gravel at 3 sites and sand at 11 sites.

Based on field measurements from the 14 reference and gaged streams, bankfull channel cross-section area, width, mean depth, and estimated discharge were found to be strongly correlated to watershed drainage area. The regression hydraulic geometry regional curve relationships are summarized below, with watershed drainage area (DA) in square miles, channel bankfull area (A_{bkf}) in square feet, channel bankfull width (W_{bkf}) and mean depth (d_{bkf}) in feet, and bankfull discharge (Q_{bkf}) in cubic feet per second.

$A_{bkf} = 16.2\ DA^{0.653}$ $R^2 = 0.959$

$W_{bkf} = 13.3\ DA^{0.350}$ $R^2 = 0.951$

$d_{bkf} = 1.20\ DA^{0.305}$ $R^2 = 0.936$

$Q_{bkf} = 36.5\ DA^{0.699}$ $R^2 = 0.948$

Stream bedform profile data were collected for the 5 reference streams with discernable riffle-pool sequences. Many of the measured streams have low-gradient plane beds dominated by sand, which precludes riffle and pool measurements. A wide range of parameters was observed. Median riffle and pool length ratios range from 0.9 to 4.5 for riffles and 1.0 to 4.0 for pools. Median pool spacing ratios range from 2.0 to 8.7. Median riffle slope ratios range from 1.0 to 2.9.

Stream pattern data were collected for the 5 meandering reference streams with discernable planform parameters that could be measured in the field. Median meander wavelength ratios range from 3.3 to 10.5, belt width ratios range from 1.7 to 3.4, and radius of curvature ratios range from 1.4 to 4.1.

Ecoregion 65 (Southeastern Plains)

Stream morphology data were collected at 15 reference and gaged streams in the Southeastern Plains Ecoregion of South Carolina (EPA Level III Ecoregion 65), with drainage areas ranging from 0.25 to 51.9 square miles. Twelve of these streams are located within Level IV Ecoregion 65c (Sand Hills). Three sites are at USGS gage stations. The study includes 4 C and 11 E Rosgen type streams based on the measured entrenchment ratios, width/depth ratios, and slopes. Several streams have valleys so wide that they preclude measurement, and have entrenchment ratios reported as >10.0. The lowest entrenchment ratio is 3.2. Width/depth ratios are highly variable, and range from 6.1 to 25.1. Reach channel slopes range from 0.0004 ft/ft for the largest river to 0.0113 ft/ft for the smallest stream channel. The median streambed particle size (D_{50}) is classified as sand for all streams except two, where D_{50} is gravel.

Based on field measurements from the 15 reference and gaged streams, bankfull channel cross-section area, width, mean depth, and estimated discharge were found to be strongly correlated to watershed drainage area. The regression hydraulic geometry regional curve relationships are summarized below, with watershed drainage area (DA) in square miles, channel bankfull area (A_{bkf}) in square feet, channel bankfull width (W_{bkf}) and mean depth (d_{bkf}) in feet, and bankfull discharge (Q_{bkf}) in cubic feet per second. With 12 of the 15 data points collected from streams located within Level IV Ecoregion 65c (Sand Hills), these relationships could be considered representative of both Level III Ecoregion 65 and Level IV Ecoregion 65c.

$A_{bkf} = 6.5\ DA^{0.774}$ $R^2 = 0.924$

$W_{bkf} = 8.7\ DA^{0.356}$ $R^2 = 0.848$

$d_{bkf} = 0.73\ DA^{0.430}$ $R^2 = 0.895$

$Q_{bkf} = 9.2\ DA^{0.830}$ $R^2 = 0.856$

Stream bedform profile data were collected for the subset of reference sites that appeared to have variations in streambed elevations within the reach. However, field observations and data analyses did not result in discernable riffle-pool sequences. Rather than riffles and pools, variations in bedform are generally due to tree roots, vegetation in the channel, woody debris, and accumulations of sand. This is typical of low-slope, sand bed streams in coastal plain ecoregions. As a result, profile data (i.e., riffle slopes and lengths, pool lengths, and pool spacings) could not effectively be measured.

Stream pattern data were collected for the 4 meandering reference streams with discernable planform parameters that could be assessed in the field. Median meander wavelength ratios range from 3.6 to 8.5, belt width ratios range from 1.9 to 3.5, and radius of curvature ratios range from 1.4 to 4.8.

Ecoregion 63 (Middle Atlantic Coastal Plain)

Stream morphology data were collected at 15 reference and gaged streams in the Middle Atlantic Coastal Plain Ecoregion of South Carolina (EPA Level III Ecoregion 63), with drainage areas ranging from 0.35 to 14.3 square miles. The study includes 8 C and 7 E Rosgen type streams based on the measured entrenchment ratios, width/depth ratios, and slopes. Nearly all of the streams have valleys so wide that they preclude measurement, and have entrenchment ratios reported as >10.0. The lowest entrenchment ratio is 5.5. Width/depth ratios are highly variable, and range from 6.4 to 41.1. Reach channel slopes range from 0.0004 ft/ft to 0.0065 ft/ft. The median streambed particle size (D_{50}) is classified as sand for all streams.

Based on field measurements from the 15 reference streams, bankfull channel cross-section area, width, mean depth, and estimated discharge were found to be correlated to watershed drainage area. The regression hydraulic geometry regional curve relationships are summarized below, with watershed drainage area (DA) in square miles, channel bankfull area (A_{bkf}) in square feet, channel bankfull width (W_{bkf}) and mean depth (d_{bkf}) in feet, and bankfull discharge (Q_{bkf}) in cubic feet per second.

$A_{bkf} = 8.0\ DA^{0.797}$ $\quad R^2 = 0.895$

$W_{bkf} = 10.0\ DA^{0.484}$ $\quad R^2 = 0.783$

$d_{bkf} = 0.81\ DA^{0.307}$ $\quad R^2 = 0.632$

$Q_{bkf} = 7.4\ DA^{0.841}$ $\quad R^2 = 0.843$

Stream bedform profile data were not collected from streams within this ecoregion. In these low-slope, sand bed streams, riffle-pool sequences were not discernible. Rather, variations in bedform are generally due to tree roots, vegetation in the channel, woody debris, and accumulations of sand. This is typical of streams in coastal plain ecoregions. As a result, profile data (i.e., riffle slopes and lengths, pool lengths, and pool spacings) could not effectively be measured.

Stream pattern data were collected for the 6 meandering reference streams with discernable planform parameters that could be assessed in the field. Median meander wavelength ratios range from 2.5 to 13.6, belt width ratios range from 1.3 to 8.1, and radius of curvature ratios range from 1.2 to 5.6.

Large Woody Debris (LWD)

Large Woody Debris (LWD) data were collected and analyzed at all 50 of the streams surveyed for morphology throughout South Carolina. LWD is defined as dead wood over 1 meter in length and at least 10 cm in diameter. The LWD Index (LWDI) score was calculated for each stream to represent the relative function of the LWD pieces or debris dams in retaining organic matter, providing fish habitat, and affecting channel/substratum stability depending on LWD size, location, orientation, and stability.

The median LWDI score for the 50 streams is 189, with higher median scores in Ecoregions 65 and 63 (Southeastern Plains and Middle Atlantic Coastal Plain); perhaps due to increased numbers of fallen trees and broken limbs and more limited human disturbance in these areas. The LWDI results for these 50 streams may be used to compare with disturbed or restored stream systems to evaluate the relative prevalence of LWD in supporting natural stream functions. It should be noted that some disturbed streams could be expected to have high LWDI scores due to unstable streambanks and resulting fallen trees or due to recent storms. In a stream restoration project, LWDI may be enhanced by the strategic addition of logs and woody debris to the restoration channel in the form of vanes, revetments, riffle wood, or other habitat structures.

Results of this study should be considered an initial database of reference stream large woody debris information. The database developed in this study should be supplemented with additional data collected on reference, disturbed, and restored streams using the same quantification method to support future analyses of LWD in South Carolina streams.

TABLE OF CONTENTS

ATTACHMENTS

I. INTRODUCTION

Reference stream morphology relationships are valuable tools for assessing stream condition and estimating design ranges for channel morphology in restoration projects. Bankfull regional curves that relate bankfull discharge and channel cross-sectional area, width, and mean depth to drainage area are practical tools for identifying target channel bankfull dimensions (Cinotto, 2003; Keaton *et al*., 2005; Brockman *et al*., 2012). Bankfull regional curves are valuable when assessing incised systems where incipient-flooding bankfull indicators are difficult to identify in the field. Other valuable reference stream morphology relationships for assessment and restoration planning describe channel profile and pattern parameters including riffle, pool, step, and meander features (Zink *et al*., 2012; Helms *et al*., 2016).

Leopold and Maddock (1953) developed the concept of hydraulic geometry relationships to describe how channel dimensions depend on discharge. They described channel width, depth, and velocity as power functions of average annual discharge for 20 large rivers in the Great Plains and Southwestern United States (Dingman, 2007). Leopold *et al.* (1964) described the application of bankfull hydraulic geometry relationships based on bankfull discharge, the highest flow a channel conveys before accessing its floodplain. Dunne and Leopold (1978) introduced the application of drainage area as a surrogate for discharge where flow data are not available. They developed these relationships on a regional level where geology, soil, climate, and hydrology factors are relatively uniform.

Bieger *et al.* (2015) compiled bankfull regional curve data from over 50 publications to compare relationships for physiographic regions at different spatial levels and to assess the performance of drainage area as a surrogate for bankfull discharge. They determined that data derived from smaller regions produce more reliable regression equations and that bankfull discharge is a better predictor of channel dimensions than drainage area. The regional curves for physiographic divisions of the United States presented by Bieger *et al.* (2015) are valuable for comparing local curves for smaller regions.

South Carolina contains the following five EPA Level III Ecoregions, shown in Figure 1-1:

66: Blue Ridge
45: Piedmont
65: Southeastern Plains
63: Middle Atlantic Coastal Plain
75: Southern Coastal Plain

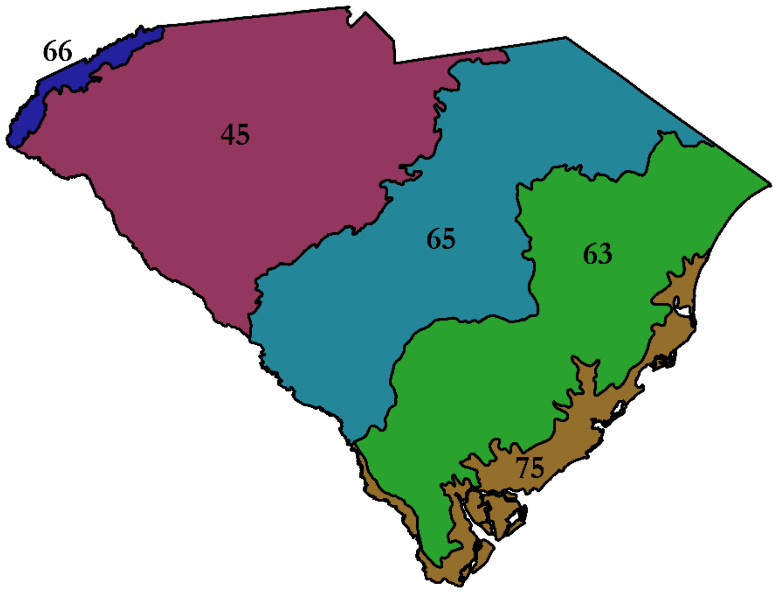


Figure 1-1. EPA Level III Ecoregions of South Carolina (USEPA, 2013).

For Ecoregions 66, 45, 65, and 63, geomorphological data were collected based on reference stream conditions to improve restoration effectiveness. This includes reference stream hydraulic geometry relationships (i.e., regional curves) for predicting stable stream morphology (dimension, pattern, and profile) related to channel-forming discharge and drainage area. These tools may be used in site assessment, project selection, restoration design and implementation, determining ecological goals, and follow-up monitoring for evaluating the success of ecosystem restoration projects in South Carolina.

Data were collected from 50 stable streams across the state ranging in size from 5 to 80 feet wide with drainage areas ranging in size from 0.06 to 94.7 square miles (Figures 1-2 and 1-3). Where available, United States Geological Survey (USGS) gage station sites were surveyed to relate stream morphology data to a long-term hydrologic record. Bankfull stage indicators at a USGS gage often provided the opportunity to quantify the channel-forming discharge and exceedance probability of the bankfull flow event. For reference streams without gages, natural equilibrium stream segments with clearly identifiable incipient-floodplain bankfull stage indicators were surveyed to determine morphology parameters. These ungaged reference streams were mostly located in forested, protected lands such as State Parks, State Forests, National Forests, and National Wildlife Refuges. Some reference stream locations coincided with monitoring sites used by the South Carolina Department of Natural Resources (SCDNR). In each ecoregion, several other streams were visited to evaluate their potential for inclusion in this study but were rejected due to local instability or other factors affecting their geomorphic conditions.

Figure 1-2. Example of a small stream included in the study (0.81 square miles), Ecoregion 65.

Figure 1-3. Example of a large stream included in the study (55.6 square miles), Ecoregion 45.

The objectives of this study were to: (1) develop bankfull regional curves for Ecoregions 45, 65, and 63 in South Carolina, (2) validate pre-existing regional curves for Ecoregion 66 of North Carolina and Tennessee for use in South Carolina, (3) describe other reference stream morphology relationships for these ecoregions to be used in stream assessment and natural channel design parameter estimation, and (4) collect and analyze large woody debris (LWD) data from reference streams across the ecoregions.

All reference stream assessments included collection of dimension (cross-sectional) data. As conditions allowed, pattern and profile data were collected for a subset of the reference sites.

Data collected at all reference sites included:

- Rosgen stream type
- valley type
- drainage area (DA)
- bankfull riffle cross-section area (A_{bkf})
- bankfull riffle width (W_{bkf}) and mean depth (d_{bkf}) for calculating width-to-depth ratio (WDR)
- width of floodprone area (W_{fpa}) for calculating entrenchment ratio (ER)
- maximum depth at top of bank and bankfull stage for calculating bank height ratio (BHR)
- channel water surface slope (S)
- sinuosity (k)
- median substrate size classification
- estimated Manning roughness coefficient (n)

The subset of reference sites with profile data included collection of:

- riffle slopes (S_{riffle})
- riffle lengths (L_{riffle})
- pool spacings (p-p)
- pool lengths (L_{pool})

The subset of reference sites with pattern data included collection of:

- meander wavelengths ($L_{meander}$)
- belt widths (W_{blt})
- radius of curvature of meander bends (R_c)

II. MORPHOLOGY FIELD DATA COLLECTION

Site Selection

Reference streams were selected in consultation with SCDNR and other local stream professionals generally based on the following criteria:

- Watersheds with drainage areas ranging between approximately 0.1 and 100 square miles
- Watersheds with stable land use, mostly forested, over the past several decades
- Stream channels and floodplains in equilibrium with active bankfull stage indicators (bank height ratios near 1.0)
- Stream channels with freely-formed meander patterns in low-gradient valleys
- No valley restrictions throughout the reference reach or upstream/downstream that may influence channel form
- Healthy riparian forest buffers
- Accessible for data collection and protected for future access

At each site, the stream reach upstream and downstream of the morphological study location was inspected to ensure that the reach generally met the stated guidelines and to assist with identifying consistent bankfull indicators.

Bankfull Identification

There is general agreement that channel size is related to the channel-forming discharge, defined as the discharge that, if maintained indefinitely, would produce the same channel form as the actually long-term hydrograph (Biedenharn and Copeland, 2000). Bankfull measurements, when they can be determined, provide a common method of comparing design parameters and expressing hydraulic geometry. Toward that end, researchers typically identify the bankfull elevation throughout a stream, which may or may not be the same elevation as the top of the streambank. This results in the use of uniform terminology to allow for temporal and spatial comparisons among streams. Practically, a monitoring professional needs to be able to identify the bankfull elevation while in the stream channel. This bankfull elevation is frequently identical to that of the adjoining floodplain (Wolman and Leopold, 1957) (Figure 2-1). When an obvious floodplain break does not exist, the bankfull elevation can be identified using other topographic changes in the bank and changes in sediment size (Dunne and Leopold, 1978). In cases where these bankfull indicators did not exist at cross-sections, one can use indicators from elsewhere in the stream reach to identify the approximate bankfull elevation at a cross-section (Leopold, 1994). The presence of bankfull indicators can be dependent on stream type, climate, vegetation, and physiographic region, and may not be universally applicable. Identifying a specific bankfull elevation that represents a stream requires considerable experience.

Figure 2-1. Example of bankfull elevation identical to adjoining floodplain, Ecoregion 45.

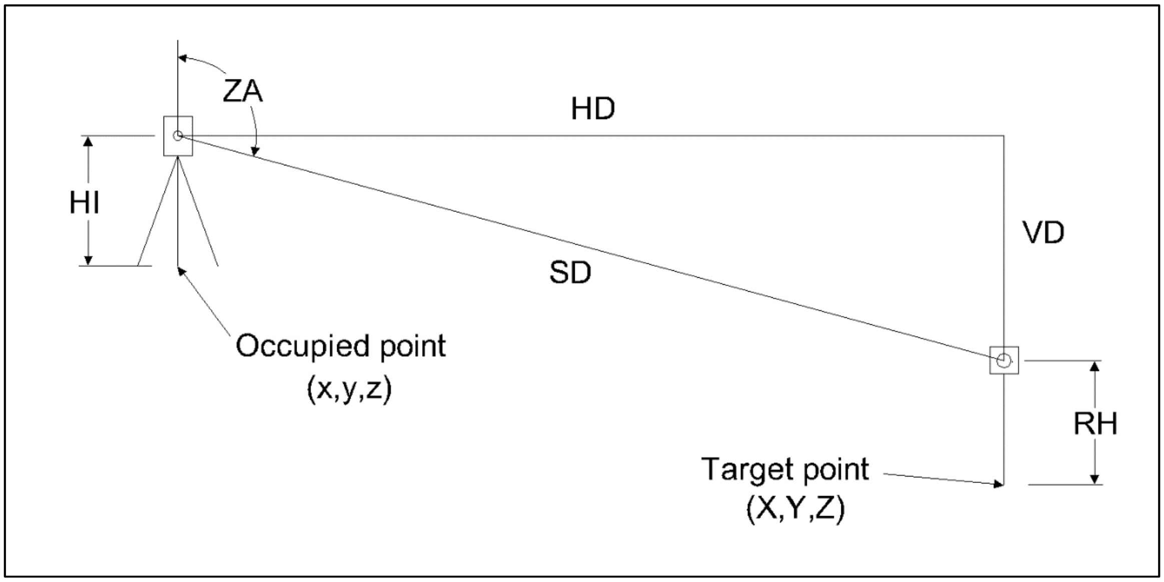
Survey Overview and Procedures

Historically, geomorphic data was collected in streams using a measuring tape and level (Harrelson *et al*., 1994). This method could be used to produce two-dimensional data (i.e., cross-sections and longitudinal profiles), but not three-dimensional data (i.e., plan views). Data collected with a tape and level could be subject to inaccuracies from tape sag, manual recording error, and limitations with line of sight. Additionally, challenges could exist with the replication of measurements in future years. More recently, three-dimensional surveying technology has been applied to stream monitoring. These methods allow for the collection of three-dimensional data (i.e., x, y, and z coordinates for any point of interest) while avoiding the aforementioned limitations. These data can then be processed with software, such as AutoCAD, to represent the stream as a plan view, longitudinal profile, and cross-sections.

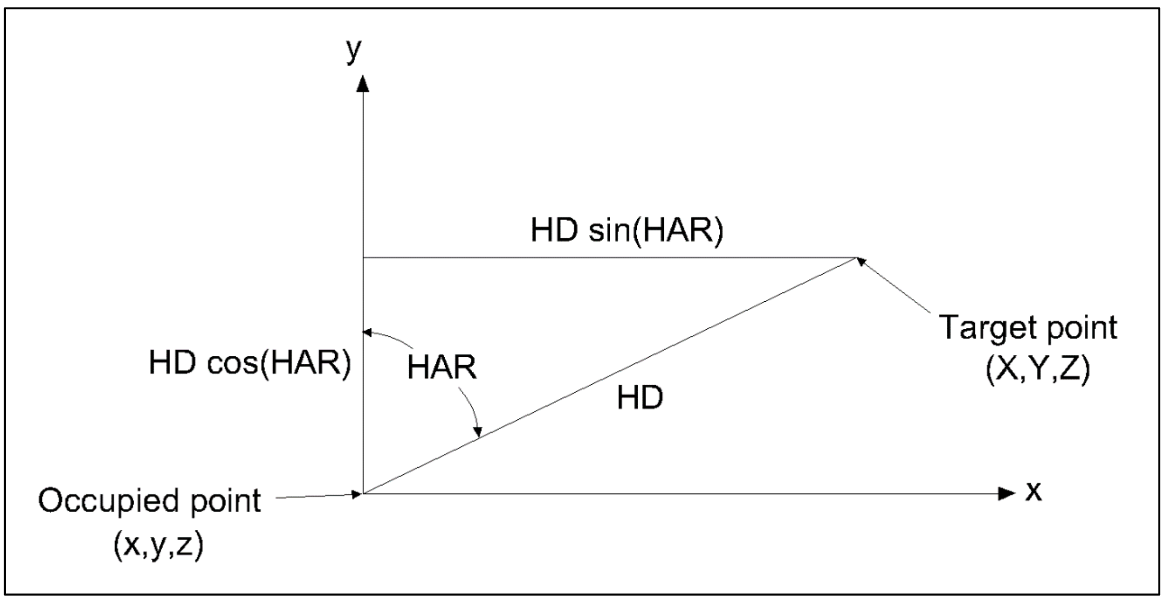
Several technologies can be used to conduct three-dimensional surveys: ground-based LIDAR, GPS, and total station. The methods do have different advantages and disadvantages, with regards to cost, time in the field, data processing time, reliability, and the ability to survey any point of interest (Resop and Hession, 2010). For example, GPS technology relies on communication with satellites, which can be limited in areas of dense tree cover. Also, LIDAR has limitations with line of sight, as it cannot capture features obscured by rocks or vegetation (Heritage and Hetherington, 2007). Until recently, LIDAR was also limited by the inability to collect data below the water surface. However, advances in technology now allow for the use of LIDAR to survey streambed features (McKean *et al*., 2009). Due to the combination of cost, availability, and ease of use, the total station is currently the predominant method used for geomorphic stream monitoring (Figure 2-2), and was used for most streams in this study.

Figure 2-2. Using a total station to survey a stream.

A total station combines a theodolite with an electronic distance meter (EDM). The theodolite is a mechanical instrument used to measure the horizontal angle of rotation (HAR) and zenith (i.e., vertical) angle (ZA). The EDM transmits a laser beam to a prism, then receives the reflection of the laser. Based on the time required for this reflection, the EDM calculates a slope (i.e., straight-line) distance (SD) between the total station and prism. An electronic data collector records the HAR, ZA, and SD, which can be combined with the height of instrument over the occupied point (HI) and rod height over the target point (RH), to calculate coordinates for any point of interest (Figure 2-3).



(a)



(b)

Figure 2-3. Total station geometry in a) profile view, and b) plan view.

The horizontal (HD) and vertical (VD) components of the SD are:

$$HD = SD \sin(ZA)$$

$$VD = SD \cos(ZA)$$

Assuming the occupied point has coordinates (x, y, z), and the target point has coordinates (X, Y, Z), then:

$$X = x + HD \sin(HAR)$$

$$Y = y + HD \cos(HAR)$$

$$Z = z + HI + VD - RH$$

Surveys should be done during low-flow conditions. The use of a standard set of abbreviations can increase efficiency while surveying (Table 2-1).

Table 2-1. Common abbreviations used in stream surveying.

T	Thalweg
M	Thalweg at maximum pool
P	Thalweg at head of pool
S	Thalweg at top of step
R	Thalweg at head of riffle
W	Water surface
B	Bankfull indicator
TOB	Top of bank
TTRIB	Thalweg of tributary
TCONF	Common thalweg at confluence
X1	Cross-section 1 point
X1W	Water surface at cross-section 1
BM	Benchmark
TBM	Temporary benchmark

At most sites in this study, a total station was used to survey points as required to represent the cross-sections, longitudinal profile, and plan view of the channel. During the survey of each cross-section, points were recorded at breaks in slope between the left and right endpoints. The water surface elevation at the cross-section was also noted.

III. MORPHOLOGY DATA ANALYSIS

Cross-sections

Cross-section dimensions (e.g., area, width, and mean depth) are frequently reported in geomorphic assessment and monitoring studies. With the bankfull elevation as a reference, area (A), width (W), and maximum depth (d_{max}) can be directly measured for a cross-section (Figure 3-1). Mean depth (d) can then be calculated as A/W. Additionally, the width of the flood-prone area (W_{fpa}) can be measured as the width of the floodplain at an elevation of two times maximum depth above the thalweg. Measurement of W_{fpa} requires surveying points beyond the endpoints of the bankfull cross-section.

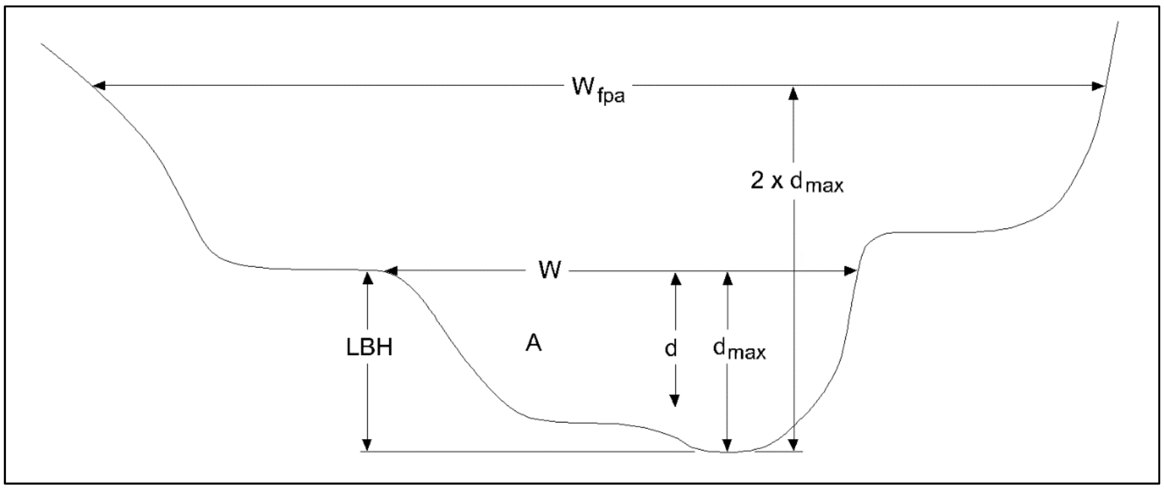


Figure 3-1. Typical cross-section measurements.

Four dimensionless ratios are typically calculated for riffle cross-sections:

Maximum depth (d_{max}) *ratio* = d_{max}/d

Width/depth (W/d) *ratio* = W/d; The W/d ratio serves as a relative index of channel shape

Entrenchment ratio (ER) = W_{fpa}/W; Along with W/d ratio, the ER has implications for stream classification (Rosgen, 1994)

Bank height ratio (BHR) = LBH/d_{max}; LBH is the low bank height, measured as the vertical distance between the thalweg and top of the lower bank

Longitudinal Profile

The longitudinal profile is used to document channel elevation, and slopes and lengths of streambed features. The bed profile of an alluvial stream frequently includes the geomorphic units of riffles, runs, pools, and glides. Additionally, some streams may have step features. Identifying these features is best done using a combination of field observations and a plotted longitudinal profile of the streambed and water surface (Figures 3-2 and 3-3).

Figure 3-2. Example of streambed with riffles and pools, Ecoregion 66.

The longitudinal profile survey should include points along the channel thalweg, water surface, and top of bank. Thalweg points should be recorded at the start and end of observed bed features, as well as other breaks in longitudinal slope, in order to accurately characterize the bed profile (Zimmerman *et al.*, 2008). If there is flow in the channel, a point should be surveyed on the water surface immediately above every point surveyed on the thalweg. The beginning and ending points of a measured longitudinal profile should be at features of the same type (typically the head of a riffle), to allow for an accurate computation of average water surface slope ($S_{average}$).

Horizontal and vertical dimensions, and therefore slope, can be measured from the water surface profile for every bed feature (Figure 3-3). The most commonly reported of these are:

Riffle length (L_{riffle}); The horizontal distance between the beginning and end of each riffle

Pool length (L_{pool}); The horizontal distance between the beginning and end of each pool

Riffle slope (S_{riffle}); The slope, measured at the low-flow water surface profile, for each riffle

Pool spacing: The horizontal distance between deepest point in one pool and the deepest point in the subsequent pool

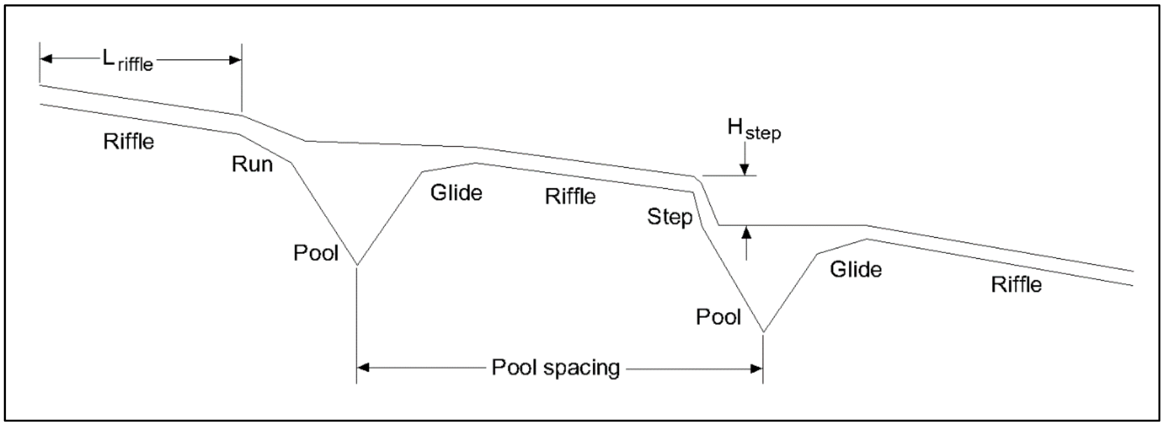


Figure 3-3. Typical longitudinal profile measurements.

These four measurements yield another set of dimensionless ratios:

Riffle length ratio = L_{riffle}/W

Pool length ratio = L_{pool}/W

Riffle slope ratio = $S_{riffle}/S_{average}$

Pool spacing ratio = Pool spacing divided by W; Pool spacing ratio has been documented to be a function of stream slope (Chin *et al.*, 2009), with ratios reported between 3 and 9 (Beschta and Platts, 1986) and between 5 and 7 (Leopold *et al.*, 1964) for riffle-pool systems

Pattern

The pattern of a stream channel can be described by three types of measurements made from a plan view (Figure 3-4): meander wavelength ($L_{meander}$), belt width (W_{blt}), and radius of curvature (R_c).

Figure 3-4. Typical pattern measurements.

Each of the three types of pattern measurements can be divided by W to calculate dimensionless ratios: belt width (W_{blt}) ratio, meander wavelength ($L_{meander}$) ratio, and radius of curvature (R_c) ratio. When multiple meanders exist on a stream, the range and median or mean are typically used to describe these values. Each stream reach will have just one value for sinuosity, the ratio of total stream length to the straight-line distance between the beginning and end of the reach.

Discharge Estimation

A common method for estimating velocity and discharge is Manning equation, developed in the 19th century to describe energy losses in open channels. As the field of hydraulic engineering expanded, this equation has been applied to studies of watershed processes and natural channels. The Manning equation, in English units, is:

$$v = \frac{1.486 * \left(R^{2/3}\right) * \left(S^{1/2}\right)}{n}$$

v is velocity (feet/second), R is the hydraulic radius (feet), S is water surface slope (feet/feet), and n is a dimensionless coefficient describing channel roughness, known as Manning's n.

With n values ranging from 0.033 to 0.150 for natural channels (Chow, 1959), practitioners benefit from experience in choosing the most appropriate value. Familiarity with values for n is perhaps best gained by observing photos of different roughness conditions, such as those presented by Barnes (1967). For an analytical estimation of n, at least ten methods exist, summarized by Marcus *et al.* (1992). One of the more commonly-used methods is from Cowan (1956), which segregates the channel into characteristics that can be assessed visually: sediment size (n_0), irregularity within a cross-section (n_1), variation among cross-sections (n_2), obstructions (n_3), vegetation (n_4), and sinuosity (m):

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) * m$$

Suggested values for these factors are in Table 3-1. Detailed guidance for choosing each of these values is provided by many sources, including Arcement and Schneider (1989).

Table 3-1. Values for Cowan equation (Cowan, 1956; Benson and Dalrymple, 1967).

n_0: sediment type	sand	0.026 – 0.035
	gravel	0.028 – 0.035
	cobble	0.030 – 0.050
	boulder	0.040 – 0.070
n_1: irregularity within cross-section	smooth	0.000
	minor	0.005
	moderate	0.010
	severe	0.015
n_2: changes in cross-section area and shape	gradual	0.000
	alternating occasionally	0.005
	alternating frequently	0.010 – 0.015
n_3: effect of obstructions	negligible	0.000
	minor	0.010 – 0.015
	appreciable	0.020 – 0.050
	severe	0.040 – 0.060
n_4: effect of vegetation	low	0.005 – 0.010
	medium	0.010 – 0.025
	high	0.025 – 0.050
	very high	0.050 – 0.100
m: degree of meandering (sinuosity)	minor (1.0 – 1.2)	1.00
	appreciable (1.2 – 1.5)	1.15
	severe (>1.5)	1.30

The need to estimate roughness coefficients is eliminated when a reliable long-term streamflow record exists for a site (Figure 3-5). The USGS stage-discharge relationship can be combined with hydraulic geometry at a cross-section to estimate discharge at the bankfull stage.

(a)

(b)

Figure 3-5. Example of USGS gage station components: a) data recorder/transmitter and b) staff gage and pressure transducer.

As a result, two methods were used to estimate bankfull discharge for the streams in this study. When available, the long-term USGS flow record was reviewed to determine the discharge associated with the bankfull stage identified in the field (USGS, 2020). For the ungaged streams, the Manning equation was applied using estimates for roughness (Manning's n) based on the Cowan method. For some gaged streams in this study, the flow record was not sufficient to determine bankfull discharge. In these cases, the Manning equation was used. Power functions were then used to correlate bankfull discharge, cross-sectional area, width, and mean depth with drainage area (Leopold *et al.*, 1964; Leopold, 1994).

IV. SUMMARY OF STATEWIDE MORPHOLOGY RESULTS

Morphology data were collected from 50 reference and gaged streams across South Carolina within Ecoregions 66, 45, 65, and 63 (Figure 4-1). Across the state, study streams ranged from 5 to 80 feet wide with drainage areas ranging from 0.06 to 94.7 square miles. Eleven of the study sites were located at United States Geological Survey gage stations.

Results of this study should be considered an initial database of reference stream morphology for the State of South Carolina. Additional stream data should be added as more reference streams are identified and measured during assessment and design projects. Stream assessment and restoration practitioners should carefully consider the natural variability demonstrated in these data. Designers should not use this information as the sole basis for planning restoration projects, but should evaluate evidence from hydrologic and hydraulic monitoring and modeling, nearby reference stream morphology, and existing stream conditions in order to determine appropriate restoration design parameters.

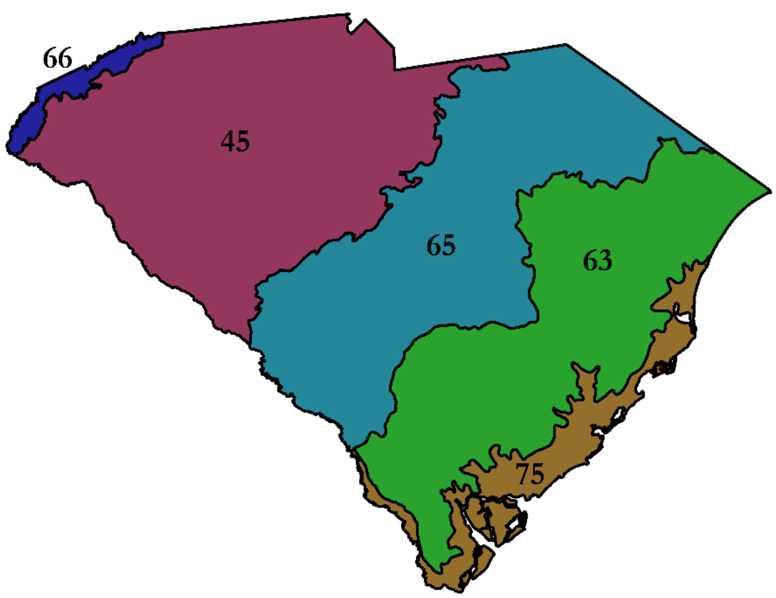


Figure 4-1. EPA Level III Ecoregions of South Carolina (USEPA, 2013).

The study included 6 B, 16 C, and 28 E Rosgen type streams based on the measured entrenchment ratios, width/depth ratios, and slopes. Of the 50 streams, the median streambed particle size (D_{50}) was classified as sand at 39 sites, gravel at 9 sites, and cobble at 2 sites.

For all study sites, the entrenchment ratios, calculated as the width of the floodprone area divided by the bankfull channel width, range from 1.4 to over 10.0. Width/depth ratios, calculated as the bankfull riffle channel width divided by the mean riffle bankfull depth, range from 6.1 to 41.1. Reach channel slopes, measured using water surface elevation differences from the first step or riffle to the last step or riffle surveyed, range from 0.0004 to 0.0555 ft/ft.

Bankfull Channel Dimensions

The regression hydraulic geometry regional curve relationships for the four ecoregions are summarized below, with watershed drainage area (DA) in square miles, channel bankfull area (A_{bkf}) in square feet, channel bankfull width (W_{bkf}) and mean depth (d_{bkf}) in feet, and bankfull discharge (Q_{bkf}) in cubic feet per second.

Ecoregion 66 (Blue Ridge) South Carolina + North Carolina + Tennessee

$A_{bkf} = 20.1\ DA^{0.694}$ $R^2 = 0.972$

$W_{bkf} = 17.7\ DA^{0.400}$ $R^2 = 0.948$

$d_{bkf} = 1.13\ DA^{0.296}$ $R^2 = 0.922$

$Q_{bkf} = 93.4\ DA^{0.771}$ $R^2 = 0.940$

Ecoregion 45 (Piedmont) South Carolina

$A_{bkf} = 16.2\ DA^{0.653}$ $R^2 = 0.959$

$W_{bkf} = 13.3\ DA^{0.350}$ $R^2 = 0.951$

$d_{bkf} = 1.20\ DA^{0.305}$ $R^2 = 0.936$

$Q_{bkf} = 36.5\ DA^{0.699}$ $R^2 = 0.948$

Ecoregion 65 (Southeastern Plains) South Carolina

$A_{bkf} = 6.5\ DA^{0.774}$ $R^2 = 0.924$

$W_{bkf} = 8.7\ DA^{0.356}$ $R^2 = 0.848$

$d_{bkf} = 0.73\ DA^{0.430}$ $R^2 = 0.895$

$Q_{bkf} = 9.2\ DA^{0.830}$ $R^2 = 0.856$

Ecoregion 63 (Middle Atlantic Coastal Plain) South Carolina

$A_{bkf} = 8.0\ DA^{0.797}$ $R^2 = 0.895$

$W_{bkf} = 10.0\ DA^{0.484}$ $R^2 = 0.783$

$d_{bkf} = 0.81\ DA^{0.307}$ $R^2 = 0.632$

$Q_{bkf} = 7.4\ DA^{0.841}$ $R^2 = 0.843$

Figures 4-2 through 4-5 compare individual regional curves for the four ecoregions. Some similarities do exist among ecoregions, though differences among the ecoregions are pronounced. For example, the cross-section area curves for the Blue Ridge (66) and Piedmont (45) are very similar. The same is true for the Southeastern Plains (65) and Middle Atlantic Coastal Plain (63). However, there is a large difference in cross-section area curves between Ecoregions 66/45 and 65/63. This is generally true for width, mean depth, and discharge, though it is most pronounced for cross-section area. Additionally, comparisons between the Blue Ridge and Piedmont regional curves suggest that width/depth ratios differ between those two ecoregions: streams in Ecoregion 66 tend to be wider and shallower, while large streams in Ecoregions 45 tend to be narrower and deeper. These trends, along with additional interpretations of the data, have meaningful consequences for the choice of stream design parameters throughout the state of South Carolina.

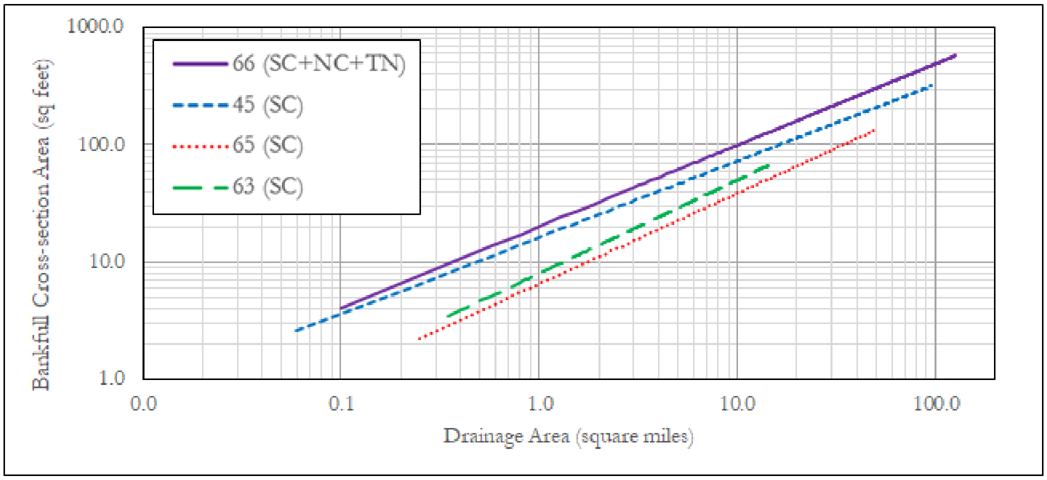


Figure 4-2. Comparison of bankfull riffle cross-section area related to drainage area.

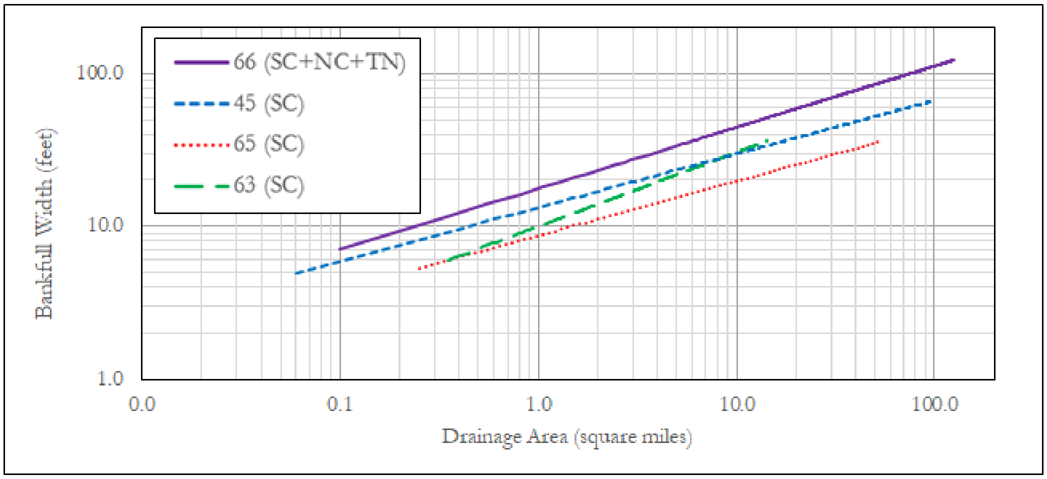


Figure 4-3. Comparison of bankfull riffle cross-section width related to drainage area.

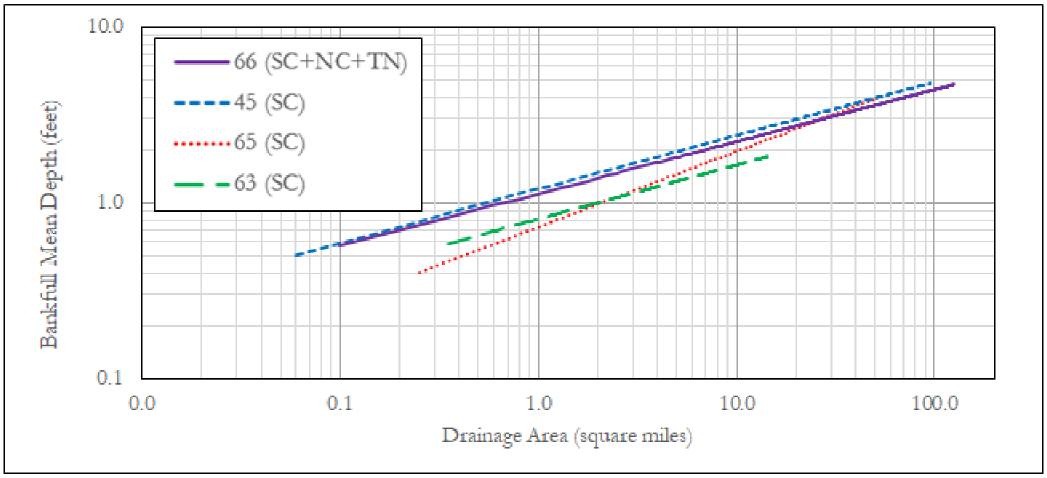


Figure 4-4. Comparison of bankfull riffle cross-section mean depth related to drainage area.

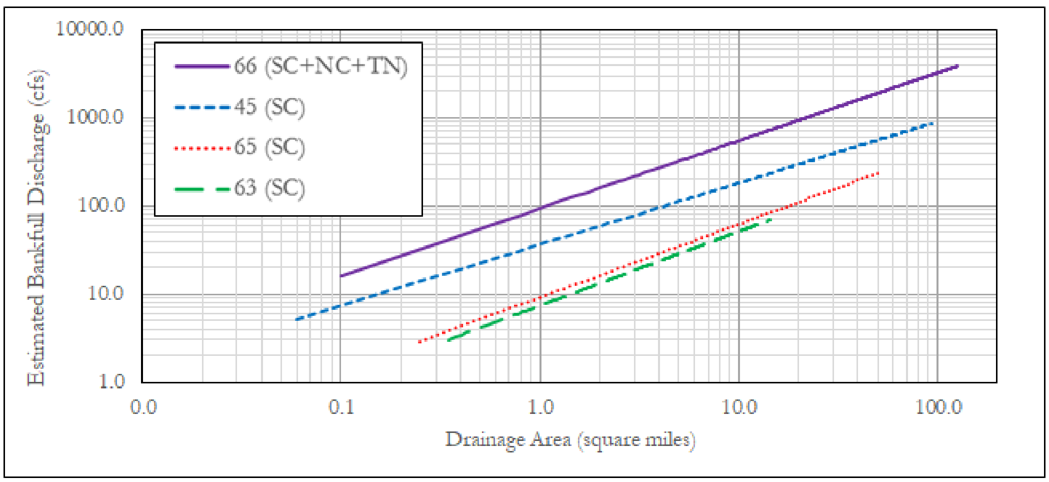


Figure 4-5. Comparison of estimated bankfull discharge related to drainage area.

Stream bedform profile data (i.e., riffle slopes and lengths, pool lengths, and pool spacings) were collected for the subset of reference sites that appeared to have variations in streambed elevations within the reach. This resulted in profile data from Ecoregions 66 and 45. While profile data were collected for some streams in Ecoregion 65, field observations and data analyses did not result in discernable riffle-pool sequences. Rather than riffles and pools, variations in bedform in this ecoregion were generally due to tree roots, vegetation in the channel, woody debris, and accumulations of sand. This is typical of low-slope, sand bed streams in coastal plain ecoregions. As a result, profile data could not effectively be measured for Ecoregion 65. In Ecoregion 63, stream bedform profile data were not collected; in these low-slope, sand bed streams, riffle-pool sequences were not discernible. For the streams in Ecoregions 66 and 45 with measurable profile data, median riffle and pool length ratios range from 0.9 to 4.5 for riffles and 1.0 to 4.0 for pools. Median pool spacing ratios range from 2.0 to 8.7. Median riffle slope ratios range from 1.0 to 2.9 (Table 4-1).

Table 4-1. Summary of Stream Morphology Bedform Profile Parameters.

Ecoregion	Range of Drainage Areas (sq mi)	Range of median riffle length ratios	Range of median pool length ratios	Range of median pool spacing ratios	Range of median riffle slope ratios
66 (Blue Ridge)	0.11 – 2.01	1.4 – 3.3	1.2 – 2.0	2.4 – 3.5	1.0 – 1.7
45 (Piedmont)	0.18 – 4.94	0.9 – 4.5	1.0 – 4.0	2.0 – 8.7	1.0 – 2.9
South Carolina (all sites)	0.11 – 4.94	0.9 – 4.5	1.0 – 4.0	2.0 – 8.7	1.0 – 2.9

Stream pattern data were collected for the meandering reference streams with discernable planform parameters that could be measured in the field. This resulted in pattern data for streams in all four ecoregions. For all streams with measured pattern data, median meander wavelength ratios range from 2.5 to 13.6, median belt width ratios range from 1.3 to 8.1, and median radius of curvature ratios range from 1.2 to 5.6 (Table 4-2).

Table 4-2. Summary of Stream Morphology Pattern Parameters.

Ecoregion	Range of Drainage Areas (sq mi)	Range of median meander wavelength ratios	Range of median belt width ratios	Range of median radius of curvature ratios
66 (Blue Ridge)	0.27 – 0.56	4.7 – 6.3	2.6 – 2.6	2.1 – 2.1
45 (Piedmont)	0.18 – 4.94	3.3 – 10.5	1.7 – 3.4	1.4 – 4.1
65 (Southeastern Plains)	0.38 – 3.61	3.6 – 8.5	1.9 – 3.5	1.4 – 4.8
63 (Middle Atlantic Coastal Plain)	0.35 – 4.99	2.5 – 13.6	1.3 – 8.1	1.2 – 5.6
South Carolina (all sites)	0.18 – 4.99	2.5 – 13.6	1.3 – 8.1	1.2 – 5.6

V. LARGE WOODY DEBRIS

Large Woody Debris (LWD) data were collected and analyzed at all 50 of the streams surveyed for morphology throughout South Carolina. Drainage areas range from 0.06 to 94.7 square miles and reach slopes ranging from 0.0004 to 0.0555 ft/ft (Table 5-1). LWD is defined as dead wood over 1 meter in length and at least 10 cm in diameter. The LWD Index (LWDI) score was calculated for each stream to represent the relative function of the LWD pieces or debris dams in retaining organic matter, providing fish habitat, and affecting channel/substratum stability depending on LWD size, location, orientation, and stability.

The median LWDI score for the 50 streams is 189, with higher median scores in Ecoregions 65 and 63 (Southeastern Plains and Middle Atlantic Coastal Plain); perhaps due to increased numbers of fallen trees and broken limbs and more limited human interventions in these areas. The LWDI results for these 50 streams may be used to compare with disturbed or restored stream systems to evaluate the relative prevalence of LWD in supporting natural stream functions. It should be noted that some disturbed streams could be expected to have high LWDI scores due to unstable streambanks and resulting fallen trees or due to recent storms. In a stream restoration project, LWDI may be enhanced by the strategic addition of logs and woody debris to the restoration channel in the form of vanes, revetments, riffle wood, or other habitat structures.

Reference streams in this study generally had forested floodplains with stable streambanks and watersheds. Typical vegetation included various native hardwood and some evergreen tree species ranging in age from less than 20 to greater than 50 years. Based on field observations, the variability in large woody debris density and functionality found in these reference streams is attributed largely to the natural randomness of fallen trees and broken limbs existing temporarily or long-term within the 100-meter observation reach of each reference stream. Stream systems with recent disturbance due to wind storms, ice, or floods seemed to have more LWD pieces and debris dams.

Results of this study should be considered an initial database of reference stream large woody debris information. The database developed in this study should be supplemented with additional data collected on reference, disturbed, and restored streams using the same quantification method to support future analyses of LWD in South Carolina streams.

Table 5-1. LWD reference stream characteristics for each ecoregion and statewide.

Ecoregion	Number of Reference Streams	Range of Drainage Areas (sq mi)	Range of Slopes (ft/ft)
66 (Blue Ridge)	6	0.11 – 20.8	0.0066 – 0.0555
45 (Piedmont)	14	0.06 – 94.7	0.0005 – 0.0143
65 (Southeastern Plains)	15	0.25 – 51.9	0.0004 – 0.0113
63 (Middle Atlantic Coastal Plain)	15	0.35 – 14.3	0.0004 – 0.0065
South Carolina (all sites)	50	0.06 – 94.7	0.0004 – 0.0555

LWD data were collected and analyzed using the protocol described by Harman *et al.* (2017). The Large Woody Debris Index (LWDI) was calculated as outlined by the U.S. Forest Service (USFS) General Technical Report Monitoring Wilderness Stream Ecosystems (Davis *et al.*, 2001). Following this methodology, "Large woody debris is described as the organic matter over 1 meter in length and at least 10 cm in diameter at one end (sticks to logs). When multiple pieces of debris accumulate in the stream channel and retard water flow, a debris dam is formed" (Davis *et al.*, 2001). The LWDI score represents the relative function of the large woody debris pieces or debris dams in retaining organic matter, providing fish habitat, and affecting channel/substratum stability depending on LWD size, location, orientation, and stability of the wood piece or debris dam.

For each reference stream, a 100-meter reach was selected where it would produce the highest LWDI score based on observed density of LWD pieces and debris dams. Each LWD piece observed within the sampling reach was scored from 1 to 5 based on functionality in the categories of length, diameter, location, type, structure, stability, and orientation. Increasing scores indicated greater contributions to stream functions within each category. Each LWD debris dam consisting or 3 or more touching LWD pieces was scored from 1 to 5 in the categories of length, height, structure, location, and stability.

Within each score box on the LWD data sheet, the number of observed LWD pieces or debris dams fitting into that box was multiplied by the score for that box, and these values were summed across each category to produce a total category score. The total piece score and total dam score were calculated by summing the category scores for pieces and dams, respectively. Since debris dams are considered more important in contributing to stream functions, the total dam score was multiplied by a factor of 5 and added to the total piece score to determine the total LWDI score for each reference stream. LWDI summary results for the 50 reference streams in the ecoregions are listed in Table 5-2. For each ecoregion, example reference stream photos are shown in Figures 5-1 through 5-4.

Table 5-2. LWDI summary results for each ecoregion and for the 50 sites statewide.

Ecoregion	Median LWDI	25th Percentile LWDI	75th Percentile LWDI	Range of LWDI
66 (Blue Ridge)	161	126	207	74 – 275
45 (Piedmont)	137	111	186	83 – 265
65 (Southeastern Plains)	202	156	296	117 – 514
63 (Middle Atlantic Coastal Plain)	240	169	345	106 – 454
South Carolina (all sites)	189	135	265	74 - 514

As an example, in Ecoregion 66, UT Matthews Creek (Site 1) contained 14 LWD pieces and no debris dams in the sample reach with a drainage area of 0.11 square miles, slope of 0.0350 ft/ft, and bankfull dimensions of 9.9 feet wide and 0.6 feet deep (Figure 5-1). The piece score of 275 and dam score of 0 were used to calculate the LWDI score of 275 for this reference stream, the highest score of Ecoregion 66 streams.

Figure 5-1. UT Matthews Creek (Ecoregion 66) reference stream photo showing LWD pieces.

In Ecoregion 45, Allison Creek (Site 12) contained 10 LWD pieces and 1 debris dam in the sample reach with a drainage area of 40.4 square miles, slope of 0.0015 ft/ft, and bankfull dimensions of 48.9 feet wide and 5.1 feet deep (Figure 5-2). The piece score of 174 and dam score of 15 were used to calculate the LWDI score of 249 for this reference stream, the second-highest score of Ecoregion 45 streams.

Figure 5-2. Allison Creek (Ecoregion 45) reference stream photo showing LWD pieces and debris dam.

In Ecoregion 65, Toby Creek (Site 10) contained 14 LWD pieces and 1 debris dam in the sample reach with a drainage area of 10.7 square miles, slope of 0.0015 ft/ft, and bankfull dimensions of 20.4 feet wide and 2.0 feet deep (Figure 5-3). The piece score of 310 and dam score of 12 were used to calculate the LWDI score of 370 for this reference stream, the third-highest score of Ecoregion 65 streams.

Figure 5-3. Toby Creek (Ecoregion 65) reference stream photo showing LWD pieces and debris dam.

In Ecoregion 63, Big Branch (Site 8) contained 7 LWD pieces and no debris dams in the sample reach with a drainage area of 2.03 square miles, slope of 0.0019 ft/ft, and bankfull dimensions of 14.2 feet wide and 1.2 feet deep (Figure 5-4). The piece score of 155 and dam score of 0 were used to calculate the LWDI score of 155 for this reference stream, among the lowest scores of Ecoregion 63 streams.

Figure 5-4. Big Branch (Ecoregion 63) reference stream photo showing LWD pieces.

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South Carolina Blue Ridge, Ecoregion 66
Stream Morphology Results

In the South Carolina Blue Ridge, Ecoregion 66, six streams were visited in April 2019, to collect geomorphic data for comparison to hydraulic geometry regional curves available for the Blue Ridge Ecoregion in North Carolina and Tennessee (Figure 1 and Table 1). Site 6 is an active USGS gage on the Middle Saluda River with a watershed drainage area of 20.8 square miles. The other five sites are reference streams in forested watersheds with drainage areas ranging from 0.11 to 2.01 square miles.

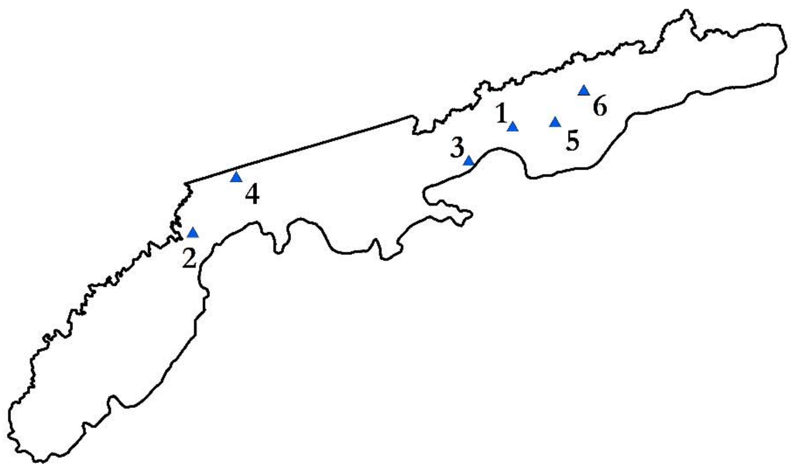

Figure 1. Reference Stream Sites in Ecoregion 66, South Carolina.

Table 1. Reference Stream Sites.

Site	Stream name	Source/Location	Latitude	Longitude	Drainage area (mile^2)
1	UT Matthews Creek	Asbury Hills Camp	35.075628	-82.638887	0.11
2	Crane Creek	Sumter National Forest	34.943975	-83.095603	0.27
3	Green Creek	Table Rock State Park	35.034476	-82.701337	0.35
4	Howard Creek	Sumter National Forest	35.010530	-83.034919	0.56
5	Wattacoo Creek	Naturaland Trust	35.081739	-82.578104	2.01
6	Middle Saluda River	USGS gage	35.120115	-82.537465	20.8

The Middle Saluda River USGS gage station was included in this study because the long-term records for flow stage and discharge can be used to quantify the specific channel-forming discharge exceedance probability for bankfull conditions. Discharge can be reported in terms of exceedance probability (or return period) to assist in determining channel-forming discharges and morphological indicators in ungaged watersheds. The Middle Saluda gage site is at a stable stream location in a relatively undisturbed watershed with field indicators of bankfull stage near a riffle downstream of the gage.

The reference streams in this Ecoregion were selected in consultation with SCDNR and other local stream professionals to identify reference reaches generally based on the following criteria:

- Watersheds with drainage areas ranging between approximately 0.1 and 10 square miles (with the exception of the USGS gage station)
- Watersheds with stable land use, mostly forested, over the past several decades
- Stream channels and floodplains in equilibrium with active bankfull stage indicators (bank height ratios near 1.0)
- Stream channels with freely-formed meander patterns in low-gradient valleys and natural step-pool bedforms in high-gradient valleys
- No valley restrictions throughout the reference reach or upstream/downstream that may influence channel form
- Healthy riparian forest buffers
- Accessible for data collection and protected for future access

For each stream site, field data on stream geomorphological characteristics were collected to establish hydraulic geometry relationships, in addition to collecting large woody debris (LWD) information[1]. The geomorphological characteristics were collected following the methods outlined in the most revised version of the North Carolina SQT Field User Manual[2] and the LWD assessment was in accordance with the most revised version of the Application of the Large Woody Debris Index Field User Manual developed by Stream Mechanics and Ecosystem Planning & Restoration. All reference stream assessments included collection of dimension (cross-sectional) data. As conditions allowed, pattern and profile data were collected for a subset of the reference sites.

Data collected at all reference sites included:

- Rosgen stream type
- valley type
- drainage area (DA)
- bankfull riffle cross-section area (A_{bkf})
- bankfull riffle width (W_{bkf}) and mean depth (d_{bkf}) for calculating width-to-depth ratio (WDR)
- width of floodprone area (W_{fpa}) for calculating entrenchment ratio (ER)
- maximum depth at top of bank and bankfull stage for calculating bank height ratio (BHR)
- channel water surface slope (S)
- sinuosity (k)
- median substrate size classification
- estimated Manning roughness coefficient (n)

The subset of reference sites with profile data included collection of:

- riffle slopes (S_{riffle})
- riffle lengths (L_{riffle})
- pool spacings (p-p)
- pool lengths (L_{pool})

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[1] Large Woody Debris Assessment https://stream-mechanics.com/wp-content/uploads/2017/12/LWDI-Manual_V1.pdf

[2] NC SQT https://stream-mechanics.com/wp-content/uploads/2017/09/Data-Collection-and-Analysis-Manual_NC-SQT-v3.0.pdf; currently under revision.

The subset of reference sites with pattern data included collection of:

- meander wavelengths ($L_{meander}$)
- belt widths (W_{blt})
- radius of curvature of meander bends (R_c)

Field measurement results are presented in the appendix and in the tables and graphs below. Table 2 summarizes riffle cross-section dimension geomorphic parameters used for Rosgen stream classification. Most of the streams in Ecoregion 66 are B streams with typical entrenchment ratios of about 2. One reference stream is an E stream with a wider valley and entrenchment ratio exceeding 3. Width/depth ratios are highly variable, ranging from 8 to 16.

Table 2. Morphology Dimensions.

Site	Drainage area (mile²)	Channel slope (ft/ft)	Cross-section area (ft²)	Bankfull width (ft)	Bankfull mean depth (ft)	Width/ depth ratio	Entrench-ment ratio	Rosgen Stream Class
1	0.11	0.0350	6.0	9.9	0.6	16.2	2.0	B4
2	0.27	0.0171	6.0	8.4	0.7	11.8	1.8	B4c
3	0.35	0.0555	10.7	11.2	1.0	11.7	2.5	B3a
4	0.56	0.0136	13.4	11.2	1.2	9.3	3.6	E4
5	2.01	0.0066	36.1	17.7	2.0	8.7	1.8	B4c
6	20.8	0.0067	166.8	50.4	3.3	15.2	2.0	B3c

Table 3 summarizes estimated bankfull hydraulic parameters (velocity and discharge) for each stream based on gage station data if available and the Manning equation for ungaged streams. The Manning equation, in English units, is:

$$v = \frac{1.486 * \left(R^{2/3}\right) * \left(S^{1/2}\right)}{n}$$

where v is average velocity (feet/second), R is the hydraulic radius (feet), S is average water surface slope (feet/feet), and n is a dimensionless coefficient describing channel roughness, known as Manning's n, which ranges from 0.033 to 0.150 for natural channels. The Cowan (1956) method was used to estimate the Manning's n values based on sediment size, irregularity within a cross-section, variation among cross-sections, obstructions, vegetation, and sinuosity. The bankfull discharge is estimated as the product of average velocity and riffle bankfull cross-section area.

For these six streams, Manning's n values range from 0.047 to 0.060, which match expected values for natural mountain streams. Estimated bankfull average velocities for the study streams range from 2.6 to 5.1, with variations due primarily to slope and bankfull depth.

Table 3. Estimated Bankfull Hydraulic Parameters.

Site	Drainage area (mile²)	Manning's n	Estimated Bankfull Velocity (ft/s)	Estimated Bankfull Discharge (cfs)
1	0.11	0.047	4.0	24
2	0.27	0.054	2.6	16
3	0.35	0.060	5.1	55
4	0.56	0.054	3.2	43
5	2.01	0.047	3.6	131
6	20.8	*	4.8	794

* Bankfull velocity and discharge were determined using the USGS gage stage-discharge relationship for the field-measured bankfull stage, rather than the Manning equation.

The graphs in Figures 2 through 5 show relationships of measured riffle bankfull morphological parameters and estimated discharge to watershed drainage area (i.e. regional curves). The six data points representing South Carolina streams are plotted along with reference data from Ecoregion 66 in North Carolina and Tennessee. The best fit regression lines represent the combination of data from all three states.

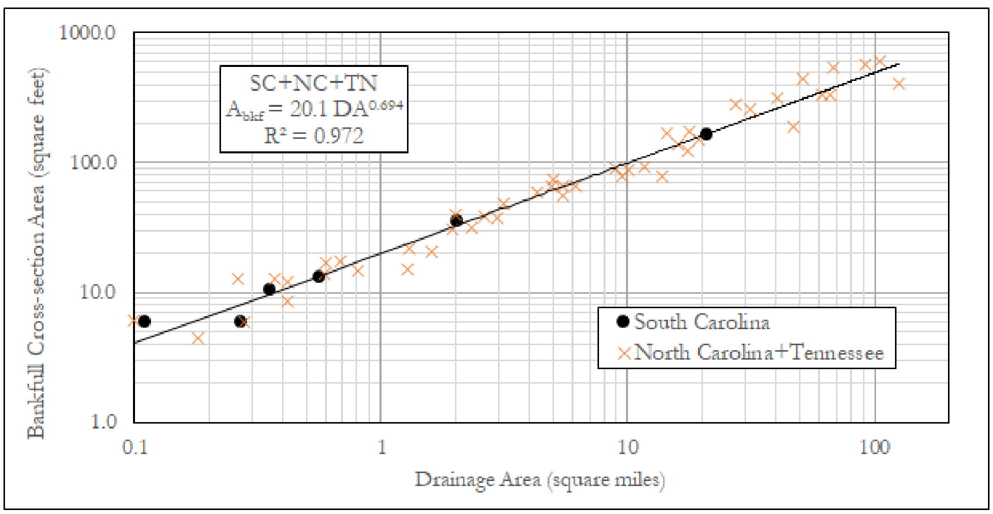


Figure 2. Bankfull riffle cross-section area related to drainage area for Ecoregion 66 streams with best-fit regression equations for SC+NC+TN.

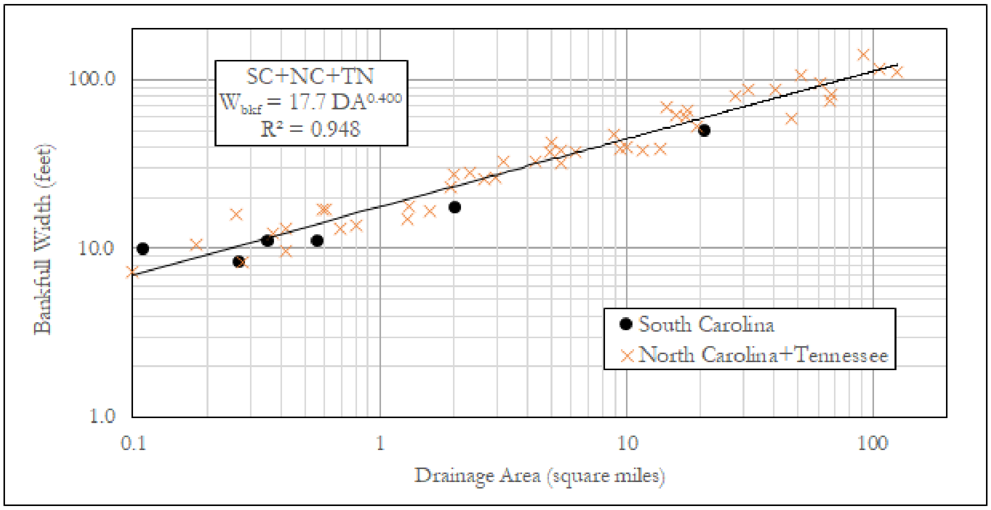


Figure 3. Bankfull riffle cross-section width related to drainage area for Ecoregion 66 streams with best-fit regression equations for SC+NC+TN.

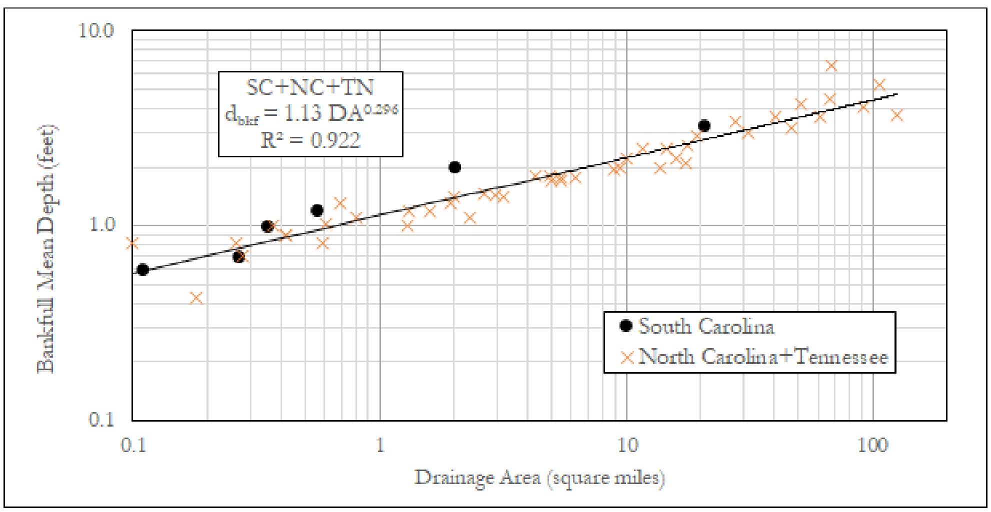


Figure 4. Bankfull riffle mean depth related to drainage area for Ecoregion 66 streams with best-fit regression equations for SC+NC+TN.

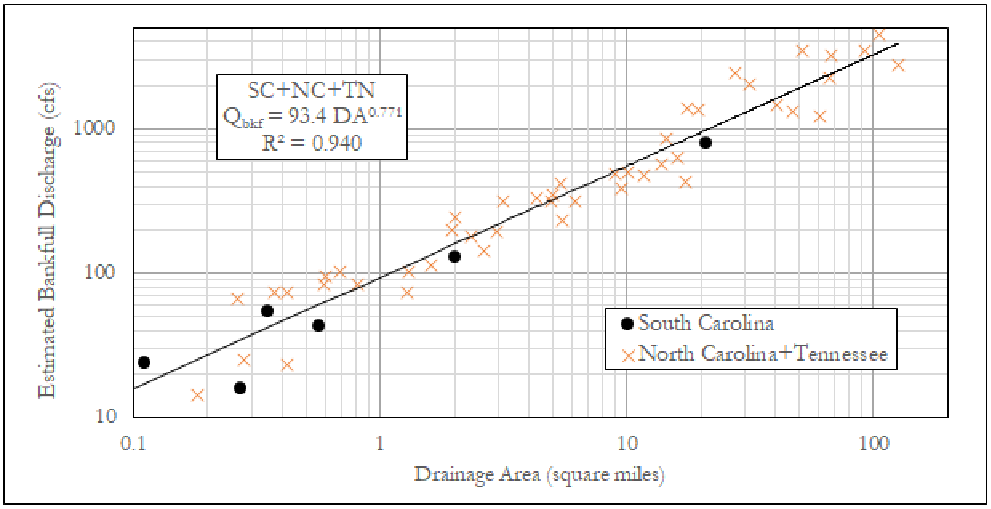


Figure 5. Estimated bankfull discharge related to drainage area for Ecoregion 66 streams with best-fit regression equations for SC+NC+TN.

The South Carolina stream parameters generally fit within the variability measured within this ecoregion in North Carolina and Tennessee. Overall, the South Carolina stream information matches well with North Carolina and Tennessee data, suggesting that the composite South Carolina + North Carolina + Tennessee regional curves are appropriate for use in Ecoregion 66 in South Carolina.

Table 4 summarizes stream bedform profile data for the reference streams with discernable riffle-pool sequences. Median riffle and pool length ratios range from 1.4 to 3.3 for riffles and 1.2 to 2.0 for pools. Median pool spacing ratios range from 2.4 to 3.5. Median riffle slope ratios range from 1.0 to 1.7. Median step height ratios for the two reference streams with discernable steps range from 0.06 to 0.10. For each stream, the median profile parameters and the median dimensionless ratios are listed. These profile parameter ratios are similar to those measured in reference streams within Ecoregion 66 in North Carolina and Tennessee.

Table 5 summarizes stream pattern data for the 2 meandering reference streams with discernable planform parameters. Median meander wavelength ratios for this small sample size range from 4.7 to 6.3, belt width ratios are 2.6, and radius of curvature ratios are 2.1. For each stream, the median pattern parameters and the median dimensionless ratios are listed. These pattern parameter ratios are similar to those observed in reference streams within Ecoregion 66 in North Carolina and Tennessee.

Table 4. Stream Morphology Bedform Profile Parameters.

Site	Drainage area (mile^2)	Median riffle length [ratio to bankfull width] (ft [none])	Median pool length [ratio to bankfull width] (ft [none])	Median pool spacing [ratio to bankfull width] (ft [none])	Median riffle slope [ratio to channel slope] (ft/ft [none])	Median step height [ratio to bankfull width] (ft [none])
1	0.11	16.5 [1.7]	11.5 [1.2]	24.0 [2.4]	0.0348 [1.0]	0.64 [0.06]
2	0.27	11.5 [1.4]	13.0 [1.5]	20.0 [2.4]	0.0280 [1.6]	-
3	0.35	37.0 [3.3]	14.0 [1.3]	35.5 [3.2]	0.0668 [1.2]	1.13 [0.10]
4	0.56	30.0 [2.7]	20.0 [1.8]	39.0 [3.5]	0.0220 [1.6]	-
5	2.01	55.0 [3.1]	36.0 [2.0]	58.0 [3.3]	0.0114 [1.7]	-

Table 5. Stream Morphology Pattern Parameters.

Site	Drainage area (mile^2)	Sinuosity (ft/ft)	Median meander wavelength [ratio to bankfull width] (ft [none])	Median belt width [ratio to bankfull width] (ft [none])	Median radius of curvature [ratio to bankfull width] (ft [none])
2	0.27	1.30	53 [6.3]	22 [2.6]	18 [2.1]
4	0.56	1.30	53 [4.7]	29 [2.6]	24 [2.1]

Table 6 summarizes Large Woody Debris (LWD) assessments for each stream, including the numbers of LWD pieces and dams and the LWD Index scores. The LWDI is 74 at the USGS gage and ranges from 123 to 275 at the five reference streams.

Table 6. Large Woody Debris Assessment Results for Reference Streams, Ecoregion 66.

Site	Number of Pieces	Number of Dams	Piece Score	Dam Score	LWDI
1	14	0	275	0	275
2*	7	0	135	0	135
3	10	0	187	0	187
4*	6	1	124	18	214
5	7	0	123	0	123
6	4	0	74	0	74

* The United States Forest Service indicated that LWD has historically been added to Crane Creek (Site 2) and Howard Creek (Site 4). The LWD assessment results may be affected by this manipulation.

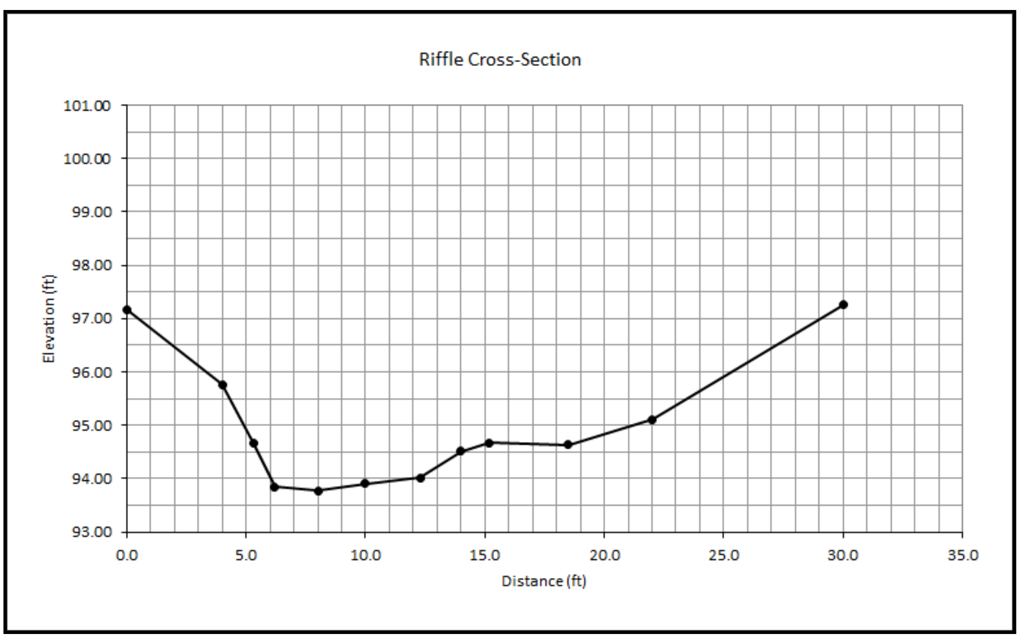
APPENDIX

ECOREGION 66, SOUTH CAROLINA

1. UT Matthews Creek
Ecoregion 66, South Carolina

Latitude: 35.075628
Longitude: -82.638887
Drainage area: 0.11 square miles
Median particle size: gravel
Longitudinal slope: 0.0350 feet/foot
Stream classification: B4

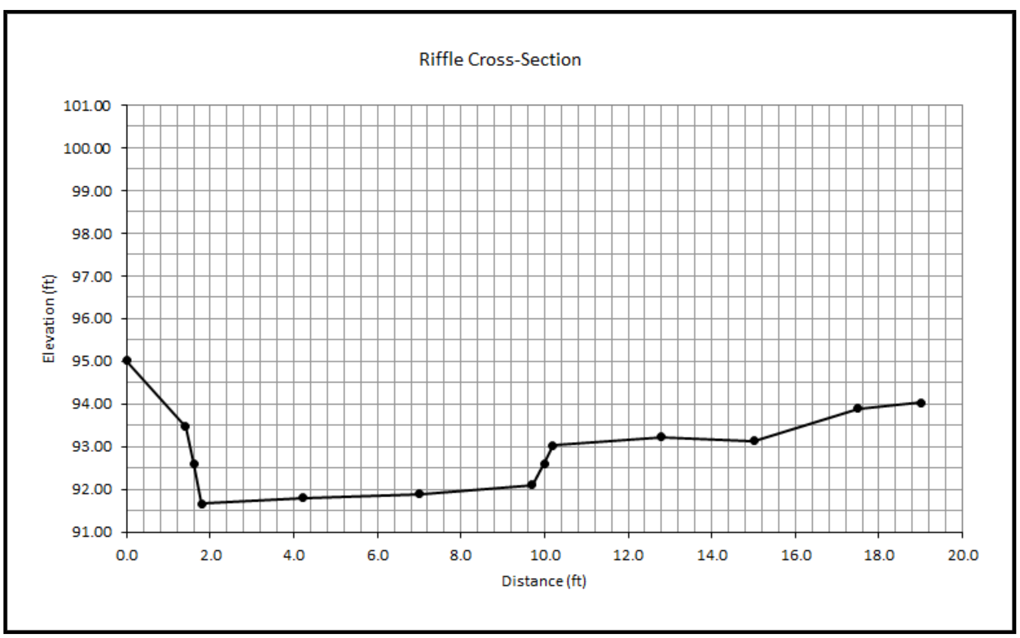
Area (square feet) =	6.0
Width (feet) =	9.9
Mean depth =	0.6
Max depth =	0.9
Width/depth ratio =	16.2
Entrenchment ratio =	2.0



2. Crane Creek
Ecoregion 66, South Carolina

Latitude: 34.943975
Longitude: -83.095603
Drainage area: 0.27 square miles
Median particle size: gravel
Longitudinal slope: 0.0171 feet/foot
Stream classification: B4c

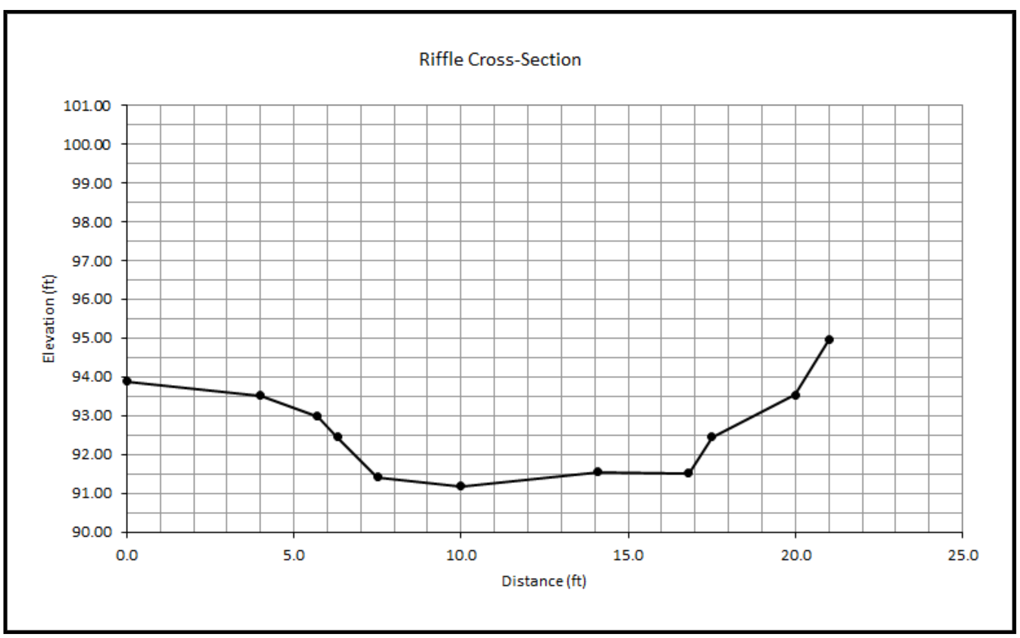
Area (square feet) =	6.0
Width (feet) =	8.4
Mean depth =	0.7
Max depth =	0.9
Width/depth ratio =	11.8
Entrenchment ratio =	1.8



3. Green Creek
Ecoregion 66, South Carolina

Latitude: 35.034476
Longitude: -82.701337
Drainage area: 0.35 square miles
Median particle size: cobble
Longitudinal slope: 0.0555 feet/foot
Stream classification: B3a

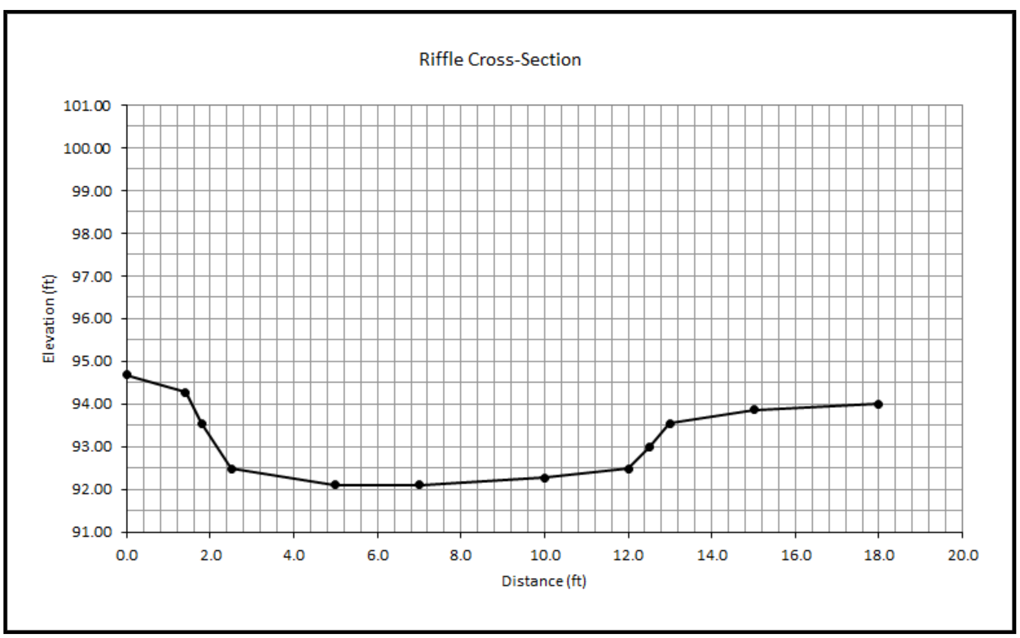
Area (square feet) =	10.7
Width (feet) =	11.2
Mean depth =	1.0
Max depth =	1.3
Width/depth ratio =	11.7
Entrenchment ratio =	2.5



4. Howard Creek
Ecoregion 66, South Carolina

Latitude: 35.010530
Longitude: -83.034919
Drainage area: 0.56 square miles
Median particle size: gravel
Longitudinal slope: 0.0136 feet/foot
Stream classification: E4

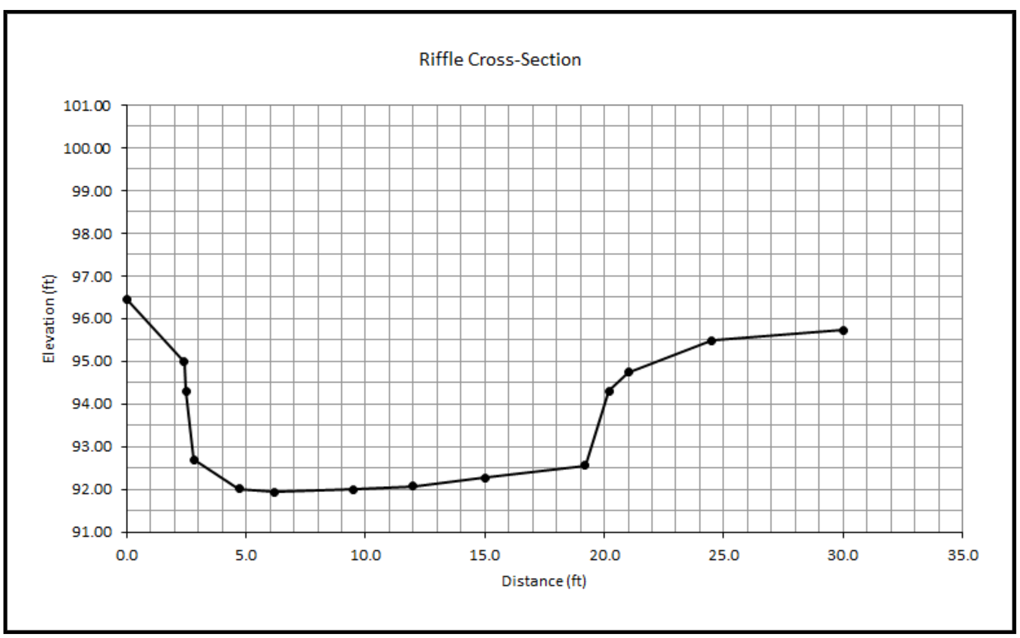
Area (square feet) =	13.4
Width (feet) =	11.2
Mean depth =	1.2
Max depth =	1.5
Width/depth ratio =	9.3
Entrenchment ratio =	3.6



5. Wattacoo Creek
Ecoregion 66, South Carolina

Latitude: 35.081739
Longitude: -82.578104
Drainage area: 2.01 square miles
Median particle size: gravel
Longitudinal slope: 0.0066 feet/foot
Stream classification: B4c

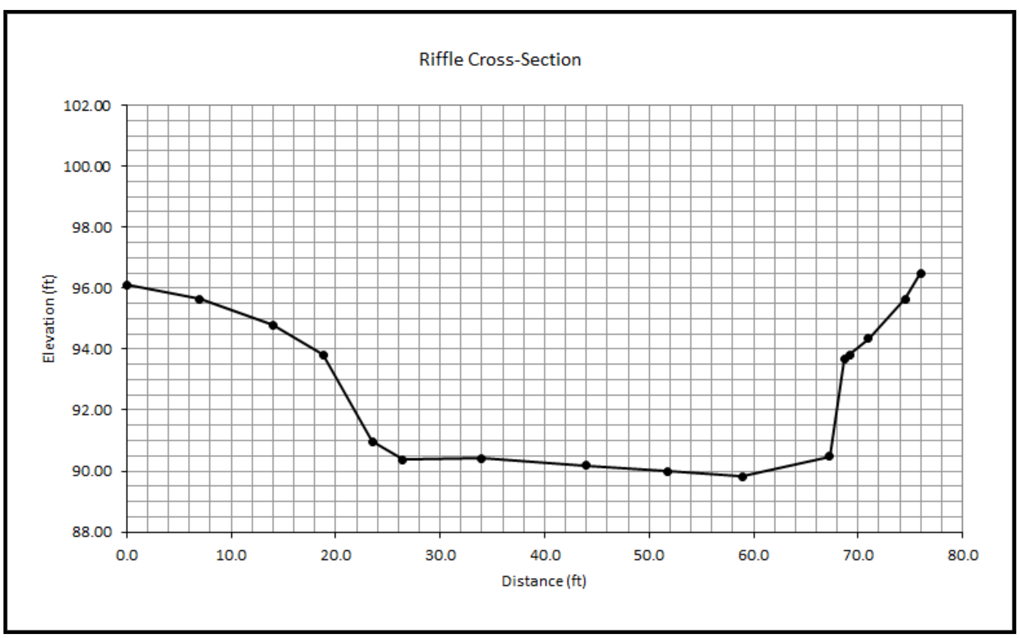
Area (square feet) =	36.1
Width (feet) =	17.7
Mean depth =	2.0
Max depth =	2.4
Width/depth ratio =	8.7
Entrenchment ratio =	1.8



6. Middle Saluda River
Ecoregion 66, South Carolina

Latitude: 35.120115
Longitude: -82.537465
Drainage area: 20.8 square miles
Median particle size: cobble
Longitudinal slope: 0.0067 feet/foot
Stream classification: B3c

Area (square feet) =	166.8
Width (feet) =	50.4
Mean depth =	3.3
Max depth =	4.0
Width/depth ratio =	15.2
Entrenchment ratio =	2.0



South Carolina Piedmont, Ecoregion 45
Stream Morphology Results

In the South Carolina Piedmont, Ecoregion 45, geomorphic data were collected from 14 streams between October and December 2019 (Figure 1 and Table 1). Seven sites are at USGS gage stations with drainage areas ranging from 9.73 to 94.7 square miles, while the remaining seven are ungaged reference streams in forested watersheds with drainage areas ranging from 0.06 to 4.94 square miles. Several other streams were visited to evaluate their potential for inclusion in this study but were rejected due to local instability or other factors affecting their geomorphic conditions.

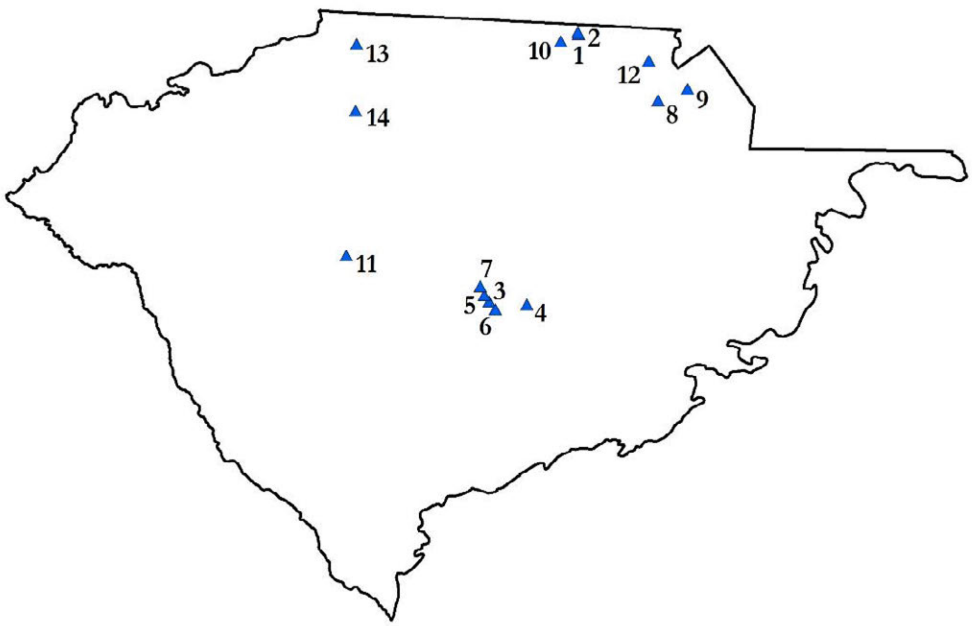


Figure 1. Reference Stream Sites in Ecoregion 45, South Carolina.

Table 1. Reference Stream Sites.

Site	Stream name	Source/Location	Latitude	Longitude	Drainage area ($mile^2$)
1	UT2 Long Branch	Kings Mountain NMP	35.137778	-81.376944	0.06
2	UT1 Long Branch	Kings Mountain NMP	35.144167	-81.378611	0.18
3	UT Indian Creek	Sumter National Forest	34.393515	-81.673764	0.18
4	UT Kings Creek	Sumter National Forest	34.385354	-81.546552	0.32
5	Pages Creek	Sumter National Forest	34.410620	-81.689626	2.02
6	Joshuas Branch	Sumter National Forest	34.372311	-81.653166	2.98
7	Headleys Creek	Sumter National Forest	34.435460	-81.703539	4.94
8	Tools Fork Creek	USGS Gage	34.954997	-81.106668	9.73
9	Big Dutchman Creek	USGS Gage	34.986998	-81.007374	16.8
10	Kings Creek	USGS Gage	35.118134	-81.437161	27.9
11	South Rabon Creek	USGS Gage	34.517892	-82.155741	30.0
12	Allison Creek	USGS Gage	35.065105	-81.138798	40.4
13	South Pacolet River	USGS Gage	35.106304	-82.129122	55.6
14	South Tyger River	USGS Gage	34.920927	-82.129849	94.7

The USGS gage stations were included in this study because long-term records for flow stage and discharge can be used to quantify the specific channel-forming discharge exceedance probability for bankfull conditions. Discharge can be reported in terms of exceedance probability (or return period) to assist in determining channel-forming discharges and morphological indicators in ungaged watersheds. The chosen gage sites are at stable stream locations in relatively undisturbed watersheds with field indicators of bankfull stage at riffles near the gages.

The ungaged reference streams in this ecoregion were selected through consultation with SCDNR and other local stream professionals, as well as extensive field reconnaisance. Reference reaches were identified generally based on the following criteria:

- Streams with drainage areas ranging between approximately 0.1 and 10 square miles (with the exception of USGS gage stations)
- Watersheds with stable land use and mostly forested over the past several decades
- Stream channels and floodplains in equilibrium with active bankfull stage indicators (i.e., bank height ratios near 1.0)
- Stream channels with freely-formed meander patterns in low-gradient valleys (less than 2% longitudinal slope)
- No valley restrictions throughout the reference reach or upstream/downstream that may influence channel form
- Healthy riparian forest buffers
- Accessible for data collection and protected for future access

Field measurements of stream geomorphological characteristics were collected to establish hydraulic geometry relationships following the methods outlined in the most current version of the North Carolina SQT Field User Manual[1]. All stream assessments included collection of bankfull riffle dimension (cross-section) data. As conditions allowed, pattern and profile data were collected for a subset of the reference sites.

Data collected at all reference sites included:

- Rosgen stream type
- drainage area (DA)
- bankfull riffle cross-section area (A_{bkf})
- bankfull riffle width (W_{bkf}) and mean depth (d_{bkf}) for calculating width-to-depth ratio (WDR)
- width of floodprone area (W_{fpa}) for calculating entrenchment ratio (ER)
- maximum depth at top of bank and bankfull stage for calculating bank height ratio (BHR)
- channel water surface slope (S)
- sinuosity (k)
- median substrate size classification
- estimated Manning roughness coefficient (n)

The subset of reference sites with pattern and profile data included collection of:

- riffle slopes (S_{riffle})
- riffle lengths (L_{riffle})
- pool spacings (p-p)
- pool lengths (L_{pool})
- meander wavelengths ($L_{meander}$)
- belt widths (W_{blt})
- radius of curvature of meander bends (R_c)

Large woody debris (LWD) information was collected in accordance with the most current version of the Application of the Large Woody Debris Index Field User Manual developed by Stream Mechanics and Ecosystem Planning & Restoration[2].

Field measurement results are presented in the appendix and in the tables and graphs below. Table 2 summarizes riffle cross-section dimension geomorphic parameters used for Rosgen stream classification. Most of the streams in Ecoregion 45 are C and E streams, typically with high entrenchment ratios. Width/depth ratios are generally between 9 and 14, with the exception of 7.7 for one of the smaller streams and near 16 for the two largest rivers. Entrenchment ratios are typically high. Six of the valleys were so wide that they precluded exact measurement; in these cases, entrenchment ratios are reported as >10.0.

[1] NC SQT https://stream-mechanics.com/wp-content/uploads/2017/09/Data-Collection-and-Analysis-Manual_NC-SQT-v3.0.pdf; currently under revision.

[2] Large Woody Debris Assessment https://stream-mechanics.com/wp-content/uploads/2017/12/LWDI-Manual_V1.pdf

Table 2. Morphology Dimensions.

Site	Drainage area (mile²)	Channel slope (ft/ft)	Cross-section area (ft²)	Bankfull width (ft)	Bankfull mean depth (ft)	Width/depth ratio	Entrench-ment ratio	Rosgen Stream Class
1	0.06	0.0118	4.7	7.0	0.7	10.5	3.3	E4
2	0.18	0.0143	4.6	7.2	0.6	11.3	>10.0	E4
3	0.18	0.0082	4.0	6.3	0.6	9.9	>10.0	E5
4	0.32	0.0077	6.5	7.1	0.9	7.7	>10.0	E5
5	2.02	0.0028	30.6	19.0	1.6	11.8	>10.0	E5
6	2.98	0.0032	28.9	20.4	1.4	14.4	>10.0	C5
7	4.94	0.0048	25.4	16.6	1.5	10.8	>10.0	E5
8	9.73	0.0019	108.5	35.6	3.0	11.7	6.5	E5
9	16.8	0.0016	116.4	35.7	3.3	11.0	1.4	B5c
10	27.9	0.0026	109.9	34.9	3.1	11.1	2.4	E4
11	30.0	0.0033	106.7	37.7	2.8	13.3	6.6	C5
12	40.4	0.0015	250.2	48.9	5.1	9.5	3.9	E5
13	55.6	0.0025	242.1	62.8	3.9	16.3	5.5	C5
14	94.7	0.0005	388.2	80.3	4.8	16.6	3.2	C5c-

Table 3 summarizes estimated bankfull hydraulic parameters (velocity and discharge) for each stream based on gage station data (if available) or the Manning equation for ungaged streams. The Manning equation, in English units, is:

$$v = \frac{1.486 * \left(R^{2/3}\right) * \left(S^{1/2}\right)}{n}$$

where v is average velocity (feet/second), R is the hydraulic radius (feet), S is average water surface slope (feet/feet), and n is a dimensionless coefficient describing channel roughness, known as Manning's n, which ranges from 0.033 to 0.150 for natural channels. The Cowan (1956) method was used to estimate the Manning's n values based on sediment size, irregularity within a cross-section, variation among cross-sections, obstructions, vegetation, and sinuosity. The bankfull discharge is estimated as the product of average velocity and riffle bankfull cross-section area.

For these streams, Manning's n values range from 0.045 to 0.054, which match expected values for natural alluvial streams in the Piedmont. Estimated bankfull average velocities for the study streams range from 1.9 to 4.1, with variations due primarily to slope and cross-section dimensions.

Table 3. Estimated Bankfull Hydraulic Parameters.

Site	Drainage area (mile^2)	Manning's n	Estimated Bankfull Velocity (ft/s)	Estimated Bankfull Discharge (cfs)
1	0.06	0.047	2.3	11
2	0.18	0.047	2.5	11
3	0.18	0.045	2.0	7.9
4	0.32	0.052	2.0	13
5	2.02	0.052	1.9	57
6	2.98	0.052	1.9	54
7	4.94	0.052	2.4	60
8	9.73	*	2.1	232
9	16.8	0.045	2.6	300
10	27.9	0.054	2.7	296
11	30.0	0.052	3.0	320
12	40.4	*	3.4	855
13	55.6	*	4.1	993
14	94.7	0.048	1.9	736

* Bankfull velocity and discharge were determined using the USGS gage stage-discharge relationship for the field-measured bankfull stage, rather than the Manning equation

The graphs in Figures 2 through 5 show riffle bankfull morphological parameters and estimated discharge related to watershed drainage area (i.e., regional curves). These graphs include data points measured in the Piedmont ecoregion of both South Carolina and North Carolina. North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina. The North Carolina data represent a combination of nine USGS gages from Harman, et al. (1999) and 16 reference streams from Lowther (2008). North Carolina data are not included in Figure 5 due to minor differences in the methodologies used to estimate bankfull discharge. Figures 2 through 5 also include best-fit regression lines for each data set in addition to the regression equations and coefficients of determination.

Figures 2 through 4 demonstrate that measured bankfull riffle cross-section area, width, and depth are typically slightly smaller in the South Carolina streams than in the assessed North Carolina streams. One reason for this result may be that many of the sites measured in South Carolina were in protected, forested watersheds with little or no impervious surface (e.g., Sumter National Forest, Kings Mountain National Military Park). These undisturbed, forested watersheds tend to dampen peak flow responses to rainfall. Additionally, USGS gage stations are abundant in the Piedmont of South Carolina, which allowed for selection of the highest-quality gaged streams for inclusion in this study. The cross-section dimensions for South Carolina streams are validated by most streams having a bankfull elevation equal to the top of bank (i.e., Bank Height Ratio = 1.0) and gages with a long-term record having a return interval of around 1.30 years for the bankfull discharge.

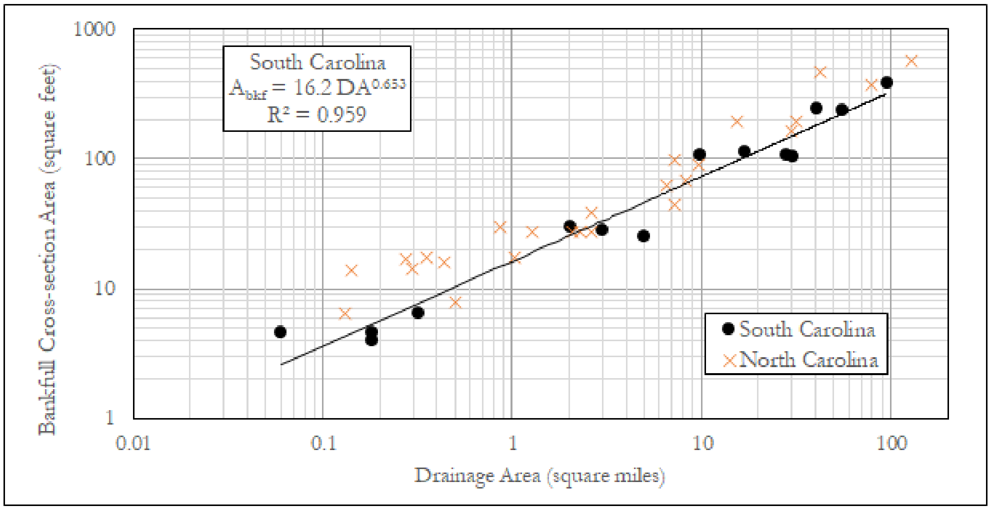


Figure 2. Bankfull riffle cross-section area related to drainage area for Ecoregion 45 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

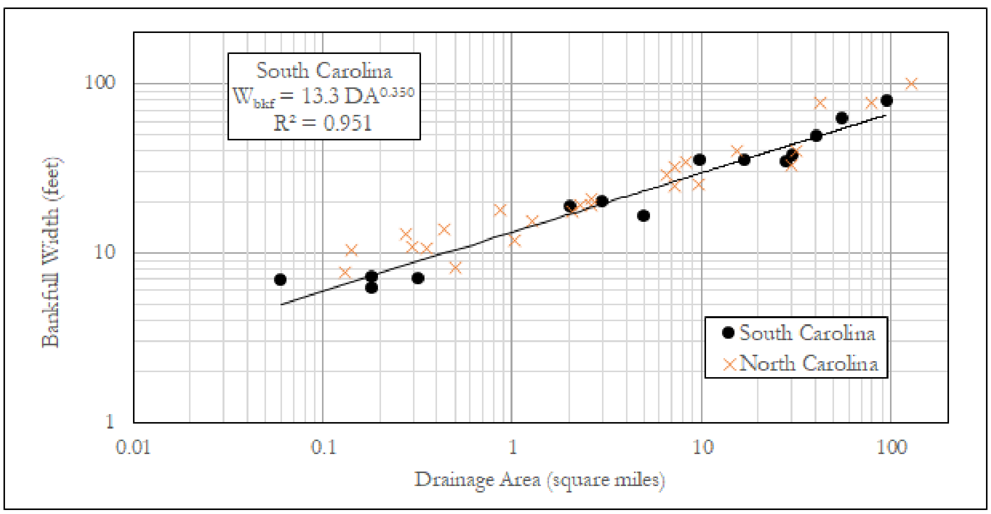


Figure 3. Bankfull riffle cross-section width related to drainage area for Ecoregion 45 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

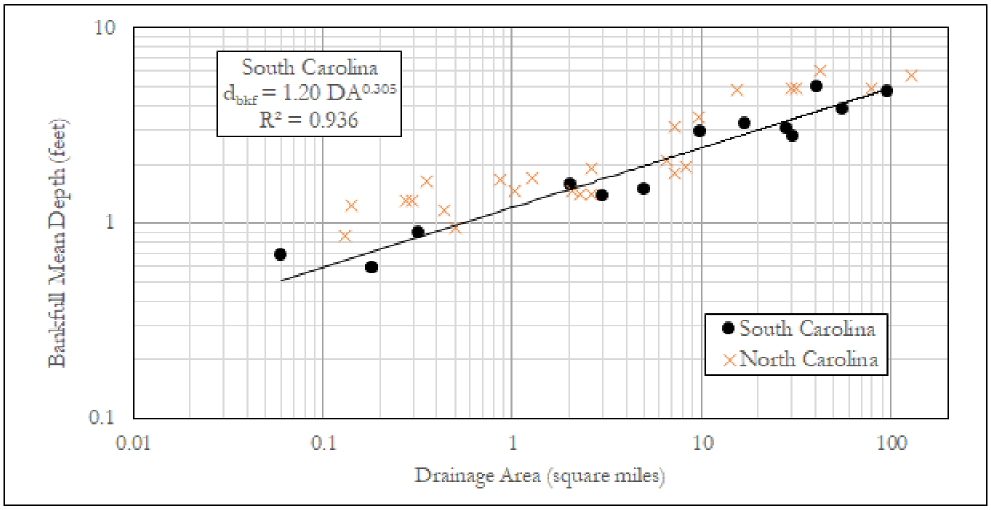


Figure 4. Bankfull riffle mean depth related to drainage area for Ecoregion 45 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

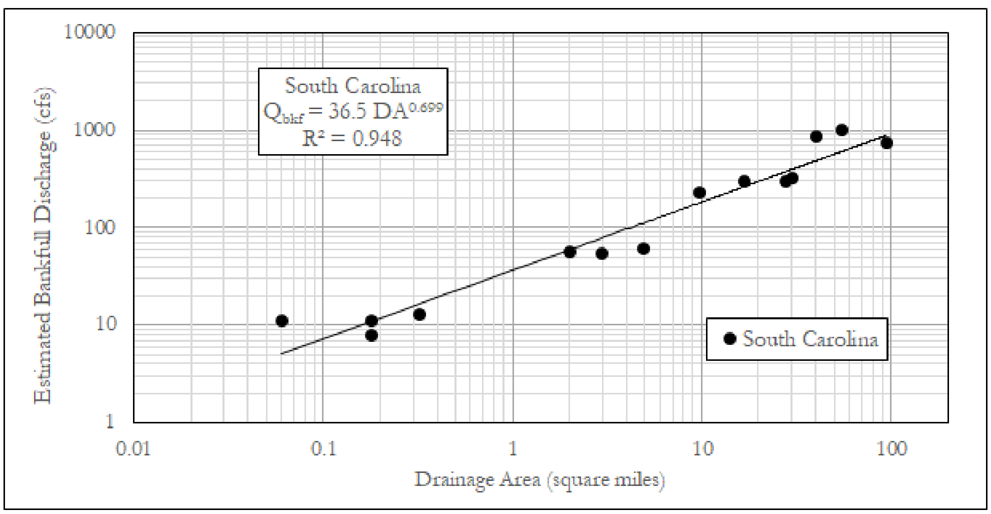


Figure 5. Estimated bankfull discharge related to drainage area for Ecoregion 45 streams.

Table 4 summarizes stream bedform profile data for the reference streams with discernable riffle-pool sequences. Many of the measured streams have low-gradient plane beds dominated by sand, which precludes riffle and pool measurements. For each stream listed, the median profile parameters and the median dimensionless ratios are presented. A wide range of parameters was observed. Median riffle and pool length ratios range from 0.9 to 4.5 for riffles and 1.0 to 4.0 for pools. Median pool spacing ratios range from 2.0 to 8.7. Median riffle slope ratios range from 1.0 to 2.9.

Table 5 summarizes stream pattern data for the meandering reference streams with discernable planform parameters that could be measured in the field. For each stream, the median pattern parameters and the median dimensionless ratios are listed. Median meander wavelength ratios range from 3.3 to 10.5, belt width ratios range from 1.7 to 3.4, and radius of curvature ratios range from 1.4 to 4.1.

Table 6 summarizes Large Woody Debris (LWD) assessments for each stream, including the numbers of LWD pieces and dams and the LWD Index scores.

Table 4. Stream Morphology Bedform Profile Parameters.

Site	Drainage area (mile²)	Median riffle length [ratio to bankfull width] (ft [none])	Median pool length [ratio to bankfull width] (ft [none])	Median pool spacing [ratio to bankfull width] (ft [none])	Median riffle slope [ratio to channel slope] (ft/ft [none])
3	0.18	28.4 [4.5]	25.0 [4.0]	55.1 [8.7]	0.0086 [1.0]
4	0.32	11.0 [1.6]	23.9 [3.4]	21.1 [3.0]	0.0220 [2.9]
5	2.02	47.3 [2.5]	31.1 [1.6]	87.2 [4.6]	0.0050 [1.8]
6	2.98	19.7 [1.0]	21.0 [1.0]	40.9 [2.0]	0.0034 [1.1]
7	4.94	14.4 [0.9]	26.9 [1.6]	43.6 [2.6]	0.0093 [1.9]

Table 5. Stream Morphology Pattern Parameters.

Site	Drainage area (mile²)	Sinuosity (ft/ft)	Median meander wavelength [ratio to bankfull width] (ft [none])	Median belt width [ratio to bankfull width] (ft [none])	Median radius of curvature [ratio to bankfull width] (ft [none])
3	0.18	1.16	66 [10.5]	18 [2.9]	26 [4.1]
4	0.32	1.33	54 [7.5]	24 [3.4]	17 [2.4]
5	2.02	1.29	110 [5.8]	45 [2.4]	46 [2.4]
6	2.98	1.29	89 [4.4]	34 [1.7]	44 [2.2]
7	4.94	1.34	55 [3.3]	30 [1.8]	24 [1.4]

Table 6. Large Woody Debris Assessment Results.

Site	Number of Pieces	Number of Dams	Piece Score	Dam Score	LWDI
1	7	0	118	0	118
2	5	0	93	0	93
3	6	0	99	0	99
4	6	0	109	0	109
5	8	0	142	0	142
6	5	0	83	0	83
7	7	0	115	0	115
8	10	1	185	16	265
9	10	0	190	0	190
10	12	0	214	0	214
11	7	0	139	0	139
12	10	1	174	15	249
13	9	0	173	0	173
14	7	0	135	0	135

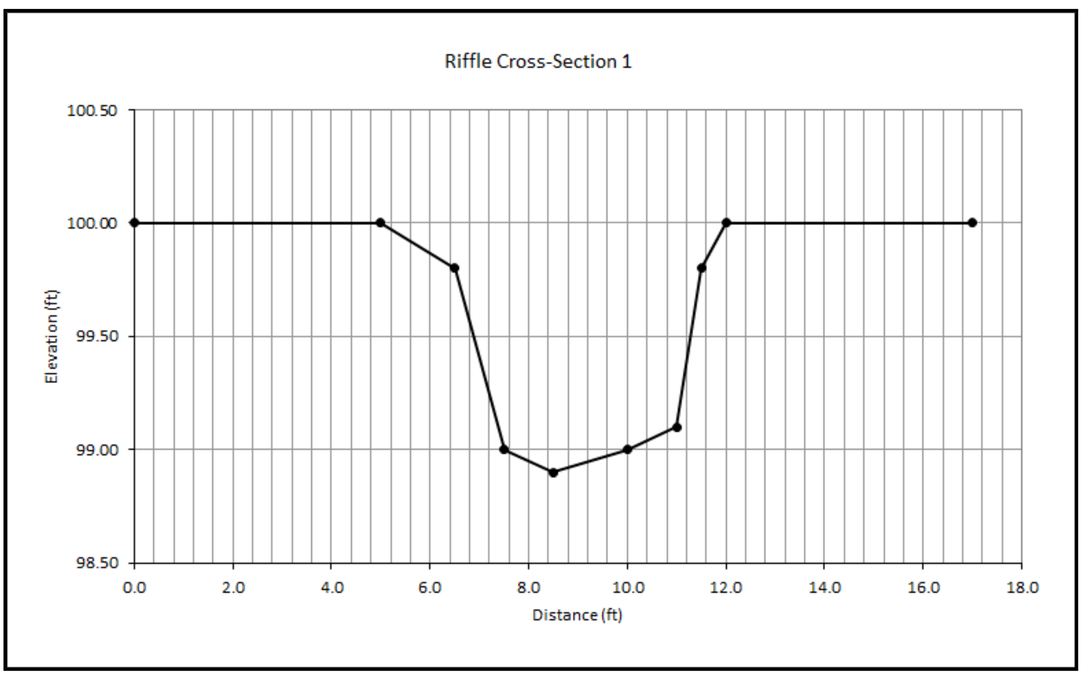
APPENDIX

ECOREGION 45, SOUTH CAROLINA

1. UT2 Long Branch
Ecoregion 45, South Carolina

Latitude: 35.137778
Longitude: -81.376944
Drainage area: 0.06 square miles
Median particle size: gravel
Longitudinal slope: 0.0118 feet/foot
Stream classification: E4

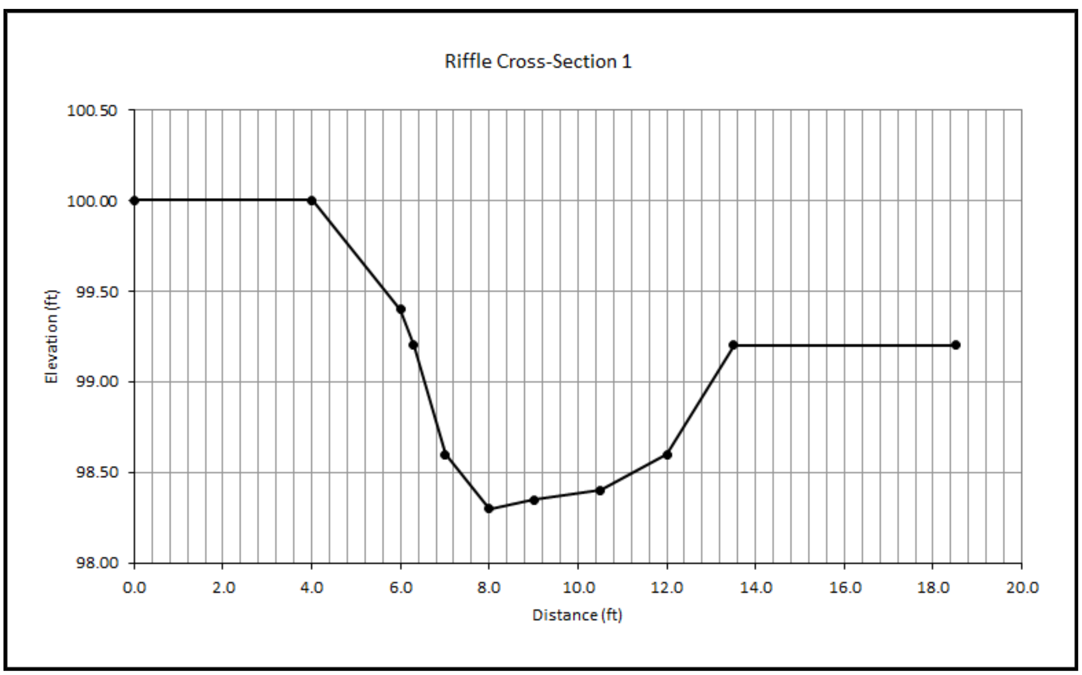
Area (square feet) =	4.7
Width (feet) =	7.0
Mean depth =	0.7
Max depth =	1.1
Width/depth ratio =	10.5
Entrenchment ratio =	3.3



2. UT1 Long Branch
Ecoregion 45, South Carolina

Latitude: 35.144167
Longitude: -81.378611
Drainage area: 0.18 square miles
Median particle size: gravel
Longitudinal slope: 0.0143 feet/foot
Stream classification: E4

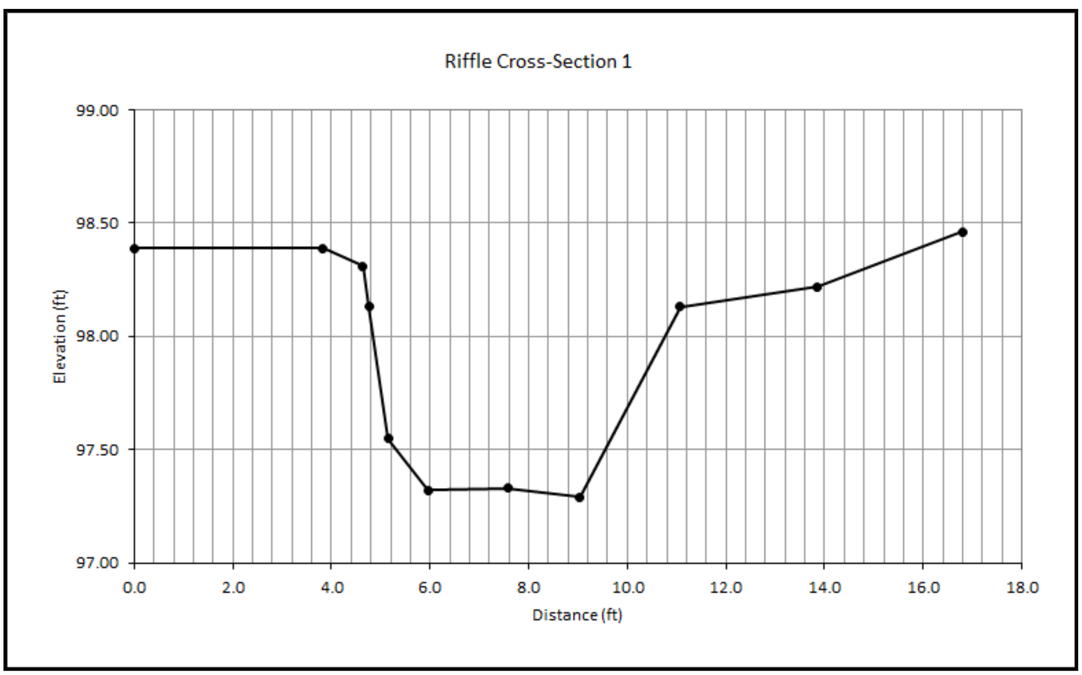
Area (square feet) =	4.6
Width (feet) =	7.2
Mean depth =	0.6
Max depth =	0.9
Width/depth ratio =	11.3
Entrenchment ratio =	>10



3. UT Indian Creek
Ecoregion 45, South Carolina

Latitude: 34.393515
Longitude: -81.673764
Drainage area: 0.18 square miles
Median particle size: sand
Longitudinal slope: 0.0082 feet/foot
Stream classification: E5

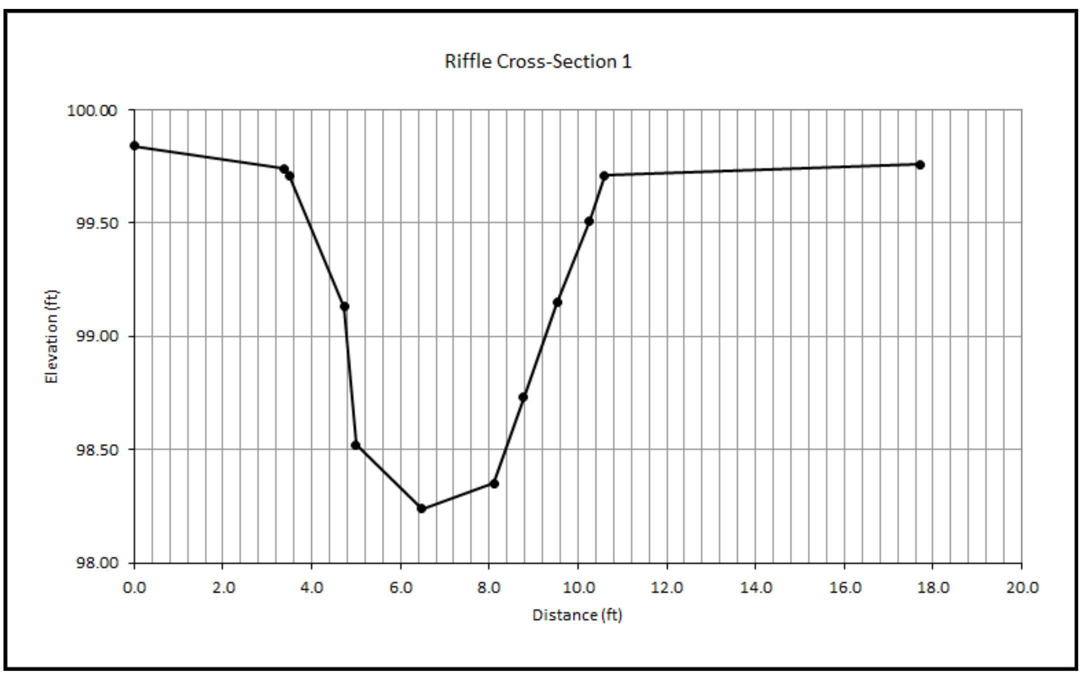
Area (square feet) =	4.0
Width (feet) =	6.3
Mean depth =	0.6
Max depth =	0.8
Width/depth ratio =	9.9
Entrenchment ratio =	>10



4. UT Kings Creek
Ecoregion 45, South Carolina

Latitude: 34.385354
Longitude: -81.546552
Drainage area: 0.32 square miles
Median particle size: sand
Longitudinal slope: 0.0077 feet/foot
Stream classification: E5

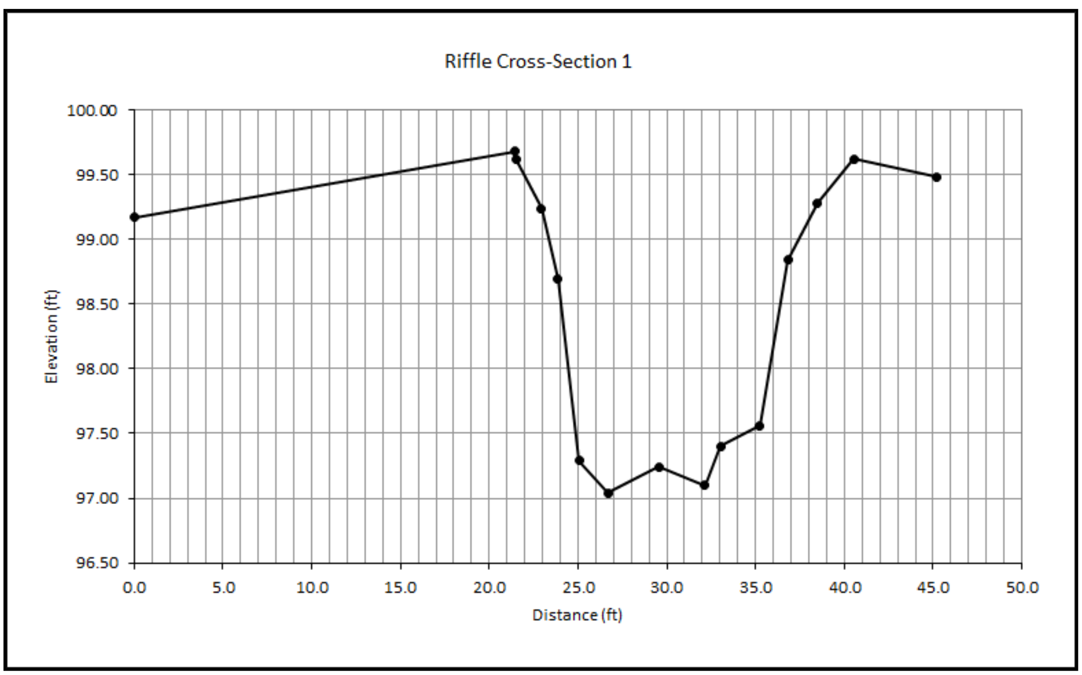
Area (square feet) =	6.5
Width (feet) =	7.1
Mean depth =	0.9
Max depth =	1.5
Width/depth ratio =	7.7
Entrenchment ratio =	>10



5. Pages Creek
Ecoregion 45, South Carolina

Latitude: 34.410620
Longitude: -81.689626
Drainage area: 2.02 square miles
Median particle size: sand
Longitudinal slope: 0.0028 feet/foot
Stream classification: E5

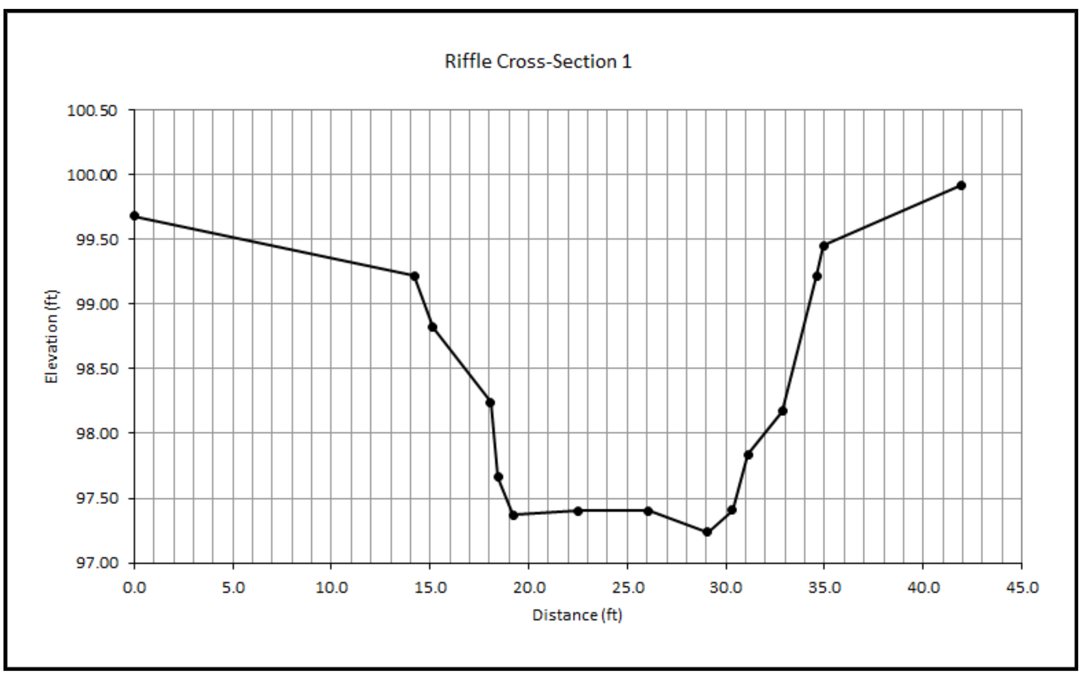
Area (square feet) =	30.6
Width (feet) =	19.0
Mean depth =	1.6
Max depth =	2.6
Width/depth ratio =	11.8
Entrenchment ratio =	>10



6. Joshuas Branch
Ecoregion 45, South Carolina

Latitude: 34.372311
Longitude: -81.653166
Drainage area: 2.98 square miles
Median particle size: sand
Longitudinal slope: 0.0032 feet/foot
Stream classification: C5

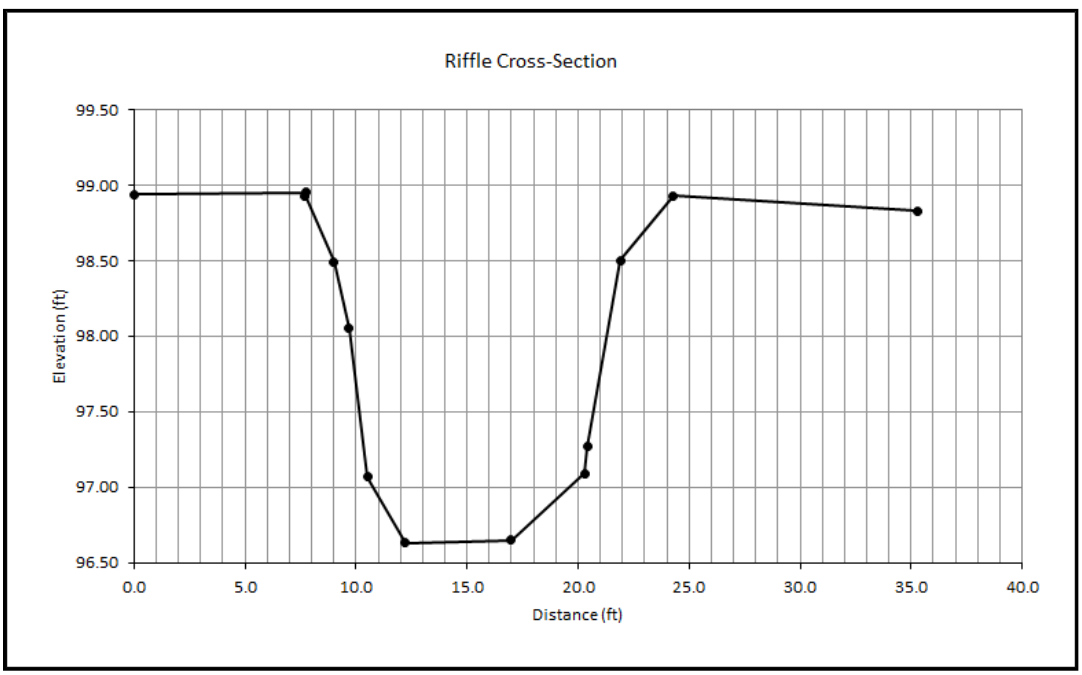
Area (square feet) =	28.9
Width (feet) =	20.4
Mean depth =	1.4
Max depth =	2.0
Width/depth ratio =	14.4
Entrenchment ratio =	>10



7. Headleys Creek
Ecoregion 45, South Carolina

Latitude: 34.435460
Longitude: -81.703539
Drainage area: 4.94 square miles
Median particle size: sand
Longitudinal slope: 0.0048 feet/foot
Stream classification: E5

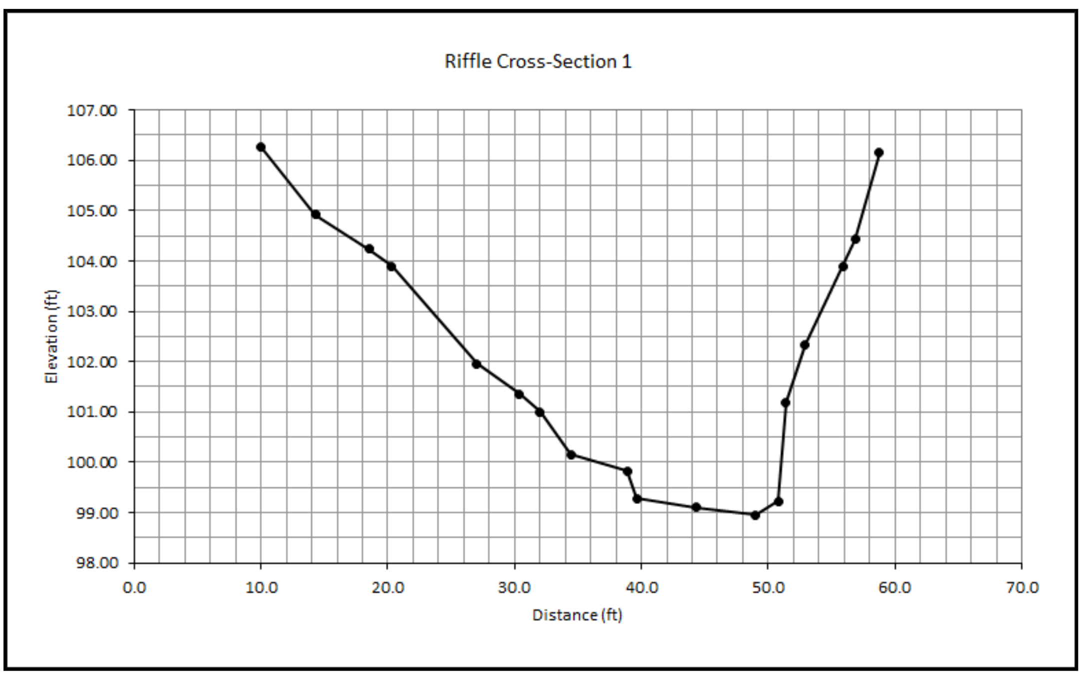
Area (square feet) =	25.4
Width (feet) =	16.6
Mean depth =	1.5
Max depth =	2.3
Width/depth ratio =	10.8
Entrenchment ratio =	>10



8. Tools Fork Creek
Ecoregion 45, South Carolina

Latitude: 34.954997
Longitude: -81.106668
Drainage area: 9.73 square miles
Median particle size: sand
Longitudinal slope: 0.0019 feet/foot
Stream classification: E5

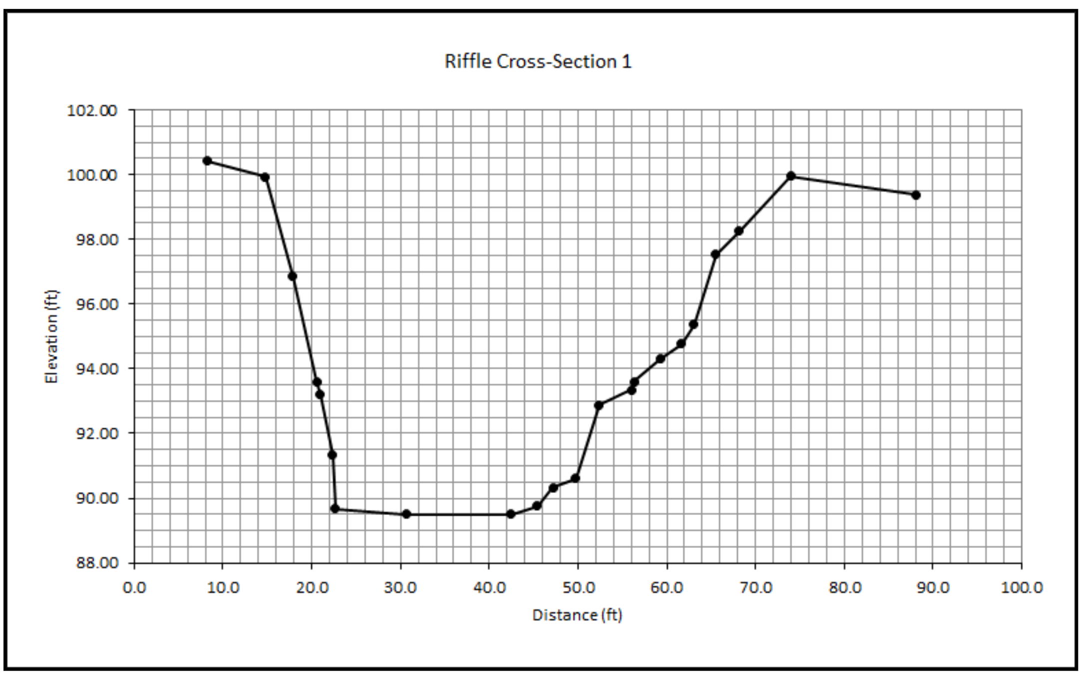
Area (square feet) =	108.5
Width (feet) =	35.6
Mean depth =	3.0
Max depth =	5.0
Width/depth ratio =	11.7
Entrenchment ratio =	6.5



9. Big Dutchman Creek
Ecoregion 45, South Carolina

Latitude: 34.986998
Longitude: -81.007374
Drainage area: 16.8 square miles
Median particle size: sand
Longitudinal slope: 0.0016 feet/foot
Stream classification: B5c

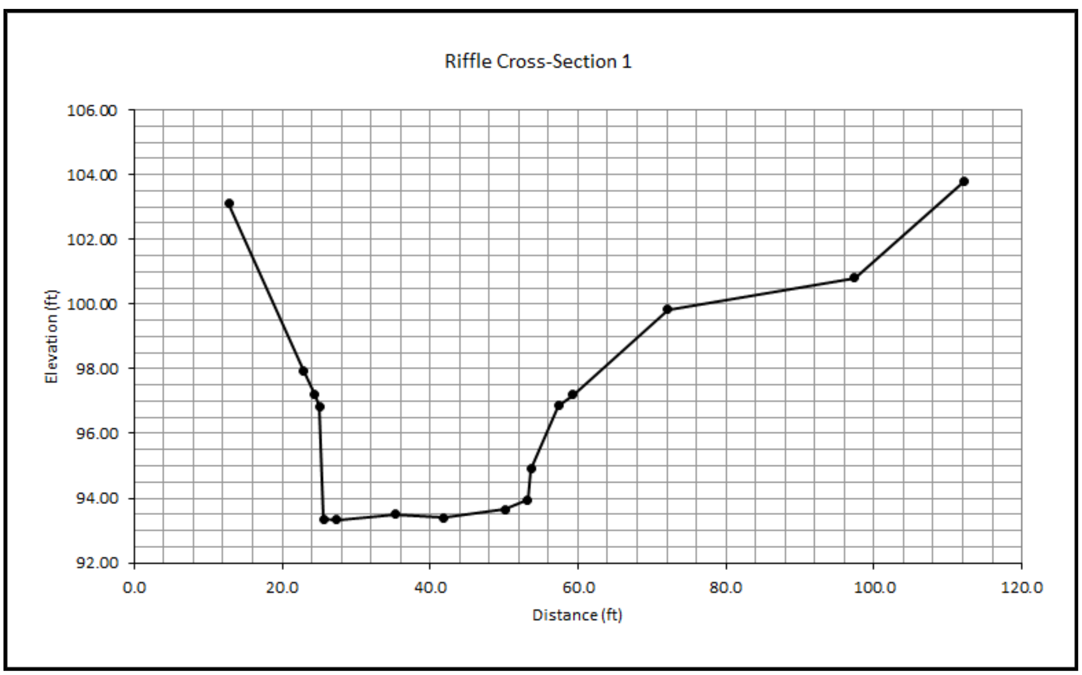
Area (square feet) =	116.4
Width (feet) =	35.7
Mean depth =	3.3
Max depth =	4.1
Width/depth ratio =	11.0
Entrenchment ratio =	1.4



10. Kings Creek
Ecoregion 45, South Carolina

Latitude: 35.118134
Longitude: -81.437161
Drainage area: 27.9 square miles
Median particle size: gravel
Longitudinal slope: 0.0026 feet/foot
Stream classification: E4

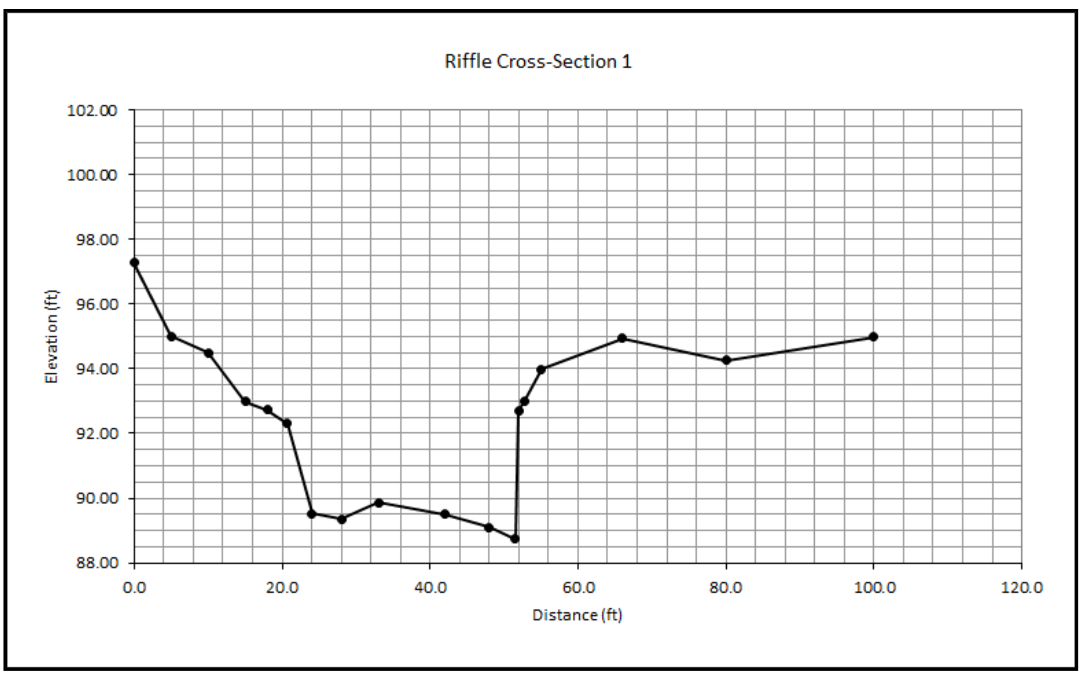
Area (square feet) =	109.9
Width (feet) =	34.9
Mean depth =	3.1
Max depth =	3.9
Width/depth ratio =	11.1
Entrenchment ratio =	2.4



11. South Rabon Creek
Ecoregion 45, South Carolina

Latitude: 34.517892
Longitude: -82.155741
Drainage area: 30.0 square miles
Median particle size: sand
Longitudinal slope: 0.0033 feet/foot
Stream classification: C5

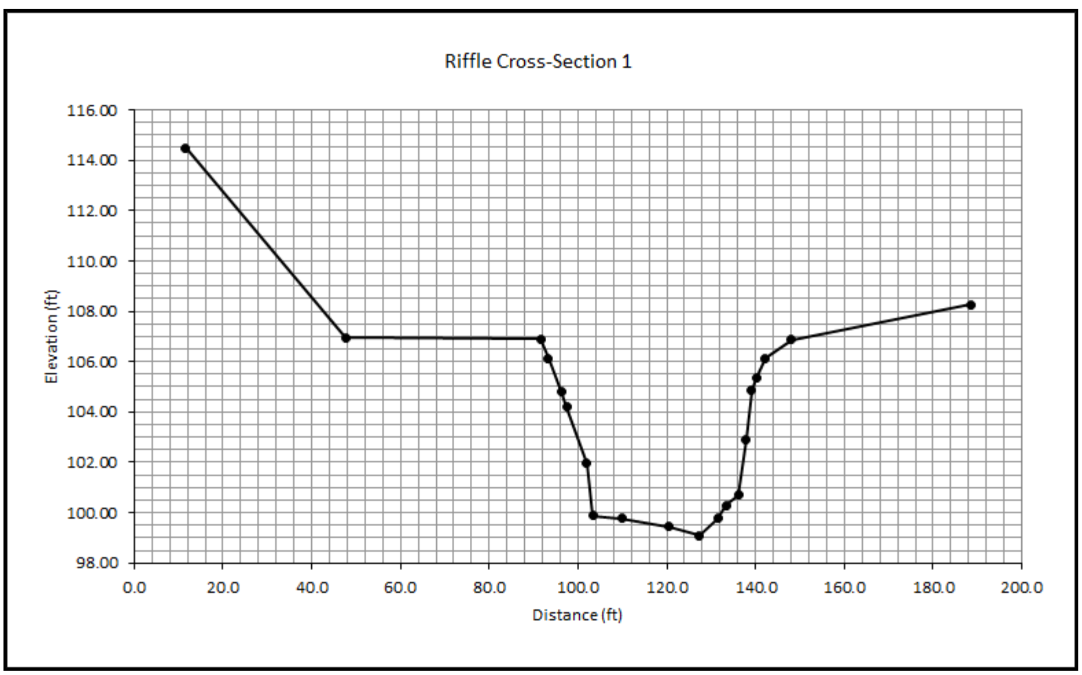
Area (square feet) =	106.7
Width (feet) =	37.7
Mean depth =	2.8
Max depth =	4.2
Width/depth ratio =	13.3
Entrenchment ratio =	6.6



12. Allison Creek
Ecoregion 45, South Carolina

Latitude: 35.065105
Longitude: -81.138798
Drainage area: 40.4 square miles
Median particle size: sand
Longitudinal slope: 0.0015 feet/foot
Stream classification: E5

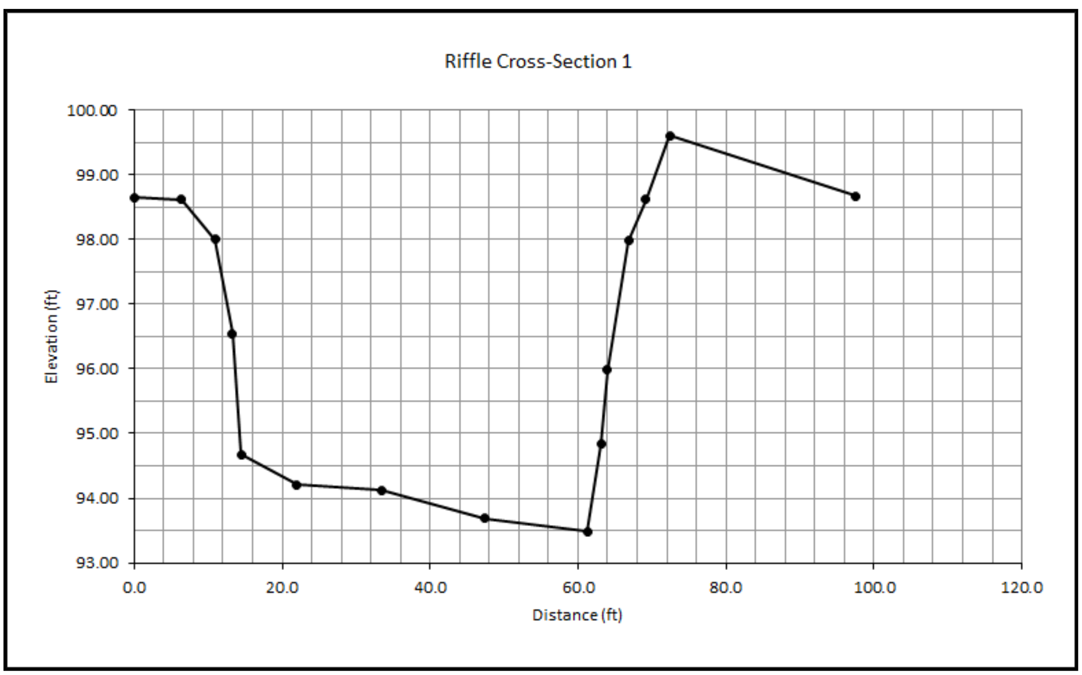
Area (square feet) =	250.2
Width (feet) =	48.9
Mean depth =	5.1
Max depth =	7.1
Width/depth ratio =	9.5
Entrenchment ratio =	3.9



13. South Pacolet River
Ecoregion 45, South Carolina

Latitude: 35.106304
Longitude: -82.129122
Drainage area: 55.6 square miles
Median particle size: sand
Longitudinal slope: 0.0025 feet/foot
Stream classification: C5

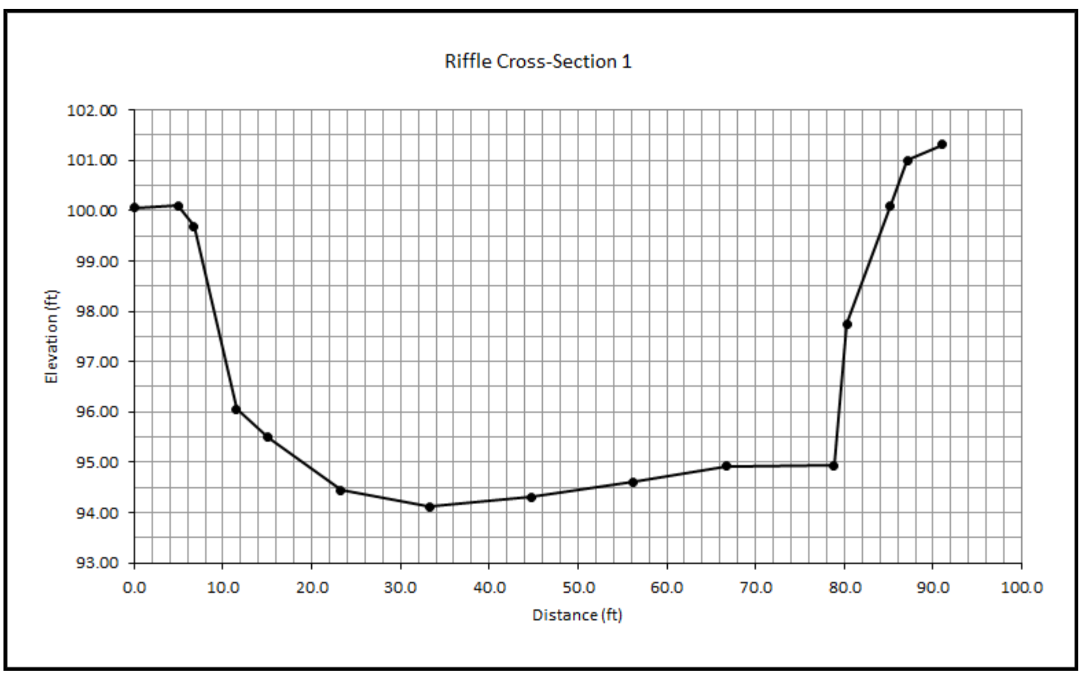
Area (square feet) =	242.1
Width (feet) =	62.8
Mean depth =	3.9
Max depth =	5.1
Width/depth ratio =	16.3
Entrenchment ratio =	5.5



14. South Tyger River
Ecoregion 45, South Carolina

Latitude: 34.920927
Longitude: -82.129849
Drainage area: 94.7 square miles
Median particle size: sand
Longitudinal slope: 0.0005 feet/foot
Stream classification: C5c-

Area (square feet) =	388.2
Width (feet) =	80.3
Mean depth =	4.8
Max depth =	6.0
Width/depth ratio =	16.6
Entrenchment ratio =	3.2



South Carolina Southeastern Plains, Ecoregion 65
Stream Morphology Results

In the South Carolina Southeastern Plains, Ecoregion 65, geomorphic data were collected from 15 streams during January and February 2020 (Figure 1 and Table 1). Twelve of these streams (all except sites 2, 10, and 11) are located within Level IV Ecoregion 65c (Sand Hills). Three sites are at USGS gage stations with drainage areas ranging from 14.7 to 51.9 square miles, while the remaining 12 are ungaged reference streams in forested watersheds with drainage areas ranging from 0.25 to 20.0 square miles. Several other streams were visited to evaluate their potential for inclusion in this study but were rejected due to local instability or other factors affecting their geomorphic conditions.

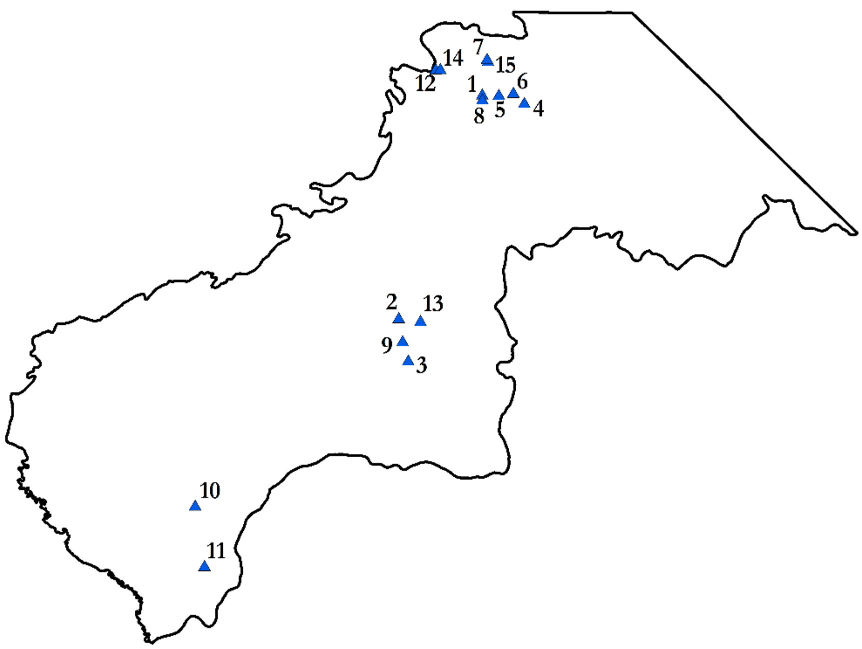


Figure 1. Reference Stream Sites in Ecoregion 65, South Carolina.

Table 1. Reference Stream Sites.

ID	Stream name	Source/Location	Latitude	Longitude	Drainage area ($mile^2$)
1	Poplar Branch	Carolina Sandhills NWR	34.559874	-80.234442	0.25
2	UT Beech Creek	Manchester State Forest	33.873469	-80.548092	0.38
3	Mill Creek	Manchester State Forest	33.742333	-80.513768	0.39
4	UT Mill Creek	Sand Hills State Forest	34.532336	-80.078090	0.42
5	UT Black Creek	Carolina Sandhills NWR	34.558225	-80.172544	0.81
6	Middle Prong Juniper Creek	Sand Hills State Forest	34.563947	-80.118820	1.32
7	Canal Branch	Carolina Sandhills NWR	34.669100	-80.215719	1.40
8	Cow Branch	Carolina Sandhills NWR	34.544613	-80.233883	1.86
9	Shanks Creek	Poinsett State Park	33.802784	-80.534618	3.61
10	Toby Creek	SCDNR Fish Site	33.296829	-81.297025	10.7
11	Wells Branch	SCDNR Fish Site	33.111540	-81.261873	13.5
12	Little Fork Creek	USGS Gage	34.638271	-80.406705	14.7
13	Brunson Swamp	Manchester State Forest	33.864224	-80.467757	20.0
14	Fork Creek	USGS Gage	34.638528	-80.389503	24.4
15	Black Creek	USGS Gage	34.663060	-80.211803	51.9

The USGS gage stations were included in this study because long-term records for flow stage and discharge can be used to quantify the specific channel-forming discharge exceedance probability for bankfull conditions. Discharge can be reported in terms of exceedance probability (or return period) to assist in determining channel-forming discharges and morphological indicators in ungaged watersheds. The chosen gage sites are at stable stream locations in relatively undisturbed watersheds with field indicators of bankfull stage near the gages.

The ungaged reference streams in this ecoregion were selected through consultation with SCDNR and other local stream professionals, as well as extensive field reconnaisance. Reference reaches were identified generally based on the following criteria:

- Streams with drainage areas ranging between approximately 0.1 and 20 square miles (with the exception of USGS gage stations)
- Watersheds with stable land use and mostly forested over the past several decades
- Stream channels and floodplains in equilibrium with active bankfull stage indicators (i.e., bank height ratios near 1.0)
- Single-thread stream channels with freely-formed meander patterns in low-gradient valleys (less than 2% longitudinal slope)
- No valley restrictions throughout the reference reach or upstream/downstream that may influence channel form
- Healthy riparian forest buffers
- Accessible for data collection and protected for future access

Field measurements of stream geomorphological characteristics were collected to establish hydraulic geometry relationships following the methods outlined in the most current version of the North Carolina SQT Field User Manual[1]. All stream assessments included collection of bankfull riffle dimension (cross-section) data. As conditions allowed, pattern data were collected for a subset of the reference sites.

Data collected for all reference sites included:

- Rosgen stream type
- drainage area (DA)
- bankfull riffle cross-section area (A_{bkf})
- bankfull riffle width (W_{bkf}) and mean depth (d_{bkf}) for calculating width-to-depth ratio (WDR)
- width of floodprone area (W_{fpa}) for calculating entrenchment ratio (ER)
- maximum depth at top of bank and bankfull stage for calculating bank height ratio (BHR)
- channel water surface slope (S)
- sinuosity (k)
- median substrate size classification
- estimated Manning roughness coefficient (n)

The subset of reference sites with pattern data included collection of:

- meander wavelengths ($L_{meander}$)
- belt widths (W_{blt})
- radius of curvature of meander bends (R_c)

Profile data were also collected for the subset of reference sites that appeared to have variations in streambed elevations within the reach. However, field observations and data analyses did not result in discernable riffle-pool sequences. Rather than riffles and pools, variations in bedform were generally due to tree roots, vegetation in the channel, woody debris, and accumulations of sand. This is typical of low-slope, sand bed streams in coastal plain ecoregions. As a result, profile data (i.e., riffle slopes and lengths, pool lengths, and pool spacings) could not effectively be measured.

Large woody debris (LWD) information was collected in accordance with the most current version of the Application of the Large Woody Debris Index Field User Manual developed by Stream Mechanics and Ecosystem Planning & Restoration[2].

Field measurement results are presented in the appendix and in the tables and graphs below. Table 2 summarizes riffle cross-section dimension geomorphic parameters used for Rosgen stream classification. Four of the streams measured in Ecoregion 65 are C streams, while the remaining 11 are E streams. Sand was the dominant bed material in all streams, with the exception of two of the larger streams (Little Fork Creek and Fork Creek), whose streambeds were predominantly gravel. Entrenchment ratios are typically very high. Nine of the valleys were so wide that they precluded exact measurement; in these cases, entrenchment ratios are reported as >10.0. Width/depth ratios are highly variable, and range from 6.1 to 25.1.

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[1] NC SQT https://stream-mechanics.com/wp-content/uploads/2017/09/Data-Collection-and-Analysis-Manual_NC-SQT-v3.0.pdf; currently under revision.

[2] Large Woody Debris Assessment https://stream-mechanics.com/wp-content/uploads/2017/12/LWDI-Manual_V1.pdf

Table 2. Morphology Dimensions.

Site	Drainage area (mile²)	Channel slope (ft/ft)	Cross-section area (ft²)	Bankfull width (ft)	Bankfull mean depth (ft)	Width/depth ratio	Entrenchment ratio	Rosgen Stream Class
1	0.25	0.0113	2.0	5.9	0.3	17.7	7.6	C5
2	0.38	0.0082	3.8	6.3	0.6	10.2	3.2	E5
3	0.39	0.0041	6.9	11.0	0.6	17.4	>10.0	C5
4	0.42	0.0077	2.9	5.3	0.5	9.8	>10.0	E5
5	0.81	0.0047	5.2	7.8	0.7	11.6	5.4	E5
6	1.32	0.0079	7.8	6.9	1.1	6.1	>10.0	E5
7	1.40	0.0012	8.3	9.4	0.9	10.5	>10.0	E5
8	1.86	0.0100	4.7	7.8	0.6	13.1	>10.0	C5
9	3.61	0.0043	11.3	10.5	1.1	9.9	>10.0	E5
10	10.7	0.0015	40.7	20.4	2.0	10.2	9.5	E5
11	13.5	0.0013	41.1	32.1	1.3	25.1	>10.0	C5
12	14.7	0.0016	103.9	30.9	3.4	9.2	4.9	E4
13	20.0	0.0007	51.1	18.7	2.7	6.8	>10.0	E5
14	24.4	0.0038	93.7	29.1	3.2	9.0	9.1	E4
15	51.9	0.0004	154.1	35.3	4.4	8.1	>10.0	E5

Table 3 summarizes estimated bankfull hydraulic parameters (velocity and discharge) for each stream based on the Manning equation. The Manning equation, in English units, is:

$$v = \frac{1.486 * \left(R^{2/3}\right) * \left(S^{1/2}\right)}{n}$$

where *v* is average velocity (feet/second), *R* is the hydraulic radius (feet), *S* is average water surface slope (feet/feet), and *n* is a dimensionless coefficient describing channel roughness, known as Manning's n, which ranges from 0.033 to 0.150 for natural channels. The Cowan (1956) method was used to estimate the Manning's n values based on sediment size, irregularity within a cross-section, variation among cross-sections, obstructions, vegetation, and sinuosity. The bankfull discharge is estimated as the product of average velocity and riffle bankfull cross-section area.

For these streams, Manning's n values range from 0.045 to 0.063, which match expected values for natural alluvial streams in this ecoregion. Estimated bankfull average velocities for the study streams are generally between 1 and 2 feet per second, though range from 0.7 to 3.7 with variations due to slope, cross-section dimensions, and channel roughness.

Table 3. Estimated Bankfull Hydraulic Parameters.

Site	Drainage area (mile^2)	Manning's n	Estimated Bankfull Velocity (ft/s)	Estimated Bankfull Discharge (cfs)
1	0.25	0.060	1.2	2.3
2	0.38	0.045	1.9	7.4
3	0.39	0.055	1.2	8.2
4	0.42	0.055	1.4	4.0
5	0.81	0.055	1.3	6.7
6	1.32	0.055	2.2	17
7	1.40	0.063	0.7	5.7
8	1.86	0.060	1.6	7.5
9	3.61	0.058	1.6	18
10	10.7	0.050	1.6	66
11	13.5	0.055	1.1	45
12	14.7	0.047	2.5	260
13	20.0	0.045	1.4	73
14	24.4	0.047	3.7	348
15	51.9	0.063	1.1	166

The graphs in Figures 2 through 5 show riffle bankfull morphological parameters and estimated discharge related to watershed drainage area (i.e., regional curves). These graphs include data points measured in Ecoregion 65 of both South Carolina and North Carolina. North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina. The North Carolina data represent eight streams, as published by Doll, et al. (2003). North Carolina data are not included in Figure 5 due to minor differences in the methodologies used to estimate bankfull discharge. Figures 2 through 5 also include best-fit regression lines for each data set in addition to the regression equations and coefficients of determination.

Figures 2 through 4 demonstrate that measured bankfull cross-section area, width, and depth are often smaller in the South Carolina streams than in the assessed North Carolina streams. One reason for this result may be that many of the sites measured in South Carolina were in protected, forested watersheds with little or no impervious surface (e.g., Carolina Sandhills National Wildlife Refuge, Manchester State Forest). These undisturbed, forested watersheds tend to dampen peak flow responses to rainfall, producing equilibrium channels with little to no incision. The cross-section dimensions for South Carolina streams are validated by most streams having a bankfull elevation equal to the top of bank (i.e., Bank Height Ratio = 1.0).

Twelve of the 15 South Carolina data points (all except sites 2, 10, and 11) in Figures 2 through 5 represent data collected from streams located within Level IV Ecoregion 65c (Sand Hills). As a result, these regional curves could be considered representative of both Level III Ecoregion 65 and Level IV Ecoregion 65c.

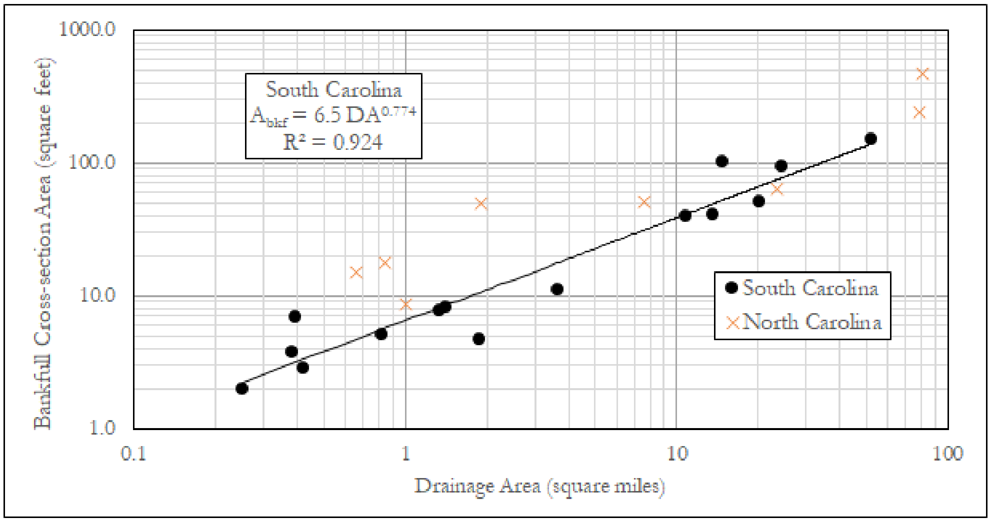


Figure 2. Bankfull riffle cross-section area related to drainage area for Ecoregion 65 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

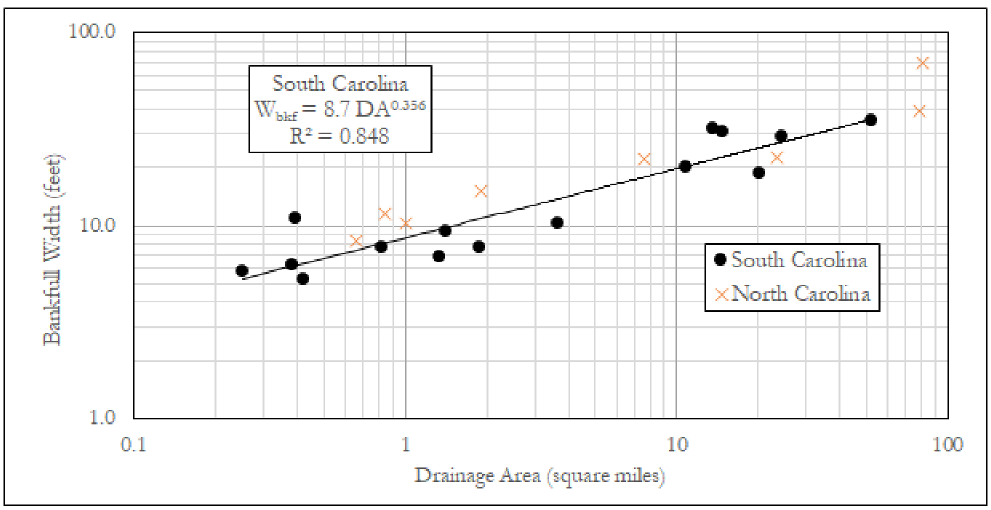


Figure 3. Bankfull riffle cross-section width related to drainage area for Ecoregion 65 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

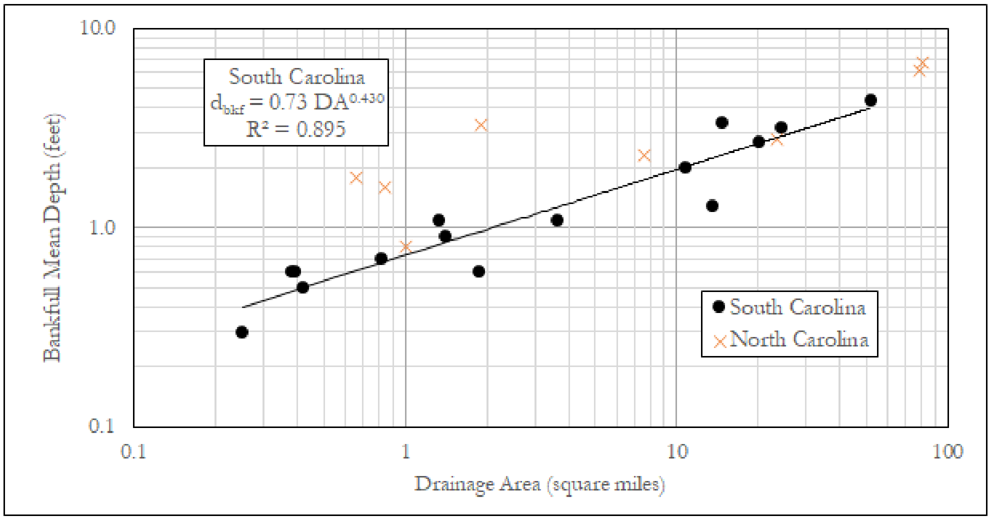


Figure 4. Bankfull riffle mean depth related to drainage area for Ecoregion 65 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

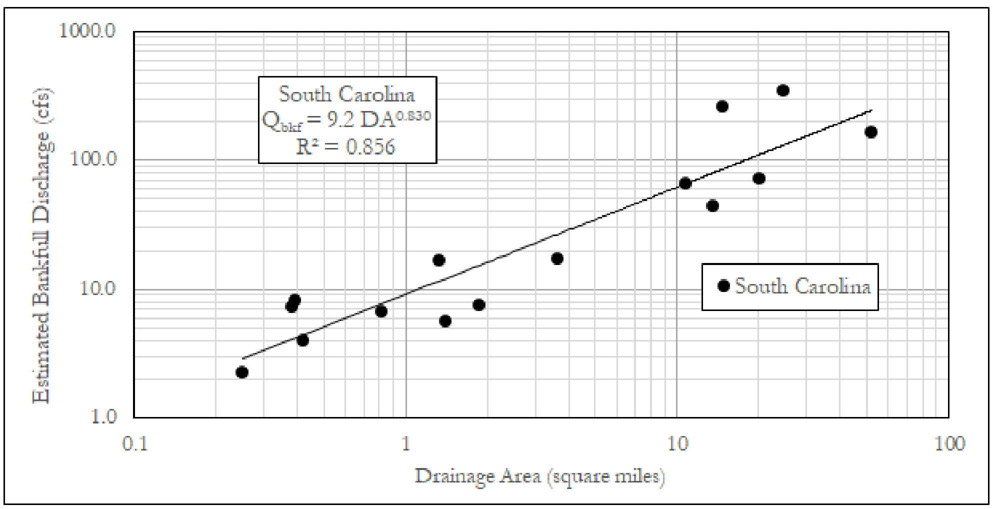


Figure 5. Estimated bankfull discharge related to drainage area for Ecoregion 65 streams.

Table 4 summarizes stream pattern data for the meandering reference streams with discernable planform parameters that could be assessed in the field. For each stream, the median pattern parameters and the median dimensionless ratios are listed. Median meander wavelength ratios range from 3.6 to 8.5, belt width ratios range from 1.9 to 3.5, and radius of curvature ratios range from 1.4 to 4.8.

Table 5 summarizes Large Woody Debris (LWD) assessments for each stream, including the numbers of LWD pieces, number of dams, and the LWD Index scores.

Table 4. Stream Morphology Pattern Parameters.

Site	Drainage area (mile^2)	Sinuosity (ft/ft)	Median meander wavelength [ratio to bankfull width] (ft [none])	Median belt width [ratio to bankfull width] (ft [none])	Median radius of curvature [ratio to bankfull width] (ft [none])
2	0.38	1.06	53 [8.5]	14 [2.2]	30 [4.8]
5	0.81	1.19	37 [4.8]	15 [1.9]	21 [2.7]
7	1.40	1.45	34 [3.6]	31 [3.3]	13 [1.4]
9	3.61	1.33	88 [8.4]	37 [3.5]	35 [3.3]

Table 5. Large Woody Debris Assessment Results.

Site	Number of Pieces	Number of Dams	Piece Score	Dam Score	LWDI
1	10	0	202	0	202
2	8	0	154	0	154
3	7	0	125	0	125
4	11	0	214	0	214
5	16	0	326	0	326
6	7	1	139	15	214
7	7	0	139	0	139
8	8	0	160	0	160
9	10	0	201	0	201
10	14	1	310	12	370
11	17	2	349	33	514
12	9	1	185	16	265
13	8	0	158	0	158
14	6	0	117	0	117
15	18	0	401	0	401

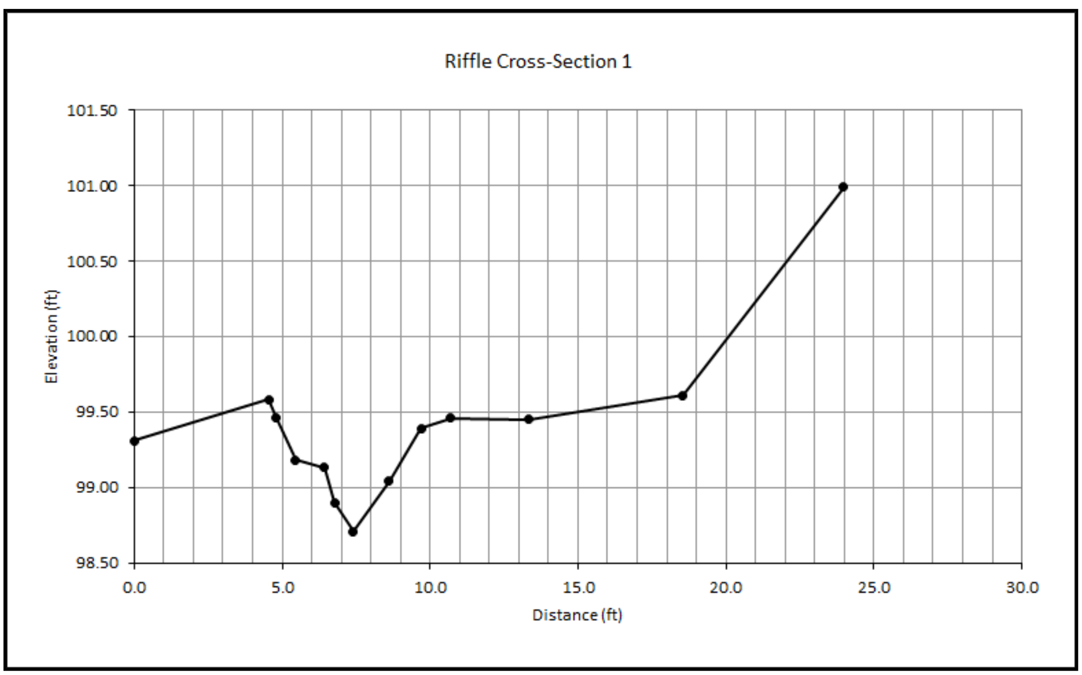
APPENDIX

ECOREGION 65, SOUTH CAROLINA

1. Poplar Branch
Ecoregion 65, South Carolina

Latitude: 34.559874
Longitude: -80.234442
Drainage area: 0.25 square miles
Median particle size: sand
Longitudinal slope: 0.0113 feet/foot
Stream classification: C5

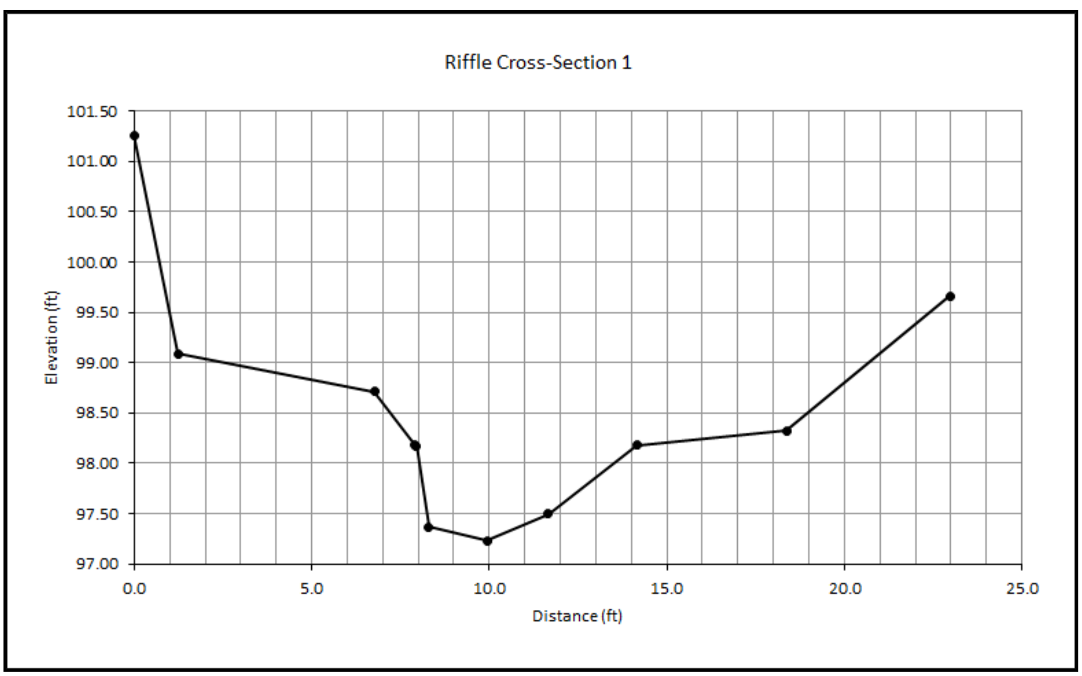
Area (square feet) =	2.0
Width (feet) =	5.9
Mean depth =	0.3
Max depth =	0.8
Width/depth ratio =	17.7
Entrenchment ratio =	7.6



2. UT Beech Creek
Ecoregion 65, South Carolina

Latitude: 33.873469
Longitude: -80.548092
Drainage area: 0.38 square miles
Median particle size: sand
Longitudinal slope: 0.0082 feet/foot
Stream classification: E5

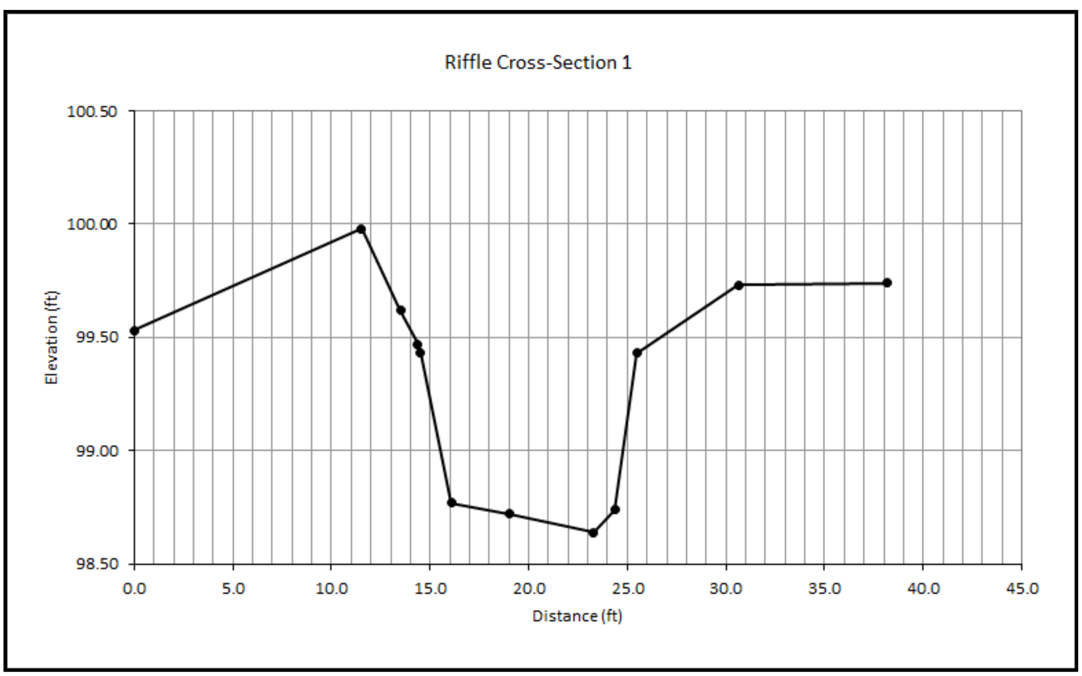
Area (square feet) =	3.8
Width (feet) =	6.3
Mean depth =	0.6
Max depth =	1.0
Width/depth ratio =	10.2
Entrenchment ratio =	3.2



3. Mill Creek
Ecoregion 65, South Carolina

Latitude: 33.742333
Longitude: -80.513768
Drainage area: 0.39 square miles
Median particle size: sand
Longitudinal slope: 0.0041 feet/foot
Stream classification: C5

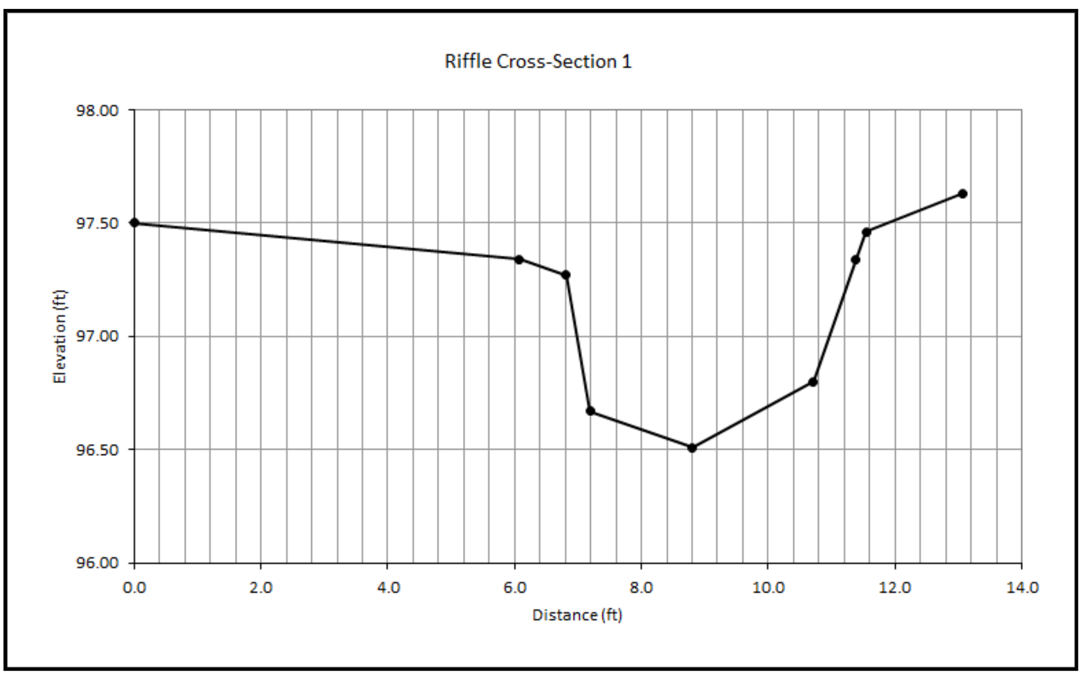
Area (square feet) =	6.9
Width (feet) =	11.0
Mean depth =	0.6
Max depth =	0.8
Width/depth ratio =	17.4
Entrenchment ratio =	>10.0



4. UT Mill Creek
Ecoregion 65, South Carolina

Latitude: 34.532336
Longitude: -80.078090
Drainage area: 0.42 square miles
Median particle size: sand
Longitudinal slope: 0.0077 feet/foot
Stream classification: E5

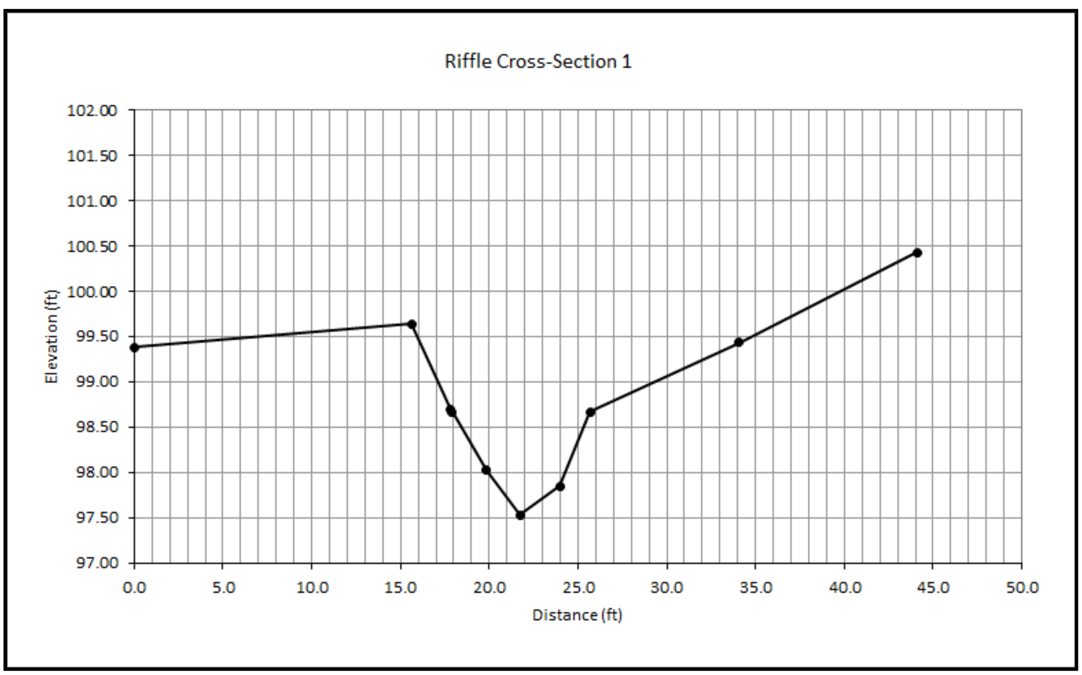
Area (square feet) =	2.9
Width (feet) =	5.3
Mean depth =	0.5
Max depth =	0.8
Width/depth ratio =	9.8
Entrenchment ratio =	>10.0



5. UT Black Creek
Ecoregion 65, South Carolina

Latitude: 34.558225
Longitude: -80.172544
Drainage area: 0.81 square miles
Median particle size: sand
Longitudinal slope: 0.0047 feet/foot
Stream classification: E5

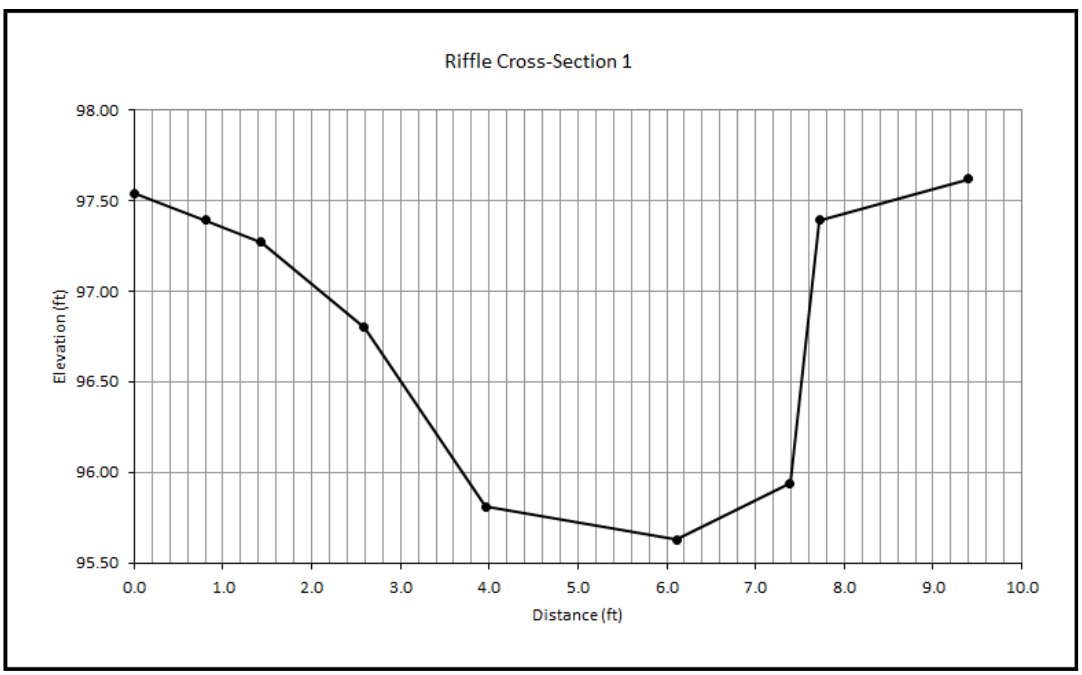
Area (square feet) =	5.2
Width (feet) =	7.8
Mean depth =	0.7
Max depth =	1.1
Width/depth ratio =	11.6
Entrenchment ratio =	5.4



6. Middle Prong Juniper Creek
Ecoregion 65, South Carolina

Latitude: 34.563947
Longitude: -80.118820
Drainage area: 1.32 square miles
Median particle size: sand
Longitudinal slope: 0.0079 feet/foot
Stream classification: E5

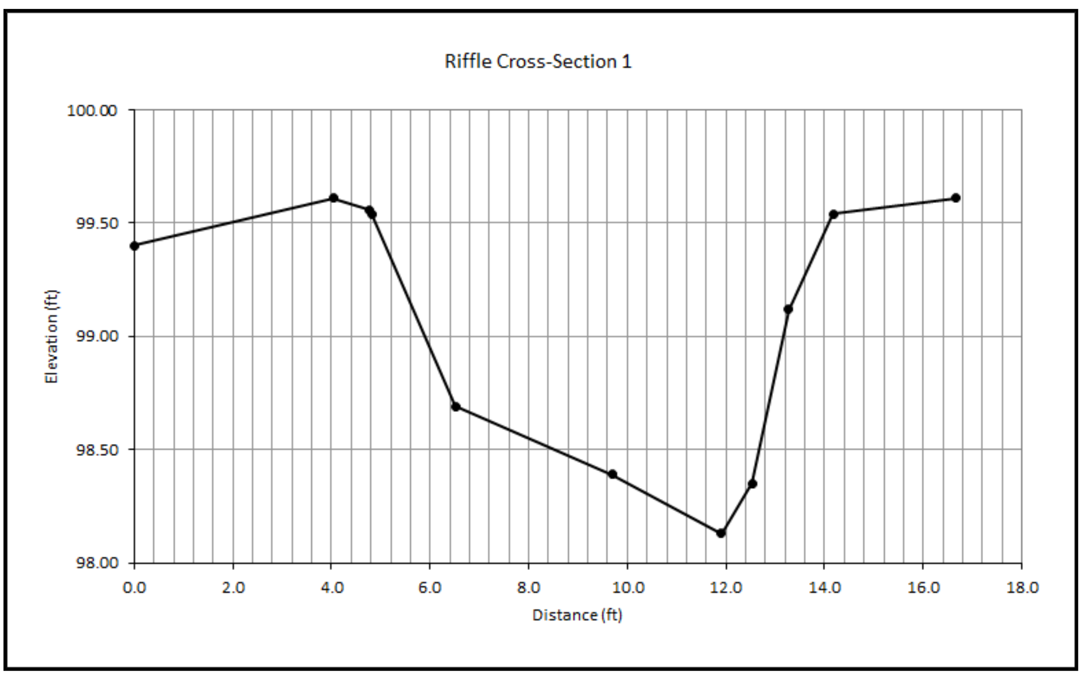
Area (square feet) =	7.8
Width (feet) =	6.9
Mean depth =	1.1
Max depth =	1.8
Width/depth ratio =	6.1
Entrenchment ratio =	>10.0



7. Canal Branch
Ecoregion 65, South Carolina

Latitude: 34.669100
Longitude: -80.215719
Drainage area: 1.40 square miles
Median particle size: sand
Longitudinal slope: 0.0012 feet/foot
Stream classification: E5

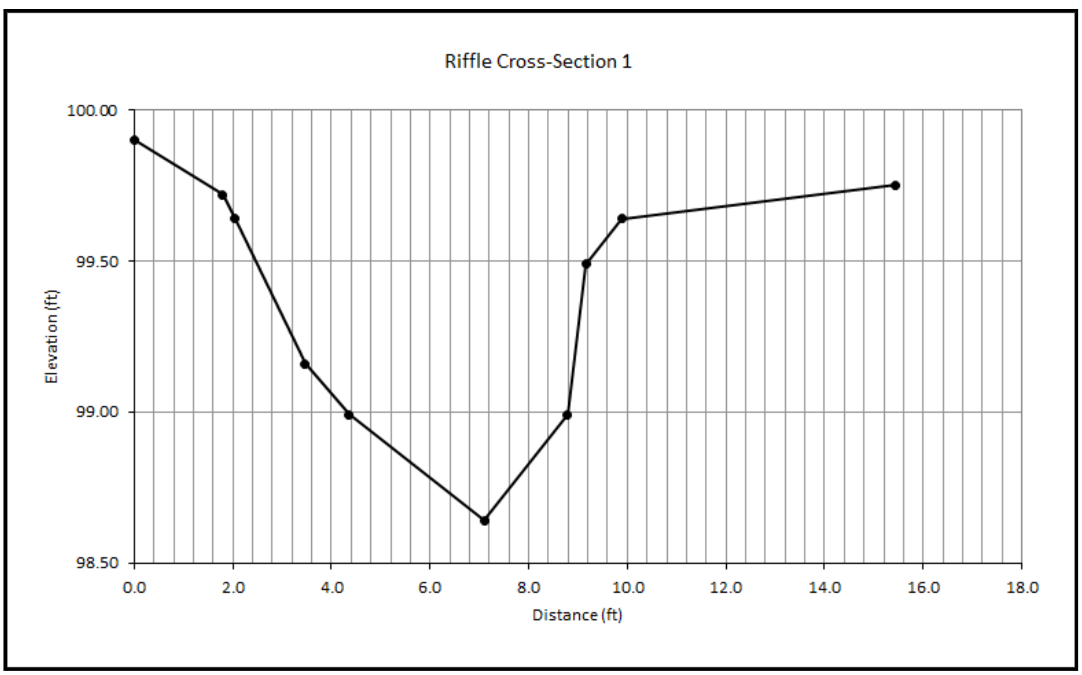
Area (square feet) =	8.3
Width (feet) =	9.4
Mean depth =	0.9
Max depth =	1.4
Width/depth ratio =	10.5
Entrenchment ratio =	>10.0



8. Cow Branch
Ecoregion 65, South Carolina

Latitude: 34.544613
Longitude: -80.233883
Drainage area: 1.86 square miles
Median particle size: sand
Longitudinal slope: 0.0100 feet/foot
Stream classification: C5

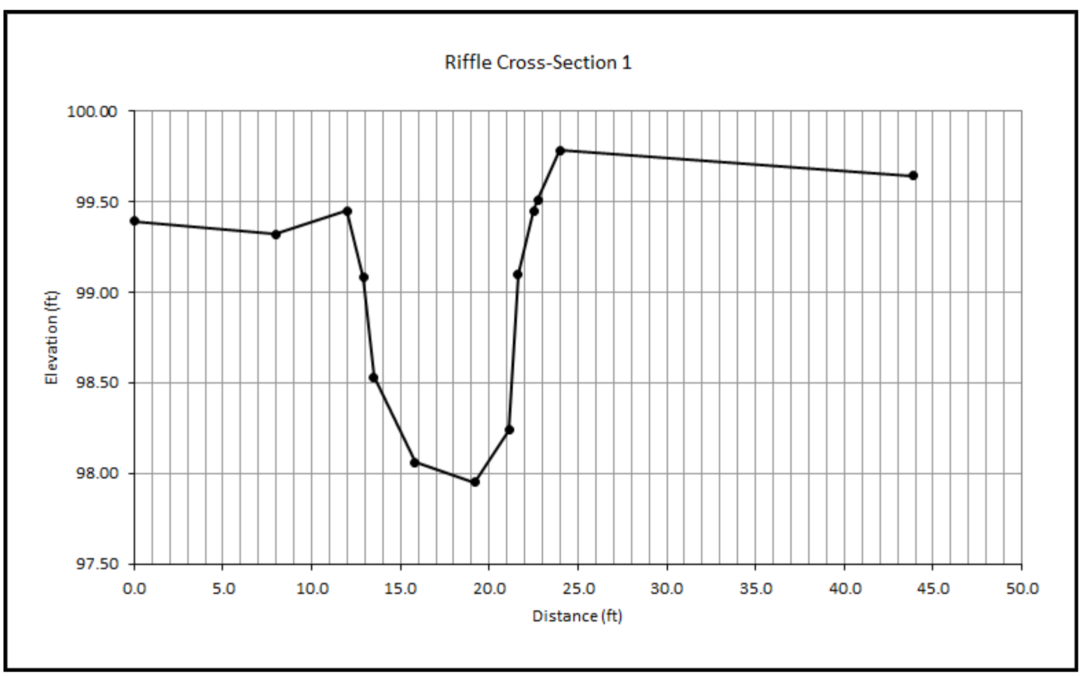
Area (square feet) =	4.7
Width (feet) =	7.8
Mean depth =	0.6
Max depth =	1.0
Width/depth ratio =	13.1
Entrenchment ratio =	>10.0



9. Shanks Creek
Ecoregion 65, South Carolina

Latitude: 33.802784
Longitude: -80.534618
Drainage area: 3.61 square miles
Median particle size: sand
Longitudinal slope: 0.0043 feet/foot
Stream classification: E5

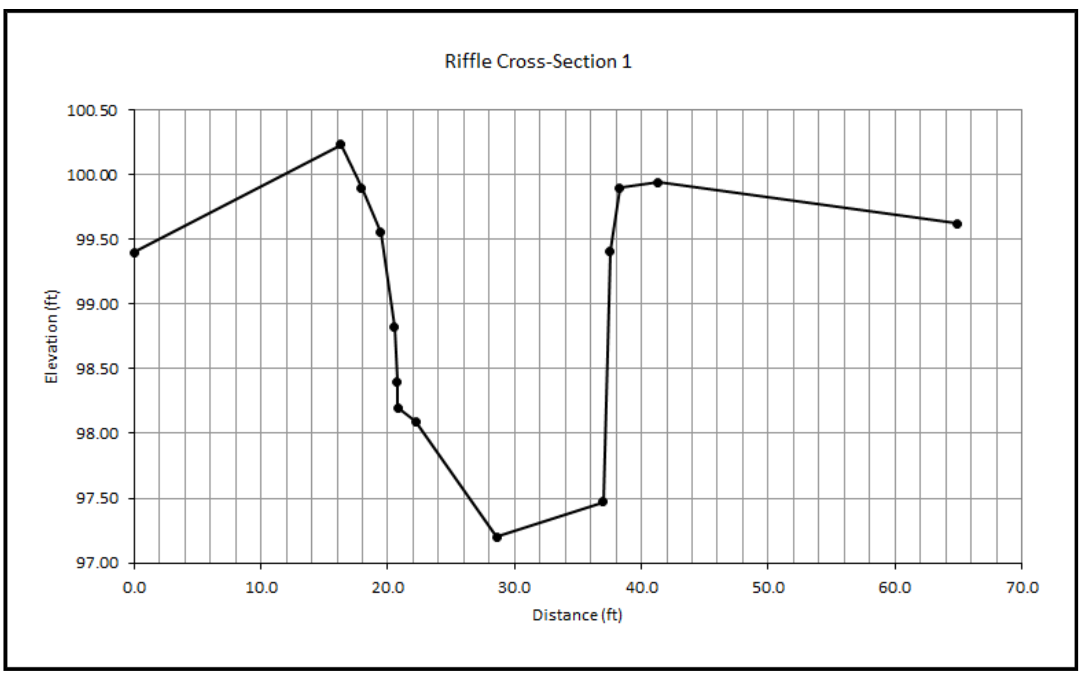
Area (square feet) =	11.3
Width (feet) =	10.5
Mean depth =	1.1
Max depth =	1.5
Width/depth ratio =	9.9
Entrenchment ratio =	>10.0



10. Toby Creek
Ecoregion 65, South Carolina

Latitude: 33.296829
Longitude: -81.297025
Drainage area: 10.7 square miles
Median particle size: sand
Longitudinal slope: 0.0015 feet/foot
Stream classification: E5

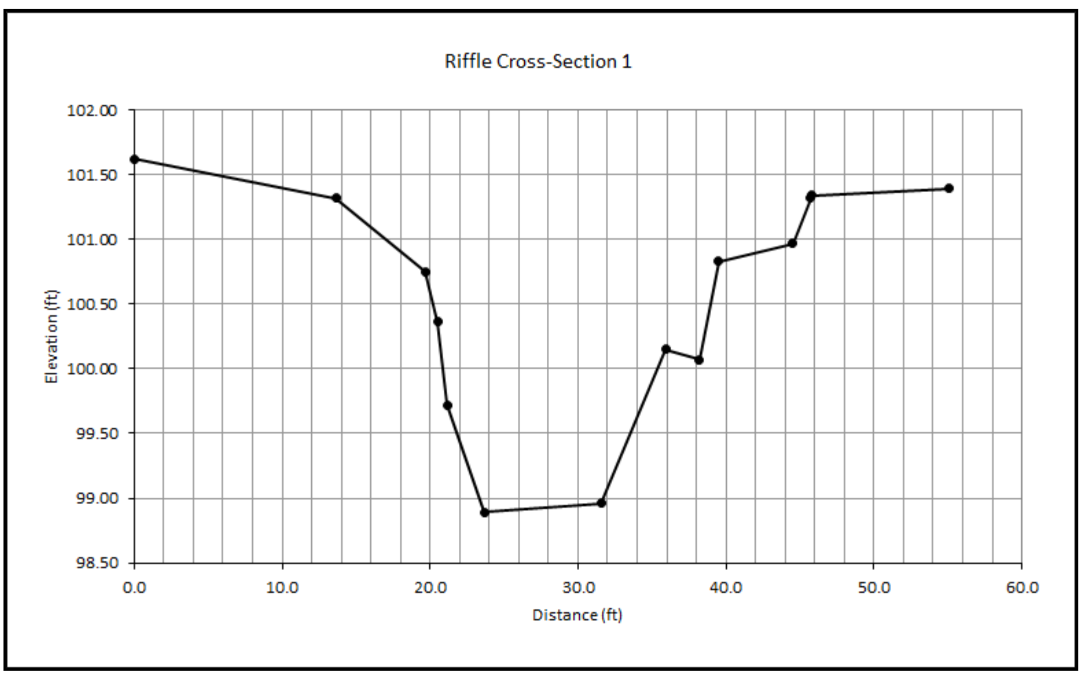
Area (square feet) =	40.7
Width (feet) =	20.4
Mean depth =	2.0
Max depth =	2.7
Width/depth ratio =	10.2
Entrenchment ratio =	9.5



11. Wells Branch
Ecoregion 65, South Carolina

Latitude: 33.111540
Longitude: -81.261873
Drainage area: 13.5 square miles
Median particle size: sand
Longitudinal slope: 0.0013 feet/foot
Stream classification: C5

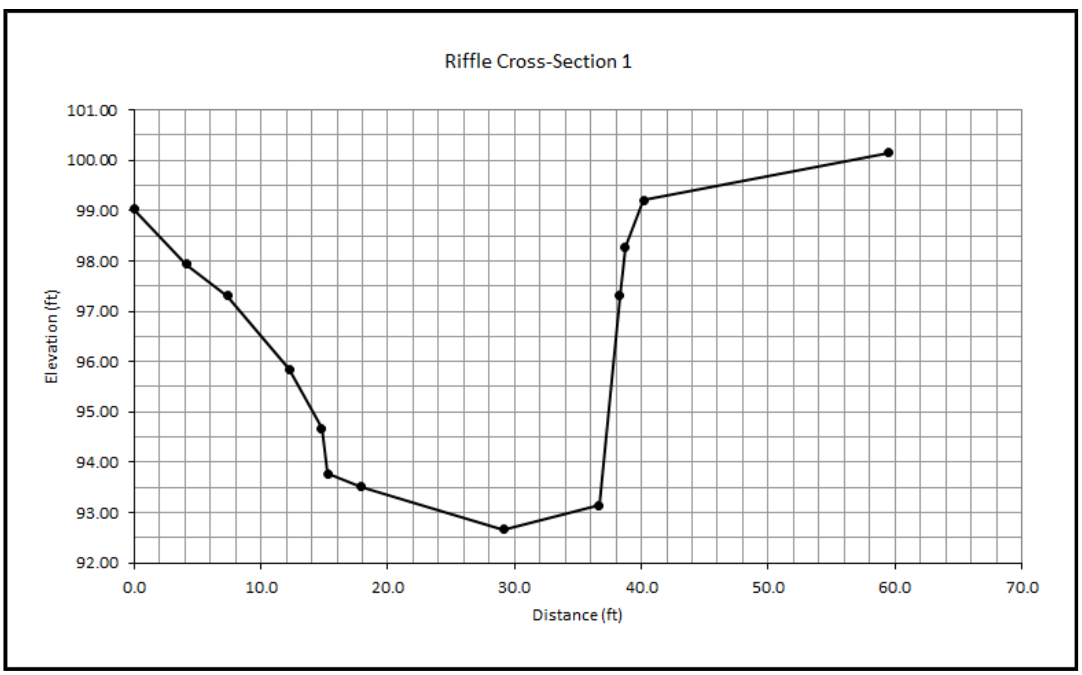
Area (square feet) =	41.1
Width (feet) =	32.1
Mean depth =	1.3
Max depth =	2.4
Width/depth ratio =	25.1
Entrenchment ratio =	>10.0



12. Little Fork Creek
Ecoregion 65, South Carolina

Latitude: 34.638271
Longitude: -80.406705
Drainage area: 14.7 square miles
Median particle size: gravel
Longitudinal slope: 0.0016 feet/foot
Stream classification: E4

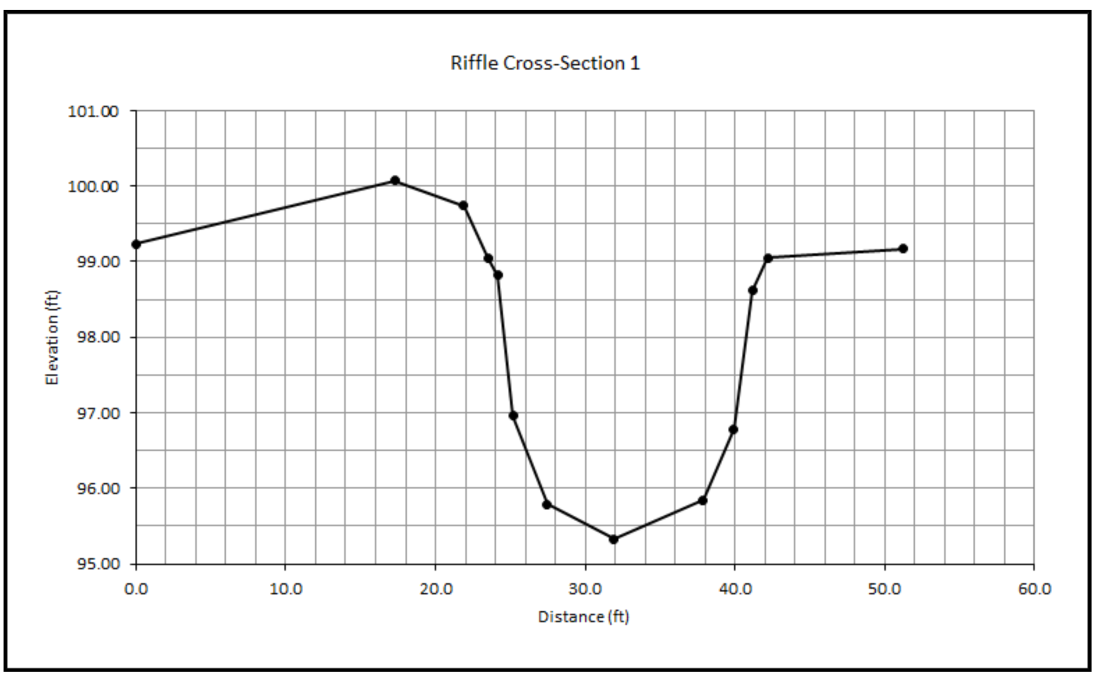
Area (square feet) =	103.9
Width (feet) =	30.9
Mean depth =	3.4
Max depth =	4.6
Width/depth ratio =	9.2
Entrenchment ratio =	4.9



13. Brunson Swamp
Ecoregion 65, South Carolina

Latitude: 33.864224
Longitude: -80.467757
Drainage area: 20.0 square miles
Median particle size: sand
Longitudinal slope: 0.0007 feet/foot
Stream classification: E5

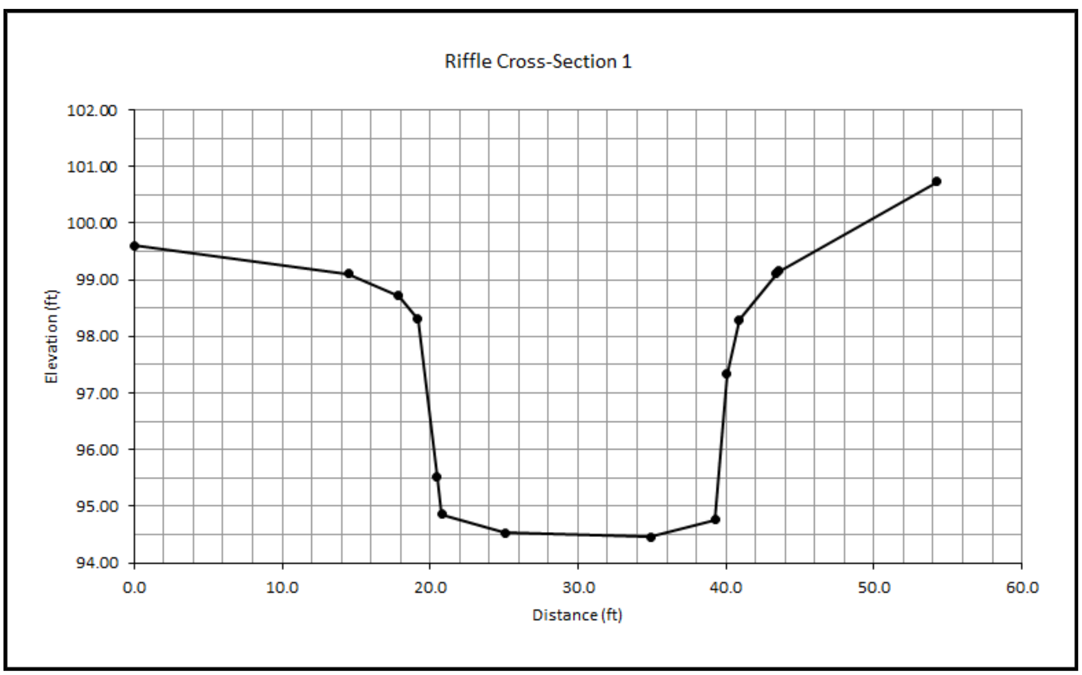
Area (square feet) =	51.1
Width (feet) =	18.7
Mean depth =	2.7
Max depth =	3.7
Width/depth ratio =	6.8
Entrenchment ratio =	>10.0



14. Fork Creek
Ecoregion 65, South Carolina

Latitude: 34.638528
Longitude: -80.389503
Drainage area: 24.4 square miles
Median particle size: gravel
Longitudinal slope: 0.0038 feet/foot
Stream classification: E4

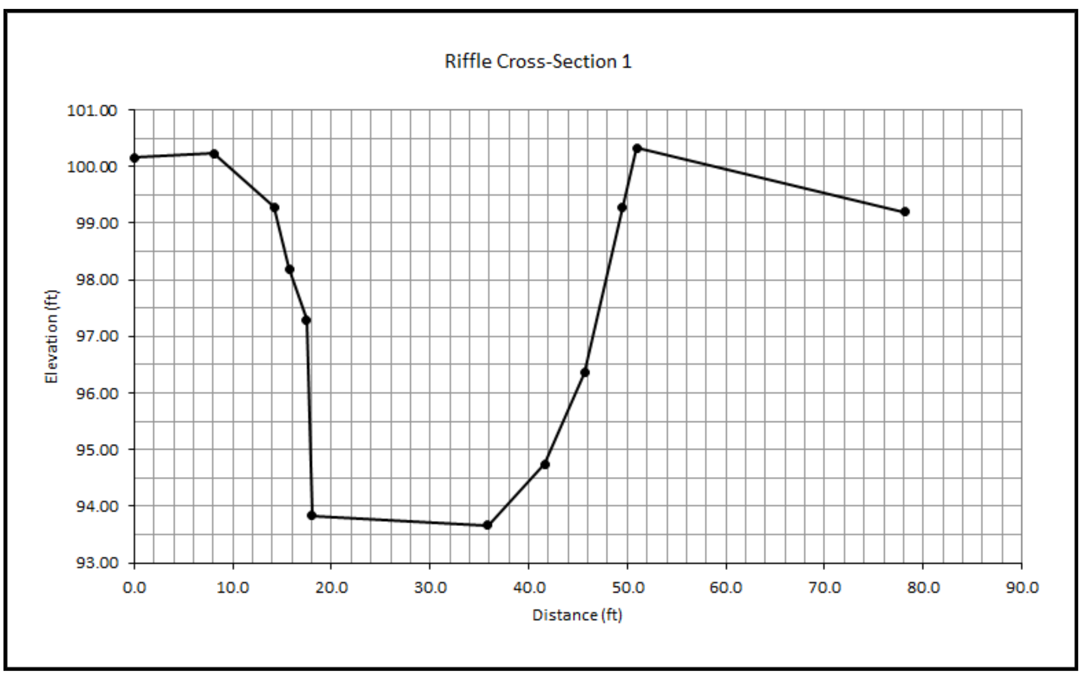
Area (square feet) =	93.7
Width (feet) =	29.1
Mean depth =	3.2
Max depth =	4.6
Width/depth ratio =	9.0
Entrenchment ratio =	9.1



15. Black Creek
Ecoregion 65, South Carolina

Latitude: 34.663060
Longitude: -80.211803
Drainage area: 51.9 square miles
Median particle size: sand
Longitudinal slope: 0.0004 feet/foot
Stream classification: E5

Area (square feet) =	154.1
Width (feet) =	35.3
Mean depth =	4.4
Max depth =	5.6
Width/depth ratio =	8.1
Entrenchment ratio =	>10.0



South Carolina Middle Atlantic Coastal Plain, Ecoregion 63
Stream Morphology Results

In the South Carolina Middle Atlantic Coastal Plain, Ecoregion 63, geomorphic data were collected from 15 streams during January and February 2020 (Figure 1 and Table 1). The sites were all ungaged reference streams in forested watersheds with drainage areas ranging from 0.35 to 14.3 square miles. Several other streams were visited to evaluate their potential for inclusion in this study but were rejected due to local instability or other factors affecting their geomorphic conditions.

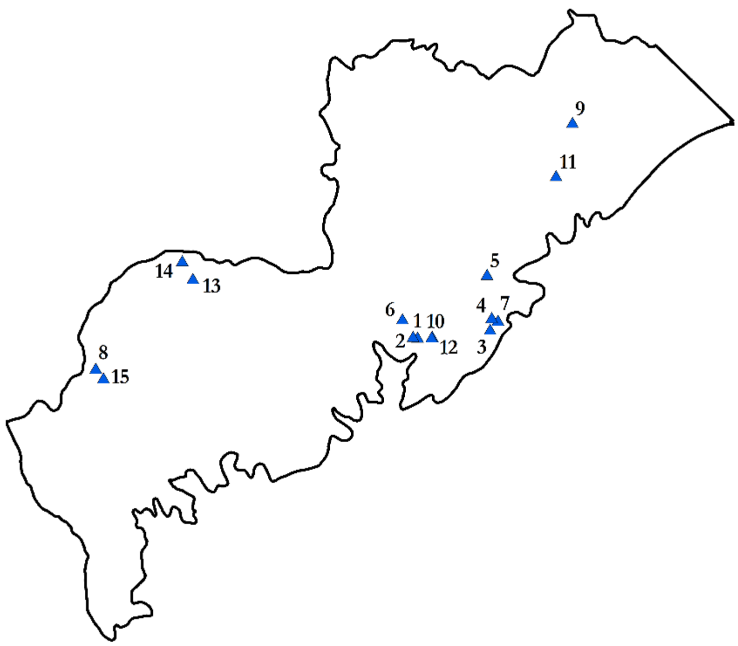


Figure 1. Reference Stream Sites in Ecoregion 63, South Carolina.

Table 1. Reference Stream Sites.

ID	Stream name	Source/Location	Latitude	Longitude	Drainage area ($mile^2$)
1	UT Nicholson Creek	Francis Marion NF	33.160604	-79.813020	0.35
2	UT Gough Creek	Francis Marion NF	33.162626	-79.831400	0.36
3	UT Cane Branch	Francis Marion NF	33.183908	-79.526605	0.57
4	Red Bluff Creek	Francis Marion NF	33.223015	-79.519964	0.58
5	UT Bond Swamp	Georgetown County	33.365872	-79.535571	0.59
6	UT Cane Gully Branch	Francis Marion NF	33.222307	-79.871977	1.27
7	Little Morgan Branch	Francis Marion NF	33.213300	-79.494886	1.31
8	Big Branch	Bamberg County	33.063887	-81.082283	2.03
9	Juniper Bay	SCDNR Fish Site	33.864485	-79.187739	2.09
10	Kutz Creek	Francis Marion NF	33.160895	-79.757817	2.45
11	Tyler Creek	SCDNR Fish Site	33.689045	-79.257043	2.78
12	Nicholson Creek	Francis Marion NF	33.162119	-79.754408	4.99
13	Buck Branch	Bowman Nature Park	33.360504	-80.698106	13.0
14	Cow Castle Creek	SCDNR Fish Site	33.419779	-80.740338	13.5
15	Savannah Creek	SCDNR Fish Site	33.031787	-81.051409	14.3

The reference streams in this ecoregion were selected through consultation with SCDNR and other local stream professionals, as well as extensive field reconnaisance. Reference reaches were identified generally based on the following criteria:

- Streams with drainage areas ranging between approximately 0.1 and 20 square miles
- Watersheds with stable land use and mostly forested over the past several decades
- Stream channels and floodplains in equilibrium with active bankfull stage indicators (i.e., bank height ratios near 1.0)
- Single-thread stream channels with freely-formed meander patterns in low-gradient valleys (less than 1% longitudinal slope)
- No valley restrictions throughout the reference reach or upstream/downstream that may influence channel form
- Healthy riparian forest buffers
- Accessible for data collection and protected for future access

Field measurements of stream geomorphological characteristics were collected to establish hydraulic geometry relationships following the methods outlined in the most current version of the North Carolina SQT Field User Manual[1]. All stream assessments included collection of bankfull riffle dimension (cross-section) data. As conditions allowed, pattern data were collected for a subset of the reference sites.

[1] NC SQT https://stream-mechanics.com/wp-content/uploads/2017/09/Data-Collection-and-Analysis-Manual_NC-SQT-v3.0.pdf; currently under revision.

Data collected for all reference sites included:

- Rosgen stream type
- drainage area (DA)
- bankfull riffle cross-section area (A_{bkf})
- bankfull riffle width (W_{bkf}) and mean depth (d_{bkf}) for calculating width-to-depth ratio (WDR)
- width of floodprone area (W_{fpa}) for calculating entrenchment ratio (ER)
- maximum depth at top of bank and bankfull stage for calculating bank height ratio (BHR)
- channel water surface slope (S)
- sinuosity (k)
- median substrate size classification
- estimated Manning roughness coefficient (n)

The subset of reference sites with pattern data included collection of:

- meander wavelengths ($L_{meander}$)
- belt widths (W_{blt})
- radius of curvature of meander bends (R_c)

Profile data were not collected from streams within this ecoregion. In these low-slope, sand bed streams, riffle-pool sequences were not discernible. Rather, variations in bedform were generally due to tree roots, vegetation in the channel, woody debris, and accumulations of sand. This is typical of streams in coastal plain ecoregions. As a result, profile data (i.e., riffle slopes and lengths, pool lengths, and pool spacings) could not effectively be measured.

Large woody debris (LWD) information was collected in accordance with the most current version of the Application of the Large Woody Debris Index Field User Manual developed by Stream Mechanics and Ecosystem Planning & Restoration[2].

Field measurement results are presented in the appendix and in the tables and graphs below. Table 2 summarizes cross-section dimension geomorphic parameters used for Rosgen stream classification. Eight of the streams measured in Ecoregion 63 are C streams, while the remaining seven are E streams. Sand was the dominant bed material in all streams. Entrenchment ratios are very high. For all but two streams, the valleys were so wide that they precluded exact measurement; in these cases, entrenchment ratios are reported as >10.0. Width/depth ratios are highly variable, and range from 6.4 to 41.1. Despite the high width/depth ratios for the streams at the upper end of this range (e.g., Nicholson Creek and Kutz Creek), they are single-thread channels with defined streambeds and banks within the measured reach.

[2] Large Woody Debris Assessment https://stream-mechanics.com/wp-content/uploads/2017/12/LWDI-Manual_V1.pdf

Table 2. Morphology Dimensions.

Site	Drainage area (mile²)	Channel slope (ft/ft)	Cross-section area (ft²)	Bankfull width (ft)	Bankfull mean depth (ft)	Width/depth ratio	Entrench-ment ratio	Rosgen Stream Class
1	0.35	0.0026	4.0	5.8	0.7	8.5	>10.0	E5
2	0.36	0.0027	4.8	9.6	0.5	18.8	5.5	C5
3	0.57	0.0007	6.5	6.7	1.0	7.0	>10.0	E5
4	0.58	0.0043	7.7	7.0	1.1	6.4	>10.0	E5
5	0.59	0.0027	3.3	7.0	0.5	14.7	>10.0	C5
6	1.27	0.0065	5.7	9.7	0.6	16.4	7.3	C5
7	1.31	0.0032	5.1	5.8	0.9	6.5	>10.0	E5
8	2.03	0.0019	16.9	14.2	1.2	12.0	>10.0	E5
9	2.09	0.0013	14.9	13.1	1.1	11.4	>10.0	E5
10	2.45	0.0017	12.8	20.9	0.6	34.3	>10.0	C5
11	2.78	0.0030	19.2	22.0	0.9	25.2	>10.0	C5
12	4.99	0.0013	46.9	43.9	1.1	41.1	>10.0	C5
13	13.0	0.0004	72.2	29.0	2.5	11.7	>10.0	E5
14	13.5	0.0005	73.2	34.1	2.1	15.9	>10.0	C5c-
15	14.3	0.0010	51.5	28.8	1.8	16.1	>10.0	C5c-

Table 3 summarizes estimated bankfull hydraulic parameters (velocity and discharge) for each stream based on the Manning equation. The Manning equation, in English units, is:

$$v = \frac{1.486 * \left(R^{2/3}\right) * \left(S^{1/2}\right)}{n}$$

where *v* is average velocity (feet/second), *R* is the hydraulic radius (feet), *S* is average water surface slope (feet/feet), and *n* is a dimensionless coefficient describing channel roughness, known as Manning's n, which ranges from 0.033 to 0.150 for natural channels. The Cowan (1956) method was used to estimate the Manning's n values based on sediment size, irregularity within a cross-section, variation among cross-sections, obstructions, vegetation, and sinuosity. The bankfull discharge is estimated as the product of average velocity and riffle bankfull cross-section area.

For these streams, Manning's n values range from 0.045 to 0.075, which match expected values for natural alluvial streams in this ecoregion. Estimated bankfull average velocities for the study streams are generally around 1 foot per second, with a range of 0.5 to 1.5, with variations due to slope, cross-section dimensions, and channel roughness.

Table 3. Estimated Bankfull Hydraulic Parameters.

Site	Drainage area (mile^2)	Manning's n	Estimated Bankfull Velocity (ft/s)	Estimated Bankfull Discharge (cfs)
1	0.35	0.050	1.0	4.1
2	0.36	0.050	0.9	4.5
3	0.57	0.060	0.5	3.4
4	0.58	0.060	1.5	11
5	0.59	0.063	0.7	2.3
6	1.27	0.063	1.2	7.0
7	1.31	0.065	0.7	5.1
8	2.03	0.052	1.2	21
9	2.09	0.060	0.9	13
10	2.45	0.075	0.6	7.1
11	2.78	0.058	1.2	24
12	4.99	0.075	0.7	34
13	13.0	0.045	1.1	79
14	13.5	0.050	1.0	73
15	14.3	0.050	1.3	66

The graphs in Figures 2 through 5 show bankfull morphological parameters and estimated discharge related to watershed drainage area (i.e., regional curves). These graphs include data points measured in Ecoregion 63 of both South Carolina and North Carolina. North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina. The North Carolina data represent seven streams, as published by Doll, et al. (2003). North Carolina data are not included in Figure 5 due to minor differences in the methodologies used to estimate bankfull discharge. Figures 2 through 5 also include best-fit regression lines for South Carolina stream data in addition to the regression equations and coefficients of determination.

Figures 2 through 4 demonstrate that measured bankfull cross-section area, width, and depth are often smaller in the South Carolina streams than in the assessed North Carolina streams. One reason for this result may be that many of the sites measured in South Carolina were in protected, forested watersheds with little or no impervious surface (e.g., Francis Marion National Forest). These undisturbed, forested watersheds tend to dampen peak flow responses to rainfall, producing equilibrium channels with little to no incision. The cross-section dimensions for South Carolina streams are validated by most streams having a bankfull elevation equal to the top of bank (i.e., Bank Height Ratio = 1.0).

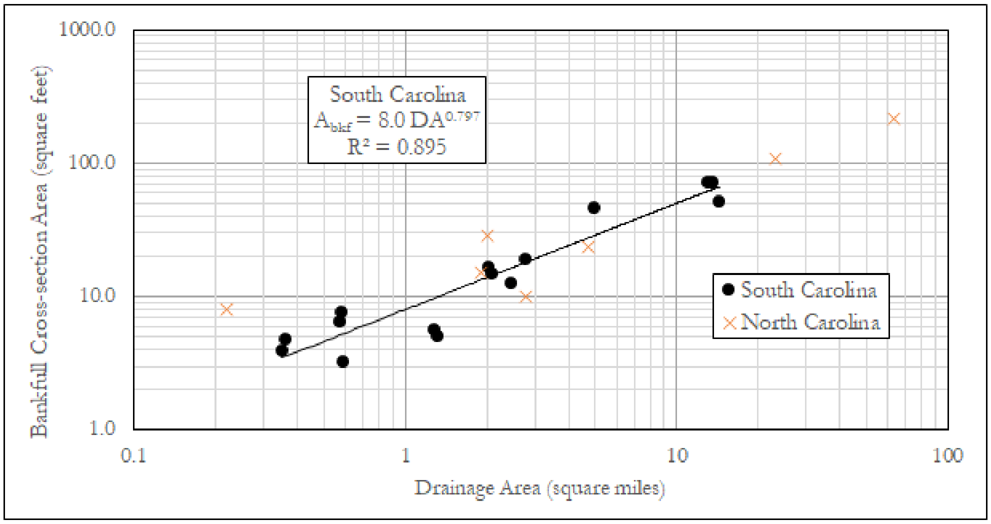


Figure 2. Bankfull riffle cross-section area related to drainage area for Ecoregion 63 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

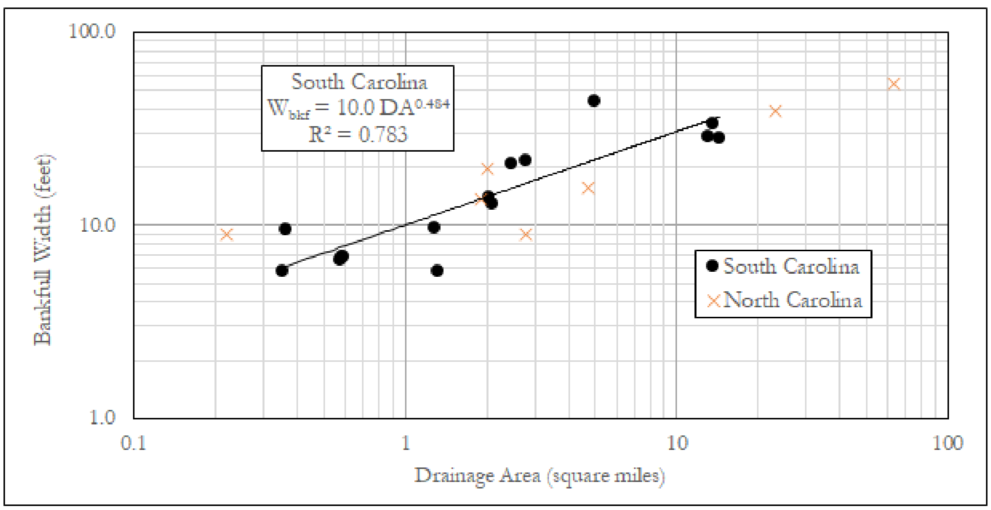


Figure 3. Bankfull riffle cross-section width related to drainage area for Ecoregion 63 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

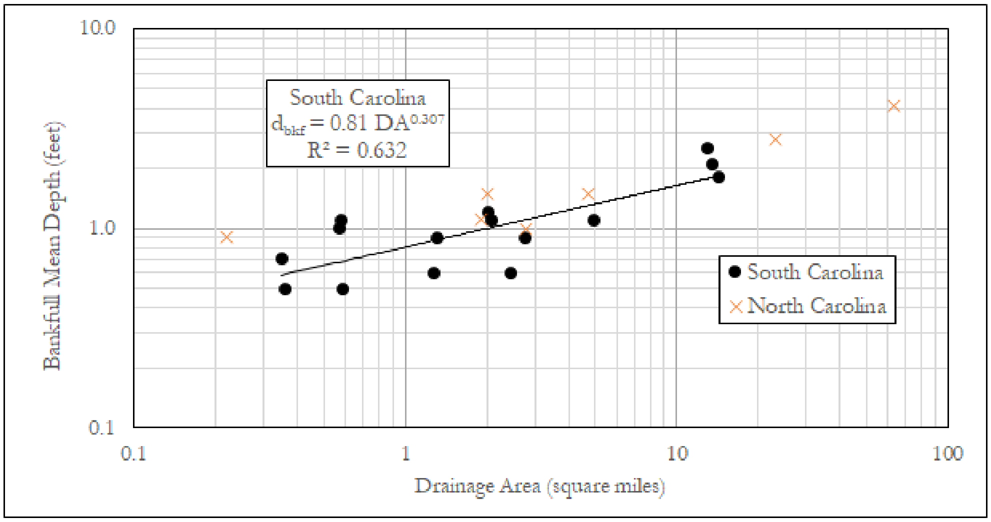


Figure 4. Bankfull riffle mean depth related to drainage area for Ecoregion 63 streams with best-fit regression equations for South Carolina data. (Note: North Carolina stream data points are shown for comparison only and should not be used for assessment or design in South Carolina.)

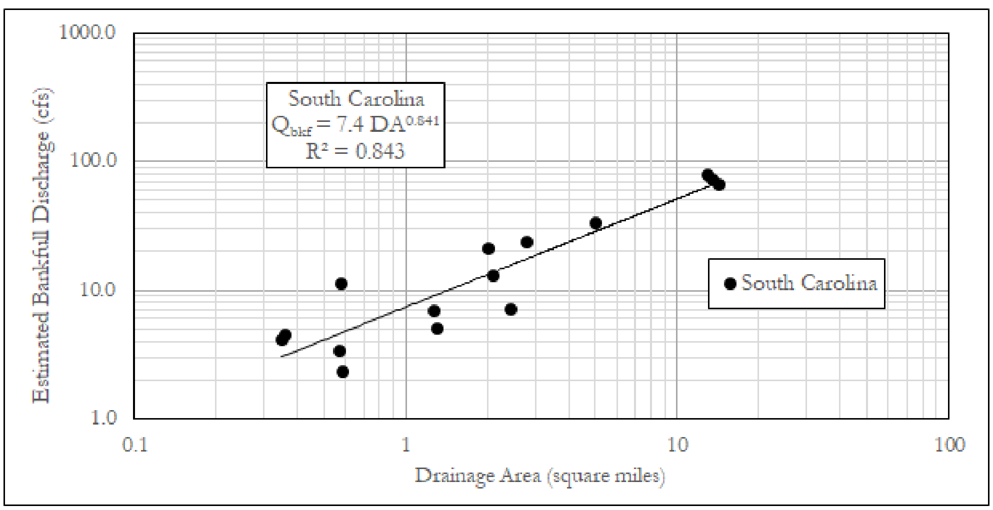


Figure 5. Estimated bankfull discharge related to drainage area for Ecoregion 63 streams.

Table 4 summarizes stream pattern data for the meandering reference streams with discernable planform parameters that could be assessed in the field. For each stream, the median pattern parameters and the median dimensionless ratios are listed. Median meander wavelength ratios range from 2.5 to 13.6, belt width ratios range from 1.3 to 8.1, and radius of curvature ratios range from 1.2 to 5.6.

Table 5 summarizes Large Woody Debris (LWD) assessments for each stream, including the numbers of LWD pieces, number of dams, and the LWD Index scores.

Table 4. Stream Morphology Pattern Parameters.

Site	Drainage area (mile^2)	Sinuosity (ft/ft)	Median meander wavelength [ratio to bankfull width] (ft [none])	Median belt width [ratio to bankfull width] (ft [none])	Median radius of curvature [ratio to bankfull width] (ft [none])
1	0.35	1.06	79 [13.6]	48 [8.1]	33 [5.6]
5	0.59	1.35	59 [8.4]	27 [3.8]	19 [2.7]
6	1.27	1.22	60 [6.2]	31 [3.2]	16 [1.7]
7	1.31	1.63	38 [6.6]	25 [4.3]	16 [2.7]
11	2.78	1.35	56 [2.5]	28 [1.3]	27 [1.2]
12	4.99	1.10	130 [3.0]	89 [2.0]	54 [1.2]

Table 5. Large Woody Debris Assessment Results.

Site	Number of Pieces	Number of Dams	Piece Score	Dam Score	LWDI
1	14	1	274	15	349
2	6	0	111	0	111
3	13	0	279	0	279
4	11	0	240	0	240
5	10	0	224	0	224
6	9	0	169	0	169
7	15	0	355	0	355
8	7	0	155	0	155
9	17	1	364	18	454
10	6	0	106	0	106
11	16	0	317	0	317
12	8	0	168	0	168
13	9	0	198	0	198
14	18	0	395	0	395
15	16	0	340	0	340

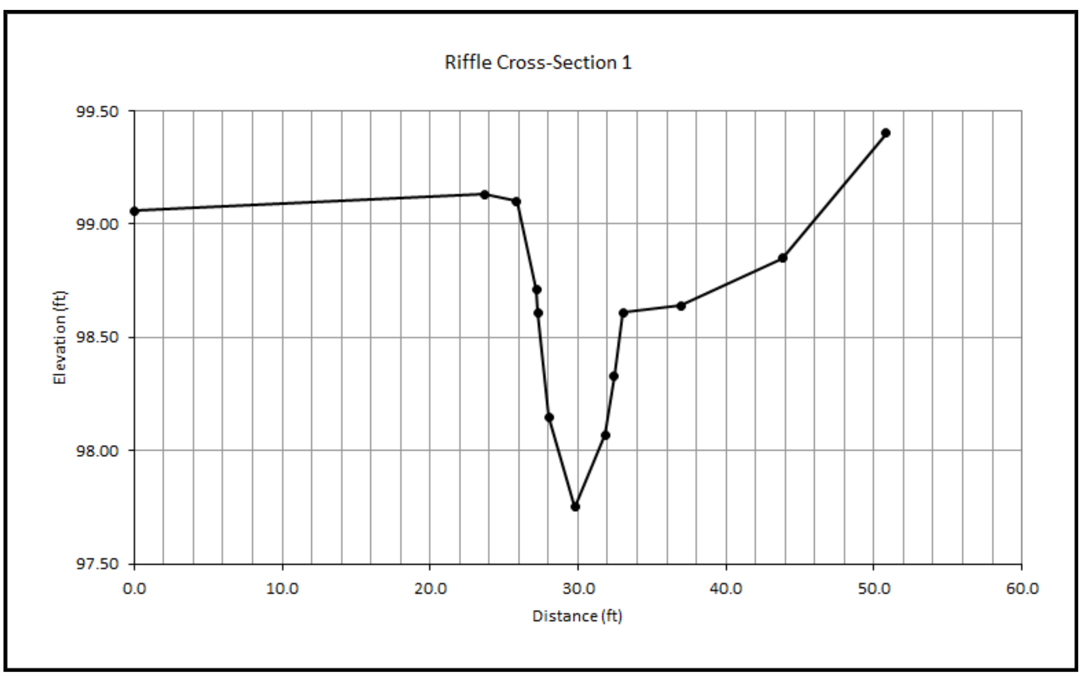
APPENDIX

ECOREGION 63, SOUTH CAROLINA

1. UT Nicholson Creek
Ecoregion 63, South Carolina

Latitude: 33.160604
Longitude: -79.813020
Drainage area: 0.35 square miles
Median particle size: sand
Longitudinal slope: 0.0026 feet/foot
Stream classification: E5

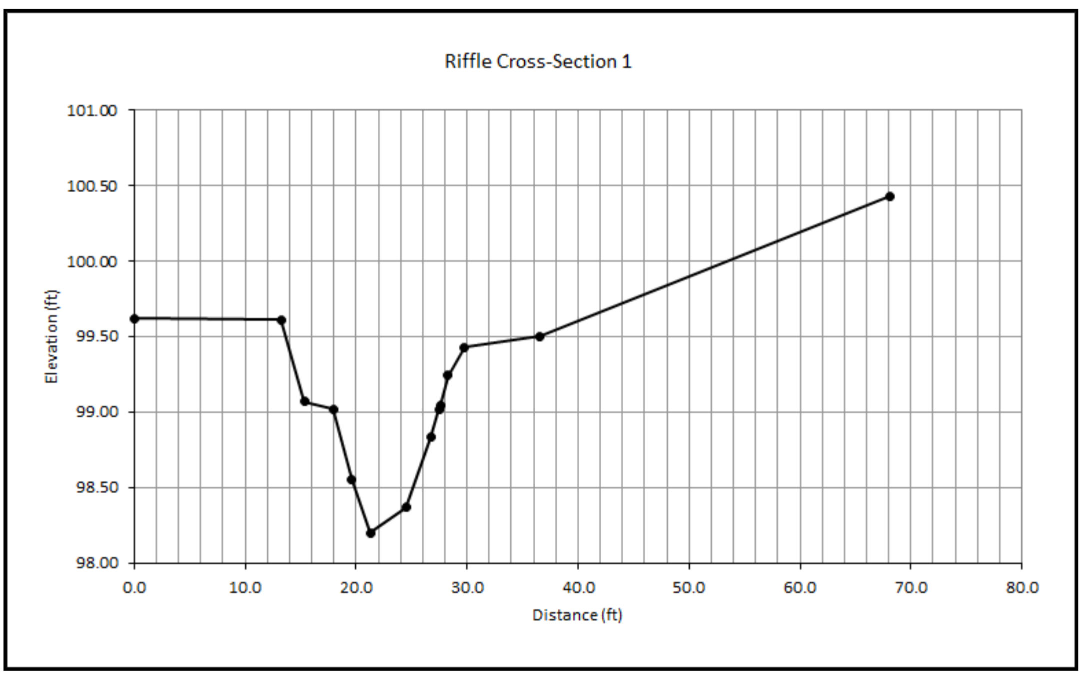
Area (square feet) =	4.0
Width (feet) =	5.8
Mean depth =	0.7
Max depth =	1.0
Width/depth ratio =	8.5
Entrenchment ratio =	>10.0



2. UT Gough Creek
Ecoregion 63, South Carolina

Latitude: 33.162626
Longitude: -79.831400
Drainage area: 0.36 square miles
Median particle size: sand
Longitudinal slope: 0.0027 feet/foot
Stream classification: C5

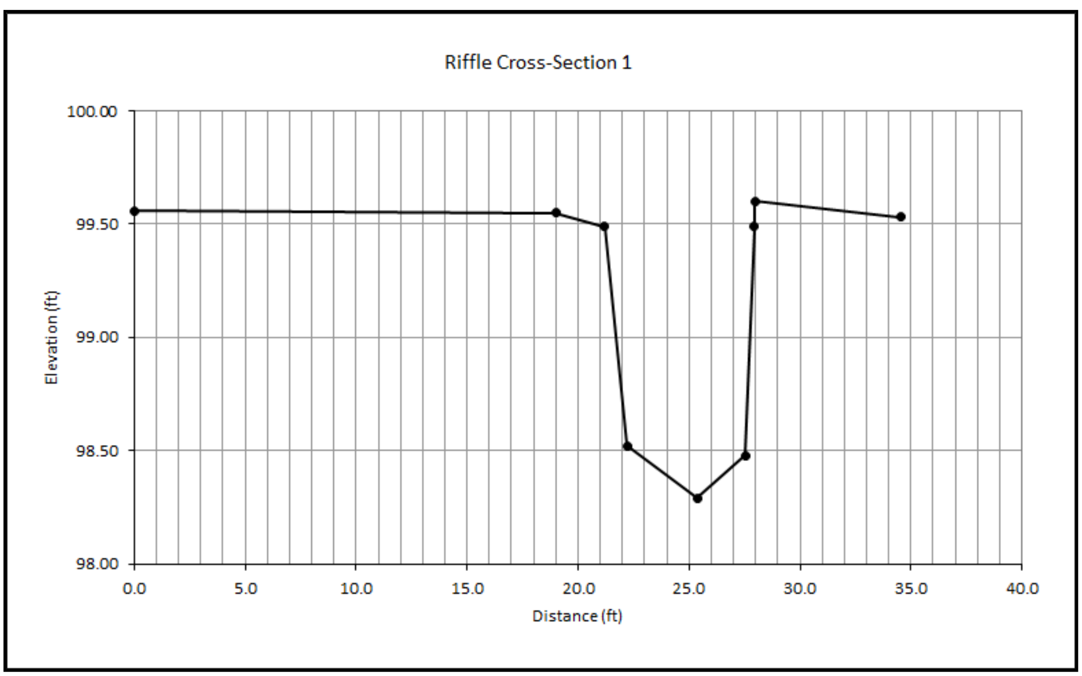
Area (square feet) =	4.8
Width (feet) =	9.6
Mean depth =	0.5
Max depth =	0.8
Width/depth ratio =	18.8
Entrenchment ratio =	5.5



3. UT Cane Branch
Ecoregion 63, South Carolina

Latitude: 33.183908
Longitude: -79.526605
Drainage area: 0.57 square miles
Median particle size: sand
Longitudinal slope: 0.0007 feet/foot
Stream classification: E5

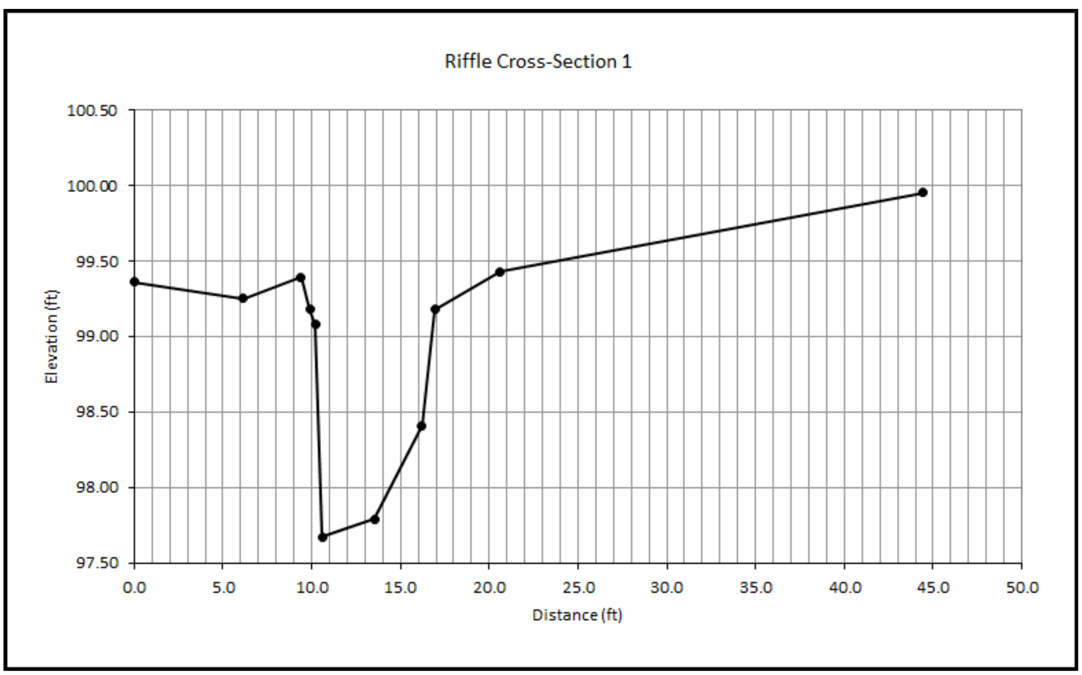
Area (square feet) =	6.5
Width (feet) =	6.7
Mean depth =	1.0
Max depth =	1.2
Width/depth ratio =	7.0
Entrenchment ratio =	>10.0



4. Red Bluff Creek
Ecoregion 63, South Carolina

Latitude: 33.223015
Longitude: -79.519964
Drainage area: 0.58 square miles
Median particle size: sand
Longitudinal slope: 0.0043 feet/foot
Stream classification: E5

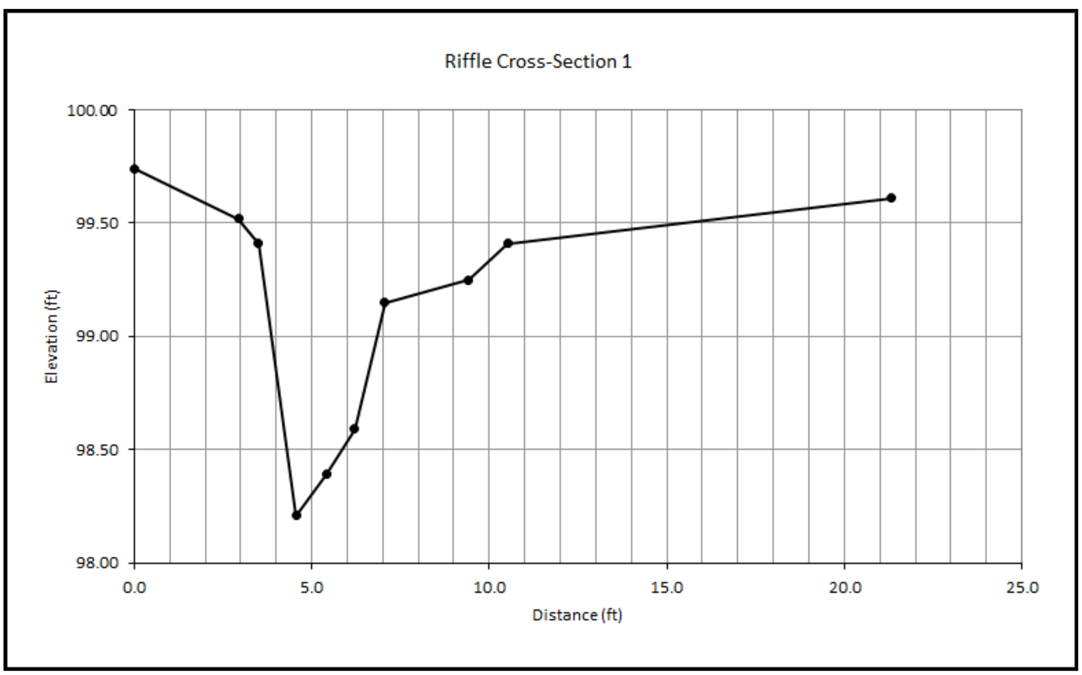
Area (square feet) =	7.7
Width (feet) =	7.0
Mean depth =	1.1
Max depth =	1.5
Width/depth ratio =	6.4
Entrenchment ratio =	>10.0



5. UT Bond Swamp
Ecoregion 63, South Carolina

Latitude: 33.365872
Longitude: -79.535571
Drainage area: 0.59 square miles
Median particle size: sand
Longitudinal slope: 0.0027 feet/foot
Stream classification: C5

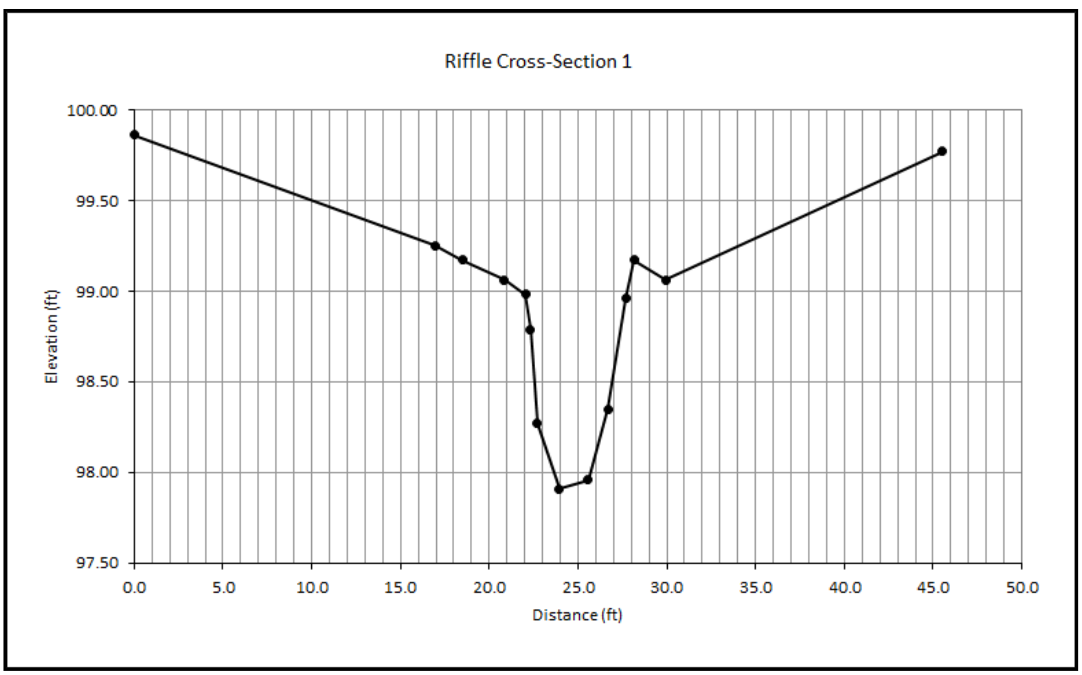
Area (square feet) =	3.3
Width (feet) =	7.0
Mean depth =	0.5
Max depth =	1.2
Width/depth ratio =	14.7
Entrenchment ratio =	>10.0



6. UT Cane Gully Branch
Ecoregion 63, South Carolina

Latitude: 33.222307
Longitude: -79.871977
Drainage area: 1.27 square miles
Median particle size: sand
Longitudinal slope: 0.0065 feet/foot
Stream classification: C5

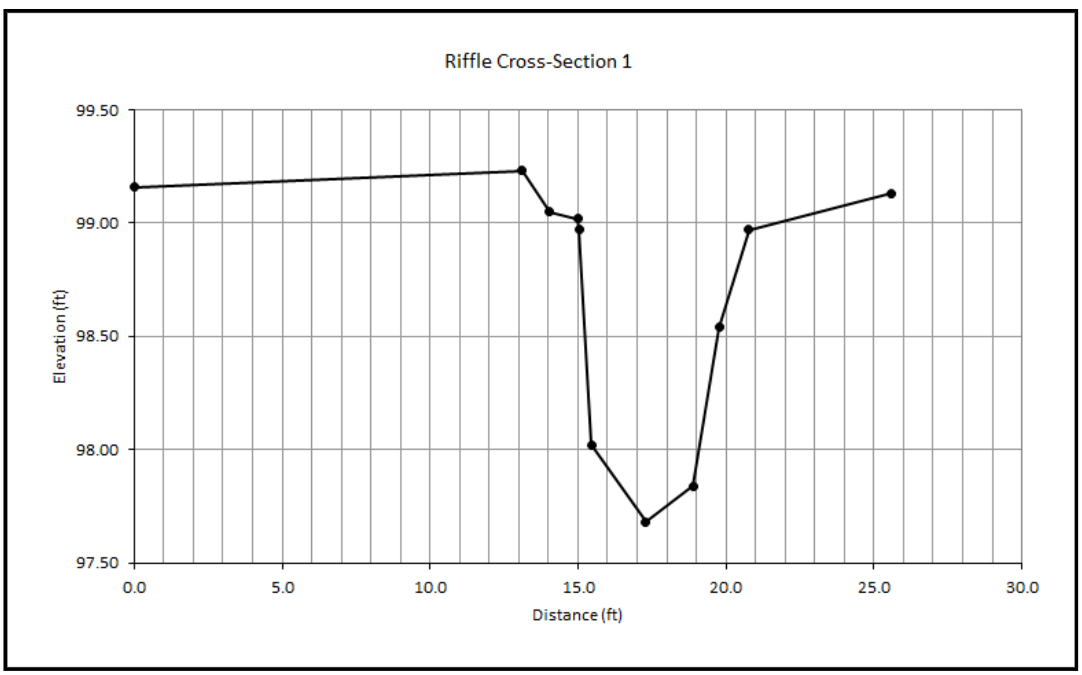
Area (square feet) =	5.7
Width (feet) =	9.7
Mean depth =	0.6
Max depth =	1.3
Width/depth ratio =	16.4
Entrenchment ratio =	7.3



7. Little Morgan Branch
Ecoregion 63, South Carolina

Latitude: 33.213300
Longitude: -79.494886
Drainage area: 1.31 square miles
Median particle size: sand
Longitudinal slope: 0.0032 feet/foot
Stream classification: E5

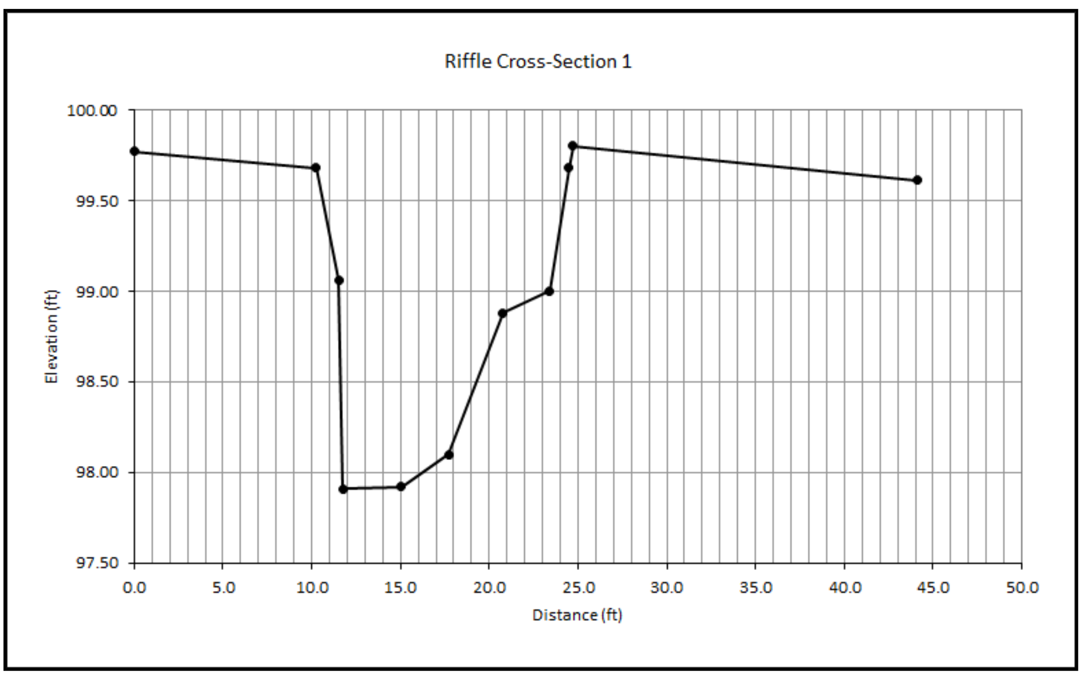
Area (square feet) =	5.1
Width (feet) =	5.8
Mean depth =	0.9
Max depth =	1.3
Width/depth ratio =	6.5
Entrenchment ratio =	>10.0



8. Big Branch
Ecoregion 63, South Carolina

Latitude: 33.063887
Longitude: -81.082283
Drainage area: 2.03 square miles
Median particle size: sand
Longitudinal slope: 0.0019 feet/foot
Stream classification: E5

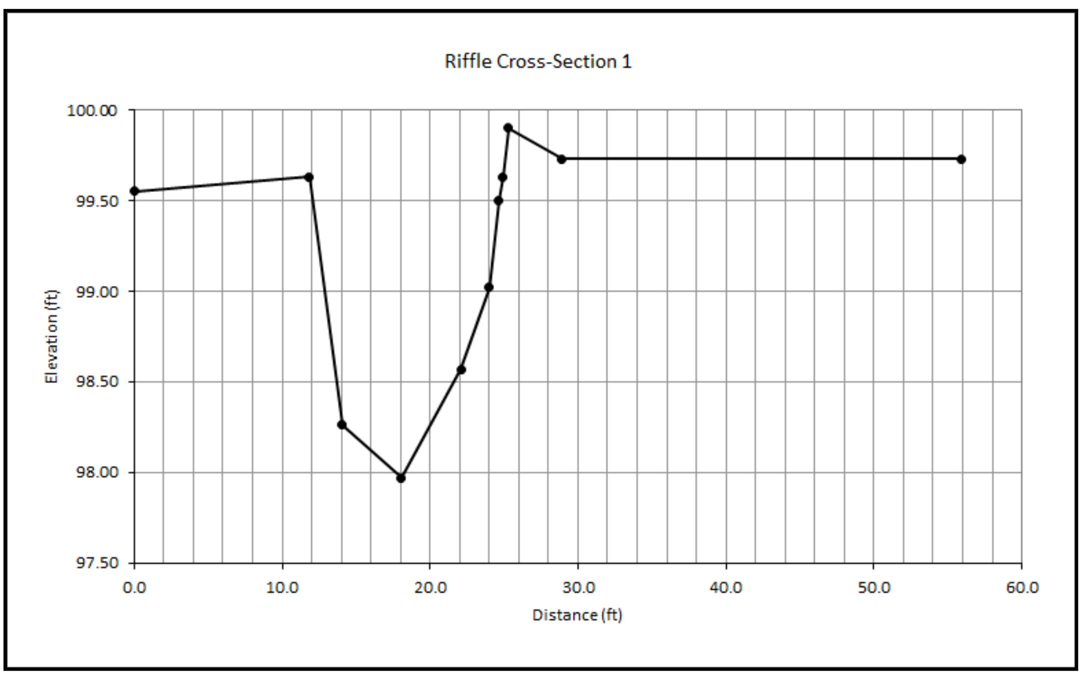
Area (square feet) =	16.9
Width (feet) =	14.2
Mean depth =	1.2
Max depth =	1.8
Width/depth ratio =	12.0
Entrenchment ratio =	>10.0



9. Juniper Bay
Ecoregion 63, South Carolina

Latitude: 33.864485
Longitude: -79.187739
Drainage area: 2.09 square miles
Median particle size: sand
Longitudinal slope: 0.0013 feet/foot
Stream classification: E5

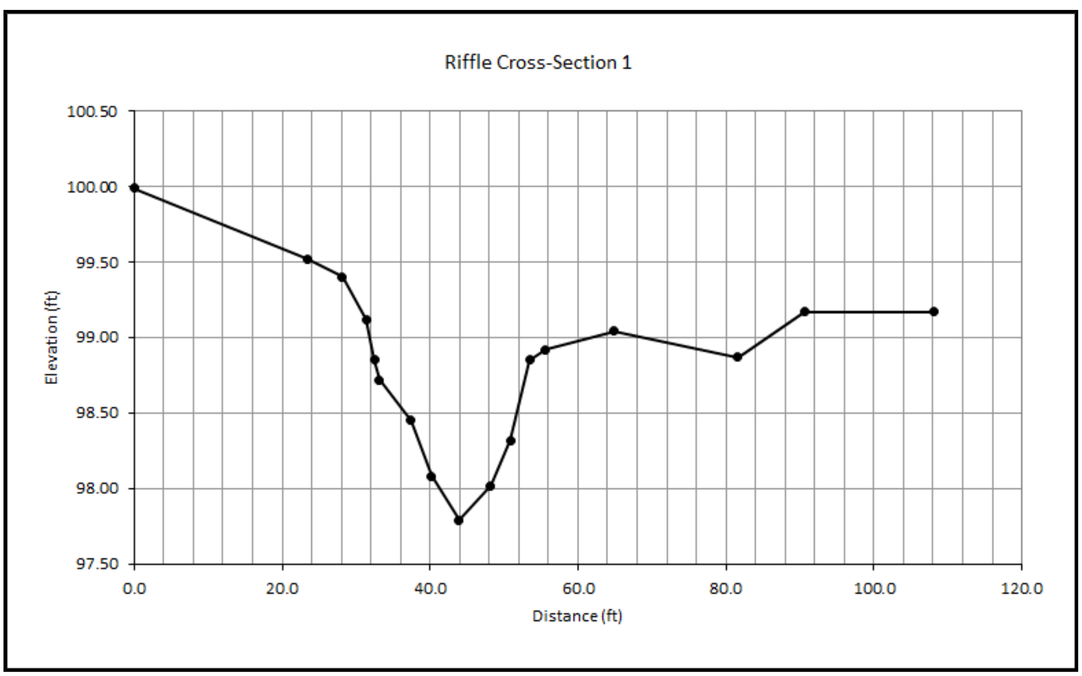
Area (square feet) =	14.9
Width (feet) =	13.1
Mean depth =	1.1
Max depth =	1.7
Width/depth ratio =	11.4
Entrenchment ratio =	>10.0



10. Kutz Creek
Ecoregion 63, South Carolina

Latitude: 33.160895
Longitude: -79.757817
Drainage area: 2.45 square miles
Median particle size: sand
Longitudinal slope: 0.0017 feet/foot
Stream classification: C5

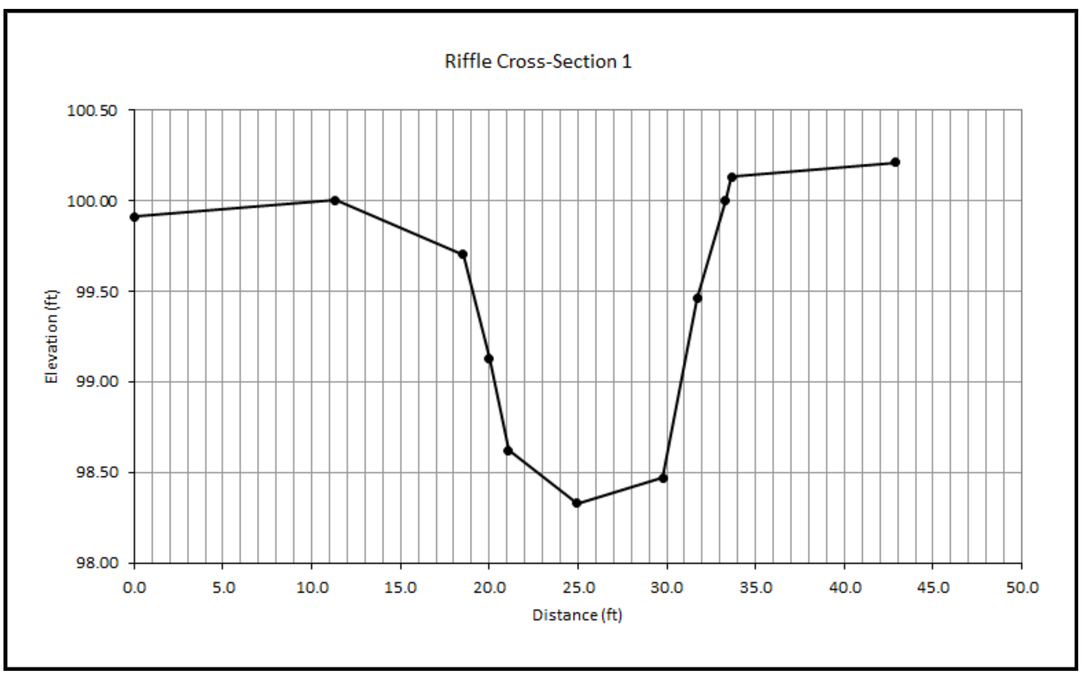
Area (square feet) =	12.8
Width (feet) =	20.9
Mean depth =	0.6
Max depth =	1.1
Width/depth ratio =	34.3
Entrenchment ratio =	>10.0



11. Tyler Creek
Ecoregion 63, South Carolina

Latitude: 33.689045
Longitude: -79.257043
Drainage area: 2.78 square miles
Median particle size: sand
Longitudinal slope: 0.0030 feet/foot
Stream classification: C5

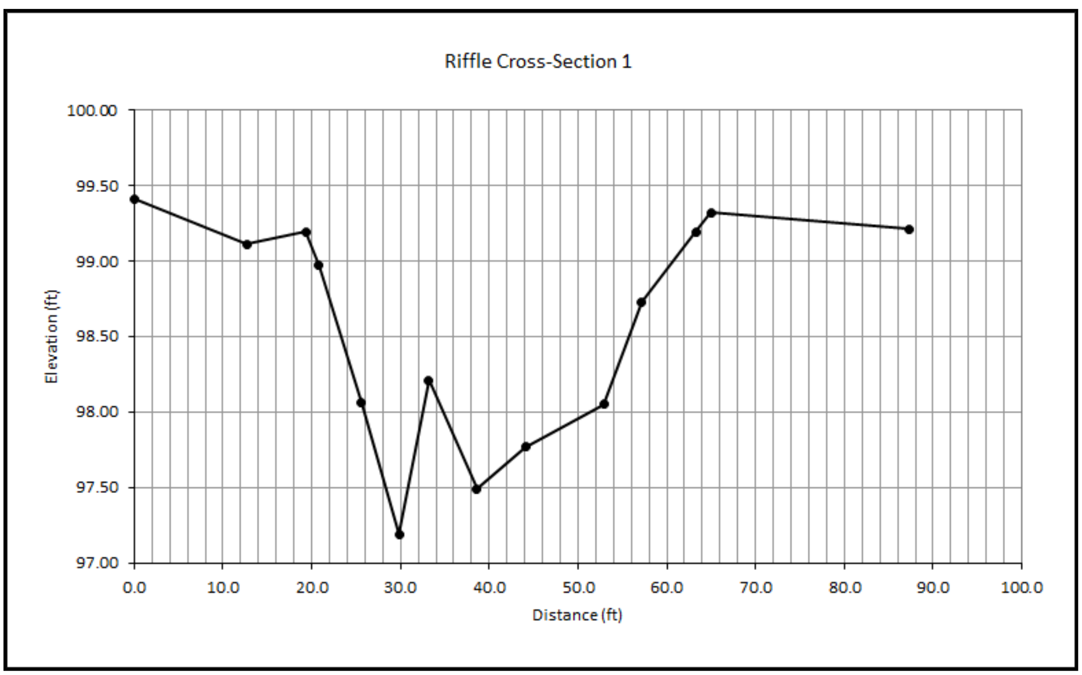
Area (square feet) =	19.2
Width (feet) =	22.0
Mean depth =	0.9
Max depth =	1.7
Width/depth ratio =	25.2
Entrenchment ratio =	>10.0



12. Nicholson Creek
Ecoregion 63, South Carolina

Latitude: 33.162119
Longitude: -79.754408
Drainage area: 4.99 square miles
Median particle size: sand
Longitudinal slope: 0.0013 feet/foot
Stream classification: C5

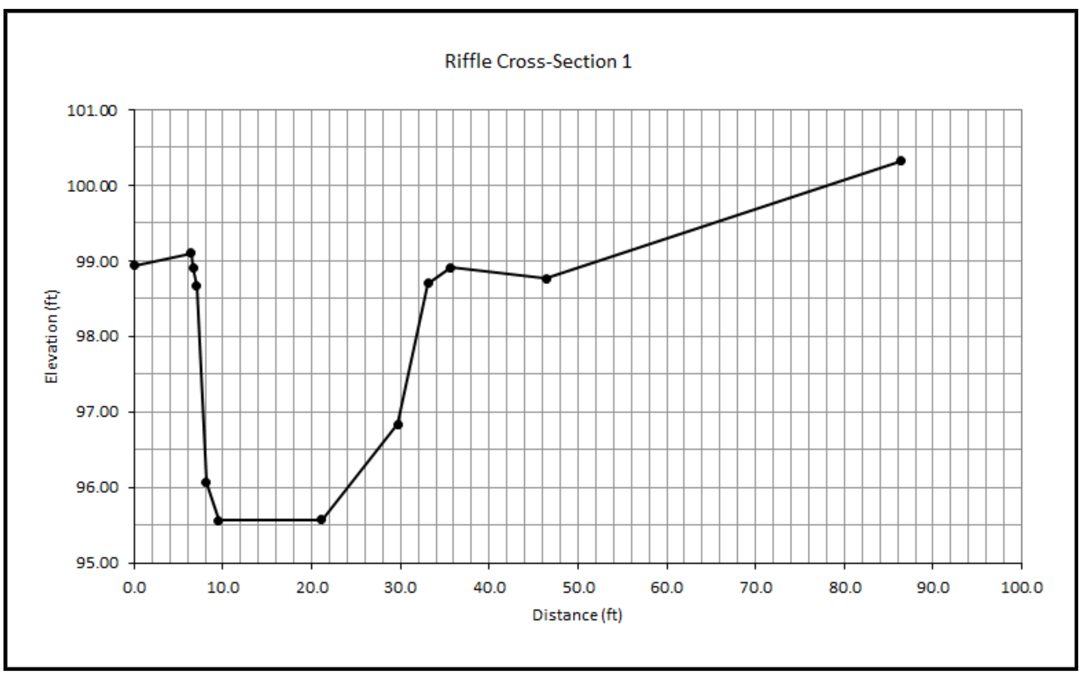
Area (square feet) =	46.9
Width (feet) =	43.9
Mean depth =	1.1
Max depth =	2.0
Width/depth ratio =	41.1
Entrenchment ratio =	>10.0



13. Buck Branch
Ecoregion 63, South Carolina

Latitude: 33.360504
Longitude: -80.698106
Drainage area: 13.0 square miles
Median particle size: sand
Longitudinal slope: 0.0004 feet/foot
Stream classification: E5

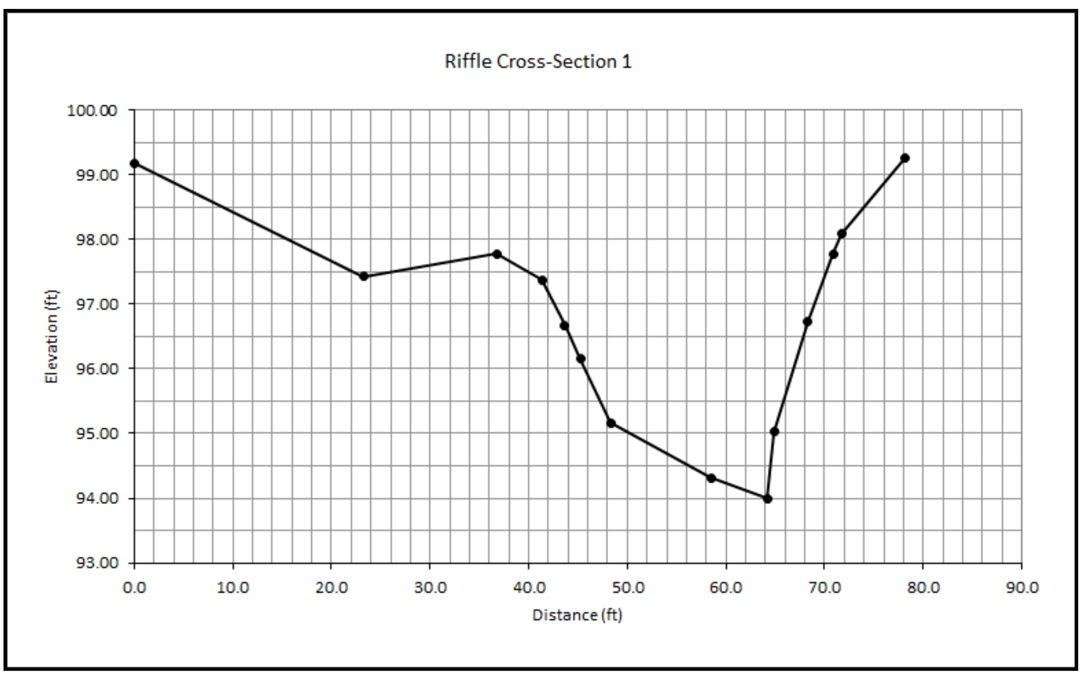
Area (square feet) =	72.2
Width (feet) =	29.0
Mean depth =	2.5
Max depth =	3.3
Width/depth ratio =	11.7
Entrenchment ratio =	>10.0



14. Cow Castle Creek
Ecoregion 63, South Carolina

Latitude: 33.419779
Longitude: -80.740338
Drainage area: 13.5 square miles
Median particle size: sand
Longitudinal slope: 0.0005 feet/foot
Stream classification: C5c-

Area (square feet) =	73.2
Width (feet) =	34.1
Mean depth =	2.1
Max depth =	3.8
Width/depth ratio =	15.9
Entrenchment ratio =	>10.0



15. Savannah Creek
Ecoregion 63, South Carolina

Latitude: 33.031787
Longitude: -81.051409
Drainage area: 14.3 square miles
Median particle size: sand
Longitudinal slope: 0.0010 feet/foot
Stream classification: C5c-

Area (square feet) =	51.5
Width (feet) =	28.8
Mean depth =	1.8
Max depth =	2.6
Width/depth ratio =	16.1
Entrenchment ratio =	>10.0