ENTRENCHED STREAM CHANNELS IN THE BLUE RIDGE MOUNTAINS

by

MICHELLE ANNE LUEBKE

(Under the Direction of David S. Leigh)

ABSTRACT

This study examined the morphological, hydraulic, and habitat characteristics of entrenched and non-entrenched paired reaches in six streams in northern Georgia and western North Carolina. Comparisons were made between stream pairs, reach types, and by degree of entrenchment. Reach pairings in all six streams showed significant differences in channel and floodplain morphology for mean depth and floodplain-to-channel width ratio, and in some pairings for width-to-depth ratio, width, area, flow area, hydraulic radius, and sediment particle size. In a few of the pairings there were significant differences between reach pairs for velocity, Froude number, shear stress, and stream power. Habitat type did not indicate consistent differences between reach types. The degree of entrenchment had strong relationships with gradient and sediment particle size, and moderate to strong relationships with morphology and channel hydraulic variables. Consistent effects on hydraulic variables or stream habitat are more attributable to reach gradient.

INDEX WORDS: entrenchment, incision, floodplains, Blue Ridge Mountains, Rosgen

ENTRENCHED STREAM CHANNELS IN THE BLUE RIDGE MOUNTAINS

by

MICHELLE ANNE LUEBKE

Bachelor of Science, University of Wisconsin, 2000

A Thesis Submitted to the Graduate Faculty of the University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2006

© 2006

Michelle Anne Luebke

All Rights Reserved

ENTRENCHED STREAM CHANNELS IN THE BLUE RIDGE MOUNTAINS

by

MICHELLE ANNE LUEBKE

Major Professor:	David S. Leigh
Committee:	Kathleen C. Parker Judith L. Meyer

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
August 2006

DEDICATION

For my two wonderful parents who have consistently taught me that with hard work and creativity, anything is possible. Your undying love, support, and encouragement have seen me through this entire process. You both are an inspiration to me every day of my life.

For my mother, whose charm and diplomacy have shown me that an intelligent woman may also be a lady. I hope to continue learning and growing in this manner.

For my father, whose love of science and pursuit of excellence has lead me along this career path. I have loved learning and sharing this phase of my life with you.

For my wonderful grandma, whose desire for knowledge and lifetime devoted to learning has been an inspiration to every life she touched. Thank you for always wanting to know more about my "embankments". You will always be remembered in our thoughts and memories.

I guess you were right, Dad…I thought I could.

ACKNOWLEDGEMENTS

Thank you to my advisor, David S. Leigh, who was not only an excellent mentor, but treated me as a colleague in this collaborative process. Your knowledge and passion for your work are an inspiration, and I feel fortunate to have had the opportunity to work with you.

Thank you to my committee members, both past and present, for all your excellent comments and suggestions that greatly improved this thesis: Judith L. Meyer, Kathleen C. Parker, George A. Brook.

Funding was provided by the NSF LTER grant (award # DEB-0218001) to the University of Georgia as well as an EPA STAR Fellowship and a UGA Graduate School Graduate Assistantship.

Thank you to everyone at the Coweeta Hydrologic Laboratory for problem-solving, expertise, and coffee chats during my field seasons in the beautiful Southern Appalachians. Thank you to Bill McLarney for introducing me to the area and helping in the initial site selection.

Thank you to everyone who helped at all the various stages along the way. Without you, I still might be stuck in the river, behind a computer, or buried in a thesaurus.

Field assistance: Mark Laser, Dan Smelter, Fran Luebke, Julie Tuttle, Justin Ellis, Louis Manglass, Joseph Abrams, Travis Gray, Charles Marshall, Bill McLarney, Kaitlin McLean, Erin McDonald, James Rogers, Ginger Root, Paul Stoy

GIS assistance: Tommy Jordan, Louis Manglass, Ned Gardiner, Adam Hinely, Jason Ridgeway, Nate Vodas

Modeling assistance: Bill Tollner

Writing, proofreading, and idea bouncers: Fran Luebke, Neill Luebke, Mara Loeb, David Hare

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

MORPHOLOGICAL, HYDROLOGICAL, AND HABITAT CHARACTERISTICS OF ENTRENCHED CHANNELS

1. Introduction

The term entrenchment has been inconsistently defined and frequently used interchangeably with the term incision. This paper proposes a definition of entrenchment as a non-genetic term for the disconnection of the channel from a well-developed floodplain. Incision is a process caused by instability in the channel due to degradation (Schumm et al. 1984, Darby and Simon 1999). While previous studies define the causes of entrenchment (see Montgomery 1999) and assign ratios to quantify the degree of entrenchment (Rosgen 1994, 1996, 2001; Walters et al. 2003), no studies to date have documented the morphological or hydraulic characteristics of the channel types, nor the subsequent effects on stream habitat. Thus, the purpose of this study was to determine the morphological, hydrological, and habitat characteristics of entrenched stream reaches.

The floodplain has long been viewed as an integral component of the natural channel due to the genetic association between channels and the floodplains they construct (Junk et al. 1989, Nanson and Croke 1992, Poff et al. 1997). Floodplains can be viewed as indicative of the balance between stream power and shear stress or between the morphology and sedimentology of the stream (Graf 1984, Nanson and Croke 1992). Sediment transport, channel morphology, and floodplain morphology also are dependent on climatic conditions and human impacts on streams (Dunne and Leopold 1978, Habersack and Nachtnebel 1994, Knox 2000). These impacts may be direct, such as construction of dams, channelization, or habitat modification, or impacts may be indirect, such as urbanization or deforestation throughout the watershed. Such pressures can cause morphological adjustments in channels, eroding bed or bank sediment, thus impairing downstream water quality and destabilizing banks (Darby and Simon 1999).

River channels with a natural flood regime usually are characterized by an adjacent floodplain that is overtopped by one- to two-year recurrence interval (RI) floods (Leopold et al. 1964, Dunne and Leopold 1978, Williams 1978). Sediment eroded from within the watershed is deposited onto the floodplain during overbank flows (Leopold et al. 1964, Dunne and Leopold 1978). A graded channel is defined as a channel that is neither eroding nor depositing sediment (Mackin 1948). When the sediment load is larger than the available stream power, the downstream floodplain aggrades. If the channel incises through the deposited sediments or if the pre-existing channel bed is not raised, the level of the alluvial surface relative to the channel bed increases, thereby limiting overbank flows. If overbank flows of greater than a five-year recurrence interval are prevented, the channel form is considered to be entrenched. When the sediment load is smaller than the available stream power, sediment is scoured from the channel bed or bank and exported downstream. This degradation results in bed-level lowering, a process known as incision (Schumm et al. 1984, Darby and Simon 1999), which results in an incised channel. Incised and entrenched channels may be indistinguishable from one another morphologically, and are frequently described interchangeably.

Entrenchment was defined as vertical containment of the river and the degree to which it is incised in the valley floor (Kellerhals et al. 1972, in Rosgen 1994). An incised channel often indicates that the stream power is disproportionately larger than sediment supply, thereby exporting in-channel sediment with the excess available power (Bagnold 1966), causing downcutting through the channel bed. An incised channel results from incision in the stream, whereas an entrenched channel is a resultant morphology from a variety of processes, including bank aggradation, channelization, dredging, or a combination of factors. Therefore, this study seeks to define entrenchment more generally as a non-genetic term for the disconnection of the channel from a well-developed floodplain, and not dependent upon incision. The critical distinction is that entrenchment is a general term for the resultant morphology and incision is a process leading to a specific type of entrenched channel.

Morphological changes in river channels are a product of the balance between sediment supply and hydrology (Mackin 1948, Leopold and Maddock 1953, Lisle 1982). As banks aggrade or the channel bed degrades, the discharge capacity of the overall channel increases. Subsequently, the alluvial surface adjacent to the channel is no longer inundated by bankfull flows and the abandoned floodplain becomes a terrace. Both entrenchment and incision are characterized by this disconnection of the channel from the adjacent alluvial surface. Through time, channels may develop a very narrow incipient floodplain within the inset flood channel (Wyzga 2001, Landwehr and Rhoads 2003), but flows are still constrained between the terraced banks. Therefore, floods must be larger in magnitude in order to overflow the valley bottomland (Schumm et al. 1984, Darby and Simon 1999, Walters et al. 2003); consequently, overbank flows will occur less frequently.

As the channel becomes more entrenched, the water table is lowered, promoting more terrestrial vegetation in riparian areas, which stabilizes the banks and creates a positive feedback between vegetation type and bank height (Marston et al. 1995). This shift in plant community also influences soil type, fauna found in the riparian zone, microbial processes, and nutrient cycling (Groffman et al. 2003). Stem density and ratio of rooting depth to channel depth, as well as particle size of bank sediments, are critical components in determining bank stability (Bendix 1999, Allmendinger et al. 2005). Channels with coarse sediment or noncohesive banks are modified more rapidly than channels with fine sediment or cohesive banks (Doyle and Harbor 2003).

Extensive information exists regarding entrenchment as a result of climate differences during the Holocene (Knox 1983, 1987; Magilligan 1985; Orbock Miller et al. 1993; Macklin and Lewin

1993; Montgomery 1999; Leigh and Webb in press). Other possible causes of entrenchment are via direct or indirect anthropogenic alterations of the watershed and the river. Direct alterations of the channel include channelization, dredging, and constructing levees. Indirect, or diffuse changes, include changes in land use or land cover within the watershed, increasing sediment input to the river, resulting in floodplain aggradation. Small streams with watersheds less than 26 km^2 have been found to be more prone to entrenchment than larger streams (Costa 1975).

In an effort to quantify the degree of entrenchment in streams, two different ratios have been developed. One is a morphological ratio determined from field measurements at channel cross-sections. This ratio, developed by Rosgen (1994), is calculated by dividing the "flood-prone" width by the "bankfull" width. He defines the flood-prone width as the width of the valley flat at twice the height of the bankfull width, while he defines bankfull width at the elevation of the floodplain adjacent to the active channel (Rosgen 1994, 1996). By these calculations, entrenched streams have values between 1 and 1.4, moderately entrenched have between 1.4 and 2.2, and slightly entrenched streams (i.e. those with a well-developed floodplain) have values greater than 2.2 (Rosgen 1994). Since entrenched reaches lack a floodplain, he defines bankfull in these areas at a scour line, bench, or top of a point bar (Rosgen 1994, 1996). These may be difficult to determine or are defined inaccurately, leading to an inaccurate calculation of the entrenchment ratio (Schumm et al. 1984, Ferguson 1987, Johnson and Heil 1996, Darby and Simon 1999, Juracek and Fitzpatrick 2003). Others have defined bankfull as the average elevation of the highest surface of exposed channel bars (Leopold and Wolman 1957, Hicken 1968, Lewis and McDonald 1973), but typically as an aid to determine floodplain height (Williams 1978). This application is based on the assumption that the highest surface of the channel bars corresponds to the height of the active floodplain (Williams 1978). In summary, a morphological distinction of entrenchment relies on subjective criteria, which potentially create considerable error in the degree of entrenchment.

An entrenchment ratio utilizing hydrologic discharge data, proposed by Walters et al. (2003), defined entrenchment as the "channel full" discharge divided by the two-year recurrence interval discharge. The term "channel full" was used to differentiate between the discharge causing inundation of the first alluvial surface adjacent to the channel, which could be a terrace or a floodplain (Walters et al. 2003), and the morphological value of bankfull, which corresponds to the active floodplain. By these calculations, streams with a well-developed floodplain should have values of approximately one or less. In this study, a third measure of entrenchment named the Relative Discharge ratio was developed. It is defined as the channel full discharge from the entrenched reach divided by the bankfull discharge (at active floodplain level) from the non-entrenched reach. This measure is for comparisons between reach pairs, rather than for an individual reach.

Six paired reaches in five tributaries of the upper Little Tennessee River in the Blue Ridge Mountains of western North Carolina and northern Georgia were chosen as representative study sites for this project. Field-based measurements of valley morphology, bed sediment composition, bed habitat structure, and hydrology were recorded between June 2004 and August 2005. These data were then modeled at different flood recurrence intervals using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) flood simulation modeling program developed for the Army Corps of Engineers (2005). The output from this program was used to evaluate and quantify the response of physical parameters in entrenched and non-entrenched reach types to floods of varying discharges. If the effects of entrenchment are dependent upon the degree of entrenchment, then by comparing the morphological and hydraulic variables measured in each study reach to the associated ratio, differences should emerge. This comparison also would reflect which ratio was most effective in assessing entrenchment. With increased pressure on water resources from humans, there is great need to understand our effects on aquatic systems, especially those that disrupt the connection between channels and floodplains.

2. Study Area

The upper Little Tennessee River watershed encompasses 1134 km^2 in the Blue Ridge physiographic province of the southern Appalachian Mountains in northern Georgia and western North Carolina. The Little Tennessee River flows north, while the tributaries primarily flow east and west into the mainstem. The mean annual temperature for the region is 12.7ºC, with a low of 2.7ºC occurring in January and a high of 22.1ºC occurring in July (NCDC 2003). The average of annual rainfall over a thirty-year period of record at the Coweeta Experiment Station low-elevation gage was 182.6 cm, with the highest monthly average (20.4 cm) falling in March (NCDC 2003). Watersheds in the Blue Ridge province have received large sediment inputs from timber harvest, agricultural activities, housing development, stream banks, and gravel roads (Van Lear et al. 1995, Riedel and Vose 2002, Leigh and Webb in press). Six paired reaches in five tributaries with watershed sizes between 5 and 25 km^2 of the upper Little Tennessee River in the Blue Ridge Mountains of western North Carolina and northern Georgia were chosen as representative study sites for this project (Figure 1).

2.1 Study streams

Betty Creek (22.2 km^2), in Dillard, GA, flows through 365 ha of property owned by the Hambidge Center (Figure 2). The non-entrenched reach (154 m) is located approximately 90 m upstream of a bridge. This reach flows past an old earthen dam that was breached by flooding in 1917. Upstream of the former dam, the floodplain is extensive on the left bank, while it is bounded by the remnants of the dam on the right bank. In the middle of the reach, the banks are constrained by the valley and roadcut on the left and the former dam on the right, looking downstream. Downstream of the former dam, the floodplain is bounded by the valley or roadcut. The floodplain in this reach is covered by trees and grasses, with a few walking paths maintained by mowing by the Hambidge Center. There is a bridge between the two reaches; however, both reaches were delineated outside the bounds of influence from this structure. The entrenched reach is located 195 meters downstream of the non-entrenched reach, and thus approximately 100 m downstream of the bridge. The entrenched reach (102 m) has pasture on the right bank. The confluence of Betty Creek with the Little Tennessee River is 8.2 km downstream of the study area. Betty Creek represents the most upstream tributary in this study.

Shope Fork Creek is a tributary of Coweeta Creek that lies entirely on US Forest Service property at the Coweeta Hydrologic Laboratory near Otto, NC. There are two paired reaches on this stream with the non-entrenched reach upstream from the entrenched reach in each pair. One pair is located in a field with a narrow riparian zone (Shope Fork 1, 8.3 km^2, Figure 3), while the other is located entirely in forest (Shope Fork 2, 8.2 km^2, Figure 4). The reaches in the forest are upstream from the reaches in the field. The forest pair (Shope Fork 2) has extensive rhododendron and other trees throughout each reach. The non-entrenched reach (53.5 m) has a narrow floodplain area on the right bank, bounded by the terraces. The left bank of the non-entrenched reach has a larger floodplain width. The entrenched reach (32 m) is located 12 m downstream and has approximately equivalent extents of Rhododendron and shrubs on each side of the stream.

The reach pair located in the field (Shope Fork 1) has a newly-constructed parking lot on the right bank. This impervious area was constructed in the summer of 2004, before these reaches were surveyed. The non-entrenched reach (56.5 m) is 3 meters upstream from the entrenched reach (43 m). This pair was selected because of the incipient floodplain in the non-entrenched reach. It serves as a comparison to the upstream pair as well as to another entrenched/incipient pairing in a larger stream (Iotla Creek). Both reaches are located in a mowed grass field with a narrow riparian zone of shrubs and perennial plants, comparable in both reaches. Shope Fork Creek flows into Ball Creek approximately 90 m downstream from the entrenched reach to form Coweeta Creek.

Coweeta Creek (18.7 km^2) flows out of the Coweeta Hydrologic Laboratory near Otto, NC, and passes through agricultural land and a rural residential area before it joins with the Little Tennessee River 5.3 km downstream of the non-entrenched reach (Figure 5). The entrenched reach has a wide vegetative zone within the valley, including trees and bushes, on the right bank, with a narrow vegetative zone bordered by residential lawns on the left bank. The entrenched reach (73 m) is located 350 meters upstream of the non-entrenched reach (131 m). The non-entrenched reach lies next to pasture with narrow riparian zones of shrubs on both sides of the channel. Both floodplain areas are used for pasture, ending with roadcuts on both sides of the valley.

Iotla Creek (12.3 km^2) is located near the Macon County Airport, north of Franklin, NC, and flows through rural residential, corn fields, and some forest before joining with the Little Tennessee River 3.9 km downstream of the study area (Figure 6). The entrenched reach (82.5 m) was straightened and potentially dredged, most likely due to the kaolin mine that used to be located in the area, as per conversations with the landowners. The non-entrenched reach (41 m) lies 160 m downstream and has an incipient floodplain within the entrenched banks. Floods of low magnitude (i.e. 2-5 year recurrence interval) may double the wetted stream width, but will still be contained by the banks of the first terrace. In both reaches, the left bank is a corn field. The right bank of both reaches has residential lawns, with little to no vegetation in the entrenched reach, and more extensive vegetation in the non-entrenched reach. The vegetation is primarily shrubs and briars, with some trees. There is pasture on the right bank of the non-entrenched reach.

Rose Creek (5.9 km^2) has the smallest catchment area and is the most downstream tributary to the Little Tennessee River of the study streams (Figure 7). The confluence with the Little

Tennessee is 157 m downstream of the entrenched reach. The non-entrenched reach (59 m) is 300 m upstream of the entrenched reach (76 m), with a culvert and hay fields between the reaches. The non-entrenched reach has a narrow riparian zone between 0 to 2 m on the left bank with a hay field in the floodplain. The right bank of the non-entrenched reach has a larger forested riparian zone between 30-45 m before constrained by the valley. The left bank of the entrenched reach lies in forest with thick shrubs and other vegetation along the reach, while the right bank has 0 to 1 m of vegetation between the channel and the hay field in the floodplain.

3. Methods

3.1 Reach determination

The entrenched reach was delineated as the maximum extent of contiguous entrenchment. The non-entrenched reach was then carefully defined outside the effects of entrenchment, either in the upstream or downstream direction. When possible, flood remnants (i.e. flood stains, deposited sediment, flotsam, or bent over vegetation) were identified. Three reaches with incipient floodplains (Iotla and Shope Fork 1 and 2) were defined as non-entrenched reaches and paired with entrenched reaches to represent an intermediate condition between entrenched and non-entrenched. Reach pairs were chosen in areas with similar slope and extents of riparian vegetation. The non-entrenched reach was delineated upstream from the entrenched reach to isolate entrenchment as the primary mechanism studied, except in Coweeta and Iotla Creeks. Both reaches in each stream pair were established with similar numbers of transects, thus reach lengths were not consistent between pairs due to localized differences in topography and channel bed.

3.2 Habitat mapping

Once each reach pair was established, maps were constructed to reflect channel bed features throughout the extent of each reach. This included microhabitats, as well as woody debris, islands, and bars. Habitat units were defined according to the standards established by the United States Environmental Protection Agency (US EPA), such as pool, glide, riffle, rapid, cascade, and falls (Kaufmann and Robison 1998). Habitat maps were then superimposed on the corresponding reach with Erdas Imagine® using a linear rubbersheeting technique and then imported into ArcMap® to calculate the area of each habitat type in each reach.

3.3 Cross section surveying

The HEC-RAS modeling program requires cross sections to be placed at representative locations where changes occur in discharge, slope, shape, and roughness (Brunner 2002). In this study, these correspond to the top of each cascade, rapid, riffle; the center of each riffle; the maximum and minimum depth of each pool; and the center of each glide. For each reach, additional cross-sections were added in habitat types that were proportionately under-represented using the aforementioned method. In these extensive habitats (i.e. riffles and glides), transects were spaced at distances equivalent to one bankfull channel width, calculated as the average width at the height of the floodplain in the non-entrenched reach pair. Only those habitat types whose widths were equal to or greater than 50% of the wetted channel width were considered for cross-sectional placement (Fitzpatrick et al. 1998). Sampling protocols suggest that stream transects should be spaced at distances greater than 3 mean stream widths due to autocorrelation (Moody and Troutman 2002, Myers and Swanson 1997). However, this study concentrated on the differences between adjacent reaches, not among transects, so autocorrelation should not be a significant source of error.

Cross sections were surveyed between the first terraces on each side of the stream, including the channel and floodplains, where present. At each cross-section, topography along a transect perpendicular to stream flow was measured at small intervals (i.e. <1m) where there was a natural change in slope. A minimum of 20 measurements were located within the wetted channel to ensure the accurate measurement of in-channel complexity (Harrelson et al. 1994). Horizontal and elevation measurements were recorded using a LaserMark LMH Series Automatic Electronic Self-Leveling Rotary Laser (CST/berger, Watseka, IL), LMH receiver, and metric stadia rod. These profiles were then entered into the HEC-RAS model at the corresponding locations on the digitized reach maps to define the three-dimensional reach profiles. Surveying took place between November 2004 and August 2005.

3.4 Sediment, depth, and velocity sampling

Sediment particle size, water depth, and flow velocity were sampled at the thalweg and at three random percentages of baseflow wetted stream width, measured from the right bank, at arbitrary intervals of one half of the bankfull width (0.5x) (Figure 8). Bankfull width was determined as the height of the active floodplain in the non-entrenched reach, and was held constant for both reach types in each pair. Channel full width was defined as the height of the first alluvial surface adjacent to the channel in the entrenched reach. All width and depth measurements, including the ratios that utilize these measurements, were for channel full or bankfull conditions in the entrenched or non-entrenched reaches, respectively. All reported depths were measured to the thalweg. Measurements occurred between 12 September and 5 October 2004.

Sediment sampling at each point at each 0.5x bankfull width included measuring a single sediment particle in a modified Wolman (1954) pebble count, measuring water depth, and visually determining predominant particle size class of the sediment in whole phi intervals in a 0.5 m diameter around the sample point. An additional 100 sediment particles were measured in a single riffle typical for the reach using the Wolman (1954) grid mapping pebble count method without replacement. This value has been determined to be adequate for precision and error estimates (Pizzuto et al. 2000, Rice and Church 1996, Fripp and Diplas 1993).

Once collected, the b-axis of each sediment particle was averaged for the reach as well as converted to a phi size and averaged for the reach. The diameter of the 50th and the 84th percentiles, and the percentage of particles less than 2 mm in diameter were also calculated for each reach. These size values are useful for sediment transport calculations.

Water velocity at 0.6 depth was measured at the thalweg at each 0.5x bankfull width using a Marsh-McBirney Flowmate™ (Frederick, MD) electromagnetic flow meter. Discharge was measured at the downstream end of each reach at the same time as the water depth and the velocity were measured. Both reaches in each pairing were measured on the same day or consecutive days with no precipitation events occurring between sample dates. The model requires discharge measurements at the upstream end of each reach, but there were no tributaries or any other inputs that might significantly change the discharge between the upstream and downstream ends of each reach, thus the measured discharges from the downstream end of the reach were used to define discharge at the upstream end of the reach.

3.5 Stratigraphy, magnitude, and genesis of entrenchment

In order to assess relative age of floodplain sediments, one auger hole in the bank on either side of the channel was sampled along the entrenched reach, determined to be typical for that reach. The auger samples were assessed to determine stratigraphy, texture, and color. Allostratigraphy was used to identify boundaries between sediment deposits that correspond to formally-accepted stratigraphic units, and to establish a relative chronology of these deposits (North American

Commission on Stratigraphic Nomenclature 1983, Autin 1992). Layers of similar deposits indicate commonalities in fluvial processes during a discrete time period. By identifying common features in soil texture and Munsell color, the alluvium was interpreted as either historic silty, historic sandy, prehistoric silty, or prehistoric sandy.

The degree of entrenchment was calculated using three different ratios. The Rosgen (1994, 1996) entrenchment ratio is defined as the width of the channel at the flood prone height divided by the width of the channel at the bankfull height. Survey data from each transect in the non-entrenched reaches were used to calculate the average depth of bankfull for each pair. This value was then applied to each transect in the paired entrenched reach to calculate the widths at the bankfull depth and the flood prone depth, defined as twice the height of the bankfull. Entrenched channels have values less than 1.4 (± 0.2) (Rosgen 1994, 1996, 2001).

The Walters et al. (2003) entrenchment ratio was calculated by dividing the average overbank discharge, determined using the output from the HEC-RAS model, by the two-year recurrence interval discharge, determined from regional flood-frequency equations. Another hydrologic entrenchment ratio, the Relative Discharge ratio, is introduced in this study. It was calculated using the average overbank discharge of the entrenched reach divided by the average overbank discharge of the non-entrenched reach. These values were determined using the output from the HEC-RAS model. The Relative Discharge ratio was used as a measure of the difference between paired reaches, rather than the difference between the entrenched overbank discharge and an arbitrary modeled discharge of the two-year recurrence interval flood, as calculated by Walters et al. (2003). Using these calculations in both the Walters et al. and the Relative Discharge ratios, a reach with a well-defined floodplain should have a value less than one.

In order to compare the three ratios in a meaningful manner, ranges were established to represent slightly entrenched, moderately entrenched, and entrenched. These designations correspond to established classes in the Rosgen method. According to the Rosgen ratio, values greater than 2.2 are considered slightly entrenched, values between 1.4 and 2.2 are considered moderately entrenched, and values less than 1.4 are considered entrenched (Rosgen 1994, 1996, 2001). The Walters et al. and the Relative Discharge ratios had no established classes, thus ranges were calculated to represent the same designations. Slightly entrenched was calculated as values between the 2- and 5-year recurrence interval discharges. Moderately entrenched was calculated as values between the 5- and 10-year recurrence interval discharges. Highly entrenched was calculated as values between the 10- and 25-year recurrence interval discharges. For purposes of this study, the designation of "entrenched" from the Rosgen ratio corresponded to the designation of "highly entrenched" to distinguish among the degrees of entrenchment, rather than implying a presence or absence of entrenchment. Two additional classifications of "not entrenched" and "extremely entrenched" were added for the Walters et al. and the Relative Discharge ratios. Recurrence intervals less than or equal to 2-years were considered "not entrenched", while those greater than 25-years were considered extremely entrenched. According to the Rosgen ratio, there is no allowance for a channel to be considered "not entrenched".

Once the ranges were established for each class, recurrence intervals were converted to the corresponding discharges for each individual reach. Discharges were then divided by the 2-year recurrence interval discharge for each individual reach. Therefore, ranges were scale dependent and slightly different among the study reaches. Both the Walters et al. and the Relative Discharge ratios utilized the same ranges.

3.6 Modeling

The HEC-RAS modeling program is a computer simulation model that runs steady and unsteady state flow calculations (Brunner 2002). It allows the user to define flood discharges through a particular stream reach and calculate in-stream channel processes and sediment transport. The reach boundaries, centerline, and flow paths were digitized in ArcMap® using aerial photographs and Global Positioning System (GPS) points, and verified using wetted width measurements determined during surveying. The photos for Macon County, NC, were obtained from the Macon County GIS website and were either one-foot resolution (Iotla and Coweeta Creeks) or two-foot resolution (Rose and Shope Fork Creeks). For Betty Creek in Rabun County, GA, a one-meter resolution digital orthographic quarter quadrangle (DOQQ) was also obtained from the North Carolina Department of Transportation website. The GPS points were collected using a Garmin GPS V with a differential correction provided by the Federal Aviation Administration's Wide Area Augmentation System (FAA WAAS). When necessary, due to impenetrable vegetation, valley profiles were extended in ArcMap® using a combination of aerial photographs, to determine distances, and triangulated irregular networks (TINs) calculated from digital elevation models (DEMs) and contour intervals, to determine elevation. Using the ArcMap® extension of HEC-GeoRAS (4.1.1), these were then input into the HEC-RAS (3.1.3) model. As discussed in the above sections, field-based measurements were used as input into the HEC-RAS flood simulation program, including cross sections, discharge, and water surface slope, to model flood characteristics for each reach type at different recurrence interval discharges. Bank stations were defined for each cross section to identify where the Manning's n coefficient of roughness changes from the channel to the left and right overbank areas. The roughness coefficients (Table 1) were determined by comparing the field sites to published roughness values (Chow 1954, 1964; Barnes 1967; Arcement and Schneider 1989)

For the purpose of this study, each reach was modeled separately to obtain the following in-stream processes: average velocity, flow area, Froude number, shear stress, stream power, and hydraulic radius. The model was run under steady state and subcritical conditions. Normal depth was used as the boundary condition on the downstream end of each reach. It was defined by the slope of the water surface at baseflow through the tops of riffles, or runs when riffles were scarce or absent at the downstream end of the reach. Using this method, the model will not default to calculations utilizing critical depth, which occurs when there are poorly-defined data in the model (Brunner 2002) and was not appropriate for this study. Slope reported for each reach, however, used the ground surface through the tops of riffles for the greatest extent of the reach possible, if riffles were not at the upstream and downstream ends of the reach.

Recurrence interval discharges were calculated using regional flood-frequency and magnitude equations (Pope et al. 2001), based on the drainage area of each study reach. These equations were developed for unregulated rural basins in the Blue Ridge-Piedmont region of North Carolina, using a one-variable regional regression model relating peak discharge to drainage area (Pope et al. 2001). Both the two- and five-year recurrence interval discharges were used to model each reach for comparison among reaches. Of particular interest to this research question were the overbank discharges for entrenched versus non-entrenched reaches; thus, each pair also was modeled using the bankfull discharge from the non-entrenched reach and the channel full discharge from the entrenched reach. In order to determine the discharge of initial inundation, the values calculated from the regional equation for each reach were plotted on a log-log scale and linearly interpolated. For recurrence intervals less than one year, discharges were calculated to the nearest 0.25 year. For those between one and 10 years, discharges were calculated to the nearest 0.5 year. For those greater than 11 years, discharges were calculated to the nearest year.

3.7 Data analysis

From the survey data, ratios were calculated and compared between reach pairs and among reach types using a student's t-test, including a width-to-depth ratio of the channel area (W:D), channel width and depth, channel full area, and a floodplain width-to-channel width ratio (Fp:W). An analysis of variance (ANOVA) was performed on these values with the stream and the reach type as the main factors and a stream*reach type interaction term. The stream (i.e. stream name) was a random factor and the reach type (i.e. entrenched or non-entrenched) was the fixed factor. The stream*reach type term was used as the error term to test for the significance of the reach type effect. The standard deviation of the Rosgen and Walters et al. entrenchment ratios were calculated to demonstrate the variability within each reach. A t-test was also used for comparison of sediment particle size both throughout the reach and in an individual riffle in each reach.

Model output included in-channel parameters such as average velocity, flow area, Froude number, shear stress, stream power, and hydraulic radius. While the model gives overbank values for shear stress, stream power, velocity, and Froude number, and energy gradient, only the channel values were used. These values were tested for statistical significance using a student's t-test to compare each cross section between reach pairs and among reach types. Hydraulic radius was compared using a t-test between reach pairs and among reach types as well. While the model provided numerical values for each parameter, these values were used primarily for statistical analyses between reach pairs and among study streams.

Spearman's rank correlation was used to compare degree of entrenchment with shear stress, stream power, reach gradient, habitat type, and sediment particle size. Relative strengths and direction of the correlations were assessed using r_s values. These correlation coefficients indicate the degree of linear association between the variables and the degree of entrenchment values. The r_s values represent the relative strength of the relationships according to accepted statistical values for weak ($0<|r_s|<0.5$) and strong ($0.5\leq|r_s|>1$).

Two- and three-factor ANOVAs were used to assess the effects of degree of entrenchment, reach gradient, and watershed size on the measures of habitat quality. Degree of entrenchment was always used as an independent variable because the scope of this study was not extensive enough at the reach- or the watershed-scale to determine the causality of this morphology. Three different treatments for degree of entrenchment were represented in the three different ratios. Reach gradient and watershed size also served as independent variables because they were not influenced by the study treatments of entrenchment or entrenchment ratios. Gradient was included because it is often identified as an important metric to geomorphological processes and habitat characteristics. Watershed size was included as a scalar to distinguish among stream sizes.

4. Results

Channel and floodplain morphology differed significantly between reach pairs for depth and floodplain-to-channel width ratio in all six pairings, and for width-to-depth ratio, width, area, flow area, hydraulic radius, and sediment particle size in some of the pairings. Hydraulic variables also differed significantly between some of the reach pairs for velocity, Froude number, shear stress, and stream power. The proportion of the reach in each habitat type did not consistently differ between reach types.

Degree of entrenchment using the three different entrenchment ratios had inconsistent correlations with morphological, hydrological, and habitat variables. The Walters et al. ratio had strong positive correlations with morphological variables and average sediment particle sizes. The Relative Discharge ratio had strong positive correlations with hydrological variables, reach gradient, and average sediment particle sizes. ANOVA models indicated that degree of entrenchment from the three different ratios was not as important in determining metrics of habitat quality as reach gradient and watershed size.

4.1 Reach morphology

Entrenchment ratios were calculated to determine the magnitude of entrenchment for each reach, using the Rosgen, Walters et al., and Relative Discharge ratios (Table 2). The ratios reflect the average for the reach, while the standard deviations show the variability within each reach. The entrenchment designation (i.e. none, slight, moderate, high, or extreme) is listed for each ratio calculation (Tables 2 and 3). The ranges assigned to these designations were based on the literature of floodplain dynamics and recurrence intervals. Therefore, the discharges corresponding to those specific recurrence intervals were individually calculated for each reach.

Due to the differences in the three entrenchment ratios, the calculated values for some entrenched reaches had great discrepancies in their entrenchment classifications. Betty Creek ranged from slightly to highly entrenched, Iotla Creek ranged from not entrenched to highly entrenched, and Shope Fork Creek 1 and 2 both ranged from moderately to extremely entrenched. Other entrenched reaches had values that were more consistently classified using the three ratios, such as Coweeta Creek, which ranged from highly to extremely entrenched, and Rose Creek, which ranged from not entrenched to slightly entrenched. A high standard deviation (σ) in the Rosgen ratio resulted in a reach spanning a number of entrenchment classifications. For example, in Betty Creek, the degree of entrenchment ranged from highly entrenched ($-1\ \sigma$) to slightly entrenched ($+1\ \sigma$).

In order to assure that the comparisons were valid between entrenched and non-entrenched reach pairs, the same entrenchment ratios were used to classify the non-entrenched reaches (Table 3). According to the Rosgen entrenchment ratio, all creeks were considered slightly entrenched, except Shope Fork Creek 2 (1.40), which had the minimal value for a moderately entrenched condition. It should be noted that there is no designation for "not entrenched" in the Rosgen entrenchment ratio, thus, "slightly entrenched" is the term for the least entrenched channel. According to the Walters et al. ratio, all creeks were considered not entrenched, except for Shope

Fork Creek 1 (1.06), which was considered slightly entrenched. By definition, the Relative Discharge ratio applies only to entrenched reaches and therefore was not applied to the non-entrenched reaches. These results validate the assumption that the entrenched and non-entrenched reaches differ.

The morphological and hydraulic characteristics of each reach were calculated from both survey data and HEC-RAS model output (Table 4). Recurrence interval discharges calculated from the regional curves and drainage areas for each study reach were used as input into the model to calculate the average overbank recurrence interval discharges and standard deviations for each reach. Overbank discharges and standard deviations were larger in entrenched reaches than in non-entrenched reaches. Overbank discharges were significantly different in all streams, except Iotla Creek, according to both an ANOVA ($0.025<p<0.05$) and t-test ($p<0.0001$) values. Iotla Creek was selected as an example of an incipient floodplain in the non-entrenched reach; however, the entrenched reach had a similar overbank discharge due to the left bank being approximately 0.5 m lower than the right bank.

Morphological attributes calculated from survey data included longitudinal slope, a width-to-depth ratio (W:D), width, depth, area, and a floodplain-to-channel width (Fp:W) ratio (Table 4). Gradient was similar between entrenched and non-entrenched reaches, except in Iotla Creek, where the entrenched reach (0.2%) was much gentler than the non-entrenched reach (1.2%), and in Coweeta Creek, where the entrenched reach was steeper (1.8%) than the non-entrenched reach (1.1%). The width and depth reported and used in these ratios were the channel full and bankfull values as defined in the entrenched and the non-entrenched reaches, respectively. Non-entrenched reaches had larger W:D ratios than entrenched reaches, while entrenched reaches had larger channel-full areas than non-entrenched reaches. Entrenched reaches were wider and deeper than non-entrenched reaches. Non-entrenched reaches also had larger floodplain-to-channel width ratios than entrenched reaches, as they should by definition. Both the W:D ratio ($0.05<p<0.10$) and the channel full area ($0.025<p<0.05$) morphologies were significantly different when values were grouped according to reach type in an ANOVA.

In individual streams, morphologies were tested for significant differences between reach pairs at a 95% confidence interval (Table 4). Betty Creek was significantly different for the W:D and channel full area ($p=0.001$ for both), as well as for depth and Fp:W ($p<0.0001$ for both). Width was not significantly different between reach pairs. Shope Fork Creek 1 was significantly different for channel full area, width, depth, and Fp:W ($p<0.0001$ for all), but not for the W:D ratio. Shope Fork 2 had significant differences in W:D, depth, channel full area, Fp:W ($p<0.0001$ for all), and width ($p=0.001$). Coweeta Creek had significant differences in W:D, depth, channel full area, Fp:W ($p<0.0001$ for all), and width ($p=0.044$). Iotla Creek had significant differences between reach pairs for W:D, depth, Fp:W ($p<0.0001$ for all), and width ($p=0.001$), but not for channel full area. Rose Creek did not have significant differences for W:D, width, or channel full area, but there were significant differences between reach pairs for depth and Fp:W ($p<0.0001$).

4.2 Degree of entrenchment assessment

The Relative Discharge ratio had a strong positive correlation with the W:D ratio, while the Walters et al. ratio had strong positive correlations with width, depth, and channel area (Table 5). The Walters et al. ratio had a strong negative correlation with the Fp:W ratio. The Relative Discharge ratio had strong positive correlations with shear stress and stream power at the 2- and 5-year RI discharges (Figure 9). However, there appeared to be threshold levels at approximately 1 in the Walters et al. ratio and at approximately 1.3 in the Relative Discharge ratio, which correspond to the boundary between entrenched and not entrenched. Above these thresholds, the Walters et al. ratio demonstrated a similar amount of variability within the entrenched reaches, and the Relative

Discharge ratio demonstrated an increasing amount of variability with degree of entrenchment. When the reaches were separated into entrenched or not entrenched as determined by the specific ratio, these relationships could be quantified as follows. In the Walters et al. ratio, shear stress and stream power at each modeled discharge had stronger relationships with degree of entrenchment in the entrenched reaches (r_s=0.77), while the non-entrenched reaches had weaker relationships (r_s=0.2). In the Relative Discharge ratio, reaches had strong relationships with shear stress and stream power (r_s=0.71). In the Rosgen ratio, entrenched reaches had weak positive relationship with shear stress and stream power (r_s=0.14), while non-entrenched reaches had strong negative relationships with shear stress (r_s=-0.77) and stream power (r_s=-0.94).

Both the Relative Discharge and the Walters et al. ratios had strong positive correlations with reach gradient and average sediment particle size in the reach and in a riffle, while the Rosgen ratio had weak negative correlations with these three variables (Table 5, Figure 10). Neither gradient nor particle size demonstrated a consistent trend with the degree of entrenchment according to the Rosgen ratio. Reach gradient increased with a greater degree of entrenchment according to the Walters et al. and the Relative Discharge ratios. The variability in the non-entrenched reaches was attributable to incipient versus well-defined floodplains. Incipient floodplain reaches had higher gradients than both the entrenched and the well-defined floodplain reaches. Sediment particle size showed similar thresholds as shear stress and stream power for the Walters et al. and the Relative Discharge ratios. Once the stream was classified as entrenched, both reach and riffle sediment particle sizes were consistently larger. There was great variability in the non-entrenched reaches, but this variability was not dependent on whether the non-entrenched reaches had incipient or well-defined floodplains.

The proportion of the reach in each habitat type did not demonstrate a consistently strong relationship with the degree of entrenchment from any given ratio (Table 5). The Rosgen ratio had a strong positive correlation with pool habitat. The Relative Discharge ratio had a strong negative correlation with glide habitat, a weak positive correlation with riffle habitat, and a strong positive correlation with rapid habitat. In all ratios, glide area decreased, riffle area increased, and rapid area increased with a greater degree of entrenchment. Pool area decreased with a greater degree of entrenchment according to the Rosgen ratio, but had no change with a greater degree of entrenched according to the Walters et al. or the Relative Discharge ratios.

The ANOVA models were developed to assess the effect of degree of entrenchment on measures of habitat characteristics (Table 6). The Relative Discharge ratio consistently had the highest R^2 values and was the only entrenchment ratio to significantly contribute to any model (rapid habitat, p=0.006). For all the other models, the entrenchment ratios did not significantly contribute to the predictive ability. Therefore, the same models were calculated without entrenchment ratios and were found to be of equivalent prediction (Table 6).

4.3 Habitats

The values reported in Table 7 indicate the proportion of each reach in EPA-designated habitat types. The category for "other" refers to the other channel bed features, including bars, woody debris, and boulders, that were not included as habitats. While non-entrenched reaches tended to have more microhabitat diversity (see Figures 11-16), the total area of each habitat type did not indicate any consistent relationship with reach type among creeks. Entrenched reaches in Betty, Coweeta, and Iotla Creeks had more areas of higher-velocity habitats (i.e. riffle, rapid, cascade), while their paired non-entrenched reaches had more areas of lower-velocity habitats (i.e. glide and pool). Neither Rose nor either pair in Shope Fork Creek showed these same trends. Shope Fork Creek is a high-gradient stream that has an incipient floodplain in the first pair (Shope Fork 1) and step-pool morphology in the non-entrenched reach of the second pair (Shope Fork 2).

Since degree of entrenchment did not show consistent or strong relationships with habitat characteristics in the study reaches, habitat types were compared to other measured variables. It was determined that gradient had strong relationships with habitat type. As gradient increased, the glide area decreased (r_s=-0.80), riffle area increased (r_s=0.57), and rapid area increased (r_s=0.83).

4.4 Sediment

Sediment particle size was calculated in both the reach and a riffle characteristic for the reach (Table 8). Sediment size in a single riffle was significantly different between reach types and consistently larger in the entrenched reaches for Shope Fork 1 ($p=0.007$), Iotla ($p<0.0001$), and Rose ($p<0.0001$) Creeks using an independent samples t-test. Particle size organized by reach type (i.e. entrenched or non-entrenched) for all pairings was also significantly different in both the reach and the riffle using an ANOVA ($p<0.05$).

Sediment particle size had strong relationships with gradient in reaches and riffles (Figure 17). Entrenched reaches plotted above the regression line, while non-entrenched reaches plotted below the line, except for the non-entrenched reach in Betty Creek and the entrenched reach in Shope Fork Creek 2. This indicates larger sediment particle sizes in entrenched reaches, as well as increasing sediment size with an increase in gradient. This was demonstrated by the other particle size measurements, including D_{50}, D_{84}, and percent finer than 2 mm, which had strong relationships in the reach (r_s=0.65, 0.75, and -0.66, respectively) as well as the riffle (r_s=0.82, 0.68, and -0.25, respectively). The only sediment variable that had a weak relationship was percent finer than 2mm in the riffle (r_s=-0.25), which is likely due to the lack of occurrence of fines in riffles in the study reaches. When particle size was used as a predictor, there were strong relationships with habitat. Similar to gradient, as reach and riffle sediment particle size increased, glide area decreased (r_s=-0.79 and -0.83, respectively), riffle area increased (r_s=0.74 and 0.74, respectively), and rapid area increased

(r_s=0.63 and 0.66, respectively). Thus, higher velocity habitats, such as riffles and rapids, are characterized by larger particle size; lower velocity habitats, such as glides, are characterized by smaller particle size.

Particle size also had strong relationships with shear stress and stream power at all modeled discharges (Figure 17). As shear stress and stream power increased, so did the average particle size in the reach. At bankfull discharges (i.e. 2-year RI), shear stress and stream power had strong positive correlations with average sediment particle size in the reach (r_s=0.70 and 0.73, respectively) and in a riffle (r_s=0.86 and 0.85, respectively). These forces act directly on the sediment, and thus, it follows that there is a strong association among these variables. However, particle size was significantly different between reach types only for Coweeta ($p<0.0001$) and Rose ($p<0.0001$) Creeks (Table 8).

4.5 Stratigraphy

Auger samples of sediment from each bank along one transect per entrenched reach yielded a variety of soil stratigraphic profiles with channel gravels underlying each sample (Figure 18). All of the entrenched reaches, except Shope Fork Creek 1, had historic sediment on at least one bank, indicating historical aggradation of the valley floor. This historical aggradation was typically one-half to one meter thick. The bed of the modern stream is at approximately the same elevation as prehistoric gravels, indicating that modern streams have not incised below prehistoric stream bed levels. More detailed stratigraphy from each core as well as the interpretation of these results may be found in Appendix A.

The left bank in Betty Creek was historical silty alluvium (0-72 cm) over prehistoric sandy alluvium (72-155 cm). The historic silty alluvium ranged in texture from silt loam to sandy silt loam and in color from brown to very dark grayish brown. The prehistoric sandy alluvium ranged in texture from sandy loam to loamy sand and gravels and in color from light yellowish brown to dark yellowish brown. The right bank was historic sandy alluvium (0-88 cm), with a texture of loamy sand and gravels and a color of dark grayish brown, light olive brown, and dark olive brown.

In Shope Fork Creek 1, both cores had prehistoric sandy alluvium (0-81 cm). The core from the left bank ranged in texture from sandy loam to silt loam and in color from light olive brown to very dark grayish brown. The core from the right bank ranged in texture from sandy loam to coarse sand and gravels, with colors ranging within the browns and yellow browns.

In Shope Fork Creek 2, the core from the left bank had historic sandy alluvium throughout (0-68 cm). Textures from this core ranged from loamy sand to sandy loam. Gravels were found throughout the entire core from the left bank. Colors from this core ranged within the yellowish browns. The right bank had historic sandy alluvium (0-40 cm) over prehistoric sandy alluvium (40-80 cm). The historic sandy alluvium had textures from loamy sand to coarse loamy sand and colors from brown to very dark grayish brown. The prehistoric sandy alluvium had textures from loamy sand to coarse loamy sand and gravels, with colors from dark to very dark brown.

Three cores were taken in Coweeta Creek due to the different levels adjacent to the stream. The upper core on the left bank was prehistoric silty alluvium (0-105 cm), with some sand fining upward. Textures varied from sandy clay loam to silt loam, with colors ranging from light olive brown to yellowish and grayish browns. The lower core on the left bank had historic sandy alluvium fining upward (0-55 cm), with textures from loamy sand to coarse sand and gravels and colors within the yellowish and grayish browns. The core on the right bank also had historic sandy alluvium fining upward (0-82 cm), with textures between fine loamy sand and very coarse sand and gravels and colors within the yellowish and grayish browns.

In Iotla Creek, the left bank was historic sandy alluvium (0-165 cm) over prehistoric silty alluvium (165-210 cm). The historic sandy alluvium ranged in texture from silt loam to very coarse sand and gravels and in color from light yellowish brown to very dark brown. The prehistoric silty alluvium was a very dark brown silt loam with gravels. The right bank was historic graded silty alluvium (0-145 cm) fining upward over prehistoric sandy alluvium (145-180 cm). The historic silty alluvium ranged in texture from silt loam to silty clay loam, with a layer of coarse sandy loam between 50 to 90 cm in depth, and in color from brown to light yellowish brown and grayish brown. The prehistoric sandy alluvium was brown sandy clay loam with gravels.

Rose Creek had historic silty alluvium (0-85 cm) over prehistoric silty alluvium (85-110 cm) on the left bank. The historic silty alluvium was primarily brown to dark yellowish brown silt loam. The prehistoric silty alluvium ranged in texture from silt loam to silty clay loam and gravels and in color from very dark brown to very dark gray. The core from the right bank had historic silty alluvium throughout (0-100 cm), with yellowish to grayish brown silt loam and silty clay loams with gravels.

4.6 Hydraulic Modeling

Output from the models are presented as averages for each discharge at each reach (Table 9) and as the associated p-values for significant differences between reach pairs using a student's t-test at a 95% confidence interval (Table 10). Flow area, shear stress, stream power, and hydraulic radius are for the channel area only, and do not include overbank areas.

Betty Creek: There were no differences between the reaches at any modeled discharge. The non-entrenched reach was overbank at the 2-year RI discharge and higher, while the entrenched reach was overbank at the 10-year RI discharge. Betty has a 5.5-year floodplain with natural levees adjacent to the channel due to historical vertical accretion. The channel itself appears to be entrenched, but the surrounding areas, especially the right bank, appear to function as a conduit for

5-year RI floods and larger. Therefore, at the 10-year discharge, the entrenched reach may resemble the non-entrenched reach because it has connected with lower-lying overbank areas.

Shope Fork Creek 1: The only significant differences in the channel between the reach types were in the flow area at the entrenched overbank discharge and the hydraulic radius at the 5- and 10-year RI discharges. These metrics indicate morphological differences, rather than hydraulic differences. The non-entrenched reach had an incipient floodplain with a 0.25-year RI and an overbank 5-year RI discharge, while the entrenched reach was not overbank at any of the modeled discharges.

Shope Fork Creek 2: There were no significant differences in the channel between the reach types. The non-entrenched reach was overbank at the 0.5-year RI discharge and higher, while the entrenched reach was not overbank at any of the modeled discharges and represented one of the most extreme values for entrenchment in this study.

Coweeta Creek: There were significant differences between the entrenched and non-entrenched reaches for both morphological and hydraulic variables. Flow area, a morphological channel variable, was significant at the non-entrenched overbank, and 0.5-, 2-, and 5-year RI discharges. The hydraulic channel variables that were significantly different were: velocity, Froude number, shear stress, and stream power. Velocity and Froude number were significantly different at each of the modeled discharges, with higher mean values in the entrenched reach. Channel shear stress was significantly different at the non-entrenched overbank and the 0.5-year RI discharges. In both of these instances, the mean channel shear values were greater in the non-entrenched reach than in the entrenched reach. Channel power was significantly different at the 5-year RI discharge, with a greater mean value in the entrenched reach. The non-entrenched reach was overbank at the 0.5-year RI discharge and higher, while the entrenched reach was not overbank at any of the modeled discharges up to a 10-year RI.

Iotla Creek: Morphological channel variables that were significantly different between reach types were flow area at the 10-year RI discharge and hydraulic radius at all modeled discharges. Significantly different hydraulic channel variables included velocity at a 5-year RI discharge; Froude number at the non-entrenched overbank, and 0.5-, 2-, 5-, and 10-year RI discharges; and shear stress at the 5-year RI discharge. Mean values were greater in the non-entrenched reach than in the entrenched reach. Both the non-entrenched and entrenched reaches were overbank at the 2-year RI discharge and higher and, by definition, are not entrenched. However, according to the Rosgen entrenchment ratio (1.36, Table 2), this stream is entrenched (i.e. ratio <1.4).

Rose Creek: There were significant differences between the entrenched and non-entrenched reaches for both morphological and hydraulic variables. Morphological channel variables that were significantly different between reach types were flow area and hydraulic radius at the 2-, 5-, and 10-year RI discharges. Hydraulic channel variables that were significantly different were velocity and shear stress at the entrenched overbank and the 0.5-year RI discharges. These variables had greater mean values in the entrenched reach than in the non-entrenched reach. The non-entrenched reach was overbank at the 0.5-year RI discharge and higher, while the entrenched reach was overbank at the 2-year RI discharge and higher. This stream was not considered entrenched by either the Rosgen ratio or the Walters et al. ratio, and only slightly entrenched by the Relative Discharge ratio.

5. Discussion

The purpose of this study was to determine the morphological, hydraulic, and habitat characteristics of entrenched stream reaches. This included comparisons to non-entrenched reaches, which were characterized by either incipient or well-defined floodplains, and to the degree of entrenchment as determined by three different ratios. This study determined that entrenched channels have a distinct morphology from non-entrenched channels, but habitat, sediment particle size, and hydraulic variables had inconsistent differences among study reaches. Channel morphology, sediment particle size, habitat type, and hydraulic variables were not strongly predicted by the degree of entrenchment. Reach gradient was a better predictor of sediment particle size and habitat type than degree of entrenchment, and was not seen as responsible for significant differences between reach types within pairs.

5.1 Geographic setting

In order to understand how the streams in this study relate to other floodplains, all reaches were classified into orders and suborders described by Nanson and Croke (1992). Due to a specific stream power at bankfull discharge of approximately 10 W/m^2 in each study reach, and a predominant sediment particle size for overbank areas composed of silt to fine gravels, the entrenched reaches were classified as either medium-energy, non-cohesive, lateral-migration floodplains (B3) or low-energy, cohesive, laterally-stable, single-channel floodplains (C1) (Nanson and Croke 1992). Lateral migration implies floodplain formation, which does not apply to entrenched reaches. Therefore, despite specific stream powers greater than 10 in Betty (11.5 W/m^2), Shope Fork 1 (15.2 W/m^2), and Coweeta (10.7 W/m^2) Creeks, the entrenched reaches would be indicative of C1-type floodplains. The non-entrenched reaches had slightly lower values for specific stream power (4.9 - 10.8 W/m^2), classifying them as C1-type floodplains as well. The streams were dominated by overbank sedimentation and characterized by low rates of migration. These types of streams may have depositional features such as backswamps and low levees due to the low available stream power (Nanson and Croke 1992). Both backswamps and levees were present in Betty, Coweeta, and Rose Creeks, while Iotla Creek and both Shope Fork Creek 1 and 2 had levees only. An increase in stream power causes a laterally-stable, single-channel floodplain to form a lateral migration/backswamp floodplain (Nanson and Croke 1992). This may be occurring in the entrenched reach in Betty Creek, as indicated by a lateral point bar currently being constructed, but major lateral migration or floodplain formation has not occurred. Although the study reaches were classified according to well-documented floodplain types, the differences between reach types could not be distinguished. Thus, another floodplain classification method was utilized to group the study reaches.

This approach, defined by Jacobson and Coleman (1986), uses descriptions of accretion deposits found in the Maryland Piedmont to classify floodplains. The accretion deposits were defined as very recent, agricultural, or pre-settlement chronostratigraphic units (Jacobson and Coleman 1986). Agricultural deposits correspond with the designation of "historic" from the stratigraphic interpretation, while the pre-settlement deposits correspond with the "prehistoric" designation. The "very recent" deposits were generally not present in the entrenched reaches. Using these definitions, the study reaches were then classified into one of these three time periods.

Very recent deposits correspond only with actively-constructing floodplains, which are present in most non-entrenched reaches in this study, but were not sampled by augering. The non-entrenched reaches in Betty, Coweeta, and Rose Creeks are representative of the very recent period, and are classified as existing in the final stage of floodplain and channel evolution, resulting in reworking agricultural accretions and depositing relatively coarse, very recent historical sediment (Jacobson and Coleman 1986). The non-entrenched reaches in Shope Fork Creek 1 and 2 and Iotla Creek, however, have only developed incipient floodplains. Thus, these three reaches are in transition between the agricultural and the very recent periods. In each of these instances, bankfull flows may increase the wetted width, but larger, more infrequent floods are constrained within the surrounding terraced banks. Banks composed primarily of agricultural accretions are actually historical terraces that are no longer indicative of the present hydrologic and sediment regime, which requires reworking of these deposits to create new floodplains with a much lower bankfull capacity (Jacobson and Coleman 1986).

The entrenched reaches in Betty, Coweeta, Iotla, and Rose Creeks were classified in the agricultural period as they have not yet developed new floodplains. These deposits vary in thickness and in texture, but are cohesive enough to withstand bank shear stresses. A number of researchers on the southeastern Piedmont have documented that excess sediment was eroded during periods of deforestation and intensive agriculture, resulting in vertical accretion of floodplains due to deposition of historical sediment (Happ 1945, Costa 1975, Jacobson and Coleman 1986, Leigh 1996, Harden 2004). As the watershed became reforested, sediment input to the stream declined and within-channel sediment was exported, causing the channel to incise (Costa 1975, Jacobson and Coleman 1986, Darby and Simon 1999). Harden (2004) found that channels affected by land use change in the southern Appalachian region currently remain in transition. In time, the sediment will be reworked by the stream, creating new floodplains.

Shope Fork Creek 1 was the only entrenched reach found to have both banks composed entirely of prehistoric deposits, which would classify this stream into the pre-settlement period. The upstream entrenched reach, Shope Fork Creek 2, however, had historic and prehistoric deposits, classifying the stream into the agricultural period. Researchers have found that in addition to becoming entrenched due to historical deposition, many streams remain entrenched since the Holocene. Leigh and Webb (in press) found a stream in the Blue Ridge that was a relict of Holocene entrenchment and had not been affected by historical sediment deposition. In this study, however, three of the five streams indicate both historical and Holocene entrenchment. Betty, Shope Fork, and Coweeta Creeks each have at least one bank that is primarily or entirely composed of prehistoric sediment.

Variations in sediment age can indicate morphological and spatial variability within a stream as well as between streams. The adjacent entrenched and non-entrenched morphologies utilized for this study are also indicative of spatial variability in the region. Price and Leigh (in press) documented four stream reaches in the upper Little Tennessee River watershed that were all in the final stage of floodplain and channel evolution, with well-developed floodplains, and were not entrenched as a consequence of extensive forest clearing in the region around the turn-of-the-century. The reaches in this study, however, represent each phase in the development of a new floodplain, with entrenchment serving as the earliest phase (Figure 19). This development may be affected by changes within the watershed.

It is well-documented that channels respond to changes in hydrology or sediment load (Mackin 1948, Leopold and Maddock 1953, Lisle 1982). Floodplains have a corresponding response to such changes, but the rate may be orders of magnitude slower than the channel (Magilligan and McDowell 1997, McDowell and Magilligan 1997). A similar lag time in geomorphic responses of channels has been found in areas of human manipulation (James 1989, Nanson and Croke 1992, Urban and Rhoads 2003, Harden 2004). This has profound implications on floodplains in areas of human manipulation.

5.2 Entrenched Channels vs. Channels with Floodplains

Entrenchment has been defined in this study as a morphological condition whereby the channel is disconnected from its active floodplain. From the results generated in this study, entrenched channels are morphologically distinct from non-entrenched channels. Channels are typically wider, deeper, less connected to the adjacent land surface, and require larger floods to inundate their adjacent valley flats. The floodplain areas are much smaller, if present at all, and are less topographically varied. The average channel bed particle size throughout the reach as well as in an individual riffle was not significantly different in all study reaches. Habitat types were not consistently different between reach types.

Entrenched reaches had significantly larger overbank discharges than non-entrenched reaches, except in one of the incipient floodplain pairs (Iotla). Despite significant differences in morphological characteristics and overbank discharges between the entrenched and non-entrenched reaches in this study, there were no consistent significant differences in hydraulic variables or habitat types between reaches. In only three streams (Coweeta, Iotla, and Rose Creeks) were there significant differences between reach types for channel sheer stress and in only one stream (Coweeta Creek) were there significant differences between reach types for channel stream power. In fact, Rose Creek was determined to be "not entrenched" by two of the three ratios, and yet had significantly different channel hydraulic variables between reaches.

Coweeta and Rose Creeks had significantly larger sediment particle size throughout the reach, as well as significantly different channel shear stresses at the 0.5-year RI discharge and either the non-entrenched overbank (Coweeta=0.48 RI) or the entrenched overbank (Rose=0.6 RI) discharges. Others have found that significant erosion occurs at high-frequency flood events (e.g. bankfull) (Wolman 1959, Magilligan and Stamp 1997). In this instance, however, Coweeta Creek had a significantly larger mean sediment size in the entrenched reach and significantly larger shear stress in the non-entrenched reach, despite a steeper gradient in the entrenched reach. Rose Creek had significantly larger means for both shear stress and particle size in the entrenched reach. These differences cannot be attributed to differences in gradient between reach types.

5.3 Degree of Entrenchment

The reaches in this study represent varying degrees of entrenchment, and thus serve as a continuum of entrenched morphology. Rose Creek, although it clearly has tall, straight bank faces, was not determined to be entrenched by either the Rosgen or the Walters et al. ratios, and only slightly entrenched by the Relative Discharge ratio, and serves as the least entrenched pair in this study. Coweeta Creek was the most consistently classified as entrenched, and serves as the most entrenched pair in this study. However, when morphological characteristics, hydraulic variables, sediment particle size, and habitat type were compared to degree of entrenchment, there were inconsistent relationships for a given ratio, as well as inconsistent relationships among ratios.

The Rosgen ratio, developed as a measure of the morphology of entrenchment, had weaker relationships to morphological characteristics than the Walters et al. ratio. The Rosgen ratio was not the best predictor of any hydraulic variable, sediment particle size, or habitat type, except percent of pool. Variability among reach types and classification types was great, and the same trends that were present in the Walters et al. and the Relative Discharge ratios and supported in the literature, were not identified by the Rosgen ratio. This ratio was consistently not informative, meaning assumptions about channel dynamics with certain entrenchment values are not appropriate using the Rosgen ratio.

The Walters et al. and the Relative Discharge ratios had stronger relationships than the Rosgen ratio with all measured variables. The Walters et al. ratio was better at predicting morphological characteristics, while the Relative Discharge ratio was better at predicting hydraulic variables, gradient, sediment particle size, and habitat characteristics. For shear stress, stream power, and sediment particle size, there were threshold values in each ratio that corresponded to the boundary between entrenched and not entrenched. Above these values, the variables were consistently high, but below these values, the variables had greater scatter. While the Walters et al. ratio assigns entrenchment values to individual reaches, the Relative Discharge ratio assigns values to reach pairs. Therefore, according to the Relative Discharge ratio, streams with high values have the greatest disparity between reaches. The two streams falling below this threshold and classified as slightly entrenched were Iotla and Rose Creeks. These streams have consistently classified differently than the other study streams. They are fine-grained, low gradient streams that had lower overbank discharges than any of the other streams.

The Walters et al. ratio had much higher variance within the reaches classified as not entrenched, reflecting the incipient and dynamic nature of the study streams. Scatter decreases predictability of channel and hydraulic variables and may explain why significant differences between reach pairs were not seen in all streams, both of which are typical for a channel currently in adjustment. Whether the non-entrenched reach was characterized by a well-defined or an incipient floodplain was not reflected by grouping or trends with any of the variables. This designation is only applicable to the reach and should not be used as an assumption of the state of the entire stream. Upstream linkages to the drainage network may be in different phases of adjustment. The mere presence of an entrenched reach would indicate that the stream is not in the final phase of floodplain development along its entire length. This adjustment affects a number of reach-scale characteristics, including gradient.

In order to dissipate energy, a stream may migrate laterally or decrease in gradient. Meandering streams have low energy and gentle gradients, and are characterized by lateral migration. Laterally-stable, single-thread channels have higher energy focused on bank erosion and/or channel bed degradation. If bank stability is greater than bank shear stress, the energy would be primarily focused on the channel bed (Bendix 1999, Allmendinger et al. 2005). Cohesiveness, bank height, and vegetation density play an important role in determining overall bank stability. The cohesiveness of the banks, and thus, the erodibility, is dependent upon sediment size (Nanson and Croke 1992). Bank sediment particle size was similar for all entrenched reaches, with finer sediment in Iotla and Rose Creeks. Bank height was similar within each reach, but significantly different between most entrenched and non-entrenched reach pairs. The incipient floodplains (Shope Fork 1 and 2, and Iotla Creeks) had a significantly different bankfull height, but the height of the surrounding terraces was not significantly different than the bank height in the entrenched reach pair. Riparian vegetation increases root cohesion, infiltration, and roughness (Howard 1999, Micheli and Kirchner 2002, Steiger and Gurnell 2002, Hession et al. 2003), but was held as constant as possible between pairs. Therefore bank stability should not vary greatly among study reaches.

Not only were the banks similar in stability, but they also were cohesive and stabilized by vegetation, minimizing potential channel widening or lateral migration. Bank undercutting was most pronounced in Rose Creek, and bank slumping was most pronounced in Iotla Creek, but these two reaches had the most fine-grained and cohesive bank sediment. In other regions, bank widening is a typical response to entrenchment and incision (Schumm et al. 1984, Darby and Simon 1999). The streams in this study may have more cohesive banks than other regions due to high clay content, extensive forest cover throughout the watershed, and an absence of plowing in areas adjacent to the channel.

With an absence of lateral migration and bank widening, there is a characteristic change in gradient. This study showed a distinct and strong positive relationship between degree of entrenchment and reach gradient in the Walters et al. and the Relative Discharge ratios. The non-entrenched reaches with incipient floodplains had steeper gradients than both the entrenched reaches and the well-developed floodplain reaches. A high gradient increases both shear stress and stream power, identifying these areas as higher energy than the other study reaches. The presence of an incipient floodplain indicates that the streams are beginning to carve a new floodplain from the aggraded sediment, further confirming that these streams are currently in a period of adjustment. Whether the gradients in the study reaches have changed in bed level as a response to channel entrenchment (e.g. migration of knick points), or whether channel entrenchment occurred in areas with steep gradients, is not known.

Reach gradient had stronger relationships with sediment particle size and habitat type than with degree of entrenchment. Although degree of entrenchment had a strong correlation with reach gradient in the Relative Discharge ratio, there were weak correlations with reach gradient in the Rosgen and Walters et al. ratios. Gradient was determined to have more influence on average sediment particle size and habitat variables. Sediment particle size also had stronger relationships with habitat type than degree of entrenchment. These relationships were found by Walters et al. (2005) in the Piedmont region of Georgia, relating gradient to habitat quality.

The relation of sediment particle size to shear stress and stream power were more indicative of the dynamics within channels because these forces act directly on sediment. These are more descriptive relationships than with degree of entrenchment because they relate to gradient and channel dimensions. These may be more predictable relationships since entrenched channels prevent most overbank flows, and are much simpler than incipient or well-developed floodplain areas.

5.3 Entrenchment ratios

Entrenchment ratios were developed to numerically represent the degree of entrenchment in stream channels. Reach variation resulted in large standard deviations both for the entrenchment ratio calculations and for the overbank discharges. Not only did the scale of the reaches vary among study streams, but the reaches were relatively short in the context of the watershed-scale. For this reason, findings should be viewed at the reach-scale, rather than extrapolated to a larger scale. Variations within and among the study reaches may be due to weaknesses in the various ratio calculation techniques, or to the methodological design of pairing entrenched and non-entrenched reaches. The existence of both reach types in close proximity indicates that the entrenched morphology is spatially variable and may not have the same characteristics of a stream entrenched throughout its entire watershed.

As previously discussed, the Rosgen ratio assumes that the bankfull level in the entrenched area can be extrapolated from the tops of point bars or flood scars, creating errors in the computation of the ratio (Ferguson 1987, Johnson and Heil 1996, Darby and Simon 1999, Juracek and Fitzpatrick 2003). While useful for calculating the channel bank morphology, low values (i.e. entrenched) may be misleading due to low levees adjacent to the channel. As determined in this study, levees may have small breaches that increase connectivity between channels and backwater areas before being overtopped.

The Walters et al. ratio numerically represents entrenchment more intuitively than the Rosgen ratio. By definition, as entrenchment increases, the ratio value increases. It allows for a channel to be classified as "not entrenched" if the overbank discharge is equal to or smaller than the 2-year RI discharge. As determined in this study, bankfull discharge may be much lower than the 2-year recurrence interval discharge, and therefore the Walters et al. ratio may underestimate the degree of entrenchment.

The Relative Discharge ratio was modified from the Walters et al. ratio and only differs in the discharge used in the denominator. This ratio calculates the degree of entrenchment for each individual stream, rather than comparing it to an arbitrarily-selected bankfull discharge value. While useful for this study due to the pairing of entrenched and non-entrenched reaches, the Relative Discharge ratio may not be as applicable for other studies since it requires a paired non-entrenched reach. As observed during site selection for this project, many tributaries of the upper Little Tennessee River with entrenchment lack a non-entrenched area that would be sufficient for use as a paired reach. Thus, each ratio has limitations for measuring entrenchment, and should be applied in situations that reflect the purpose for which it will be used (i.e. morphological or hydraulic assessment).

This study determined that the degree of entrenchment does not consistently predict hydraulic variables or certain habitat characteristics. Variability present in each study stream was better predicted by reach gradient than by degree of entrenchment. Therefore, while entrenchment ratios are convenient tools for communicating information regarding channel morphology (i.e. Rosgen ratio) or overbank discharges (i.e. Walters et al. and Relative Discharge ratios), these values should not be used outside of the purpose for which they were developed.

5.4 Model limitations

The HEC-RAS model is a one-dimensional flow model, while the application in this study would have ideally been as a two- or three-dimensional flow model. Therefore, the backwater and floodplain areas filled with water at the same time and rate as the channel, even without defined connectivity between the areas. That means that the levees at the edge of the bank were not overtopped before many of the depressions behind the levees or floodplain surfaces were inundated, resulting in lower overbank discharges. This did not change the overbank RI discharges of the non-entrenched reaches as much as the entrenched reaches. The entrenched reaches were chosen for their bank levels, and the adjacent depressions were not taken into consideration during reach selection. It is important to take backwater areas into account when determining degree of entrenchment in the field. Although it may appear as though the banks are creating an entrenched condition, there may be overland or subsurface connections that allow these areas to remove water from the channel, thus mitigating the flows through these reaches. For this reason, the backwater areas were not removed and modeled as simple channels. The likelihood of small breaches, animal burrows, or other conduits of water may not be readily identified, but could help mitigate floods.

Ideally, it would have been interesting to run each model as a paired reach in order to understand if the placement of the entrenched and non-entrenched reaches in the landscape affected modeled variables. This would have required additional cross-section surveys in order to define the channel between reaches, and was thus deemed beyond the scope of this project.

6. Conclusions

Entrenchment is variable at different scales, both temporally and spatially. Rivers are dynamic systems that change according to climate, land use/land cover, and human impacts. There is a common public assumption that changes in the channel are areas of concern because they jeopardize human usage and because they are viewed as abnormal (Kondolf et al. 2002). However, in some instances entrenchment predates human settlement and should not be viewed as abnormal (Leigh and Webb in press). Historical sediment, although a relict of past land use activities, becomes reworked by the channel, creating new, incipient floodplains that may evolve over the decadal scale or longer (Jacobson and Coleman 1986). Small-scale changes in streams are normal aspects of this dynamism and therefore should not be removed from a long-term perspective.

Existing literature has predominantly focused on defining and quantifying entrenchment, but these values vary depending upon morphological and/or hydraulic metrics. Values also differ within reaches, as well as within physiographic regions. Entrenched channels have a distinct morphology when compared to well-defined floodplains. When compared along a continuum of the degree of entrenchment, effects on hydraulic variables or stream habitat were inconsistent and more attributable to reach gradient. Therefore, entrenchment ratios should be used for classification of channel types, and should not be used as a proxy for hydrological or habitat conditions. Entrenchment of stream channels may be more indicative of the first developmental stage in a dynamic process of floodplain formation following extensive floodplain aggradation. Geomorphic responses of the channel and floodplain have been found to occur over the decadal time scale or longer. These conclusions have implications for informing stream restoration projects that entrenched streams are not necessarily of poor quality and may not necessitate restoration efforts.

References

Allmendinger, N.E., J.E. Pizzuto, N. Potter, Jr., T.E. Johnson, and W.C. Hession. 2005. The influence of riparian vegetation on stream width, Eastern Pennsylvania, USA. Geological Society of America Bulletin. 117: 229-243.

Arcement, G.J., Jr. and V.R. Schneider. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. U.S. Geological Survey Water-Supply Paper 2339, 38 p.

Autin, W.J. 1992. Use of alloformations for definition of Holocene meander belts in the middle Amite River, southeastern Louisiana. Geological Society of America Bulletin. 104: 233-241.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. U.S. Geological Survey Professional Paper 422-I.

Barnes, H.H.,Jr. 1967. Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 213 p.

Bendix, J. 1999. Stream power influence on southern California riparian vegetation. Journal of Vegetation Science. 10: 243-252.

Brunner, G.W. 2002. HEC-RAS River Analysis System User's Manual, Version 3.1. US Army Corps of Engineers Hydraulic Engineering Center. CPD-68.

Chow, V.T. 1959. Open-channel hydraulics. McGraw Hill, New York.

Chow, V.T. 1964. Handbook of applied hydrology. McGraw Hill, New York.

Costa, J.E. 1975. Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland. Geological Society of America Bulletin. 86: 1281-1286.

Darby, S. and A. Simon. 1999. Incised River Channels: Processes, Forms, Engineering and Management. John Wiley and Sons, New York.

Doyle, M.W. and J.M. Harbor. 2003. A scaling approximation of timescales of equilibrium adjustments in sand-bed and gravel-bed rivers. Geomorphology. 54: 217-223.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. Freeman, San Francisco, CA.

Ferguson R. 1987. Hydraulic and Sedimentary Controls of Channel Pattern. In: River Channels, Environment and Process. Richards, K. (ed.) Basil Blackwell, New York.

Fitzpatrick, F.A., I.R. Waite, P.J. D'Arconte, M.R. Meador, M.A. Maupin, and M.E. Gurtz. 1998. Revised Methods for Characterizing Stream Habitat in the National Water-Quality Assessment Program. U.S. Geological Survey Water-Resources Investigations Report 98-4052.

Fripp, J.H. and P. Diplas. 1993. Surface sampling in gravel streams. Journal of Hydraulic Engineering. 119: 473-490.

Graf, W.L. 1984. Fluvial Processes in Dryland Rivers. Springer, Berlin.

Groffman, P.M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush, J.M. Grove, R.V. Pouyat, I.C. Yesilonis, and W.C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment. 1: 315-321.

Habersack, H.M. and H.P. Nachtnebel. 1994. Analysis of sediment transport developments in relation to human impacts. In: Variability in stream erosion and sediment transport. L.J. Olive, R.J. Loughran, and J.A. Kesby, (eds.) International Association of Hydrological Sciences (IAHS) Publication No. 224. pp. 385-393.

Hamilton, K. and E.P. Bergersen. 1984. Methods to estimate aquatic habitat variables. Colorado Cooperative Fishery Research Unit Report to the Bureau of Reclamation. (Available from the National Technical Information Service, Operations Division, Springfield, Virginia).

Happ, S.C. 1945. Sedimentation in South Carolina Piedmont valleys. American Journal of Science. 243: 113-126.

Harden, C.P. 2004. Fluvial response to land-use change in the Southern Appalachian region: A century of investigation. Physical Geography. 25: 398-417.

Hession, W.C., J.E. Pizzuto, T.E. Johnson, and R.J. Horwitz. 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology. 31: 147-150.

Hicken, E.J. 1968. Channel morphology, bankfull stage, and bankfull discharge of streams near Syndey. Australian Journal of Science. 30: 274-275.

Howard, A.D. 1999. Simulation of gully erosion and bistable landforms. In: Incised River Channels: Processes, Forms, Engineering and Management. Darby, S.E. and A. Simon. (eds.) John Wiley and Sons, New York.

Jacobson, R.B. and D.J. Coleman. 1986. Stratigraphy and recent evolution of Maryland Piedmont flood plains. American Journal of Science. 286: 617-637.

James, L.A. 1989. Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California. Annals of the Association of American Geographers. 79: 570-592.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain system. In: Proceedings of the International Large River Symposium (LARS). Dodge, D.P. (ed.). Canadian Special Publication of Fisheries and Aquatic Sciences, Ottawa, Canada.

Juracek, K.E. and F.A. Fitzpatrick. 2003. Limitations and implications of stream classification. Journal of the American Water Resources Association. 39: 659-670.

Kaufmann, P.R. and E.G. Robison. 1998. Physical habitat characterization. In: Environmental Monitoring and Assessment Program-Surface Waters: Field Operations and methods for measuring the ecological condition of wadeable streams. Lazorchak, J.M., D.J. Klemm, and D.V. Peck. (eds.) US EPA. EPA/620/R-94/004F.

Kellerhals, R., C.R. Neill, and D.I. Bray. 1972. Hydraulic and geomorphic characteristics of rivers in Alberta. Alberta Research Council. River engineering and surface hydrology report 72-1.

Knox, J.C. 1983. Responses of river systems to Holocene climates. In: Late-Quaternary environments of the United States. Volume 2: the Holocene. H.E. Wright, Jr., (ed.) University of Minnesota Press, Minneapolis, pp. 26-41.

Knox, J.C. 1987. Historical valley floor sedimentation in the Upper Mississippi Valley. Annals of the Association of American Geographers. 77: 224-244.

Knox, J.C. 2000. Sensitivity of modern and Holocene floods to climate change. Quaternary Science Reviews. 19: 439-457.

Kondolf, G.M., H. Piégay, and N. Landon. 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. Geomorphology. 45: 35-51.

Kondolf, G.M. and H. Piégay (eds.). 2003. Tools in Fluvial Geomorphology. John Wiley and Sons, Chichester.

Landwehr, K. and B.L. Rhoads. 2003. Depositional response of a headwater stream to channelization, east central Illinois, USA. River Research and Applications. 19: 77-100.

Leigh, D.S. 1996. Soil chronosequence of Brasstown Creek, Blue Ridge Mountains, USA. Catena. 26: 99-114.

Leigh, D.S. and P.A. Webb. in press. Holocene erosion, sedimentation, and stratigraphy at Raven Fork, Southern Blue Ridge Mountains, USA. Geomorphology.

Leopold, L.B. and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. Professional Paper 252. U.S. Geological Survey, 57.

Leopold, L.B. and M.G. Wolman. 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Professional Paper 282-B.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co., New York.

Lewis, C.P. and B.C. McDonald. 1973. Rivers of the Yukon north slope. In: Fluvial Processes and Sedimentation. National Research Council of Canada, University of Alberta, Edmonton.

Lisle, T.E. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Resources Research. 18: 1643-1651.

Mackin, J.H. 1948. Concept of a graded river. Geological Society of America Bulletin. 59: 463-512.

Macklin, M.G. and J. Lewin. 1993. Holocene river alluviation in Britain. Zeitschrift für Geomorphologie Supplement-Band. 88: 109-122.

Magilligan, F.J. 1985. Historical floodplain sedimentation in the Galena River Basin, Wisconsin and Illinois. Annals of the Association of American Geographers. 75: 583-594.

Magilligan, F.J. and P.F. McDowell. 1997. Stream channel adjustments following elimination of cattle grazing. Water Resources Bulletin. 33: 867-878.

Magilligan, F.J. and M.L. Stamp. 1997. Historical land-cover changes and hydrogeomorphic adjustment in a small Georgia watershed. Annals of the Association of American Geographers. 87: 614-635.

Marston, R.A., J. Girel, G. Pautou, H. Piégay, J. Bravard, C. Arneson. 1995. Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. Geomorphology. 13: 121-131.

McDowell, P.F. and F.J. Magilligan. 1997. Response of Stream Channels to Removal of Cattle Grazing Disturbance: Overview of Western U.S. Exclosure Studies. In: Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. S.S. Yang, E.J. Langendoen, and F.D. Shields, (eds.). Oxford, MS.

Micheli, E.R. and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 1. Remote sensing measurements of streambank migration and erodibility. Earth Surface Processes and Landforms. 27: 627-639.

Montgomery, D.R. 1999. Erosional processes at an abrupt channel head: implications for channel entrenchment and discontinuous gully formation. In: Incised River Channels: Processes, Forms, Engineering and Management. Darby, S.E. and A. Simon. (eds.) John Wiley and Sons, New York.

Moody, J.A. and B.M. Troutman. 2002. Characterization of the spatial variability of channel morphology. Earth Surface Processes and Landforms. 27: 1251-1266.

Myers, T.J. and S. Swanson. 1997. Precision of channel width and pool area measurements. Journal of the American Water Resources Association. 33: 647-659.

Nanson, G.C. and J.C. Croke. 1992. A genetic classification of floodplains. Geomorphology. 4: 459-486.

National Climate Data Center (NCDC). 2003. Climatography of the United States no. 84, 1971–2000. Accessed online at: http://hurricane.ncdc.noaa.gov/climatenormals/clim81/NCnorm.txt

North American Commission on Stratigraphic Nomenclature. 1983. North American stratigraphic code. American Association of Petroleum Geologists Bulletin. 67: 841-875.

Orbock Miller, S., Ritter, D.F., Kochel, R.C. and J.R. Miller. 1993. Fluvial responses to land-use changes and climatic variations within the Drury Creek watershed, southern Illinois. Geomorphology. 6: 309-329.

Pizzuto, J.E., W.C. Hession, and M. McBride. 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology. 28: 79–82.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The Natural Flow Regime. BioScience. 47: 769-784.

Pope, B.F., G.D. Tasker, and J.C. Robbins. 2001. Estimating the magnitude and frequency of floods in rural basins of North Carolina – Revised. U.S. Geological Survey Water-Resources Investigations Report 01-4207.

Price, K. and D.S. Leigh. in press. Morphological and sedimentological responses of streams to human impact in the southern Blue Ridge Mountains, USA. Geomorphology.

Rice, S. and M. Church. 1996. Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. Journal of Sedimentary Research. 66: 654-665.

Riedel, M.S. and J.M. Vose. 2002. Forest road erosion, sediment transport and model validation in the southern Appalachians. Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV.

Rosgen, D.L. 1994. A classification of natural rivers. Catena. 22: 169-199.

Rosgen, D.L. 1996. Applied River Morphology. Wildlife Hydrology, Pagosa Springs, CO.

Schumm, S.A., M.D. Harvey, and C.C. Watson. 1984. Incised Channels: morphology, dynamics, and control. Water Resources Publications, Littleton, Colorado.

Steiger, J. and A.M. Gurnell. 2002. Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. Geomorphology. 49: 1-23.

Urban, M.A. and B.L. Rhoads. 2003. Catastrophic Human-Induced Change in Stream-Channel Planform and Geometry in an Agricultural Watershed, Illinois, USA. Annals of the Association of American Geographers. 93: 783-796.

Van Lear, D.H. G.B. Taylor, and W.F. Hanson. 1995. Sedimentation in the Chattooga River watershed. Clemson University, Department of Forest Resources Technical Paper 19.

Walters, D.M., D.S. Leigh, M.C. Freeman, B.J. Freeman, and C.M. Pringle. 2003. Geomorphology and fish assemblages in a piedmont river basin, USA. Freshwater Biology. 48: 1950-1970.

Williams, G.P. 1978. Bankfull discharge of river. Water Resources Research. 14: 1141-1154.

Wolman, M.G. 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union, v. 35, p. 951-956.

Wolman, M.G. 1959. Factors influencing erosion of cohesive river banks. American Journal of Science. 257: 204-216.

Wyzga, B. 2001. Impact of the channelization-induced incision of the Skawa and Wisloka Rivers, Southern Poland, on the conditions of overbank deposition. Regulated Rivers: Research and Management. 17: 85-100.

Table 1: Manning's n coefficient of roughness for the left and right overbank areas, as well as the channel of each reach. Transects are named as their distance in meters from the downstream end of the reach. For Betty Creek, the reaches were separated into groups of transects with similar characteristics. The other reaches were homogeneous and thus assigned the same values.
Note: left and right banks are designated in the downstream direction.

Creek	Reach	Transects	Left Overbank	Channel	Right Overbank
Betty	**entrenched**	**1.0-56.5**	0.100	0.040	0.135
		66.3-102.5	0.085	0.040	0.123
Betty	**non-entrenched**	**292.3-321.0**	0.100	0.045	0.135
		328.1-341.3	0.085	0.045	0.135
		347.3-364.5	0.090	0.045	0.090
		368.5-390.4	0.100	0.045	0.128
		401.4-445.8	0.155	0.045	0.145
Shope Fork 1	**entrenched**	**1.0-44.2**	0.077	0.040	0.078
Shope Fork 1	**non-entrenched**	**46.7-103.2**	0.080	0.040	0.079
Shope Fork 2	**entrenched**	**1.0-33.1**	0.090	0.040	0.135
Shope Fork 2	**non-entrenched**	**65.3-118.8**	0.095	0.040	0.133
Coweeta	**entrenched**	**333.8-406.8**	0.100	0.025	0.117
Coweeta	**non-entrenched**	**2.5-133.8**	0.104	0.035	0.075
Iotla	**entrenched**	**202.35-278.75**	0.075	0.035	0.073
Iotla	**non-entrenched**	**1.0-42.4**	0.086	0.035	0.096
Rose	**entrenched**	**1.0-76.7**	0.137	0.042	0.068
Rose	**non-entrenched**	**426.7-481.4**	0.071	0.040	0.150

Table 2: Entrenchment ratios for each entrenched study reach according to three different calculation methods. Ranges for the specific classification are listed in parentheses.

	Rosgen (1994, 1996)			Walters et al. (2003)			Relative Q	
Creek	**ratio**	**st. dev.**	**entrenchment**	**ratio**	**st. dev.**	**entrenchment**	**ratio**	**entrenchment**
Betty	2.40	1.86	slight (>2.2)	1.55	0.26	moderate (1.36-2.13)	2.44	high (2.14-2.86)
Shope Fork 1	2.03	0.30	moderate (1.4-2.2)	4.11	0.75	extreme (>3.03)	3.63	extreme (>3.03)
Shope Fork 2	1.50	0.72	moderate (1.4-2.2)	3.01	0.44	high (2.37-3.30)	5.30	extreme (>3.31)
Coweeta	1.20	0.10	high (<1.4)	3.06	0.51	high (2.30-3.15)	4.72	extreme (>3.16)
Iotla	1.36	0.17	high (<1.4)	0.80	0.09	none (0-1.00)	1.09	slight (1.01-1.73)
Rose	6.81	3.97	slight (>2.2)	0.66	0.11	none (0-1.00)	1.30	slight (1.01-1.76)

Table 3: Entrenchment ratios for each non-entrenched study reach according to two different calculation methods. Ranges for the specific classification are listed in parentheses. The values for the Relative Q ratio would remain the same for both reaches.

	Rosgen (1994, 1996)			Walters et al. (2003)		
Creek	**ratio**	**st. dev.**	**entrenchment**	**ratio**	**st. dev.**	**entrenchment**
Betty	5.43	3.51	slight (>2.2)	0.64	0.18	none (0-1.00)
Shope Fork 1	3.88	1.90	slight (>2.2)	1.06	0.56	slight (1.01-1.74)
Shope Fork 2	1.40	0.41	moderate (1.4-2.2)	0.57	0.00	none (0-1.00)
Coweeta	6.63	1.49	slight (>2.2)	0.65	0.16	none (0-1.00)
Iotla	5.94	10.07	slight (>2.2)	0.71	0.31	none (0-1.00)
Rose	24.19	9.20	slight (>2.2)	0.51	0.00	none (0-1.00)

Table 4: Discharge values and morphological measurements for each study reach. Ent and non-ent refer to the entrenched and non-entrenched reach in each study stream, respectively. An asterisk following the number indicates significant differences at a 95% confidence interval between entrenched and non-entrenched reach pairs using a student's t-test.

		Recurrence interval discharges									Morphological attributes					
		in years						overbank (OB)								
Creek	**Reach**	**2**	**5**	**10**	**25**	**50**	**100**	**reach avg.**	**OB RI**	**st. dev.**	**gradient**	**W:D$^{\infty}$**	**width$^{\infty}$ (m)**	**depth$^{\infty}$ (m)**	**area$^{\infty}$ (m^2)**	**Fp:W$^{\infty}$**
Betty	**ent**	17.3	29.3	39.2	53.9	66.7	80.8	29.2*	5.50	5.0	1.0%	7.19*	11.53	1.65*	19.35*	1.44*
Betty	**non-ent**	17.3	29.3	39.2	53.9	66.7	80.8	12.0*	0.70	3.4	1.0%	10.36*	10.83	1.15*	12.52*	5.56*
Shope Fork 1	**ent**	8.7	15.1	20.5	28.6	35.7	43.7	35.6*	6≈0.8	6.5	2.6%	8.34	15.22*	1.83*	27.83*	1.35*
Shope Fork 1	**non-ent**	8.7	15.1	20.4	28.6	35.7	43.7	9.1*	2.50	4.9	2.9%	7.66	7.19*	0.95*	7.04*	4.59*
Shope Fork 2	**ent**	8.6	15.0	20.3	28.4	35.4	43.4	25.8*	21.6	3.7	2.2%	6.05*	9.38*	1.58*	14.74*	1.37*
Shope Fork 2	**non-ent**	8.6	15.0	20.3	28.4	35.5	43.4	4.9*	0.25	0.0	2.1%	13.89*	7.93*	0.59*	4.65*	3.11*
Coweeta	**ent**	15.2	25.9	34.7	47.8	59.3	71.9	46.5*	26.8	7.8	1.8%	5.62*	10.72*	1.91*	20.60*	0.23*
Coweeta	**non-ent**	15.3	26.1	35.0	48.2	59.7	72.5	9.9*	0.49	2.4	1.1%	10.66*	9.49*	0.91*	8.67*	3.78*
Iotla	**ent**	11.0	19.0	25.6	35.6	44.3	54.0	8.6	1.20	0.9	0.2%	4.33*	7.83*	1.81*	14.21	1.30*
Iotla	**non-ent**	11.4	19.6	26.5	36.7	45.7	55.7	7.9	0.72	3.4	1.2%	7.40*	9.70*	1.36*	13.42	1.72*
Rose	**ent**	6.8	12.0	16.4	23.0	28.9	35.4	4.5*	0.65	0.8	0.4%	3.68	6.52	1.24*	6.14	7.08*
Rose	**non-ent**	6.3	11.0	15.0	21.2	26.6	32.7	3.5*	0.25	0.0	0.5%	4.50	4.93	1.10*	5.45	21.77*

$^{\infty}$ The width and depth reported and used for the calculation of area and the W:D and Fp:W ratios were the channel full and bankfull values as defined in the entrenched and the non-entrenched reaches, respectively. Depth was measured to the thalweg.

Table 5: Values for r_s from Spearman's rank correlation analyses for all reaches classified according to the three different entrenchment ratios. Entrenched and non-entrenched reaches were grouped for all analyses. The Rosgen ratio was not tested for the Fp:W ratio due to the fact that floodplain width and channel width are inherent in the calculation of the Rosgen ratio.

	Rosgen (n=12)	Walters et al. (n=12)	Relative Discharge (n=6)
W:D	-0.04	-0.17	0.52
width (m)	-0.34	0.52	0.20
depth (m)	-0.51	0.79	-0.20
channel full A (m2)	-0.52	0.87	0.06
Fp:W	- -	-0.77	-0.21
Shear stress (N/m^2)			
2-year RI	-0.27	0.24	0.71
5-year RI	-0.24	0.37	0.71
Stream power (W/m)			
2-year RI	-0.36	0.36	0.71
5-year RI	-0.31	0.42	0.71
gradient	-0.32	0.45	0.83
reach particle size (mm)	-0.48	0.63	0.60
riffle particle size (mm)	-0.31	0.52	0.54
% pool	0.62	-0.19	0.26
% glide	0.34	-0.30	-0.71
% riffle	-0.46	0.28	0.49
% rapid	-0.41	0.36	0.70

Table 6: Dependent and independent variables used in three-factor ANOVA models and associated significance values.

Dependent variables	Independent variables			n	F-value	R^2 value	adjusted R^2
Reach sediment particle size	Rosgen ratio	gradient	watershed size	12	6.30	0.70	0.59
	Walters et al. ratio	gradient	watershed size	12	7.83	0.74	0.65
	Relative Discharge ratio	gradient	watershed size	6	5.44	0.89	0.73
	no entrenchment ratio	gradient	watershed size	12	10.28	0.70	0.63
Riffle sediment particle size	Rosgen ratio	gradient	watershed size	12	6.34	0.70	0.59
	Walters et al. ratio	gradient	watershed size	12	6.83	0.72	0.61
	Relative Discharge ratio	gradient	watershed size	6	3.60	0.84	0.61
	no entrenchment ratio	gradient	watershed size	12	10.46	0.70	0.63
Pool habitat	Rosgen ratio	gradient	watershed size	12	2.71	0.50	0.32
	Walters et al. ratio	gradient	watershed size	12	0.77	0.22	-0.07
	Relative Discharge ratio	gradient	watershed size	6	2.20	0.77	0.42
	no entrenchment ratio	gradient	watershed size	12	1.29	0.22	0.05
Glide habitat	Rosgen ratio	gradient	watershed size	12	5.14	0.66	0.53
	Walters et al. ratio	gradient	watershed size	12	4.88	0.65	0.51
	Relative Discharge ratio	gradient	watershed size	6	3.84	0.85	0.63
	no entrenchment ratio	gradient	watershed size	12	8.07	0.64	0.56
Riffle habitat	Rosgen ratio	gradient	watershed size	12	1.71	0.39	0.16
	Walters et al. ratio	gradient	watershed size	12	1.66	0.38	0.15
	Relative Discharge ratio	gradient	watershed size	6	9.98	0.94	0.84
	no entrenchment ratio	gradient	watershed size	12	2.79	0.38	0.25
Rapid habitat	Rosgen ratio	gradient	watershed size	12	5.99	0.69	0.58
	Walters et al. ratio	gradient	watershed size	12	5.99	0.69	0.58
	Relative Discharge ratio	gradient	watershed size	6	167.42	0.99	0.99
	no entrenchment ratio	gradient	watershed size	12	10.08	0.69	0.62

Table 7: Percent of each reach in designated habitat areas. "Other" refers to non habitat units.

Creek	Reach	pool	glide	riffle	rapid	cascade	other
Betty	**entrenched**	5%	15%	60%	3%	0%	17%
Betty	**non-entrenched**	8%	48%	31%	9%	0%	4%
Shope Fork 1	**entrenched**	7%	10%	48%	31%	0%	3%
Shope Fork 1	**non-entrenched**	12%	7%	49%	29%	0%	3%
Shope Fork 2	**entrenched**	18%	10%	45%	9%	1%	17%
Shope Fork 2	**non-entrenched**	4%	9%	69%	10%	0%	8%
Coweeta	**entrenched**	6%	31%	56%	3%	0%	4%
Coweeta	**non-entrenched**	11%	47%	42%	0%	0%	1%
Iotla	**entrenched**	7%	71%	21%	0%	0%	1%
Iotla	**non-entrenched**	10%	77%	6%	0%	0%	7%
Rose	**entrenched**	8%	70%	22%	0%	0%	0%
Rose	**non-entrenched**	19%	43%	37%	0%	0%	2%

Table 8: Sediment particle sizes determined using the Wolman (1954) pebble count in each reach and an individual riffle. An asterisk following the number indicates significant differences at a 95% confidence interval between entrenched and non-entrenched reach pairs using a student's t-test. Other variables could not be tested for significance using this method.

		Sediment particle sizes (reach)					Sediment particle sizes (riffle)				
Creek	**Reach**	**avg. mm**	**avg. φ**	**D^{50}**	**D^{84}**	**<2mm**	**avg. mm**	**avg. φ**	**D^{50}**	**D^{84}**	**<2mm**
Betty	**entrenched**	146.95	-5.75	123.00	203.00	1.25%	136.78	-5.80	107.00	194.00	0.00%
Betty	**non-entrenched**	137.46	-5.25	98.00	179.00	3.75%	119.11	-5.58	95.00	156.00	0.00%
Shope Fork 1	**entrenched**	165.13	-6.00	123.00	275.00	0.00%	162.90*	-6.06	144.00	232.00	0.00%
Shope Fork 1	**non-entrenched**	131.56	-5.38	88.00	222.00	2.11%	126.79*	-5.74	113.00	187.00	0.00%
Shope Fork 2	**entrenched**	118.51	-5.29	82.00	205.00	0.00%	133.52	-5.80	112.00	172.00	0.00%
Shope Fork 2	**non-entrenched**	116.22	-5.63	90.00	187.00	0.00%	116.18	-5.67	107.00	165.00	0.00%
Coweeta	**entrenched**	148.41*	-5.89	131.00	198.00	0.00%	96.82	-5.27	73.00	138.00	0.00%
Coweeta	**non-entrenched**	66.51*	-3.91	48.00	102.00	7.33%	105.59	-5.36	93.00	167.00	0.00%
Iotla	**entrenched**	9.76	1.17	3.00	11.00	47.37%	15.36*	-2.55	12.00	22.00	2.02%
Iotla	**non-entrenched**	5.05	1.70	0.50	6.00	51.81%	4.38*	0.62	2.00	9.00	36.36%
Rose	**entrenched**	51.77*	-1.42	10.00	131.00	28.36%	40.11*	-2.94	12.00	102.00	5.05%
Rose	**non-entrenched**	6.89*	0.41	3.00	11.00	34.57%	8.67*	-1.25	7.00	14.00	11.11%

Table 9: Output from the HEC-RAS model for each reach at different recurrence interval (RI) discharges for channel parameters only. Ent OB and none OB refer to the entrenched overbank and the non-entrenched overbank discharges specific for each reach pair, respectively.

Creek	Reach	RI Discharge	Velocity (m/s)	Flow Area (m^2)	Froude #	Shear Stress (N/m^2)	Stream Power (W/m)	Hydraulic Radius (m)
Betty	**entrenched**	**0.5-yr**	1.6	7.07	0.63	50.07	85.86	0.64
Betty	**entrenched**	**2-yr**	1.9	9.42	0.64	61.15	119.74	0.78
Betty	**entrenched**	**5-yr**	2.2	13.60	0.65	76.82	176.39	0.69
Betty	**entrenched**	**10-yr**	2.3	16.54	0.65	84.14	207.34	0.53
Betty	**entrenched**	**none OB**	1.7	7.38	0.63	51.41	89.48	0.65
Betty	**entrenched**	**ent OB**	2.2	13.56	0.65	76.74	176.06	0.69
Betty	**non-entrenched**	**0.5-yr**	1.6	7.63	0.60	60.57	108.17	0.58
Betty	**non-entrenched**	**2-yr**	1.8	9.67	0.62	74.66	151.00	0.59
Betty	**non-entrenched**	**5-yr**	2.0	13.10	0.62	86.58	194.80	0.56
Betty	**non-entrenched**	**10-yr**	2.2	15.09	0.62	95.53	229.95	0.67
Betty	**non-entrenched**	**none OB**	1.6	7.91	0.60	62.82	114.38	0.58
Betty	**non-entrenched**	**ent OB**	2.0	13.10	0.62	86.58	194.80	0.56
Shope Fork 1	**entrenched**	**0.5-yr**	1.9	2.93	0.86	75.24	149.09	0.46
Shope Fork 1	**entrenched**	**2-yr**	2.1	4.23	0.86	85.70	186.58	0.55
Shope Fork 1	**entrenched**	**5-yr**	2.4	6.50	0.86	100.44	245.94	0.67
Shope Fork 1	**entrenched**	**10-yr**	2.5	8.31	0.85	107.50	278.97	0.75
Shope Fork 1	**entrenched**	**none OB**	2.1	4.42	0.86	86.48	189.63	0.56
Shope Fork 1	**entrenched**	**ent OB**	2.7	13.07	0.82	117.56	333.78	0.75
Shope Fork 1	**non-entrenched**	**0.5-yr**	1.8	3.19	0.78	63.58	117.63	0.48
Shope Fork 1	**non-entrenched**	**2-yr**	2.0	4.53	0.79	74.07	152.70	0.56
Shope Fork 1	**non-entrenched**	**5-yr**	2.3	6.64	0.81	92.51	221.11	0.59
Shope Fork 1	**non-entrenched**	**10-yr**	2.4	8.29	0.80	100.47	258.71	0.58
Shope Fork 1	**non-entrenched**	**none OB**	2.0	4.73	0.79	75.24	157.06	0.56

Shope Fork 1	**non-entrenched**	**ent OB**	2.6	11.75	0.77	107.62	292.69	0.62
Shope Fork 2	**entrenched**	**0.5-yr**	1.6	3.49	0.79	60.15	107.06	0.43
Shope Fork 2	**entrenched**	**2-yr**	1.9	4.65	0.80	75.06	153.72	0.53
Shope Fork 2	**entrenched**	**5-yr**	2.3	6.78	0.80	94.52	227.74	0.71
Shope Fork 2	**entrenched**	**10-yr**	2.5	8.50	0.79	104.26	271.50	0.83
Shope Fork 2	**entrenched**	**none OB**	1.6	3.28	0.78	56.81	97.71	0.40
Shope Fork 2	**entrenched**	**ent OB**	2.6	10.31	0.78	110.49	303.55	0.69
Shope Fork 2	**non-entrenched**	**0.5-yr**	1.7	3.24	0.85	62.82	109.14	0.38
Shope Fork 2	**non-entrenched**	**2-yr**	2.0	4.47	0.86	77.22	155.42	0.48
Shope Fork 2	**non-entrenched**	**5-yr**	2.2	6.76	0.85	91.44	211.14	0.53
Shope Fork 2	**non-entrenched**	**10-yr**	2.4	8.39	0.84	98.71	243.36	0.54
Shope Fork 2	**non-entrenched**	**none OB**	1.6	3.03	0.85	59.67	100.11	0.36
Shope Fork 2	**non-entrenched**	**ent OB**	2.5	9.85	0.82	103.65	265.88	0.53
Coweeta	**entrenched**	**0.5-yr**	2.2	4.59	0.93	36.02	79.23	0.52
Coweeta	**entrenched**	**2-yr**	2.5	6.17	0.94	43.92	110.73	0.66
Coweeta	**entrenched**	**5-yr**	2.9	8.92	0.94	55.68	165.70	0.87
Coweeta	**entrenched**	**10-yr**	3.1	11.17	0.92	60.92	195.41	1.01
Coweeta	**entrenched**	**none OB**	2.2	4.61	0.93	36.10	79.54	0.52
Coweeta	**entrenched**	**ent OB**	3.2	14.41	0.88	61.46	203.61	0.74
Coweeta	**non-entrenched**	**0.5-yr**	1.7	5.64	0.73	46.65	87.20	0.37
Coweeta	**non-entrenched**	**2-yr**	1.9	7.64	0.72	49.85	98.15	0.35
Coweeta	**non-entrenched**	**5-yr**	2.1	10.34	0.71	57.14	125.20	0.44
Coweeta	**non-entrenched**	**10-yr**	2.3	11.95	0.72	64.43	153.31	0.51
Coweeta	**non-entrenched**	**none OB**	1.7	5.62	0.73	46.58	86.99	0.37
Coweeta	**non-entrenched**	**ent OB**	2.4	13.72	0.72	70.87	179.08	0.59
Iotla	**entrenched**	**0.5-yr**	0.9	8.00	0.26	9.56	8.53	0.94
Iotla	**entrenched**	**2-yr**	0.9	11.11	0.25	9.72	9.06	0.23
Iotla	**entrenched**	**5-yr**	1.0	13.04	0.24	10.61	10.59	0.34
Iotla	**entrenched**	**10-yr**	1.1	13.88	0.25	11.90	12.68	0.44

Iotla	**entrenched**	**none OB**	0.9	8.72	0.27	9.98	9.16	0.88
Iotla	**entrenched**	**ent OB**	0.9	9.29	0.27	10.25	9.58	0.68
Iotla	**non-entrenched**	**0.5-yr**	1.0	7.80	0.37	17.00	25.83	0.66
Iotla	**non-entrenched**	**2-yr**	1.1	10.38	0.38	20.46	34.80	0.80
Iotla	**non-entrenched**	**5-yr**	1.3	14.47	0.38	23.22	42.10	0.42
Iotla	**non-entrenched**	**10-yr**	1.3	16.46	0.36	22.41	42.75	0.39
Iotla	**non-entrenched**	**none OB**	1.0	8.20	0.38	17.52	27.08	0.68
Iotla	**non-entrenched**	**ent OB**	1.1	8.65	0.37	18.13	28.58	0.70
Rose	**entrenched**	**0.5-yr**	1.2	3.49	0.46	34.39	49.06	0.38
Rose	**entrenched**	**2-yr**	1.2	4.72	0.43	31.34	42.63	0.30
Rose	**entrenched**	**5-yr**	1.5	5.76	0.48	41.99	66.56	0.37
Rose	**entrenched**	**10-yr**	1.6	6.43	0.50	48.04	82.34	0.43
Rose	**entrenched**	**none OB**	1.2	3.02	0.46	32.14	43.58	0.53
Rose	**entrenched**	**ent OB**	1.3	3.64	0.46	34.53	49.78	0.35
Rose	**non-entrenched**	**0.5-yr**	1.0	3.07	0.38	21.83	27.78	0.20
Rose	**non-entrenched**	**2-yr**	1.2	3.48	0.42	26.07	33.65	0.23
Rose	**non-entrenched**	**5-yr**	1.3	4.10	0.44	32.51	49.27	0.32
Rose	**non-entrenched**	**10-yr**	1.4	4.47	0.46	37.61	61.24	0.38
Rose	**non-entrenched**	**none OB**	1.0	2.91	0.39	22.64	28.65	0.19
Rose	**non-entrenched**	**ent OB**	1.0	3.28	0.37	21.47	27.77	0.21

Table 10: Significance values at a 95% confidence interval for comparisons in modeled output between reach types in each stream from t-tests. Dashes indicate no significant difference at the specified confidence level. Modeled discharges include discharges at the listed recurrence intervals, and the entrenched overbank discharge (ent OB) and the non-entrenched overbank discharge (none OB) specific for each reach pair.

Creek	Discharge (m^3/s)	Velocity (m/s^2)	Flow Area (m^2)	Froude #	Shear Stress (N/m^2)	Stream Power (W/m)	Hydraulic Radius (m)
Betty	**0.5-yr**	- -	- -	- -	- -	- -	- -
Betty	**2-yr**	- -	- -	- -	- -	- -	- -
Betty	**5-yr**	- -	- -	- -	- -	- -	- -
Betty	**10-yr**	- -	- -	- -	- -	- -	- -
Betty	**none OB**	- -	- -	- -	- -	- -	- -
Betty	**ent OB**	- -	- -	- -	- -	- -	- -
Shope Fork 1	**0.5-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 1	**2-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 1	**5-yr**	- -	- -	- -	- -	- -	0.036
Shope Fork 1	**10-yr**	- -	- -	- -	- -	- -	0.030
Shope Fork 1	**none OB**	- -	- -	- -	- -	- -	- -
Shope Fork 1	**ent OB**	- -	0.046	- -	- -	- -	- -
Shope Fork 2	**0.5-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 2	**2-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 2	**5-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 2	**10-yr**	- -	- -	- -	- -	- -	- -
Shope Fork 2	**none OB**	- -	- -	- -	- -	- -	- -
Shope Fork 2	**ent OB**	- -	- -	- -	- -	- -	- -
Coweeta	**0.5-yr**	<0.0001	0.002	<0.0001	0.038	- -	- -
Coweeta	**2-yr**	<0.0001	<0.0001	<0.0001	- -	- -	- -
Coweeta	**5-yr**	<0.0001	0.006	<0.0001	- -	0.038	- -
Coweeta	**10-yr**	<0.0001	- -	<0.0001	- -	- -	- -

Coweeta	**none OB**	<0.0001	0.002	<0.0001	0.040	- -	- -
Coweeta	**ent OB**	<0.0001	- -	0.002	- -	- -	- -
Iotla	**0.5-yr**	- -	- -	0.049	- -	- -	<0.0001
Iotla	**2-yr**	- -	- -	0.020	- -	- -	<0.0001
Iotla	**5-yr**	0.032	- -	0.008	0.044	- -	<0.0001
Iotla	**10-yr**	- -	0.010	0.039	- -	- -	<0.0001
Iotla	**none OB**	- -	- -	0.048	- -	- -	<0.0001
Iotla	**ent OB**	- -	- -	- -	- -	- -	<0.0001
Rose	**0.5-yr**	0.019	- -	- -	0.040	- -	- -
Rose	**2-yr**	- -	<0.0001	- -	- -	- -	0.001
Rose	**5-yr**	- -	<0.0001	- -	- -	- -	0.005
Rose	**10-yr**	- -	<0.0001	- -	- -	- -	0.002
Rose	**none OB**	- -	- -	- -	- -	- -	- -
Rose	**ent OB**	0.017	- -	- -	0.039	- -	- -

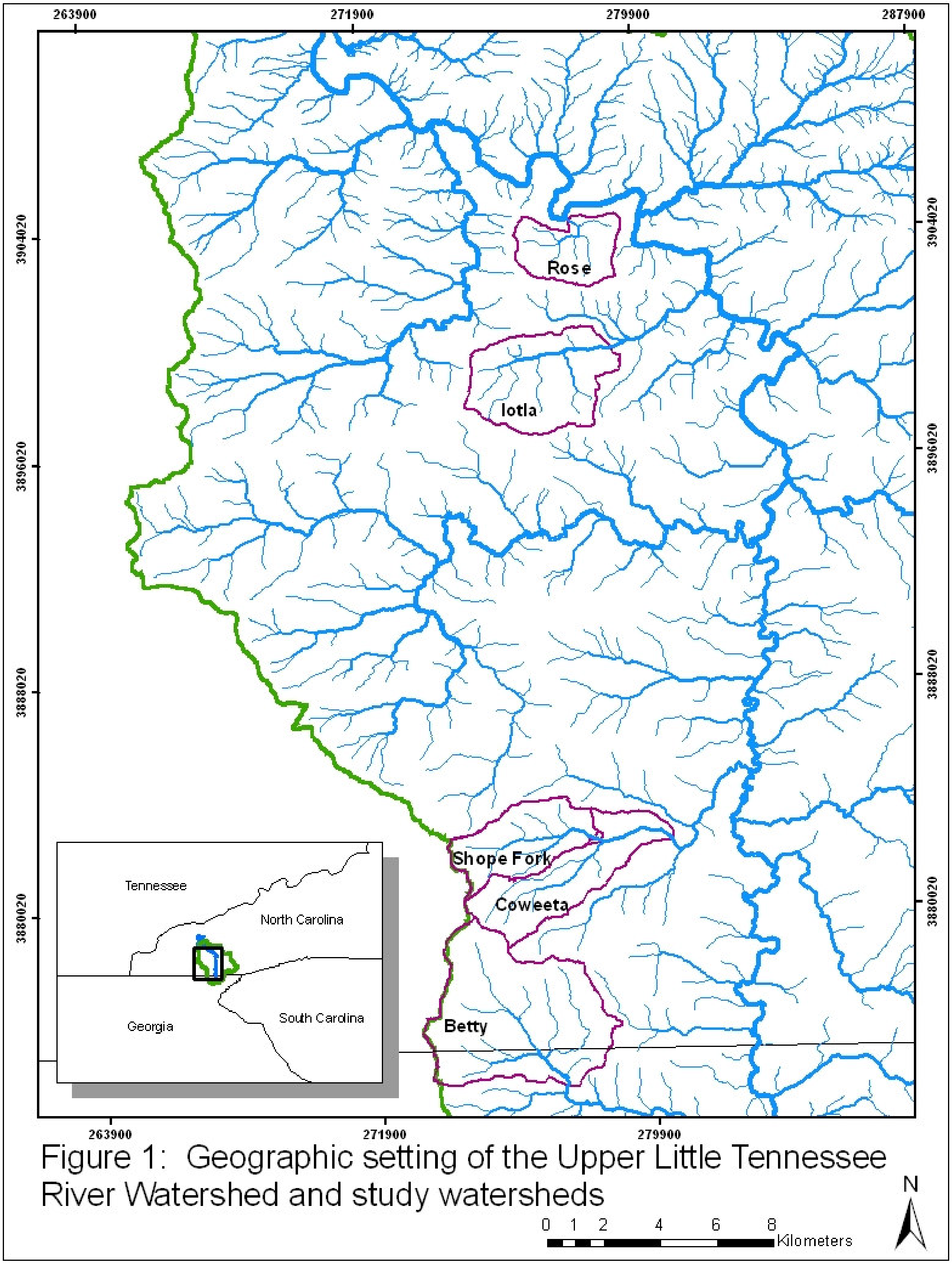

Figure 1: Geographic setting of the Upper Little Tennessee River Watershed and study watersheds

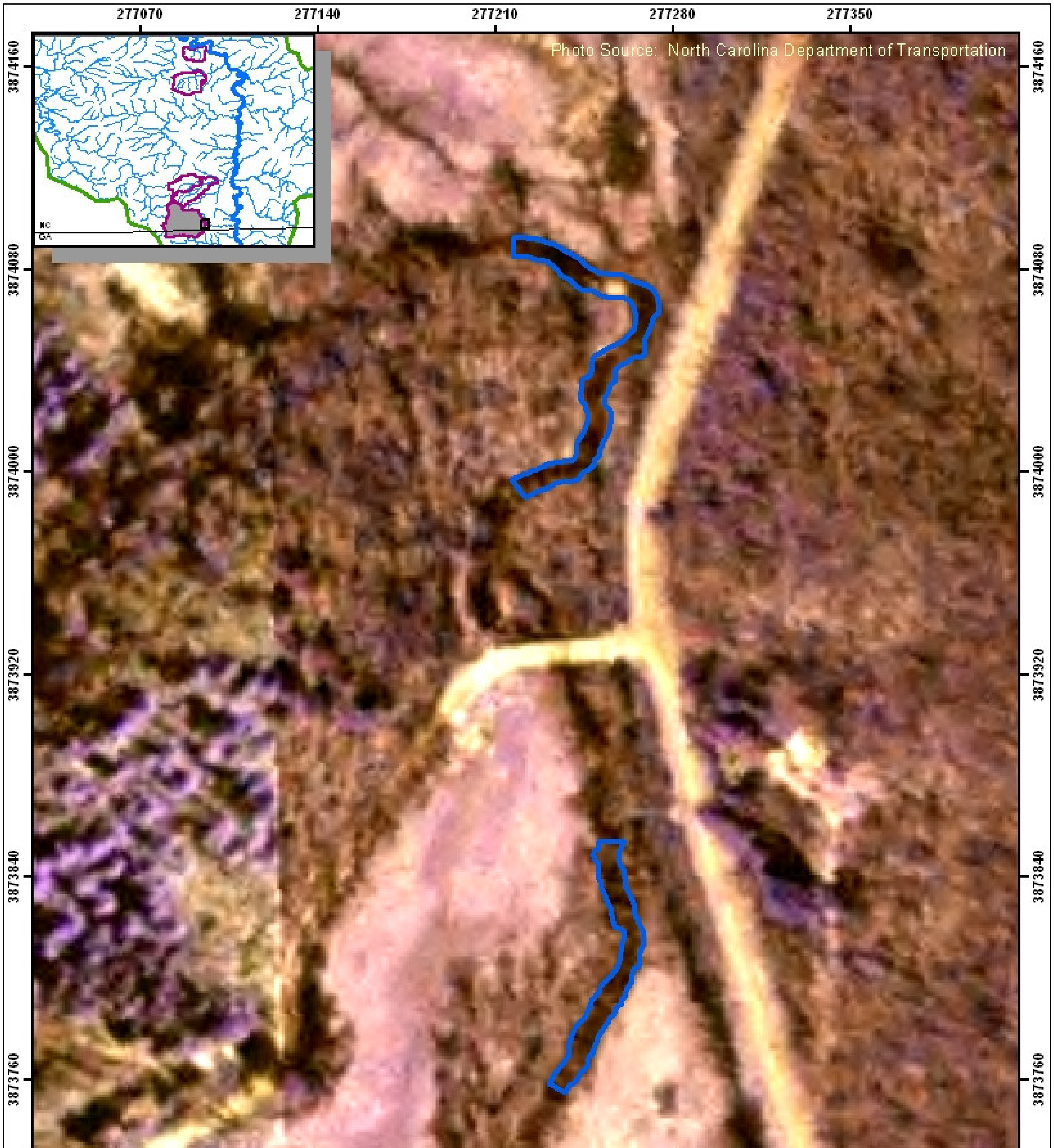

Figure 2: Betty Creek, showing the locations of the study reaches. The non-entrenched reach is upstream (above) of the entrenched reach (below). Note the location of the bridge between reaches.

Figure 3: Shope Fork Creek 1, showing the location of study reaches. The non-entrenched reach (left) is upstream from the entrenched reach (right).

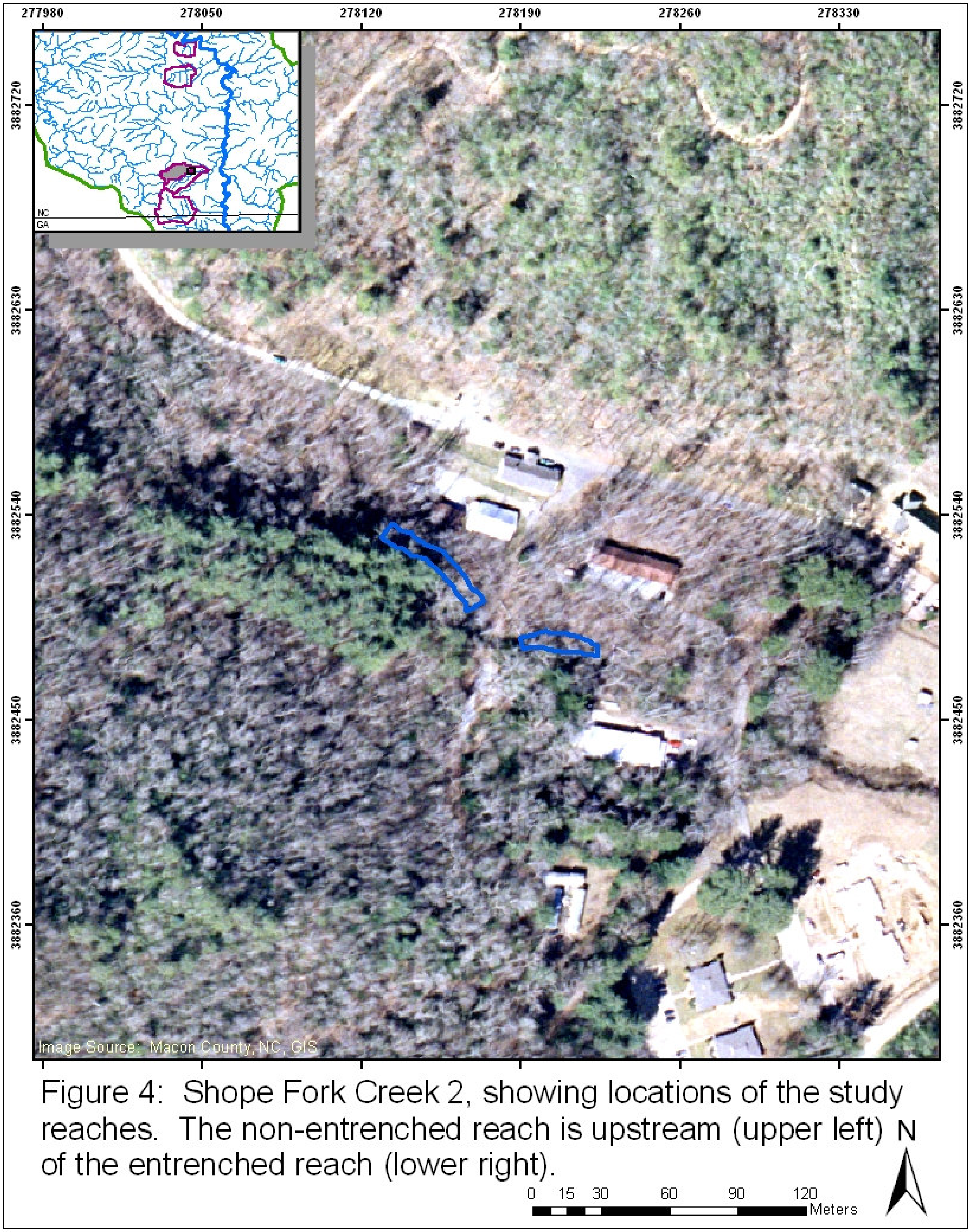

Figure 4: Shope Fork Creek 2, showing locations of the study reaches. The non-entrenched reach is upstream (upper left) of the entrenched reach (lower right).

Figure 5: Coweeta Creek, showing the locations of the study reaches. The entrenched reach (upper left) is upstream of the non-entrenched reach (lower right).

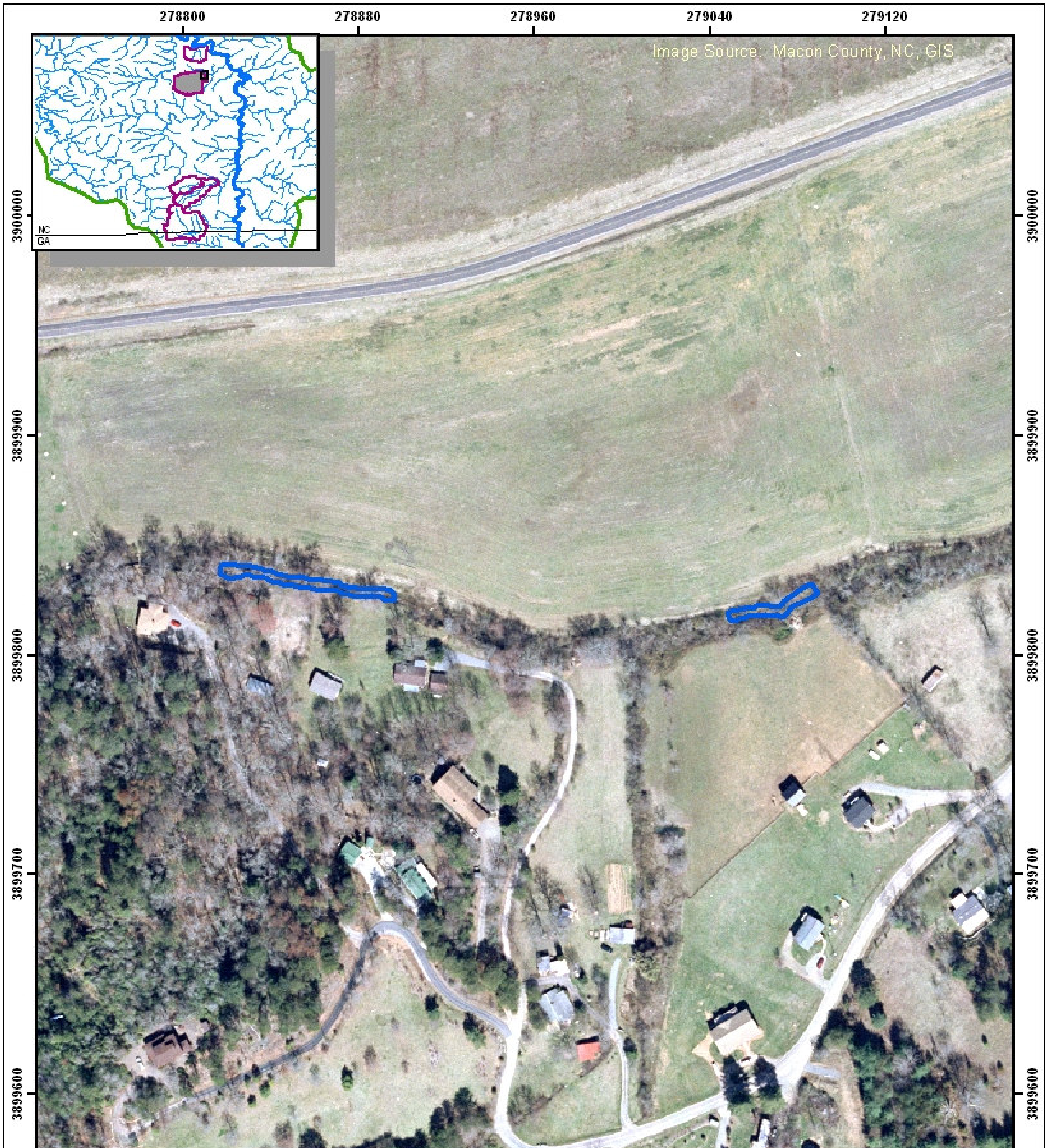

Figure 6: Iotla Creek, showing locations of study reaches. The entrenched reach is upstream (left) of the non-entrenched reach (right).

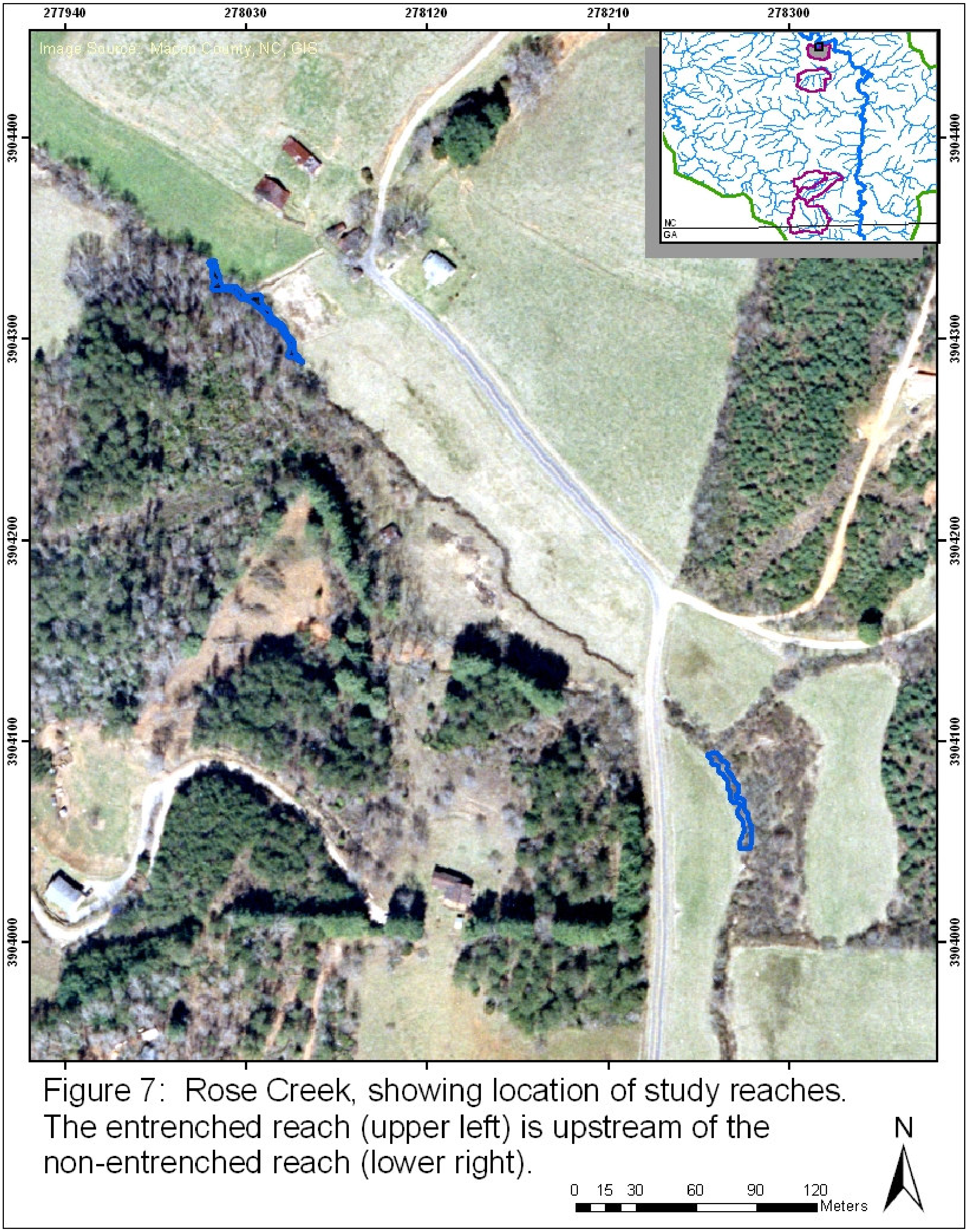

Figure 7: Rose Creek, showing location of study reaches. The entrenched reach (upper left) is upstream of the non-entrenched reach (lower right).

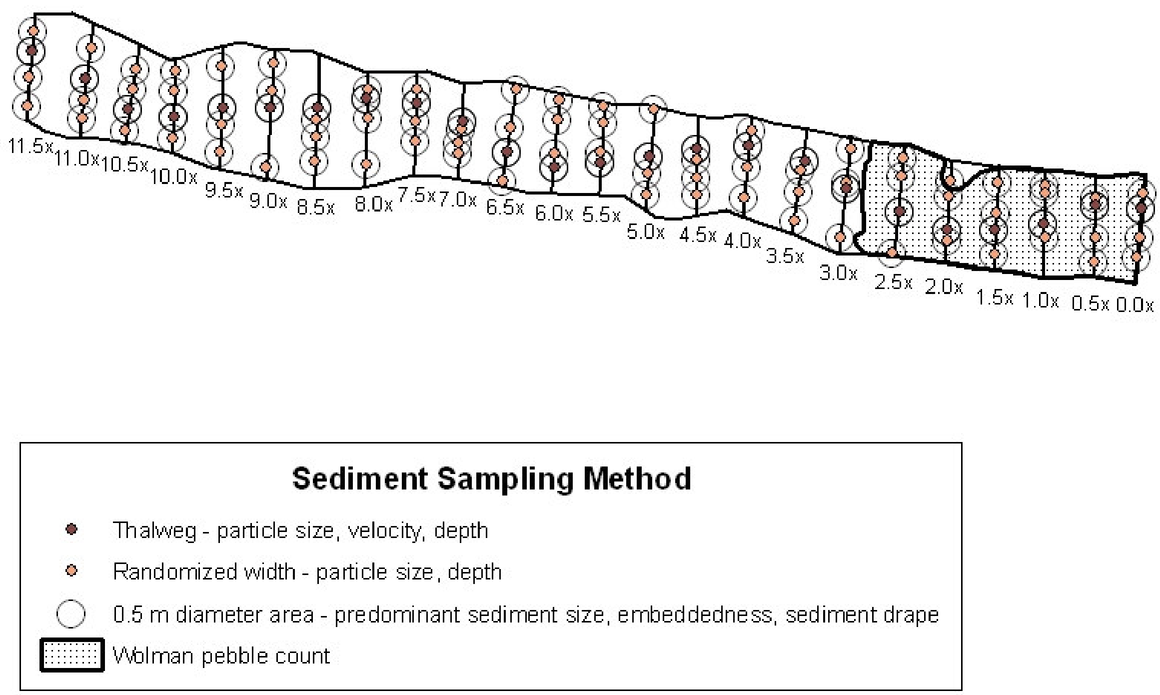

Figure 8: Sediment sampling methods. Wolman (1954) pebble count only in one representative riffle per reach.

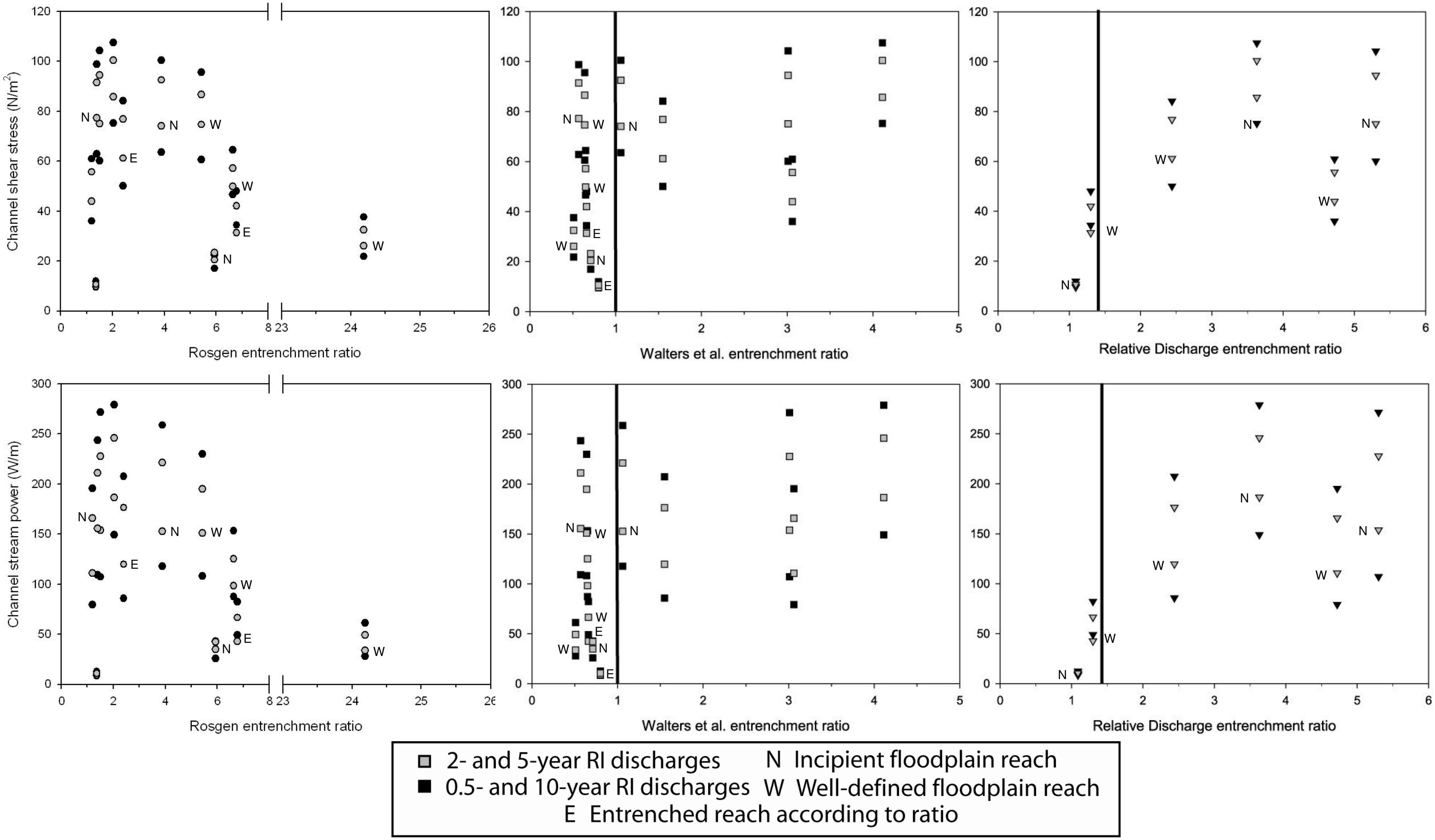

Figure 9: Comparison of the degree of entrenchment in all reaches with channel shear stress (top) and channel stream power (bottom) using the Rosgen (left), Walters et al. (middle), and Relative Discharge (right) entrenchment ratios. All ratios indicated higher values for these hydraulic variables with increasing entrenchment, but had varying amounts of predictive ability. Values of shear stress and stream power are averages for each reach at the 0.5-, 2-, 5-, and 10-year RI discharges. Thresholds are noted for the Walters et al. and the Relative Discharge ratios.

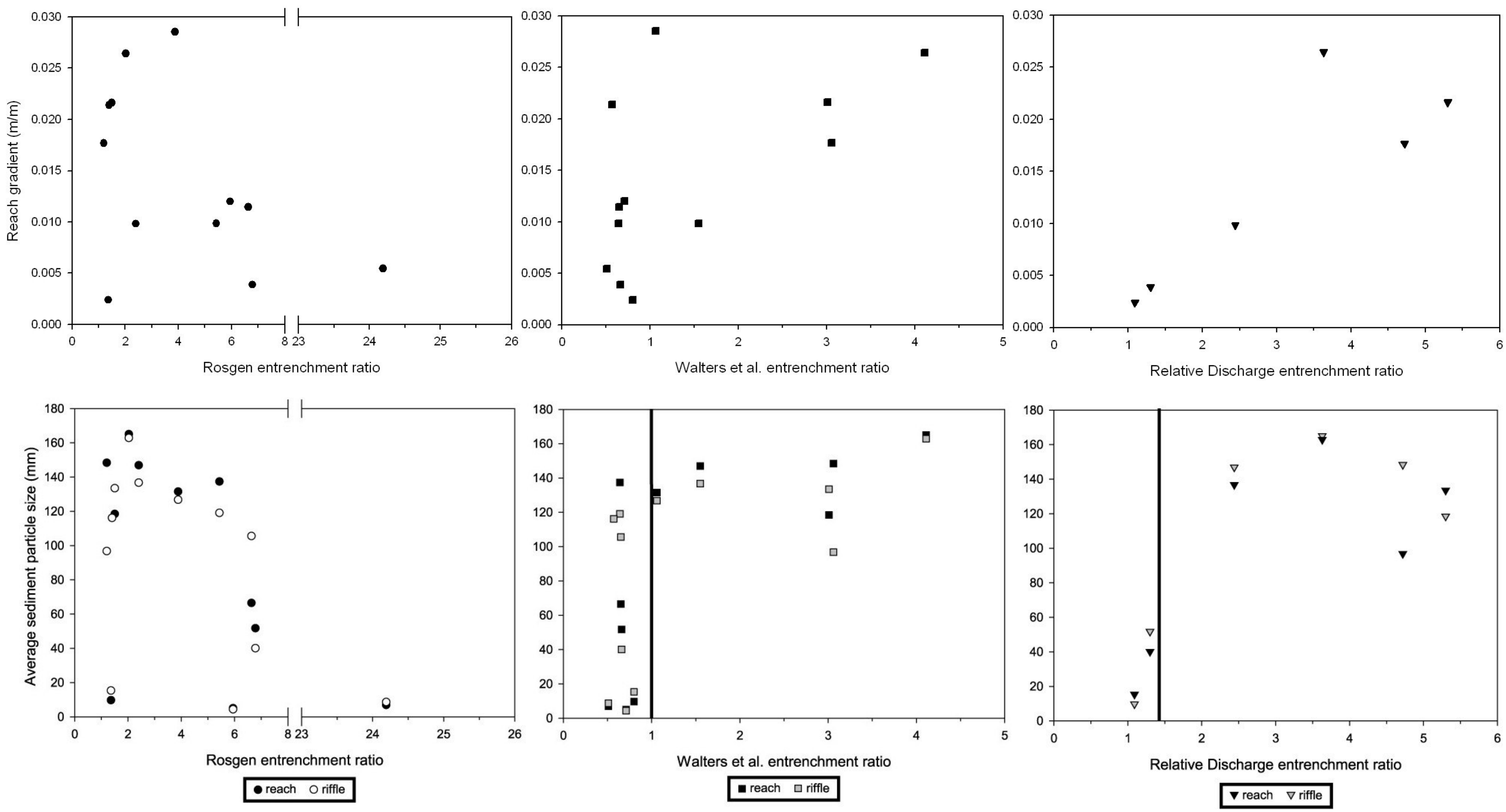

Figure 10: Comparison of the degree of entrenchment in all reaches with reach gradient (top) and average sediment particle size for each reach and each riffle (bottom) using the Rosgen (left), Walters et al. (middle), and Relative Discharge (right) entrenchment ratios. All ratios indicated steeper gradient and larger particle size with increasing entrenchment, but had varying amounts of predictive ability.

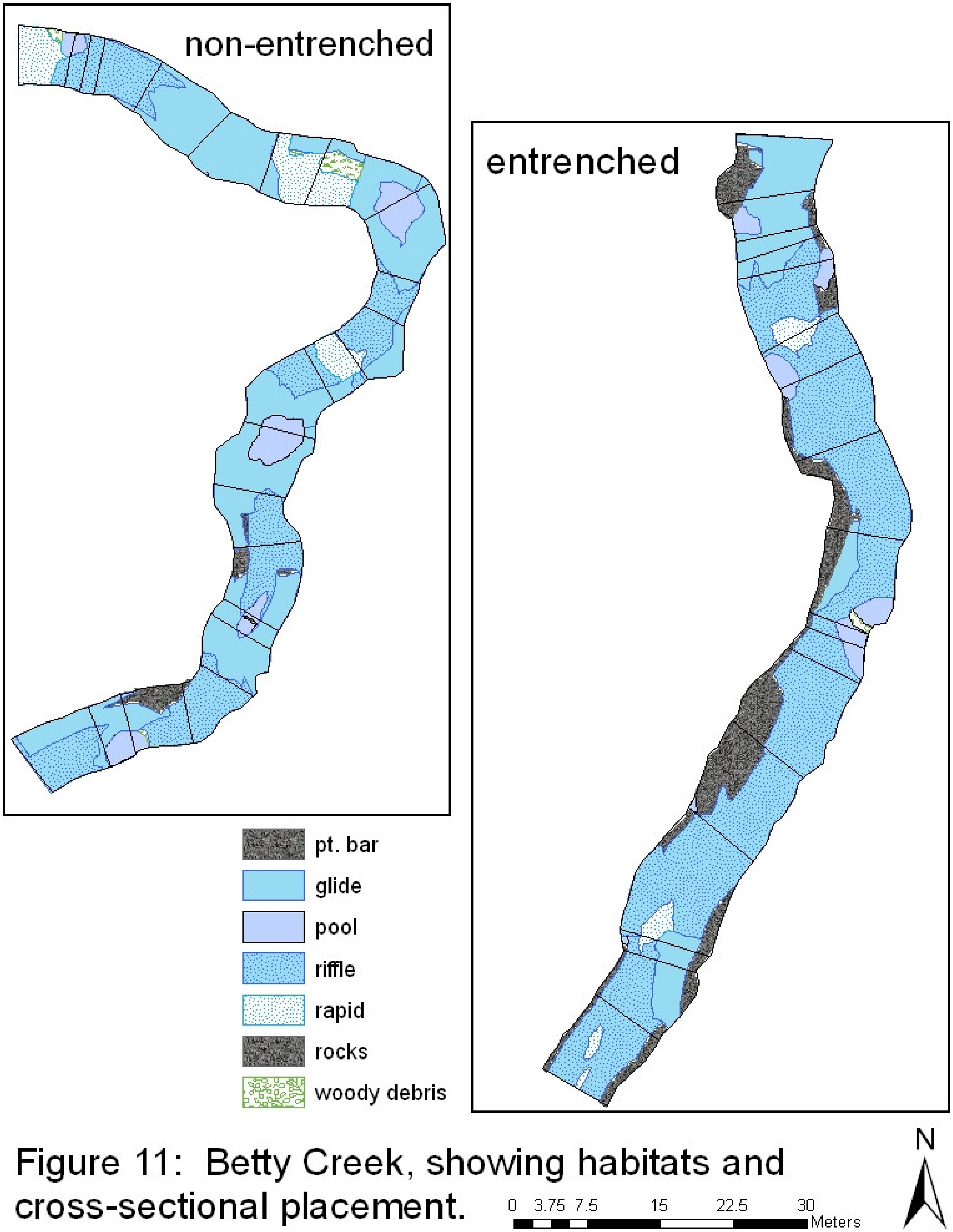

Figure 11: Betty Creek, showing habitats and cross-sectional placement.

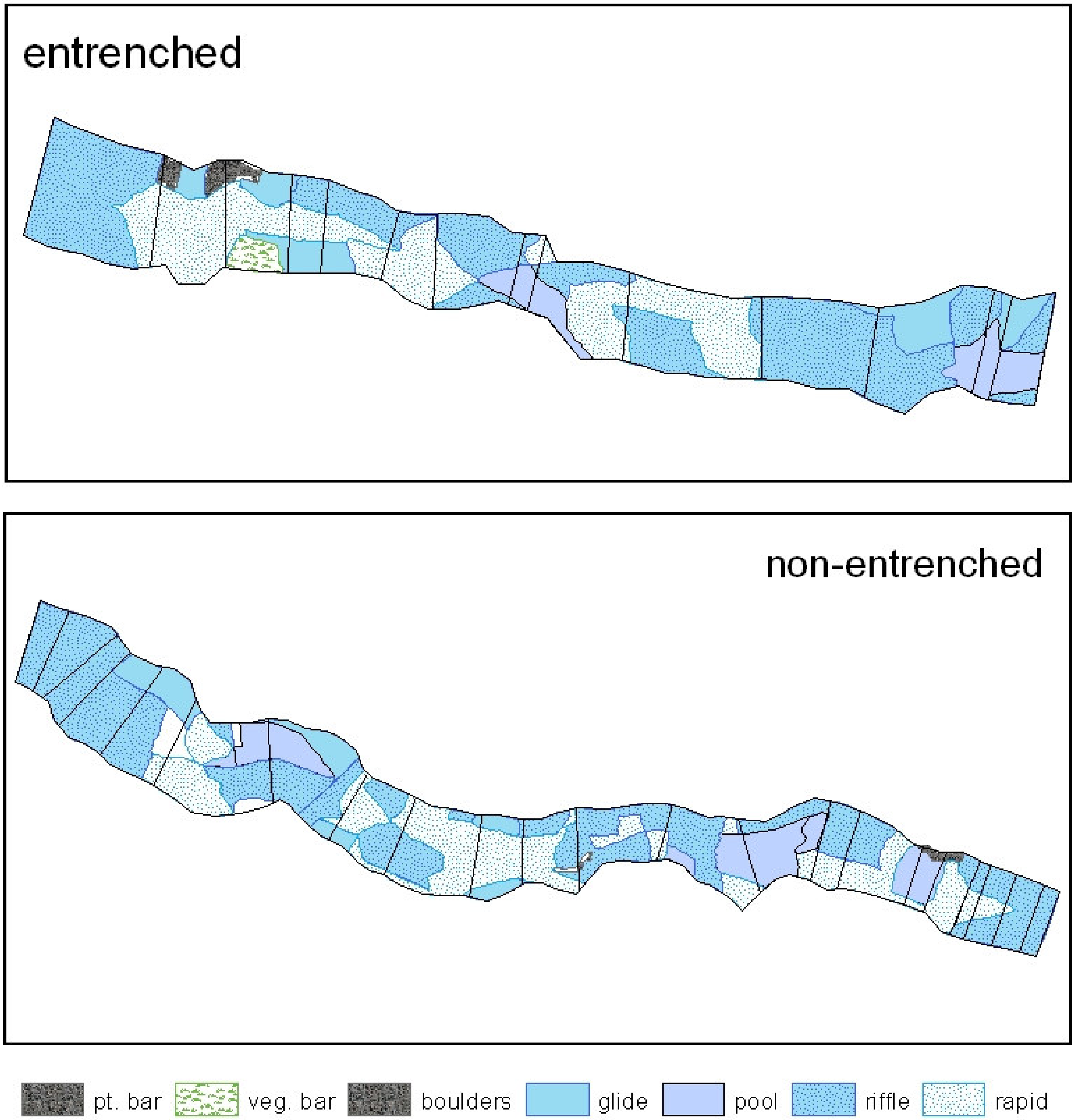

Figure 12: Shope Fork Creek 1, showing habitats and cross-sectional placement.

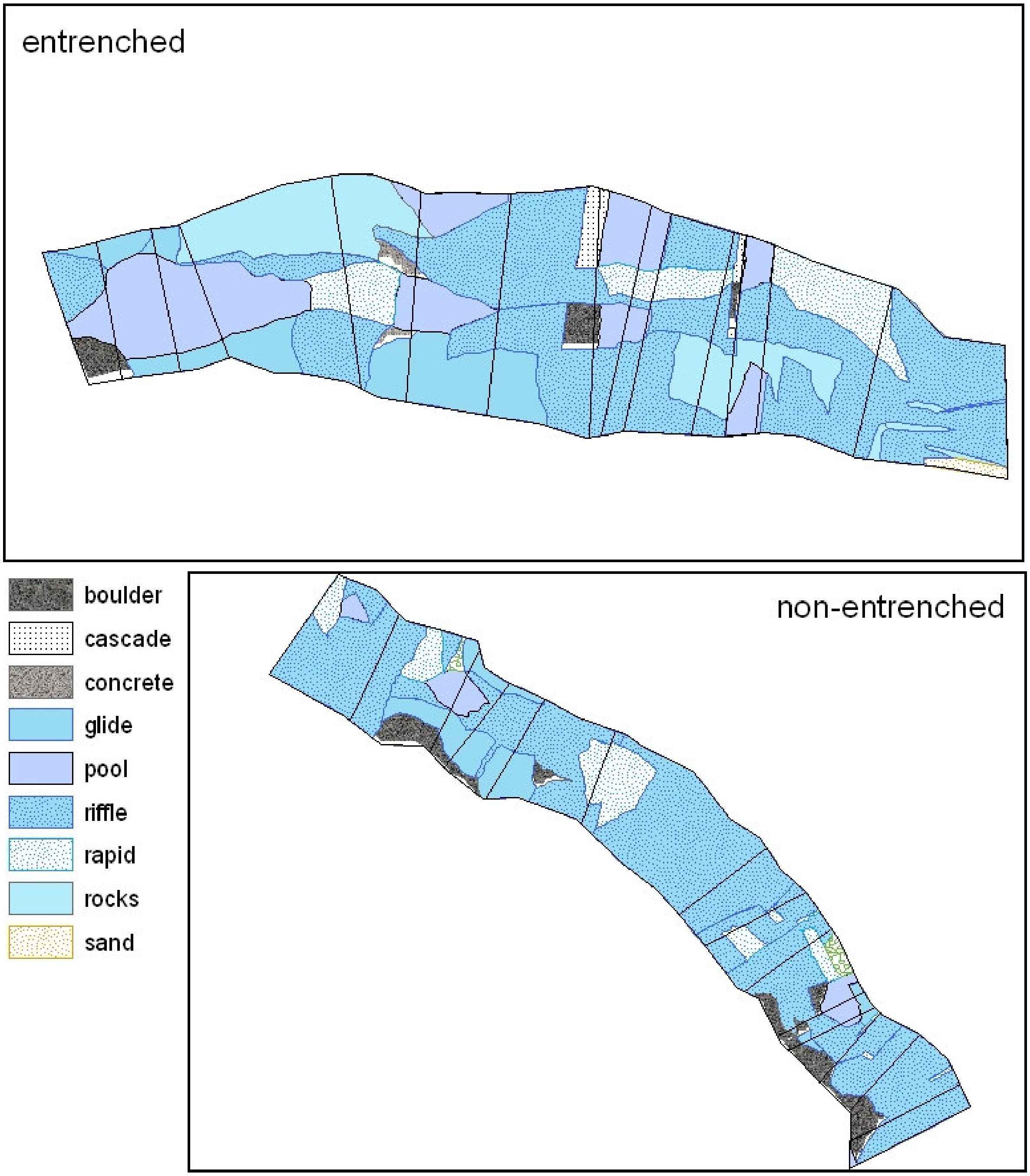

Figure 13: Shope Fork Creek 2, showing habitat maps and cross-sectional placement.

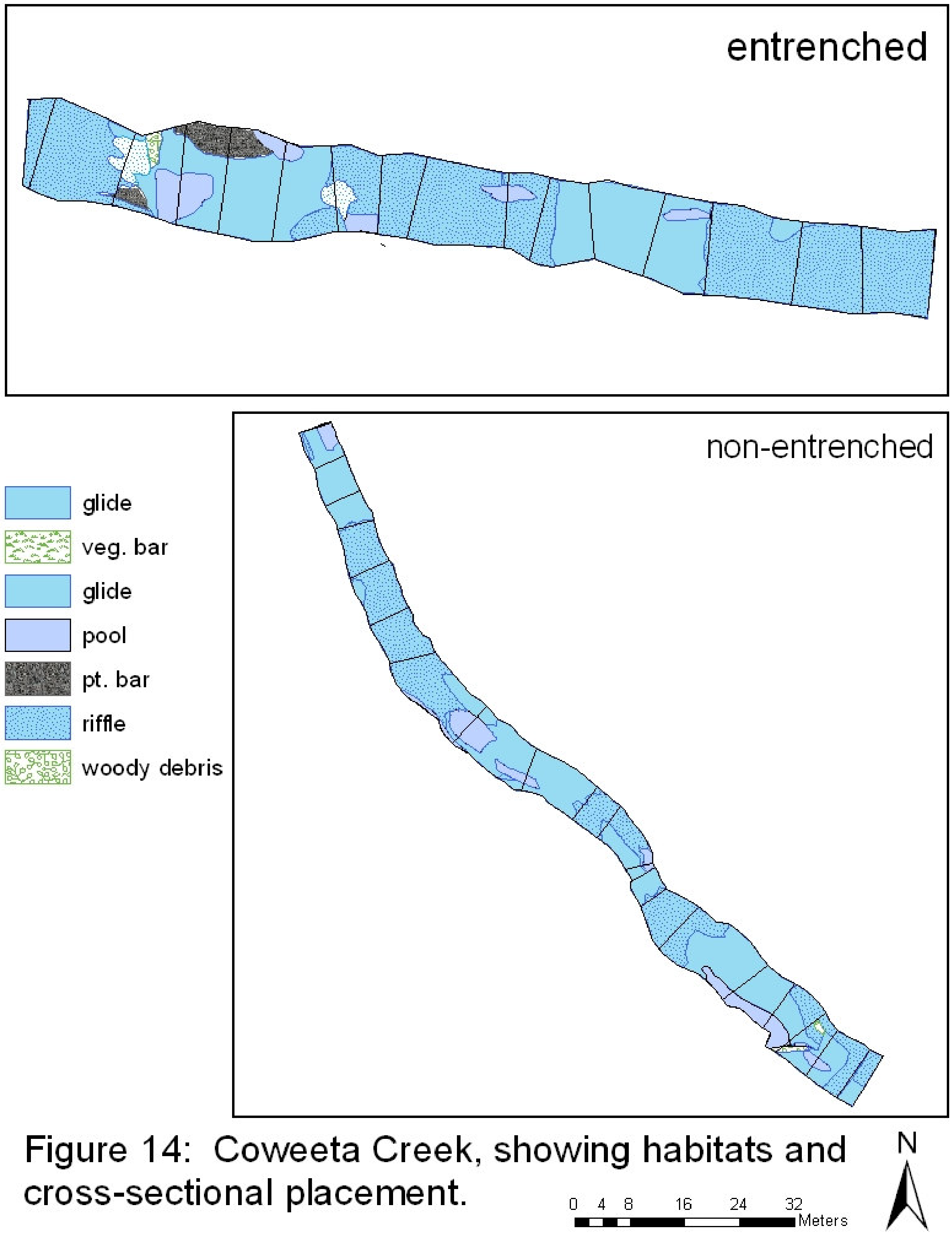

Figure 14: Coweeta Creek, showing habitats and cross-sectional placement.

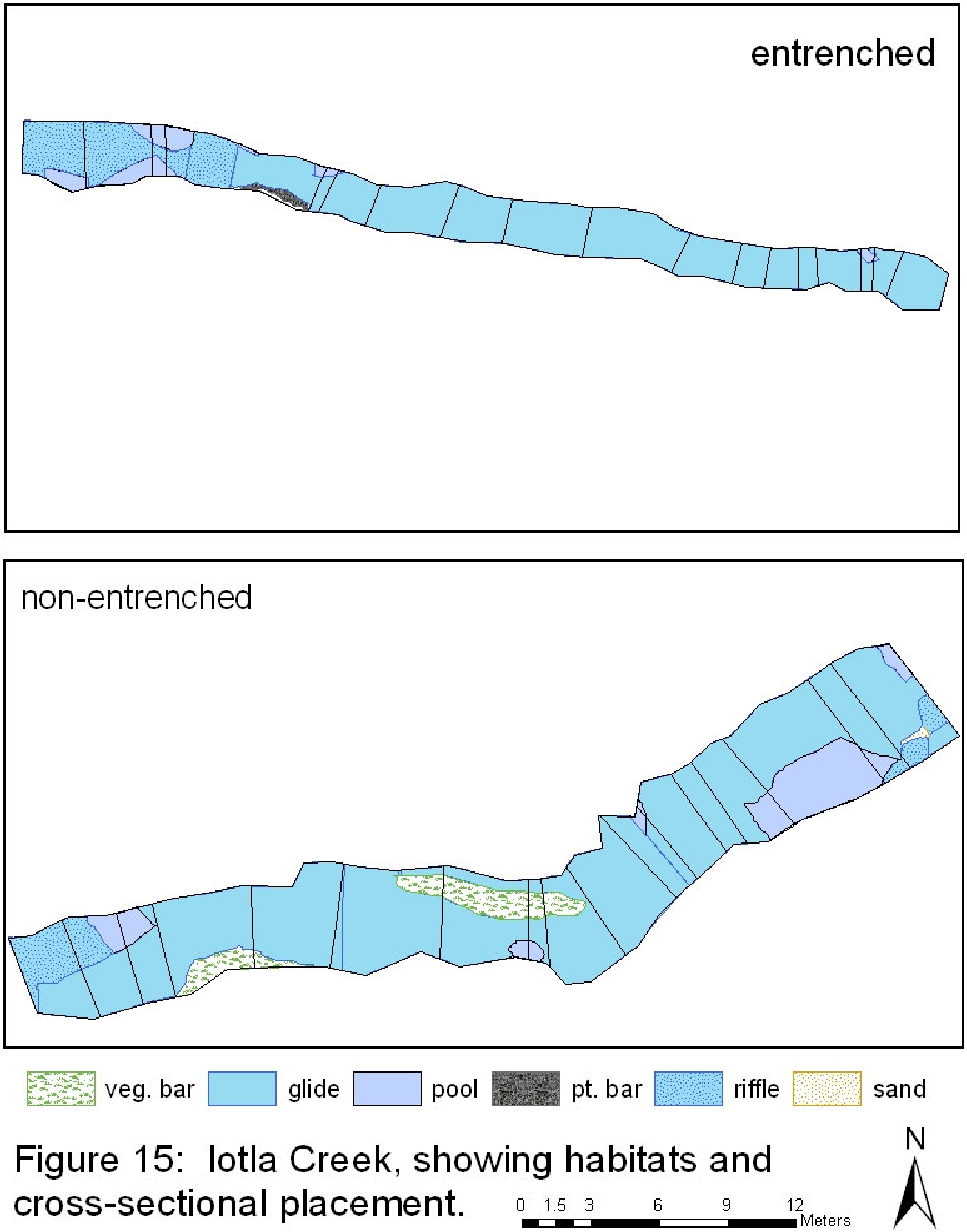

Figure 15: Iotla Creek, showing habitats and cross-sectional placement.

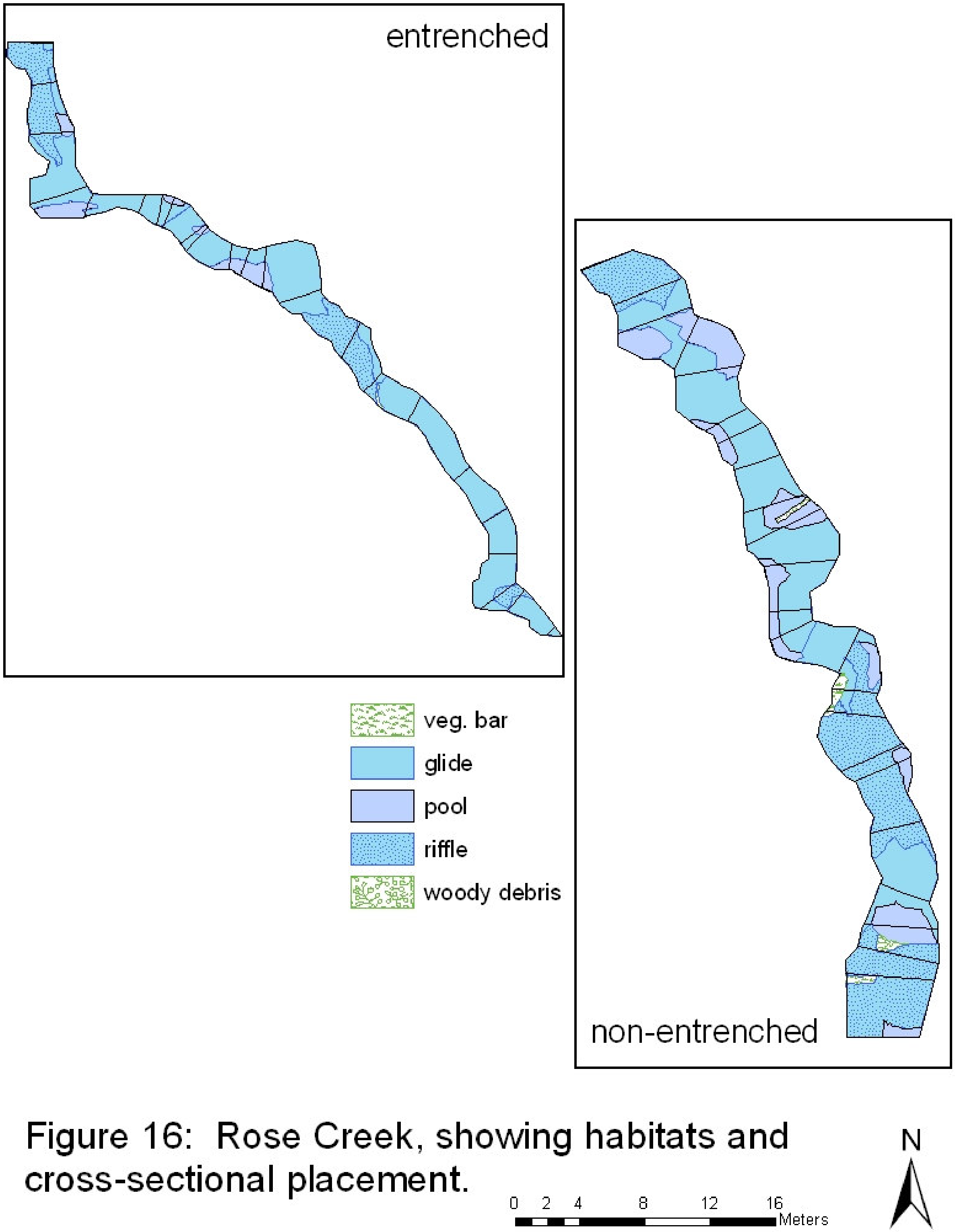

Figure 16: Rose Creek, showing habitats and cross-sectional placement.

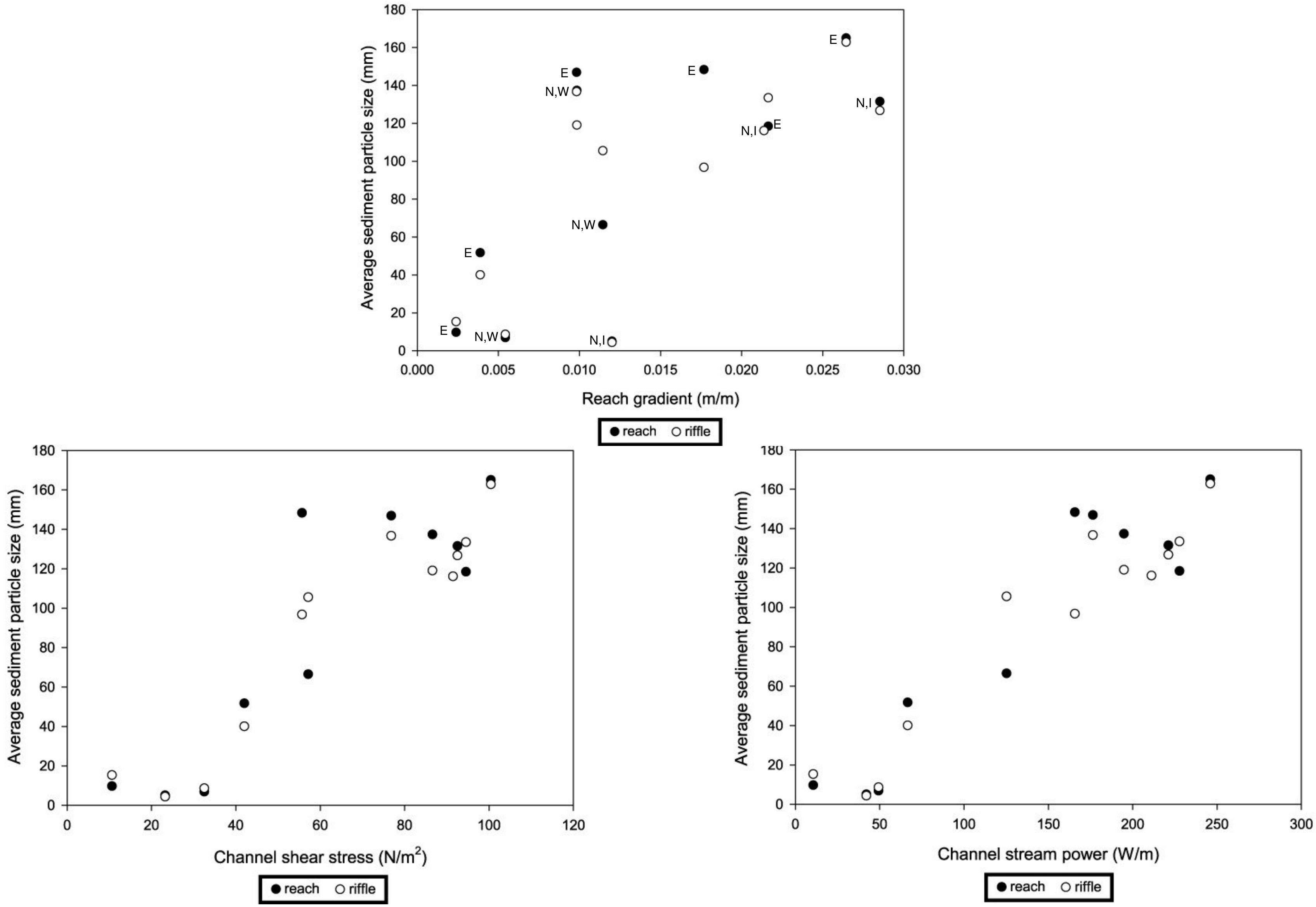

Figure 17: Comparisons of average sediment particle size in each reach and each riffle to reach gradient (top), shear stress (bottom left), and stream power (bottom right). Entrenched reaches (E) and non-entrenched reaches with incipient floodplains (N,I) or with well-developed floodplains (N,W) are noted next to the reach sediment points. Values of shear stress and stream power are for the 5-year RI discharge only.

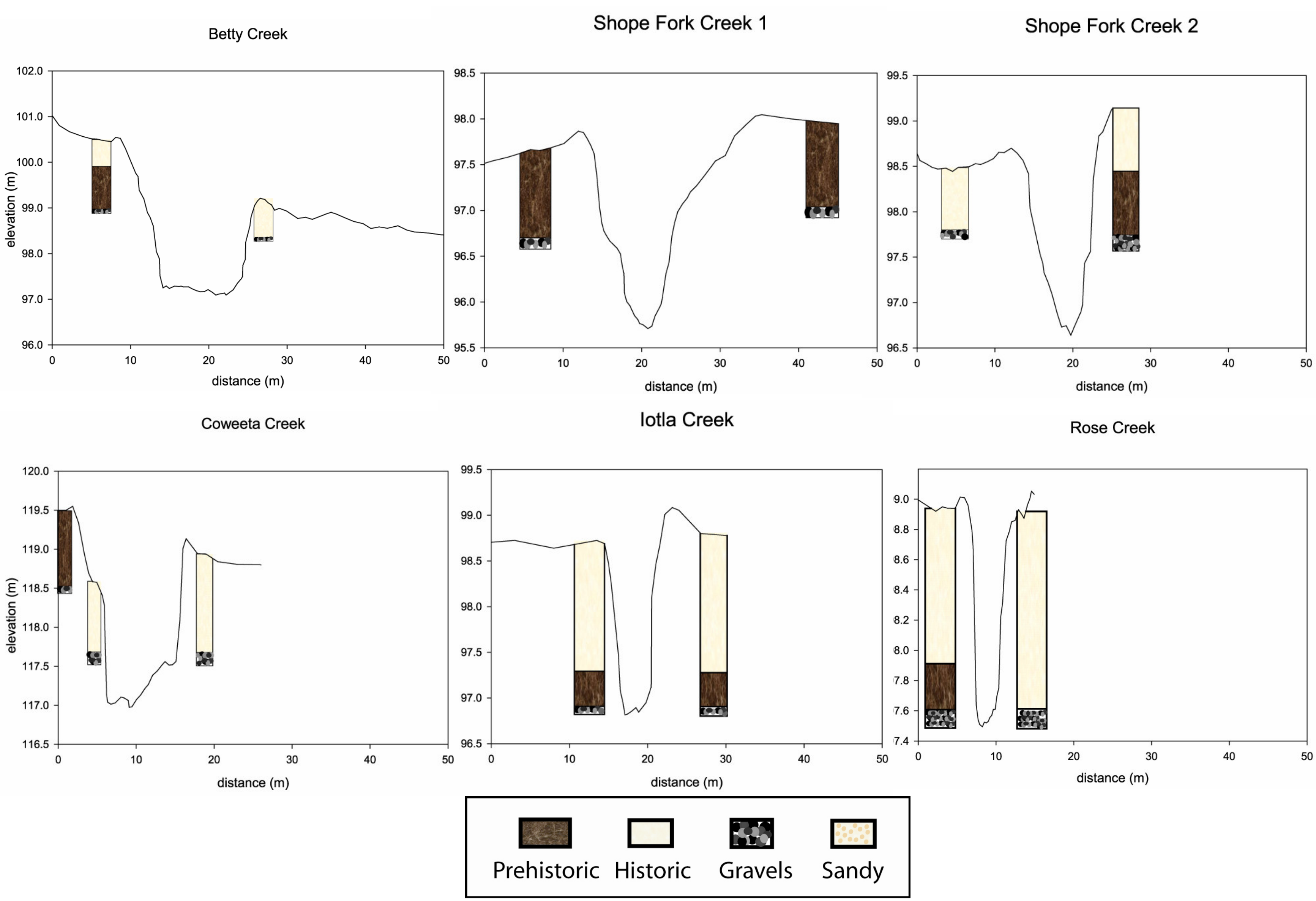

Figure 18: Allostratigraphy determined from sediment auger samples along a single transect in each entrenched reach. The cross sections are delineated looking downstream, thus the left side (0m) corresponds to the left bank.

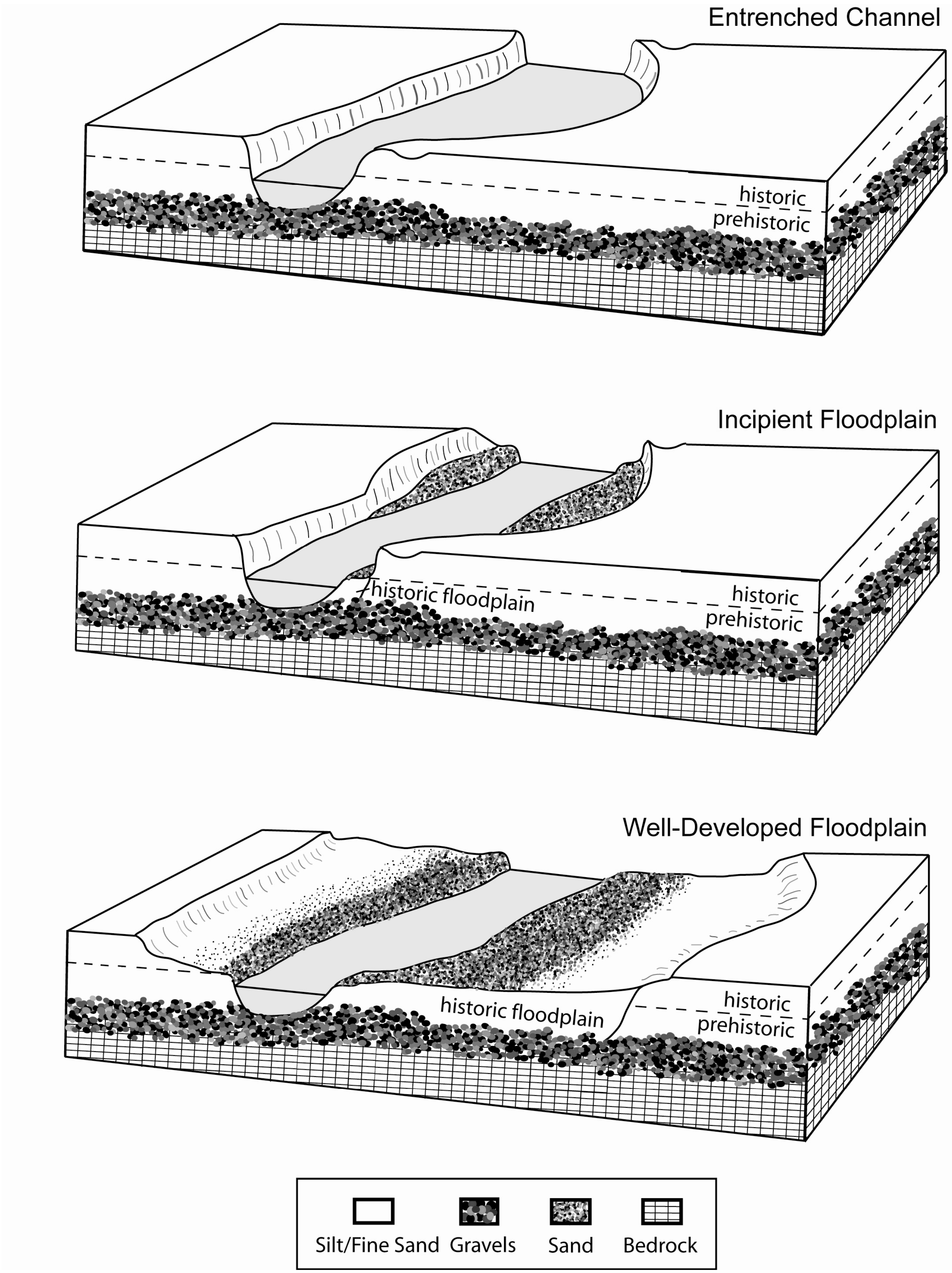

Figure 19: Schematic of floodplain development from an entrenched channel to a well-developed floodplain. Adapted from Jacobson and Coleman (1986).

Appendix A: Textures and colors for soil cores from each entrenched transect. LB indicates the core from the left bank and RB indicates the core from the right bank.

Betty Creek

	depth (cm)	period	texture	Munsell	color
LB	0-10	historical	silt loam	10YR43	brown
	10-30	historical	sandy silt loam	10YR33	dark brown
	30-40	historical	silt loam	10YR33	dark brown
	40-50	historical	silt loam	10YR32	very dark grayish brown
	50-60	historical	silt loam	10YR33	dark brown
	60-72	historical	silt loam	10YR33	dark brown
	72-80	prehistoric	sandy loam	10YR36	dark yellowish brown
	80-100	prehistoric	sandy loam	10YR54	yellowish brown
	100-130	prehistoric	fine sandy loam	10YR64	light yellowish brown
	130-150	prehistoric	sandy loam	10YR54	yellowish brown
	150-155	prehistoric	loamy sand	10YR54	yellowish brown
	155+	prehistoric	gravels		

	depth (cm)	period	texture	Munsell	color
RB	0-45	historic	loamy sand	10YR42	dark grayish brown
	45-80	historic	loamy sand and gravels	2.5Y53	light olive brown
	80-88	historic	sand and gravels	2.5Y33	dark olive brown
	88+		gravels		

Shope Fork Creek 1

	depth (cm)	period	texture	Munsell	color
LB	0-30	prehistoric	sandy loam	2.5Y42	dark grayish brown
	30-40	prehistoric	fine sandy loam	10YR43	brown
	40-50	prehistoric	silt loam	10YR43	brown
	50-60	prehistoric	sandy loam	10YR32	very dark grayish brown
	60-70	prehistoric	fine sandy loam	2.5Y53	light olive brown
	70-80	prehistoric	fine sandy loam and gravels	2.5Y42	dark grayish brown

	depth (cm)	period	texture	Munsell	color
RB	0-10	prehistoric	sandy loam	10YR43	brown
	10-20	prehistoric	sandy loam	10YR34	dark yellowish brown
	20-30	prehistoric	sandy loam	10YR46	dark yellowish brown
	30-40	prehistoric	coarse sandy loam	10YR66	brownish yellow
	40-50	prehistoric	coarse sandy loam	10YR46	dark yellowish brown
	50-60	prehistoric	coarse loamy sand and gravels	10YR54	yellowish brown
	60-80	prehistoric	coarse sand and gravels	2.5Y51	gray

Shope Fork Creek 2

	depth (cm)	period	texture	Munsell	color
LB	0-25	historic	sandy loam and gravels	10YR44	dark yellowish brown
	25-30	historic	sandy loam and gravels	10YR64	light yellowish brown
	30-60	historic	loamy sand and gravels	10YR46	dark yellowish brown
	60-68	historic	loamy sand and gravels	10YR56	yellowish brown
	68+		gravels		

	depth (cm)	period	texture	Munsell	color
RB	0-10	historic	loamy sand	10YR42	dark grayish brown
	10-20	historic	loamy sand	10YR43	brown
	20-30	historic	coarse loamy sand	10YR42	dark grayish brown
	30-40	historic	loamy sand	10YR32	very dark grayish brown
	40-50	prehistoric	loamy sand	10YR22	very dark brown
	50-80	prehistoric	coarse loamy sand and gravels	10YR33	dark brown
	80+		gravels		

Coweeta Creek

	depth (cm)	period	texture	Munsell	color
LB upper	0-3	prehistoric	silt loam	10YR33	dark brown
	3-25	prehistoric	sandy loam	10YR54	yellowish brown
	25-58	prehistoric	fine sandy loam	2.5Y53	light olive brown
	58-70	prehistoric	sandy loam	10YR33	dark brown
	70-85	prehistoric	sandy clay loam	10YR33	dark brown
	85-95	prehistoric	sandy clay loam	10YR34	dark yellowish brown
	95-100	prehistoric	sandy clay loam	10YR32	very dark grayish brown
	100-105	prehistoric	sandy loam and gravels	2.5Y32	very dark grayish brown

	depth (cm)	period	texture	Munsell	color
LB lower	0-4	historic	loamy sand	10YR33	dark brown
	4-20	historic	loamy sand	10YR43	brown
	20-25	historic	loamy sand	2.5Y53	light olive brown
	25-30	historic	coarse sand	10YR54	yellowish brown
	30-37	historic	loamy sand	10YR46	dark yellowish brown
	37-42	historic	loamy sand	10YR42	dark grayish brown
	42-50	historic	sandy loam	2.5Y32	very dark grayish brown
	50-55	historic	coarse sand and gravels	2.5Y52	grayish brown

RB	depth (cm)	period	texture	Munsell	color
	0-3	historic	loamy sand	10YR42	dark grayish brown
	3-10	historic	fine sand	2.5Y53	light olive brown
	10-20	historic	loamy sand	10YR42	dark grayish brown
	20-35	historic	fine loamy sand	10YR43	brown
	35-52	historic	fine loamy sand	10YR54	yellowish brown
	52-60	historic	sand	10YR54	yellowish brown
	60-70	historic	coarse sand	10YR44	dark yellowish brown
	70-75	historic	coarse sand	10YR52	grayish brown
	75-82	historic	very coarse sand and gravels	10YR52	grayish brown

Iotla Creek

	depth (cm)	period	texture	Munsell	color
LB	0-5	historic	loamy sand	10YR33	dark brown
	5-45	historic	gravels - spoils		
	45-80	historic	silt loam and gravels	10YR42	dark grayish brown
	80-90	historic	coarse sand and gravels	10YR64	light yellowish brown
	90-100	historic	sandy loam and gravels	10YR64	light yellowish brown
	100-110	historic	very coarse sand and gravels	10YR64	light yellowish brown
	110-125	historic	very coarse sand and gravels	10YR64	light yellowish brown
	125-130	historic	sandy loam and gravels	10YR22	very dark brown
	130-165	historic	very coarse sand and gravels	10YR64	light yellowish brown
	165-210	prehistoric	silt loam and gravels	10YR22	very dark brown

RB	depth (cm)	period	texture	Munsell	color
	0-15	historic	silt loam	7.5YR34	dark brown
	15-20	historic	silt loam	7.5YR44	brown
	20-30	historic	silt loam	10YR43	brown
	30-50	historic	silt loam	2.5Y52	grayish brown
	50-80	historic	sandy loam	2.5Y52	grayish brown
	80-90	historic	coarse sandy loam	10YR33	dark brown
	92-100	historic	silty clay loam	2.5Y63	light yellowish brown
	100-120	historic	silty clay loam	2.5Y52	grayish brown
	120-145	historic	silty clay loam - inside	2.5Y51	gray
		historic	silty clay loam - outside	10YR54	yellowish brown
	145-155	prehistoric	sandy clay loam	2.5Y42	dark grayish brown
	155-165	prehistoric	sandy clay loam	10YR43	brown
	165-175	prehistoric	sandy clay loam	10YR43	brown
	175-180	prehistoric	sandy clay - outside	10YR43	brown
		prehistoric	sandy clay - inside	7.5YR44	brown
	180+	prehistoric	sandy clay loam and gravels	7.5YR56	strong brown

Rose Creek

	depth (cm)	period	texture	Munsell	color
LB	0-3	historic	silt loam	10YR33	dark brown
	3-20	historic	silt loam	10YR46	dark yellowish brown
	20-30	historic	silt loam	7.5YR44	brown
	30-37	historic	silt loam	7.5YR46	strong brown
	37-50	historic	silt loam	7.5YR44	brown
	50-60	historic	silt loam	10YR44	dark yellowish brown
	60-75	historic	silt loam	10YR36	dark yellowish brown
	75-85	historic	silty clay loam	10YR34	dark yellowish brown
	85-95	prehistoric	silt loam	10YR32	very dark grayish brown
	95-100	prehistoric	silty clay loam	10YR31	very dark gray
	100-110	prehistoric	silty clay loam	10YR22	very dark brown
	110+	prehistoric	silty clay loam and gravels	10YR22	very dark brown

RB	depth (cm)	period	texture	Munsell	color
	0-5	historic	silt loam	10YR54	yellowish brown
	5-10	historic	silt loam	10YR46	dark yellowish brown
	10-20	historic	silt loam	10YR36	dark yellowish brown
	20-30	historic	silt loam	10YR44	dark yellowish brown
	30-50	historic	silt loam	10YR36	dark yellowish brown
	50-75	historic	silt loam	10YR44	dark yellowish brown
	75-80	historic	silt loam	10YR33	dark brown
	80-88	historic	silty clay loam	10YR43	brown
	88-90	historic	silty clay loam	10YR32	very dark grayish brown
	90-100	historic	silty clay loam and gravels	10YR42	dark grayish brown
	100+		gravels		