Stream Restoration

A Natural Channel Design Handbook

Prepared by the North Carolina Stream Restoration Institute
and North Carolina Sea Grant

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NC STATE UNIVERSITY

Contents

Preface

Streams and rivers serve many purposes, including water supply, wildlife habitat, energy generation, transportation and recreation. A stream is a dynamic, complex system that includes not only the active channel but also the floodplain and the vegetation along its edges. A natural stream system remains stable while transporting a wide range of flows and sediment produced in its watershed, maintaining a state of "dynamic equilibrium." When changes to the channel, floodplain, vegetation, flow or sediment supply significantly affect this equilibrium, the stream may become unstable and start adjusting toward a new equilibrium state. This transition may take a long time and cause big changes to water quality, habitat and adjacent property.

Stream restoration is the re-establishment of the general structure, function and self-sustaining behavior of the stream system that existed prior to disturbance. It is a holistic process that requires an understanding of all physical and biological components of the stream system and its watershed. Restoration includes a broad range of measures, including the removal of the watershed disturbances that are causing stream instability; installation of structures and planting of vegetation to protect streambanks and provide habitat; and the reshaping or replacement of unstable stream reaches into appropriately designed functional streams and associated floodplains.

This document promotes a natural channel design approach to stream restoration. It is intended primarily as a reference for natural resource professionals who plan, design, review and implement stream-restoration projects. This document is not a substitute for training and experience. Users should take advantage of training opportunities and work closely with experienced stream-restoration professionals to learn more about natural channel-design principles. Users must recognize that all stream-restoration projects are different and require applications of specific techniques to meet project objectives. This document provides a general framework and some design aids to help planners and designers address complex stream-restoration projects.

The techniques and methodologies described in this document are evolving rapidly. New design aids are being developed that will improve design efficiency and confidence. We encourage stream-restoration professionals to carefully document their experiences—including project successes and failures—so that the restoration community can better understand the appropriate techniques for various conditions.

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Introduction to Fluvial Processes

Chapter 1

Chapter 1: **Introduction to Fluvial Processes**

Streams and rivers are integral parts of the landscape that carry water and sediment from high elevations to downstream lakes, estuaries and oceans. The land area draining to a stream or river is called its watershed. When rain falls in a watershed, it runs off the land surface, infiltrates the soil or evaporates *(Figure 1.1)*. As surface runoff moves downslope, it concentrates in low areas and forms small stream channels. These are referred to as ephemeral channels, which carry water only when it rains. Downstream from ephemeral channels are intermittent streams, which carry water during wet times of the year. These streams are partially supplied by groundwater that rises to the surface as stream base flow. They dry up when groundwater levels drop. Farther downstream, where base flow is large enough to sustain stream flow throughout the year, perennial streams are formed.

The size and flow of a stream are directly related to its watershed area. Other factors that affect channel size and stream flow are land use, soil types, topography and climate. The morphology—or size and shape—of the channel reflects all of these factors. Though streams and rivers vary in size, shape, slope and bed composition, all streams share common characteristics. Streams have left and right banks and beds consisting of mixtures of bedrock, boulders, cobble, gravel, sand or silt/clay. Other physical characteristics shared by some stream types include pools, riffles, steps, point bars, meanders, floodplains and terraces. All of these characteristics are related to the interactions among climate, geology, topography, vegetation and land use in the watershed. The study of these interactions and the resulting streams and rivers is called fluvial geomorphology.

Streams are classified—or ordered—according to the hierarchy of natural channels within a watershed. The order of a stream can provide clues about other stream characteristics, including its longitudinal zone and the relative size and depth of its channel. The uppermost channels in a drainage network (i.e., headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence *(Strahler, 1957)*. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on *(Figure 1.2)*.

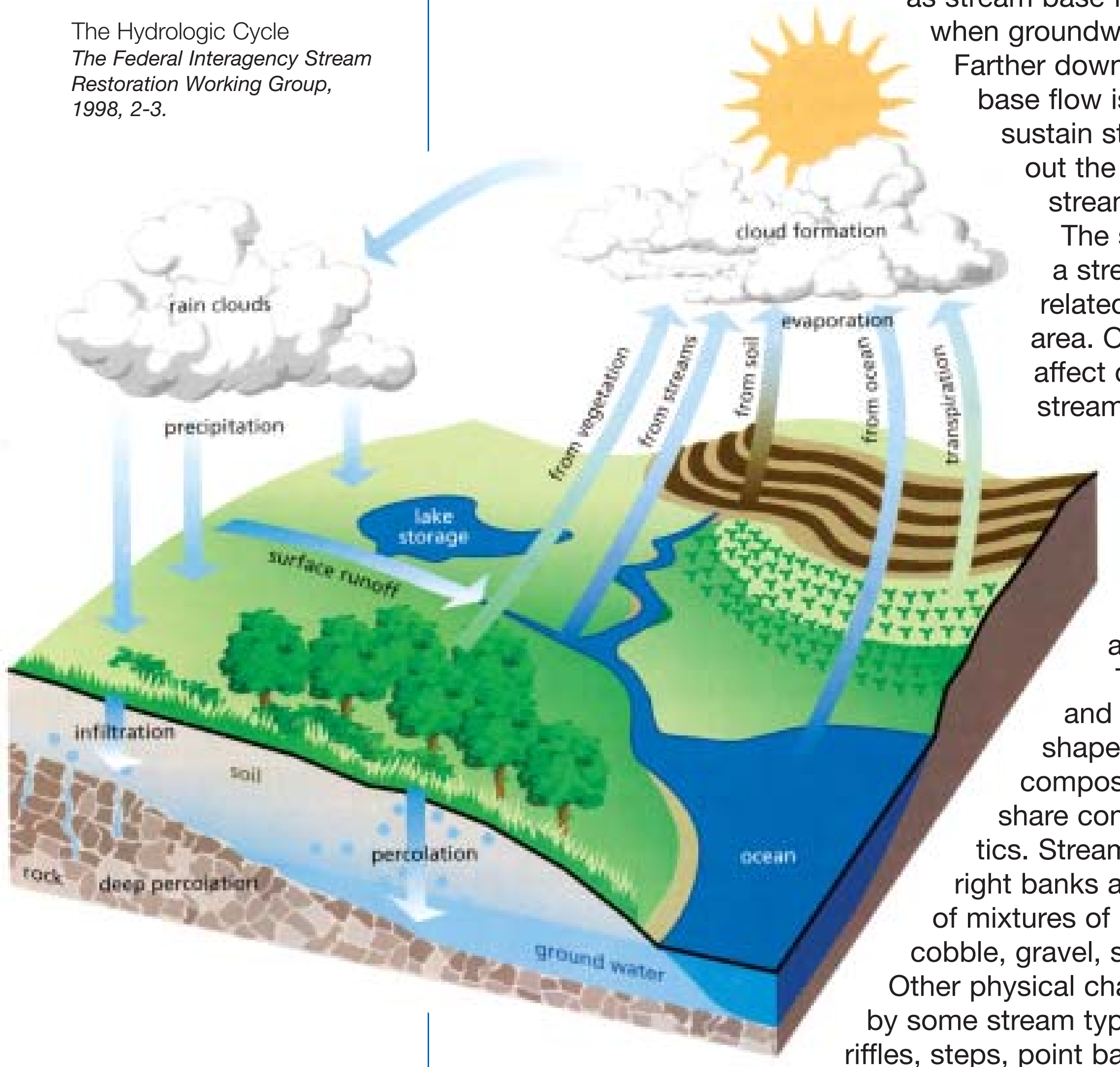


Figure 1.1

The Hydrologic Cycle
The Federal Interagency Stream Restoration Working Group, 1998, 2-3.

Figure 1.2

Stream order classification
The Federal Interagency Stream Restoration Working Group, 1998, 1-26

In addition to transporting water and sediment, natural streams provide habitat for many aquatic organisms, including fish, amphibians, aquatic insects, mollusks and plants. Trees and shrubs along the banks provide a food source and regulate water temperatures. Channel features such as pools, riffles, steps and undercut banks provide diversity of habitat, oxygenation and cover. For these reasons natural resource managers increasingly use natural channel design to restore impaired streams.

1.1. Bankfull Discharge and Stage

The most important stream process in defining channel form is the bankfull discharge, which is essentially the same as the effective—or dominant—discharge. Bankfull discharge is the flow that transports the majority of a stream's sediment load over time and thereby forms and maintains the channel. Any flow that exceeds the stage of the bankfull flow will move onto the floodplain; therefore bankfull stage is considered the incipient point of flooding. This may or may not be the top of the streambank. If the stream has become incised due to changes in the watershed or streamside vegetation, the bankfull stage may be a small bench or scour line on the streambank. In this case the top of the bank, which was formerly the floodplain, is called a terrace. A stream that has terraces close to the top of the banks is considered an incised—or entrenched—stream *(Figure 1.3)*. If the stream is not entrenched, then bankfull is near the top of the bank *(Figure 1.4)*. For examples of bankfull indicators, refer to River Course Fact Sheet Number 3 *(Appendix A)*. On aver-

Figure 1.3

Bankfull bench below top of bank in an incised channel

Figure 1.4

Bankfull is at the top of the streambank on this reference reach stream

age, bankfull discharge occurs every 1.5 years. In other words, each year there is about a 67 percent chance of a bankfull discharge event. The Rosgen stream-classification system (Rosgen, 1996) uses bankfull stage as the basis for measuring the width-to-depth and entrenchment ratios. Therefore, it is critical to correctly identify bankfull stage when classifying streams and designing stream-restoration measures. The Rosgen stream classification is discussed in detail in Chapter 3 and in River Course Fact Sheet Number 2 *(Appendix A)*.

1.2. Natural Channel Stability

A naturally stable stream channel maintains its dimension, pattern and profile such that the stream does not degrade or aggrade. Stable streams migrate across the landscape slowly over geologic time while maintaining their form and function. Naturally stable streams must be able to transport the sediment load supplied by the watershed. Instability occurs when scouring causes the channel bed to erode (degrade) or excessive deposition causes the channel bed to rise (aggrade). A generalized relationship of stream stability is shown as a schematic drawing in Figure 1.5. The drawing shows that the product of sediment load and sediment size is proportional to the product of stream slope and discharge—or stream power. A change in any one of these variables causes a rapid physical adjustment in the stream channel.

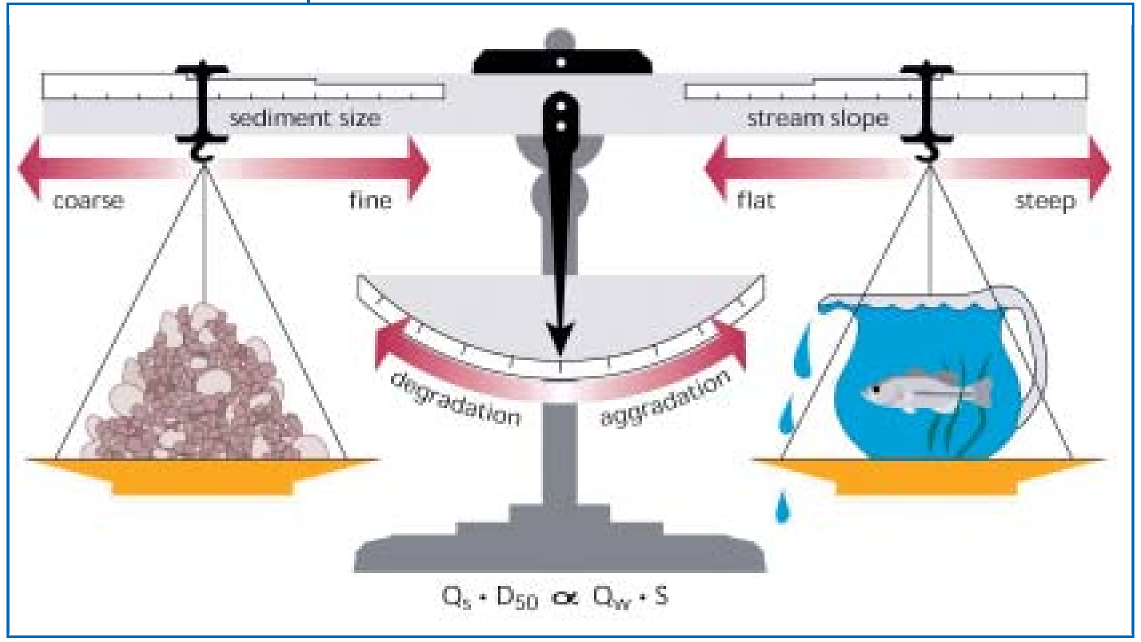


Figure 1.5

Factors affecting channel degradation and aggradation

Reproduced with permission from the American Society of Civil Engineers from Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings from the American Society of Civil Engineers. 81(745): 1-17.

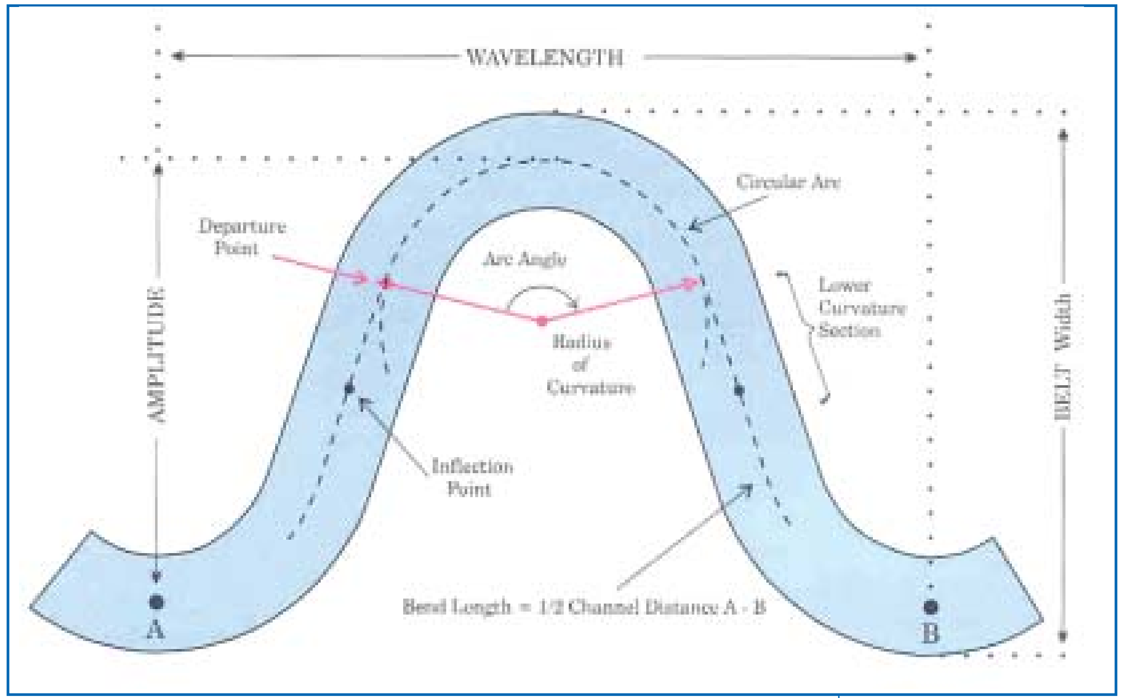


Figure 1.6

Pattern measurements of a meander bend

Rosgen, 1996, 2-6

1.3. Channel Dimension

The dimension of a stream is its cross-sectional view or perspective. Specifically, it is the bankfull cross-sectional area (bankfull width multiplied by bankfull mean depth) measured at a stable riffle in the stream. The width of a stream generally increases in the downstream direction in proportion to the square root of discharge. Stream width is a function of discharge (occurrence and magnitude), sediment transport (size and type) and the streambed and bank materials. North Carolina has a humid subtropical climate with abundant rainfall and vegetation throughout the year. Because vegetation along streambanks provides resistance to erosion, our streams are often narrower than those in more arid regions. The mean depth of a stream varies greatly from reach to reach depending on channel slope and riffle/pool or step/pool spacing.

1.4. Channel Pattern

Stream pattern refers to the "plan view" of a channel as seen from above. Natural streams are rarely straight. They tend to follow a sinuous path across a floodplain. The sinuosity of a stream is defined as the channel length following the deepest point in the channel (the thalweg) divided by the valley length, which is measured along the direction of fall of the valley. In general, channel sinuosity increases as valley gradient decreases. A meander bend increases resistance and reduces channel gradient relative to a straight reach. The geometry of the meander and spacing of riffles and pools adjust so that the stream performs minimal work. Stream pattern is qualitatively described as straight, meandering or braided. Braided channels are less sinuous than meandering streams and possess three or more channels on a given reach. Quantitatively, stream pattern can be defined by measuring meander wavelength, radius of curvature, amplitude and belt width *(Figure 1.6)*.

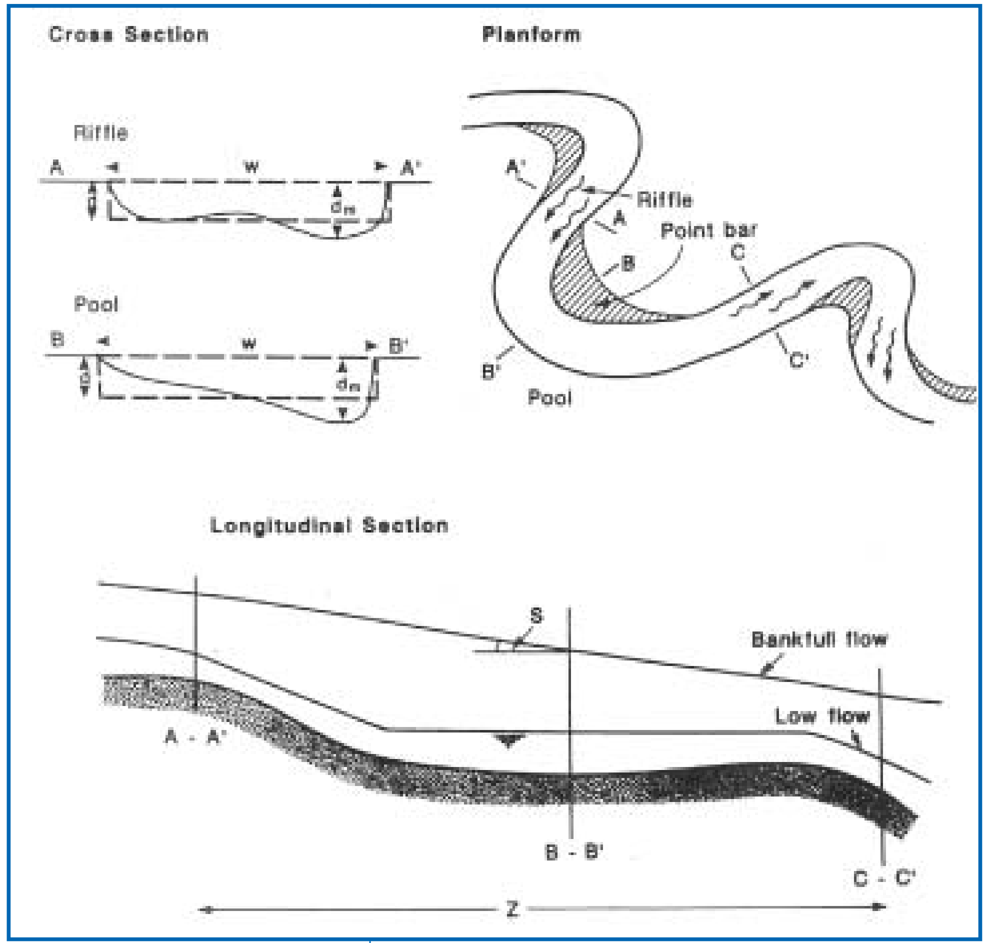


Figure 1.7

Features of natural streams
From Hey, R.D. and Heritage, G.L. (1993). Draft guidelines for the design and restoration of flood alleviation schemes. National Rivers Authority, Bristol, UK, R&D Note 154

1.5. Channel Profile

The profile of a stream refers to its longitudinal slope. At the watershed scale, channel slope generally decreases downstream. The size of the bed material also typically decreases in the downstream direction. Channel slope is inversely related to sinuosity. This means that steep streams have low sinuosity and flat streams have high sinuosity. The profile of the streambed can be irregular because of variations in bed material size and shape, riffle/pool spacing and other variables. The water-surface profile mimics the bed profile at low flows. As water rises in a channel during storms, the water-surface profile becomes more uniform *(Figure 1.7).*

1.6. Channel Features

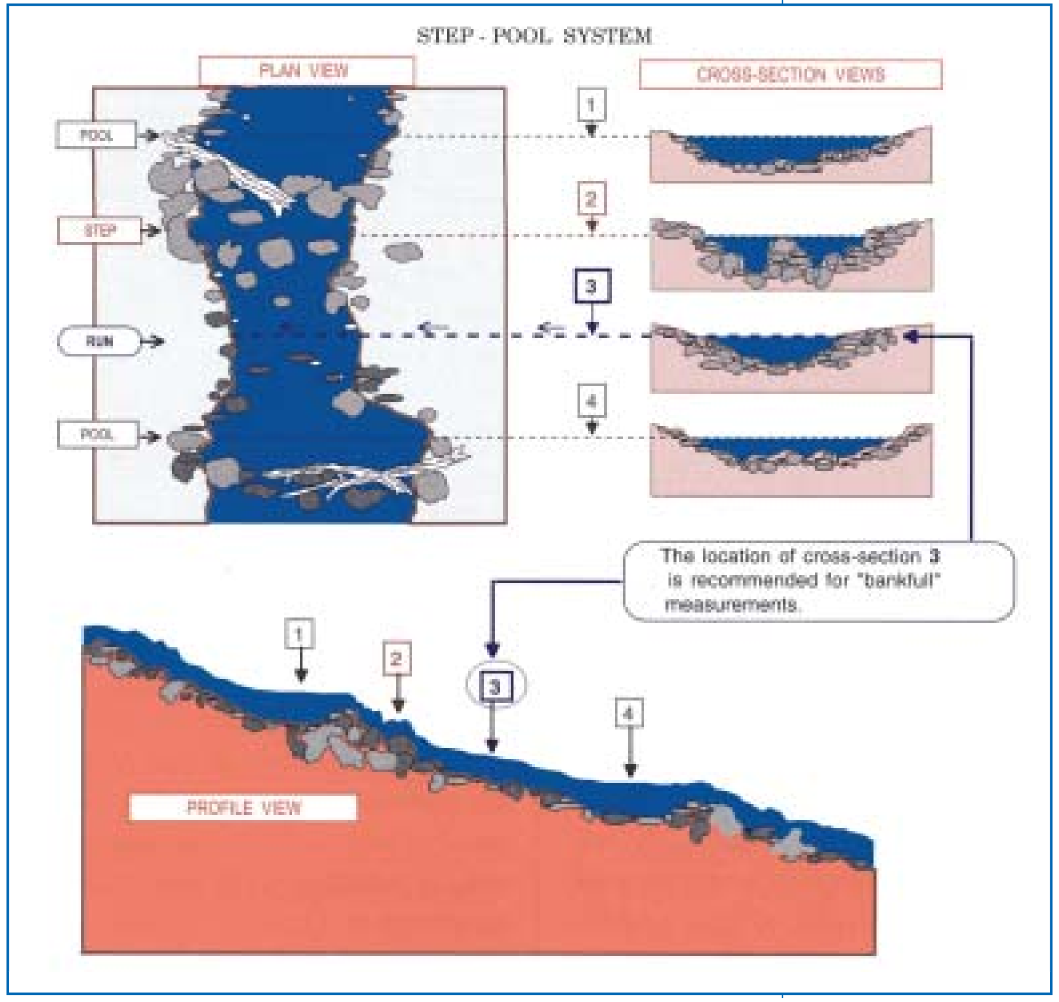
Natural streams have sequences of riffles and pools or steps and pools that maintain channel slope and stability. These features are shown in figures 1.7 and 1.8. The riffle is a bed feature that may have gravel or larger rock particles. The water depth is relatively shallow, and the slope is steeper than the average slope of the channel. At low flows, water moves faster over riffles, which removes fine sediments and provides oxygen to the stream. Riffles enter and exit meanders and control the streambed elevation. Pools are located on the outside bends of meanders between riffles. The pool has a flat surface (with little or no slope) and is much deeper than the stream's average depth. At low flows, pools are depositional features and riffles are scour features. At high flows, however, the pool scours and the bed material deposits on the riffle. This occurs because a force applied to the streambed, called shear stress, increases with depth and slope. Depth and slope increase rapidly over the pools during large storms, increasing shear stress and causing scour. Runs and glides are transitional features between riffles and pools. A run is the transitional feature between a riffle and a pool. A glide is the upward sloping area of the bed from the pool to the head of the riffle. (A flattening of the negative slope sometimes marks the start of the glide, but the glide usually begins where coarser materials have been deposited.) The inside of the meander bend is a depositional feature called a point bar, which also helps maintain channel form. Step/pool sequences are found in high-gradient streams. Steps are vertical drops often composed of large boulders, bedrock knick points, downed trees, etc. Deep pools are found at the bottom of each step. The step serves as a grade control, and the pool dissipates energy. The spacing of step pools shortens as the channel slope increases.

1.7. Biological Considerations of Stream Restoration

Stream restoration may be undertaken for a number of reasons, including to repair erosion problems or to improve fish and wildlife habitat. When the project is done correctly, using natural channel design, biological enhancements will always be a side benefit. This is because a natural channel design utilizes a reference reach, which provides a template for restoring a stable and biologically diverse stream channel *(see Chapter 6).* Biologically, stream channels include the area below bankfull as well as the floodplain. A restored stream reach should provide enhancements that are demonstrated at the reference reach. For example, establishing and protecting a vegetated buffer that includes all or part of the floodplain will provide a number of benefits. Trees and shrubs growing within the buffer will produce a root mass that

Figure 1.8

Location of features in a step-pool system
Rosgen, 1996, 5-10



will greatly increase bank stability. Leaves from these trees will shade the stream through the hottest part of the year, and when they drop in the fall, provide organic detritus that fuels food chains in lower-order streams. Riparian vegetation also provides food and hiding places for many wildlife species. Since stream corridors may be the only undeveloped areas within a watershed or the only linkage between woodlands, they are important travel routes for animals. The stems and root mass of the riparian vegetation benefit water quality by filtering sediment and other pollutants from surface and subsurface flow so these substances won’t enter the stream and harm aquatic organisms. Restoration projects should provide these benefits by replacing or enhancing riparian vegetation. Use of native plants is encouraged because they are less invasive and better for wildlife *(see Section 2.10).*

Restoration of proper dimension, pattern and profile will create a channel that moves water and sediment through the reach without causing aggradation or degradation. Restored streams enable the sorting of bed material, which results in habitat diversity. This is particularly important to such fish species as trout, which require clean gravel for reproduction. Sorting benefits aquatic organisms by providing stable habitats. In high-gradient streams, fish and other aquatic organisms use the space between gravel, cobble and boulders for resting and feeding. These sites provide an escape from swift currents higher in the water column. In many degraded streams the absence of pool habitat may limit gamefish populations. Structures used in natural channel design, such as vanes, cross-vanes, weirs and rootwads, create and maintain pool habitat, thereby improving the quality of the fishery *(see Chapter 8).* Restoration of the proper dimension will ensure that the stream is connected to the floodplain. As a result, riparian vegetation and other components that roughen the channel will mitigate damage from floodwaters. This guidebook provides examples of how to enhance the biological benefits of a restoration project *(see Chapter 8).*

1.8 Conclusions

A stream and its floodplain comprise a dynamic environment where the floodplain, channel and bedform evolve through natural processes that erode, transport, sort and deposit alluvial materials. The result is a dynamic equilibrium in which the stream maintains its dimension, pattern and profile over time, neither degrading nor aggrading. Land-use changes in the watershed, channelization, culverts, removal of streambank vegetation, impoundments and other activities can upset this balance. As a result, large adjustments in channel form, such as extreme bank erosion and/or incision, will happen. A new equilibrium may eventually result, but not before the associated aquatic and terrestrial environment are severely damaged. Understanding natural stream processes and applying this knowledge to stream-restoration projects will help create a self-sustaining stream with maximum physical and biological potential.

Chapter 2

Stream Assessment and Survey Procedures

Office Procedures

Field Procedures

Chapter 2: **Stream Assessment and Survey Procedures**

An existing-condition survey is an important first step in the stream assessment and restoration process. Data and information collected from the existing-condition survey are used to determine the stability of the project stream reach and the need for restoration. They also are used to determine the potential for restoration, and later they are essential to developing a restoration plan. The existing-condition survey is accomplished through a quantitative and qualitative investigation of the stream corridor and its watershed. A morphological investigation of the stream is a key component of the survey and includes assessment of channel dimension, pattern, profile and substrate materials. Data collected during the survey are used to determine if the stream is evolving toward stability or instability and if the cause of any instability is localized or system-wide (*see Chapter 3*). Examples of localized instability include removal of riparian vegetation and trampling of the streambanks by livestock or people. System-wide instability is often caused by channel incision, which causes headward erosion that continues upstream until it is stopped by a knick point.

At a minimum, the following steps should be completed for the existing-condition survey.

Office Procedures

2.1. Watershed Drainage Area Measurement

Delineate the project watershed boundary and calculate the drainage area. Most people use a geographic information system (GIS) with a topographic map layer such as the U.S. Geological Survey (USGS) digital line graphs *(Figure 2.1).* A topographic map and planimeter work fine as well. Depending on the length of the project reach, it may be necessary to calculate the drainage area at both upstream and downstream ends of the project.

2.2. Land-Use Survey

Complete a survey of land use in the watershed. This should include both historical (when available) and present land uses. Resources may include aerial photographs, topographic maps or zoning maps. As part of the survey, calculate the Natural Resource Conservation Service (NRCS) curve number and the percentage of impervious surface (roads, parking lots, etc.) in the watershed. The method for calculation is included in Appendix B. This information will help determine which curve—rural or urban — to use for bankfull verification *(see Appendix D for North Carolina regional curves)*.

Field Procedures

(Adapted from Harrelson, 1994)

2.3. Bankfull Identification

River Course Fact Sheet Number 3 *(Appendix A)* offers a stepwise procedure for verifying bankfull through development and use of regional curves. Complete and verify bankfull identification before proceeding with the existing-condition survey. Maintain the bankfull and inner-berm flags used in the bankfull identification procedure because they will be needed for the longitudinal-profile survey *(see Section 2.6).*

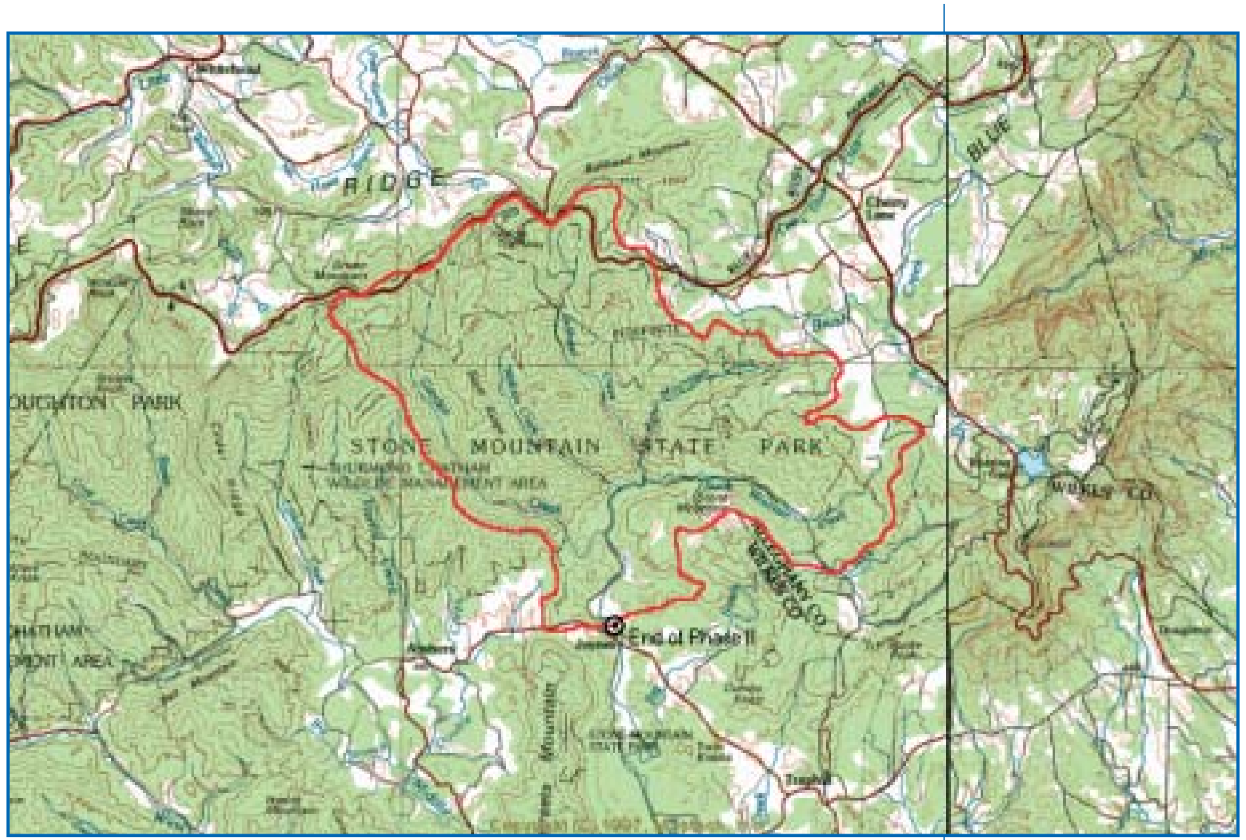


Figure 2.1

Watershed delineation for the East Prong of the Roaring River restoration project in Stone Mountain State Park, Wilkes and Alleghany counties, North Carolina

2.4. Dimension

The permanent cross section is the location for measuring channel dimensions (width, depth and cross-sectional areas), stream discharge, particle size distributions and other long-term work. Establish at least one permanent cross section over a riffle and another over a pool. Ideally, it is best to measure the dimension of several riffles and pools.

Step 1: Establish permanent markers for cross-section endpoints by driving a 4-foot-by-1/2-inch-diameter piece of rebar vertically into the ground, leaving one-half inch above the ground if it is acceptable to the landowner. Attach colored plastic caps to the top of the rebar for identification. Drive a wooden stake beside the rebar and mark the cross-section identification on the stake (usually the location of the cross section on the longitudinal survey, such as XSEC 4+05).

Step 2: Measure and note the cross-section endpoint locations with a tape. Triangulate between a benchmark, the nearest cross-section endpoint and another permanent feature, such as a large tree. Record the measurements in the field book so the cross section can be relocated for future surveys.

Step 3: Attach the zero end of the tape to the stake that is on the left when looking downstream (use a second piece of rebar or another stake to hold the tape). Stretch the tape so it is tight and level above the water from the left endpoint to the right endpoint.

Step 4: Set up the surveyor's level. Start with the surveyor's rod on the benchmark to establish the height of instrument (HI). Starting with the left endpoint stake as zero, begin the channel

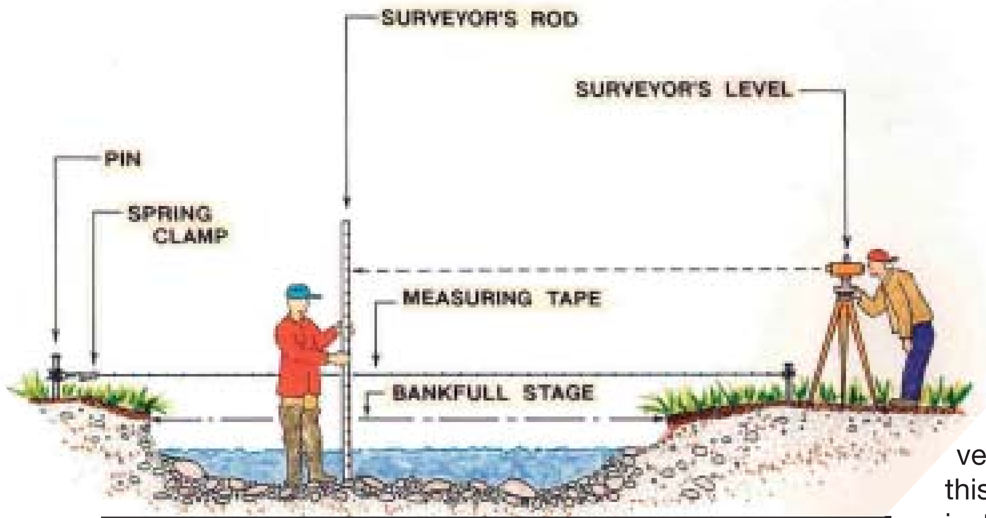


Figure 2.2

Example of surveyed cross section
Rosgen, 1996, 5-24

Figure 2.3

Cross-section survey

cross-section survey (left and right are always determined looking downstream). Record the rod reading for the top of the left pin and the ground at the left pin if they are different. Along the tape, shoot the elevation of each important feature and break in slope, such as top of bank, bankfull, inner berm, edge of water (water surface and ground) and thalweg. Note these features in the field book. For cross-section survey methods and examples of how to set up field-survey notes, see Harrelson, 1994 *(available for download at www.stream.fs.fed.us/PDFs/RM245.PDF).* Cross-section survey is shown in figures 2.2 and 2.3. Sample field data sheets are in Appendix B.

Step 5: Close the survey by setting the survey rod back on the benchmark and verifying that the foresight for this shot subtracted from the instrument height is equal to the known elevation of the benchmark.

Step 6: Calculate bankfull cross-sectional area for all riffles (A_{bkf}) and pools (A_{pool}) using the procedures outlined in River Course Fact Sheet Number 3 *(Appendix A).*

Step 7: Calculate bankfull width, W_{bkf}, as the horizontal distance between the left and right bankfull stations.

Step 8: Calculate mean depth, $D_{bkf}=A_{bkf}/W_{bkf}$.

Step 9: Calculate max depth, D_{max}, as the vertical distance between bankfull elevation and the thalweg elevation.

2.5 Pattern

Complete plan-form measurements—including sinuosity (K), meander wavelength (L_m), radius of curvature (R_c) and belt width (W_{blt})—using aerial photos if available *(figures 2.4, 2.5 and 2.6).*

Step 1: Measure sinuosity.

Sinuosity is a measure of how crooked a stream is. Specifically, it is the channel length divided by a straight-line valley length *(Figure 2.6).* The greater the number, the higher the sinuosity. Sinuosity is related to slope. Natural streams with steep slopes have low sinuosity, and streams with low slopes typically have high sinuosity. Sinuosity should be measured from large-scale aerial photographs; do not use topographic maps with scales of 1:24,000 or less.

Step 2: Measure radius of curvature at several meander bends.

Radius of curvature, $R_c=C^2/8M +M/2$, is the degree of curvature for an individual meander bend *(figures 2.7 and 2.8).*

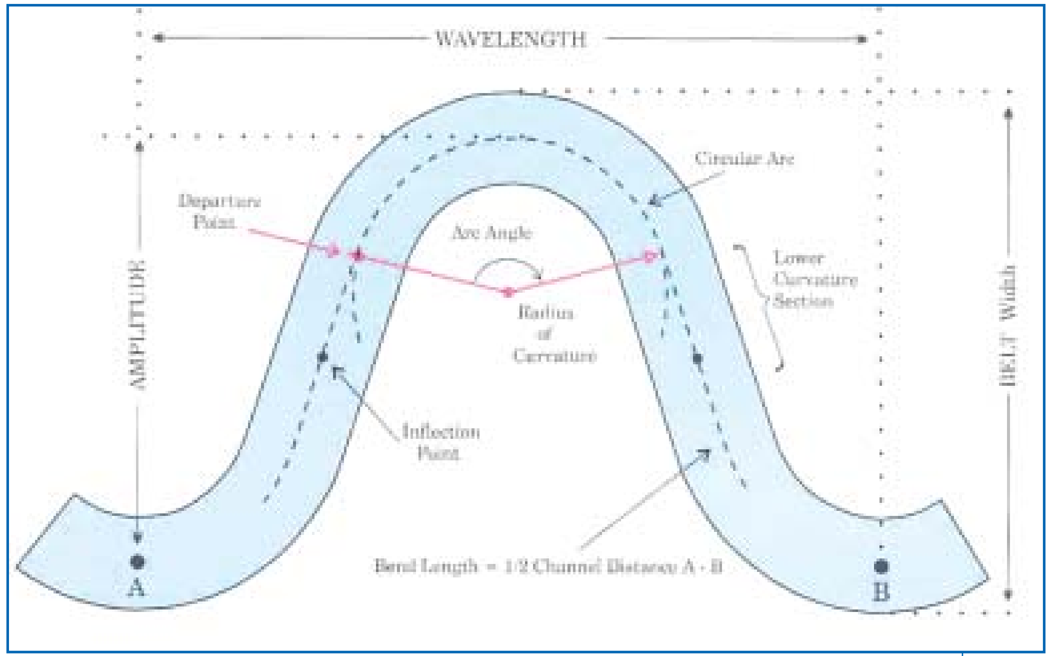


Figure 2.4

Pattern measurements of a meander bend
Rosgen, 1996, 2-6

Step 3: Measure channel belt width, W_{blt} *(figures 2.4 and 2.5).*

Belt width for a particular meander bend is the straight-line distance from the crest of the bend being evaluated to the crest of the next downstream bend. Overall belt width for a stream is the straight-line distance from the two outer-most bends of the channel.

Step 4: Measure meander wave-length, L_m *(figures 2.4 and 2.5).*

Meander wavelenth for a particular meander bend is the straight-line distance from the crest of the upstream meander to the next downstream meander.

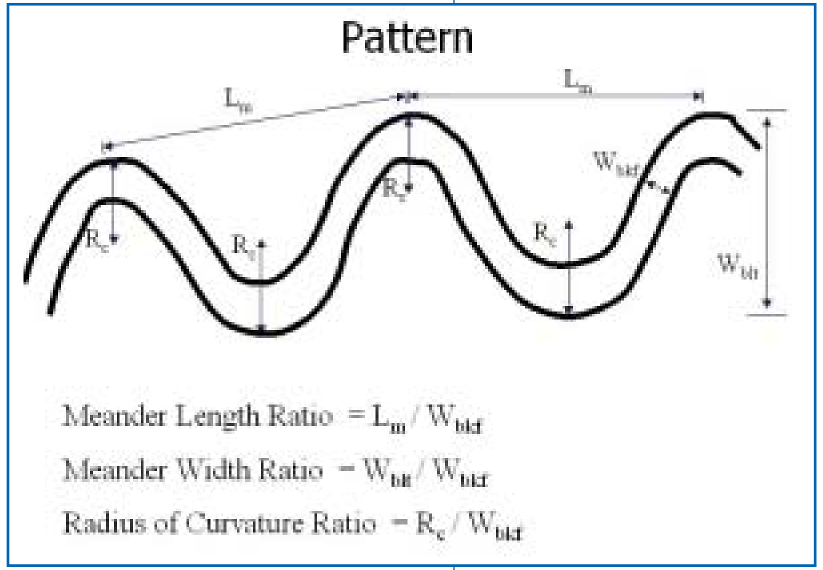


Figure 2.5

Plan-form measurements and dimensionless ratios

2.6. Profile

The longitudinal-profile survey establishes the elevation of the existing streambed, water surface, inner berm, bankfull, and top of bank or terrace features. It helps the designer determine and monitor the lengths, depths and slopes of all the stream features (or facets), including riffles, runs, pools and glides.

Step 1: Establish a benchmark for the project site. If possible use an existing USGS or Federal Emergency Management Agency (FEMA) benchmark. Permanent structures such as a concrete headwall or manhole cover also can be used. If permissible, install a permanent benchmark. Methods for establishing a benchmark are discussed in Harrelson, 1994 *(available for download at www.stream.fs.fed.us/PDFs/RM245.PDF).*

Step 2: Start the survey at a stable, upstream riffle and continue through the reach to a stable downstream riffle. The first station should be at the upstream edge (head) of the riffle. This point is the highest elevation of the riffle.

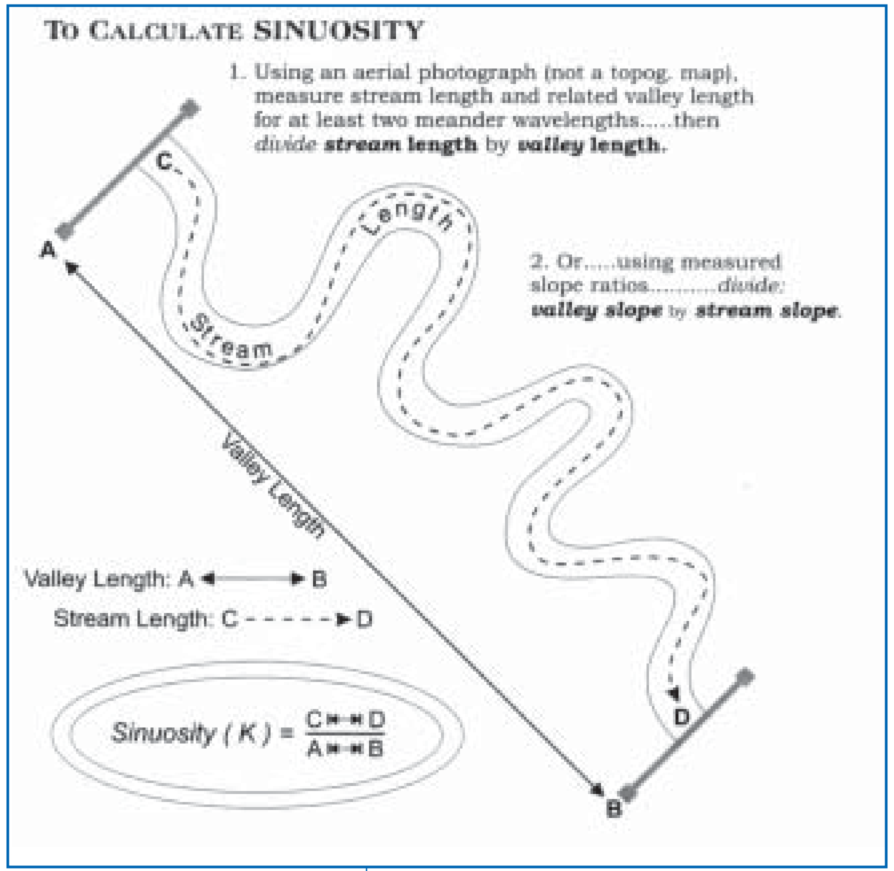


Fig. 2.6

Sinuosity measurement
Rosgen, 1998b, 211

Step 3: Set up the level so that the benchmark and as much of the site as possible are visible. This is a difficult task in North Carolina because of the dense vegetation. A lot of turning points may be necessary. The best survey locations often are in the channel, which usually means the survey instrument may be below the top of the streambank. In this case, use a hand level and survey rod to measure the distance between the survey instrument and the top of the bank. This distance is referred to as a negative foresight. When possible, set the instrument atop the bank or terrace and clear any limbs and leaves from the line of sight. Stretch a tape along the thalweg, starting at the upstream riffle. Make sure that the thalweg distance surveyed is at least 20 times the bankfull width or encompasses a minimum of two full meander wavelengths. If flags are not still in place from the bankfull identification, replace them for verification during the survey.

Step 4: Record the longitudinal station from the tape, then use the level to read a foresight for the thalweg, water surface, inner berm (if present), bankfull and top of the low bank. Collect this data at the head of every feature (riffle, run, pool and glide) and the maximum pool-depth location. Note the channel feature associated with the longitudinal station, i.e., riffle, run, pool or glide. See Harrelson, 1994 *(available for download at www.stream.fs.fed.us/PDFs/RM245.PFD)* for longitudinal-survey methods and examples of how to set up field-survey notes. Sample field data sheets are in Appendix B. Be sure to collect information for each bed feature. For a long feature such as a riffle or run, take a measurement at least every bankfull width.

Step 5: Once the longitudinal survey is finished, close the survey back to the benchmark. The longitudinal profile data will allow calculation of the length and slopes for all the stream features.

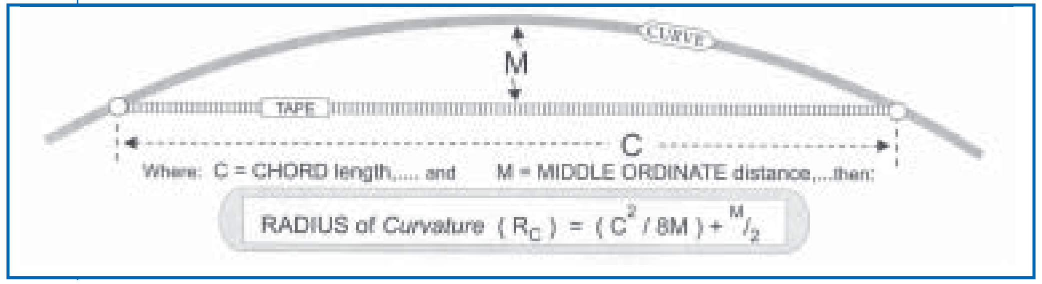


Figure 2.7

Radius of curvature
Rosgen, 1998b, 186

2.7. Substrate Analysis

The composition of the streambed and banks is an important facet of stream character. It influences channel form and hydraulics, erosion rates, sediment supply and other parameters. Each permanent reference site should include a basic characterization of bed and bank material. For more information on substrate sampling, see Bunte and Abt, 2001 *(Section 13.3)*. *You may download this report, RMRS-GTR-74, from the U.S. Forest Service's Rocky Mountain Research Station Web site, http://www.fs.fed.us/rm/main/pubs/electronic/rmrs_gtr.html.* Studies of fish habitat, riparian ecosystems or stream hydraulics may require more detailed characterization of substrates and bank materials than is provided in this manual. *See papers by Dorava (2001), Gore (1988), Merritt (1984), Frothingham (2001), Montgomery (2001) and Statzner (1988) referenced in Section 13.3.*

The composition of the streambed (substrate) influences how streams behave. Steep mountain streams with beds of boulders and cobbles act differently than low-gradient streams with beds of sand or silt. This difference may be documented by a quantitative description of the bed material called a pebble count.

There are three methods of pebble counts, each with different purposes. The first and most efficient method, a reachwide pebble count (developed by Wolman, 1954, and modified by Rosgen, 1996), samples a total of 100 pebbles from cross sections throughout the longitudinal reach of the stream. This count is used for stream classification. The second method samples 100 pebbles at a single cross section. This is for cross-section analysis. The third method also samples 100 pebbles at a riffle, but includes only the pebbles from the wetted perimeter (anywhere the water is in contact with the channel bed) at normal flow. This count is used to calculate entrainment and velocity.

Figure 2.8

Field measurement of radius of curvature

- **Reachwide characterization of the substrate (Wolman Pebble Count)**

Step 1. This technique requires two people—an observer with a metric ruler to wade the stream and a note-taker to wade or remain on the bank with a notebook. For stream characterization, sample pools and riffles in the same proportion as they occur in the study reach. Once the longitudinal profile is complete, compute the percentage of the total length of the profile that is riffle/run and the percentage that is pool/glide. For example, the reach may be 60 percent riffle/run and 40 percent pool/glide. Use these percentages to determine the number of samples to take from these features. If six riffles exist in the longitudinal profile, sample 10 pebbles (left bankfull to right bankfull) at each riffle. This will give a total of 60 pebbles in riffles, or 60 percent of the 100 pebbles sampled from the entire reach. Similarly, collect 40 pebbles from the pools. At each riffle and pool, sample the particles in a transect perpendicular to the flow of water, working from left bankfull to right bankfull. Averting the eyes, pick up the first particle touched by the tip of an index finger at the toe of a wader.

Step 2. Measure the intermediate axis of each particle collected *(Figure 2.9).* Measure embedded particles or those too large to be moved in place by using the smaller of the two exposed axes. Call out measurements for the note-taker to tally by size class. Sample pebble count data sheets are in Appendix B.

Step 3. Take one step across the channel in the direction of the opposite (right) bank and repeat the process, continuing to pick up particles until the requisite number of measurements is taken. The note-taker should keep count. Traverse the stream perpendicular to the flow. Continue to an indicator of bankfull stage on the opposite bank so that all areas between the bankfull elevations are representatively sampled. If necessary, duck under vegetation or reach through brush to get an accurate count. Move upstream or downstream to appropriate features (riffles or pools) and make additional transects to sample at least 100 particles.

After counts and tallies are complete, plot the data by size-class and frequency. Figure 2.10 is an example of a pebble-count form. A sample pebble count plot is shown in Figure 2.11.

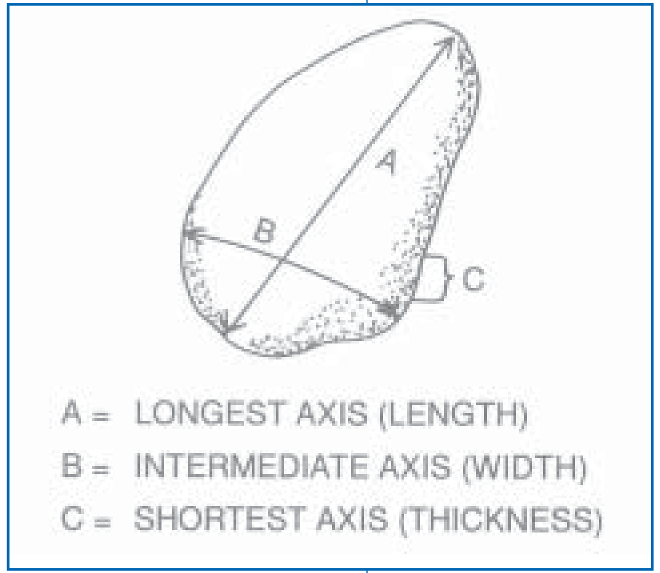


Figure 2.9

Different axes of a pebble
Harrelson, et al., 1994, 50

- **Cross-section analysis of the substrate**

Step 1. For cross-section characterization, sample pools and riffles separately with 100 counts per feature. Sample the pebbles at the cross section, moving from left bankfull elevation to right bankfull elevation, sampling at intervals that will equal 100 counts across the bankfull width of the stream. For example, if the bankfull width of the stream is 50 feet, sample a pebble every six inches to equal 100 samples.

Step 2. Follow Step 2, Reachwide Characterization.

Step 3. Follow Step 3, Reachwide Characterization (disregard last sentence in first paragraph).

- **Wetted Perimeter Cross-Section Substrate Analysis**

Step 1. Collect 100 pebbles from a riffle cross section, zigzaging from the left water's edge to the right water's edge at normal flow.

Step 2. Follow Step 2, Reachwide Characterization.

Step 3. Take a step forward and collect a pebble, then take a step backward to collect a pebble, moving across the channel in a direction perpendicular to the flow. Repeat the process, continuing to pick up particles until the requisite number of measurements is taken. The note-taker should keep count. Continue traversing the stream until all areas between the left and right edges of water are representatively sampled.

2.8 Bar, Pavement and Subpavement Sampling Methods and Scour Chains

- **Bar Sample**

Step 1. Collect a bar sample from the lower (downstream) third of a well-developed point bar in the stream. If significant bank erosion or watershed disturbance has caused sedimentation of the lower third of the bar, sample the middle of the bar.

Step 2. Place a 5-gallon bottomless bucket on the lower third of the bar, halfway between the thalweg and the bankfull elevation. Place the bucket in an area that contains a representative grouping of the maximum particle sizes found on the lower third of the bar. Remove the two largest particles from the surface covered by the bottomless bucket. Measure and record the intermediate axis (median diameter) and weigh the particles individually. The largest particle obtained from the bar is the d_i.

Step 3. Push the bottomless bucket into the bar material. Excavate the material within the sample area to a depth equal to twice the length of the intermediate axis of the d_i. Place these materials in a bucket or bag for sieving and weighing. *For fine bar material:* Push the bottomless bucket into the bar material. Excavate the material within the sample area to a depth of 4 to 6 inches. Place these materials in a separate bucket or bag for sieving and weighing.

Step 4. Wet-sieve the collected bar materials, using a standard sieve set with a 2-millimeter screen size for the bottom sieve. (The standard sieve set should include the following sizes in millimeters: 2, 4, 8, 16, 32, 64, 128 and 256.) Place a bucket below the 2-millimeter sieve to catch the smaller material. (Materials in the 256-512 millimeter range should be measured and weighed individually rather than sieved.) Weigh the sieved materials and record weights (less tare weight) by size-class. Weigh the bucket with fine materials after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand and fine material. Include the individual intermediate axis widths and weights of the two largest particles that were collected.

Step 5. Determine a material size-class distribution for all of the collected materials. The data represent the range of channel materials subject to movement or transport as bed-load sediment materials at bankfull discharge.

Step 6. Plot the cumulative frequency of each sediment-size-range fraction. From the cumulative frequency plot, determine size-class indices, i.e., d_{16}, d_{35}, d_{50}, d_{84} and d_{95}. The d_{100} should represent the actual intermediate axis width of the largest particle when plotted. The intermediate axis measurement of the largest particle will be the top end of the catch range for the last sieve that retains material. *Note:* $d_{100}=d_i$.

Figure 2.10 Pebble count field-data form (Rosgen, 1996)

Pebble Count										Pebble Count			Pebble Count		
Site:			Date:							Date:			Date:		
Party:			Reach:							Reach:			Reach:		
INCHES	PARTICLE	MILLIMETERS		PARTICLE COUNT			TOTAL#	ITEM %	%CUM	TOTAL#	ITEM %	%CUM	TOTAL#	ITEM %	%CUM
	SILT/CLAY	< .062	S/C	1	2	3									
	Very Fine	.062 – .125	S												
	Fine	.125 – .25	A												
	Medium	.25 – .50	N												
	Coarse	.50 – 1.0	D												
.04 – .08	Very Coarse	1.0 – 2	S												
.08 – .16	Very Fine	2 – 4													
.16 – .24	Fine	4 – 6	G												
.24 – .31	Fine	6 – 8	R												
.31 – .47	Medium	8 – 12	A												
.47 – .63	Medium	12 – 16	V												
.63 – .94	Coarse	16 – 24	E												
.94 – 1.26	Coarse	24 – 32	L												
1.26 – 1.9	Very Coarse	32 – 48	S												
1.9 – 2.5	Very Coarse	48 – 64													
2.5 – 3.8	Small	64 – 96	C												
3.8 – 5.0	Small	96 – 128	O												
5.0 – 7.6	Large	128 – 192	B												
7.6 – 10	Large	192 – 256	L												
10 – 15	Small	256 – 384	B												
15 – 20	Small	384 – 512	L												
20 – 40	Medium	512 – 1024	D												
40 – 160	Lrg-Very Lrg	1024 – 4096	R												
	BEDROCK		BDRK												
					TOTALS										

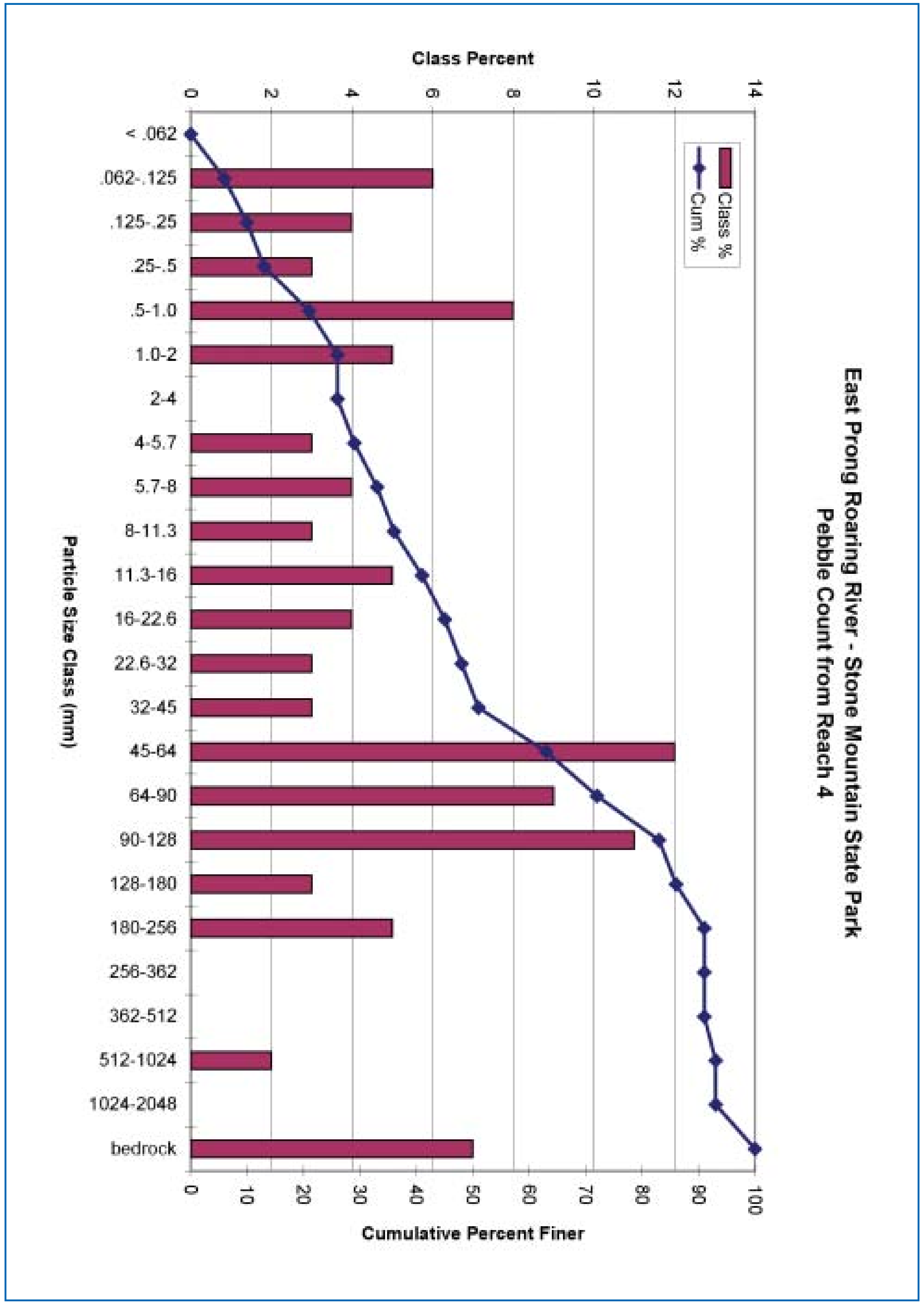


Figure 2.11 Sample pebble count cumulative frequency plot

- **Pavement Sample**

Step 1. To sample the pavement of the stream, select a representative riffle that has been surveyed in cross section. To define the sampling area, use a bottomless 5-gallon bucket to isolate a section of the riffle that is the most depositional. Locate the sample in the coarsest part of the riffle but not in the thalweg.

Step 2. Push the bucket into the riffle, being sure to eliminate flow of water through the sample area.

Step 3. Carefully remove the top veneer (surface layer only) of the particles within the sample area by picking the particles off the top, smaller particles first. Continue removing the small and then the large particles, working from one side of the sample area to the other. Weigh the largest and second largest particles and measure the length of their intermediate axes. Place the pavement material in a bag or bucket for sieving and weighing.

- **Subpavement Sample**

Step 1. Collect the subpavement sample beneath the pavement sample. The bucket should continue to define the boundaries of the sampling area. Excavate and remove the material below the pavement sample to a depth equal to twice the intermediate axis of the largest particle that was collected from the pavement sample. If an armored layer is reached, do not continue to excavate below this layer, even if a depth equal to twice the median diameter of the largest particle in the pavement layer has not been reached. Place all subpavement sample material in a separate bucket or bag for weighing and sieving. The subpavement sample is the equivalent of the bar sample; therefore, the largest particle from the subpavement sample is used in lieu of the largest particle from the bar sample for entrainment calculations (see Section 7.2). *Note: If larger particles are collected from the subpavement than from the pavement layer, discard the sample and select a new sampling location.*

Step 2. Wet-seive both the pavement and subpavement samples separately using a standard sieve set with a 2-millimeter screen size for the bottom sieve. (The standard sieve set should include the following sizes in millimeters: 2, 4, 8, 16, 32, 64, 128 and 256.) Place a bucket below the 2-millimeter sieve to catch the smaller material. (Materials in the 256-512 millimeter range should be measured and weighed individually rather than sieved.) Weigh and record each sieve fraction (less the tare weight). Weigh the bucket with fine materials after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand and fine material. Include the intermediate axis widths and weights of the two largest particles collected from the pavement and the largest collected from the subpavement.

Step 3. Determine size-class distribution for the materials by plotting the cumulative frequency of each fraction. From the cumulative frequency plot, determine size-class indices, i.e., d_{16}, d_{35}, d_{50}, d_{84}, d_{95}, for both the pavement and subpavement samples. The d_{100} should represent the actual intermediate axis width of the largest particle when plotted. The intermediate axis measurement of the largest particle will be the top end of the catch range for the last sieve that retains material. *Note:* $d_{100}=d_i$.

- **Scour Chains**
  Scour chains installed in the bed of the stream can measure the depth of scour or bed deposition. Bulk substrate samples collected in conjunction with scour-chain monitoring can help characterize bed material. Bury scour chains in the stream at a permanent cross-section riffle, with the chain extending vertically through the stream substrate. Include the location of the chain in the cross-section survey data so it can be found later. Place the top of the chain level with the existing streambed surface. When a bankfull or other sediment-transporting flow passes through the stream, material will be lifted off the bed, transported and deposited farther downstream.

The scour chain will be folded over in the downstream direction at the depth to which the bed material was scoured and newly deposited during the flow. To measure the depth of scour (length of chain from the top to the point where the chain was folded over), dig through the newly deposited material to the chain. If deposition (or aggradation), rather than scour, has occurred, the chain will remain in a vertical position, concealed by the deposited sediment load. To obtain a scour-chain substrate sample:

Step 1: Place a 5-gallon bottomless bucket over the location of the chain prior to excavating. The bucket will define the substrate sampling area.

Step 2: Collect a pavement and subpavement sample over the chain. For the subpavement sample, continue to excavate down to the chain (rather than to the depth equal to twice the intermediate axis of the largest particle found on the pavement).

2.9. Estimating Bankfull Discharge and Velocity

Discharge is the volume of water flowing through a stream channel cross section per unit time. If the stream has a USGS gage, use the stage-discharge rating table to determine the discharge for the specific elevation of the field-determined bankfull stage (see Chapter 4 for more information on gage-station analyses). However, most stream reaches are not gaged, so it probably will be necessary to estimate the bankfull discharge and velocity using other methods. Bankfull discharge, Q_{bkf}, can be estimated using Equation 1, which is Manning's equation *(Chow, 1959)*.

$$Q = \left(\frac{1.49AR^{2/3}S^{1/2}}{n}\right) \qquad \text{Equation (1)}$$

Where:
Q = Discharge (cfs)
R = Hydraulic Radius of the riffle cross-section at bankfull stage (ft)
s = Average Channel Slope (ft/ft)
n = Manning's Roughness Coefficient

Hydraulic Radius is determined using equation 2:

$$R = \frac{A}{WP} \qquad \text{Equation (2)}$$

Where:
WP = Wetted Perimeter of the channel bottom at bankfull stage (ft)
A = Cross-Sectional Area of the riffle at bankfull stage (sq. ft.)

Cross-Sectional Area and Wetted Perimeter can be calculated using the cross-section survey data. Wetted Perimeter, WP, can also be approximated using equation 3. Equation 3 assumes a rectangular channel shape.

$$WP = 2D + W \qquad \text{Equation (3)}$$

Where:
D = Average Bankfull Depth of the riffle cross-section (ft)
W = Bankfull Width at the riffle (ft)

Manning's Roughness Coefficient can be estimated by using Chow's coefficients for various channel substrate and vegetation characteristics (1959). Velocity, v, can then be determined using the Continuity Equation (Equation 4):

$$V = \frac{Q}{A} \qquad \text{Equation (4)}$$

Where:
V = Bankfull Velocity (fps)
Q = Bankfull Discharge (cfs)
A = Bankfull Cross-Sectional Area at the riffle cross-section (sq. ft.)

2.10 Assessing Riparian Condition

Compose a general description of the topography or prominent topographic features in the floodplain, as well as soil texture and type. Important features may include ditches, old crop rows, sloughs and pools, wetlands, knolls or steep banks. Note the length and width of the valley. If the project is in an urban setting, note obvious constraints, such as location of utilities, structures and roads.

Examine and describe soils throughout the floodplain. County soil-survey classifications are useful in preparing descriptions. During this initial assessment, appropriate labs, including the N.C. Department of Agriculture (NCDA) Agronomic Division's soil-testing lab, can perform soil-fertility tests. This information will help determine the nutrient needs of vegetation planted at the project site. An example of a soil-sample form is found in Appendix H.

Next, take a plant inventory. Note the type, size and relative abundance of each species in the project area. Also note and flag potential vegetation for transplanting. Utilizing on-site vegetation that might otherwise be destroyed by construction is an excellent way to save money and to maintain locally adapted plant ecotypes. Note invasive and exotic plants that occur within the project area. Throughout much of North Carolina, streambanks and floodplains are infested with invasive and exotic plants that include kudzu *(Pueraria lobata)*, English ivy *(Hedera helix)*, Chinese privet *(Ligustrum sinense)* and multiflora rose *(Rosa multiflora)*. This vegetation can outcompete native riparian plants, leading to a decrease in wildlife habitat and food diversity along the streambanks. Also, non-native vegetation often is less nutritious for native fauna. If invasive exotic plants inhabit the project area, take measures to control them before restoring native vegetation.

Chapter 3

Rosgen Stream-Classification System/ Channel Assessment and Validation Procedures

Chapter 3: **Rosgen Stream-Classification System/Channel Assessment and Validation Procedures**

The Rosgen stream-classification system categorizes streams based on channel morphology so that consistent, reproducible and quantitative descriptions can be made. Through field measurements, variations in stream processes are grouped into distinct stream types. Rosgen (1996) lists four specific objectives of stream classification:

1. To predict a stream's behavior from its appearance.
2. To develop specific hydraulic and sediment relationships for a given stream type.
3. To provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics.
4. To provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties.

The Rosgen stream classification consists of four levels of detail ranging from broad qualitative descriptions to detailed quantitative assessments. Figure 3.1 shows the hierarchy (Levels I through IV) of the Rosgen classification inventory and assessment. Level I is a geomorphic characterization that categorizes streams as "A," "B," "C," "D," "DA," "E," "F" or "G." Level II is called the morphological description and requires field measurements. Level II assigns a number (1 through 6) to each stream type that describes the dominant bed material based on the d_{50} of the reachwide pebble count. Level III is an evaluation of the stream condition and its stability; it requires an assessment and prediction of channel erosion, riparian condition, channel modification and other characteristics. Level IV is the verification of predictions made in Level III and consists of sediment transport, stream flow and stability measurements.

A hierarchical key to the Rosgen stream-classification system is shown in Figure 3.3. Use the steps outlined in Level II *(Section 3.2)* to determine the Rosgen classification for the project stream.

3.1 LEVEL I

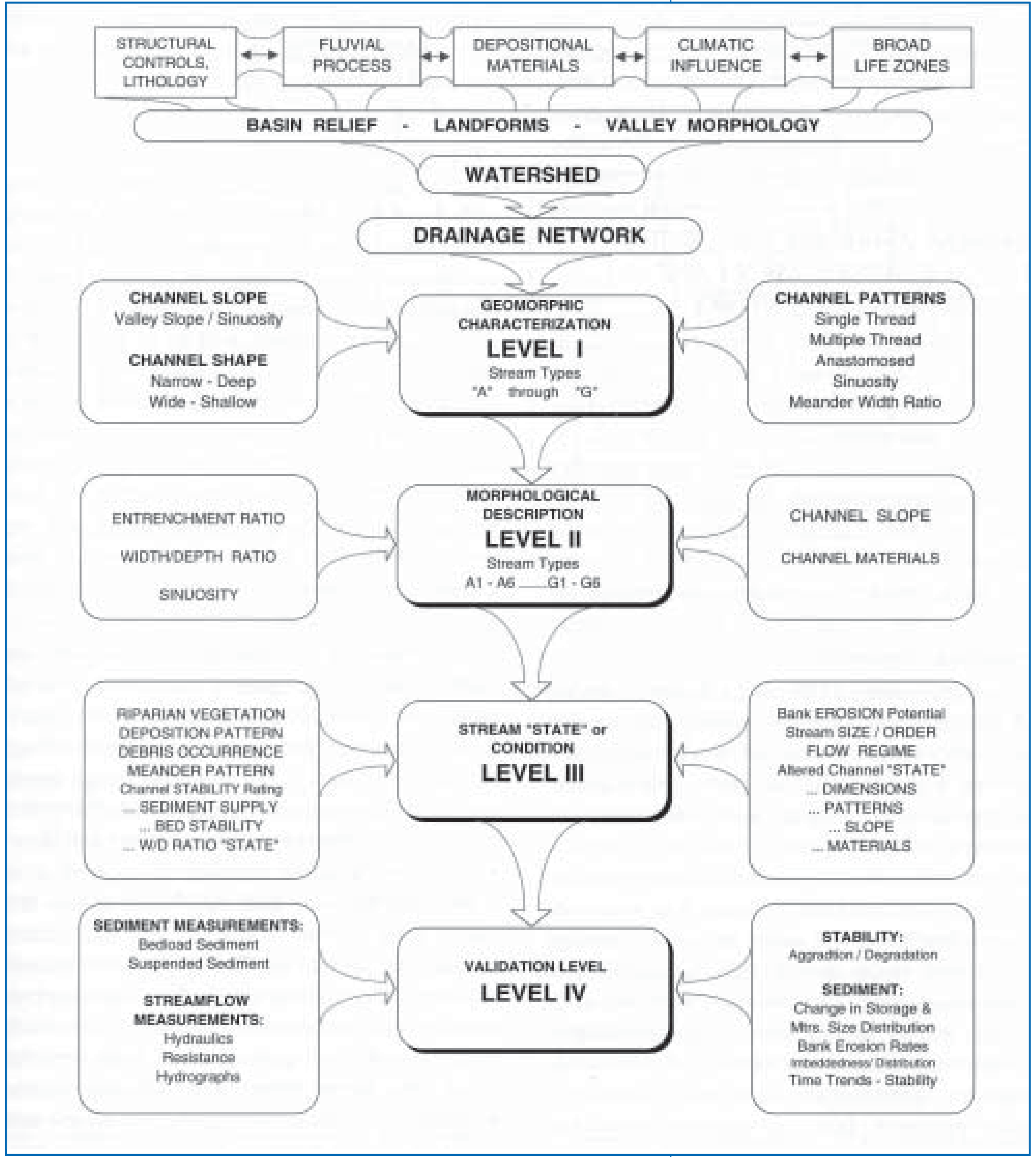
Level I is a broad-level description of Rosgen's major stream types *(Figure 3.2)*. This description is based on general map and visual assessment of valley types; landforms; and the stream's shape, slope and channel patterns. Valley morphology has a profound influence on stream type *(See Rosgen 1996, Chapter 4)*.

3.2 LEVEL II

Step 1. Determine single or braided channel. A braided channel consists of three or more distinct channels. Anything less is considered a single channel. The only stream types for braided channels are "D" and "DA." Single or braided channel determination can be made from aerial photograph or field observation.

Figure 3.1

Classification inventory and assessment
Rosgen, 1996, 3-5



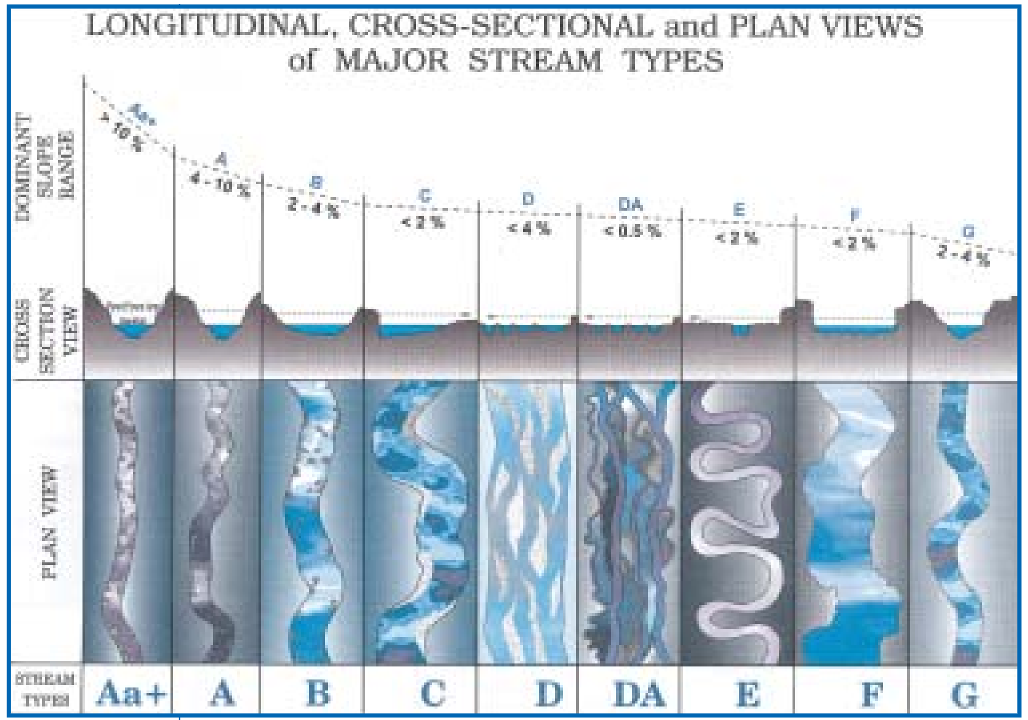


Figure 3.2

Broad-level stream classification delineation showing longitudinal, cross-sectional and plan-views of Rosgen's major stream types
Rosgen, 1996, 4-4

Step 2. Calculate entrenchment ratio. The entrenchment ratio is a field measurement of channel incision. Specifically, it is the flood-prone width divided by the bankfull width. The flood-prone width is measured at the elevation of twice the maximum depth of the channel at bankfull *(Figure 3.4)*. Lower entrenchment ratios indicate channel incision; large entrenchment ratios indicate a well-developed floodplain. An example of this measurement is shown in Figure 3.4. The following stream types are entrenched (low entrenchment ratio): "A," "F" and "G."

2a: *Obtain a rod reading for an elevation at the max (bankfull) depth location at a riffle.*

2b: *Obtain a rod reading for an elevation at the bankfull stage location.*

2c: *Subtract the Step 2 reading from the Step 1 reading to obtain a max (bankfull) depth value; then multiply the max depth value times 2 for the 2x max depth value.*

2d: *Subtract the 2x max depth value from the Step 1 reading for the Flood-prone Area (FPA) location rod reading. Move the rod upslope, online with the cross section, until a rod reading for the FPA location is obtained.*

2e: *Mark the FPA locations on each bank. Measure the distance between the two FPA locations.*

2f: *Determine the distance between the two bankfull stage locations.*

2g: *Divide the FPA width by the bankfull width to calculate the entrenchment ratio.*

Step 3. Calculate width-to-depth ratio. The width-to-depth ratio is a field measurement of the bankfull width divided by the mean bankfull depth. To calculate width-to-depth ratio, first determine the bankfull cross-sectional area and average bankfull depth *(see River Course Fact Sheet Number 2, Appendix A)*. The bankfull

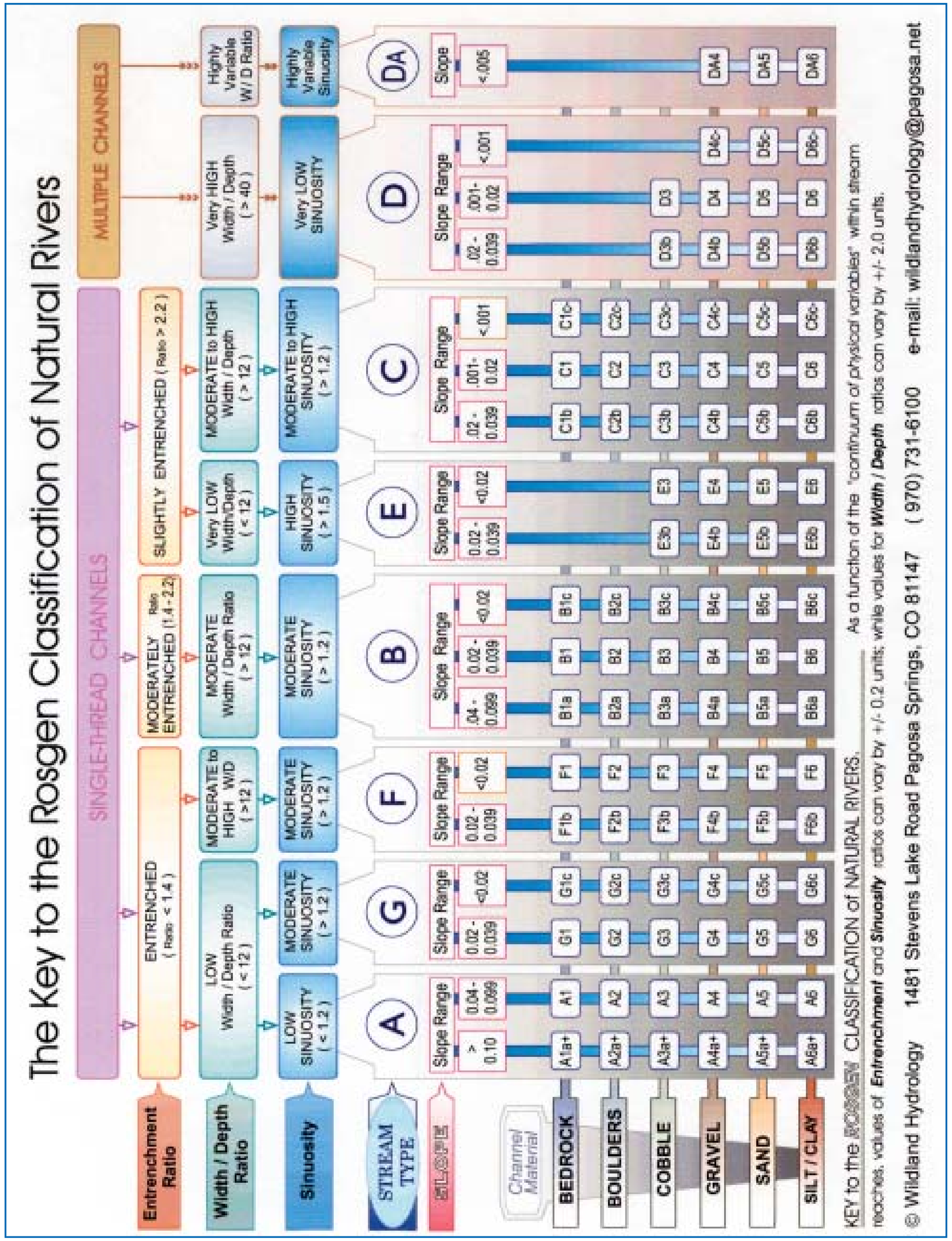


Figure 3.3

Rosgen classification of natural rivers
Rosgen, 1996

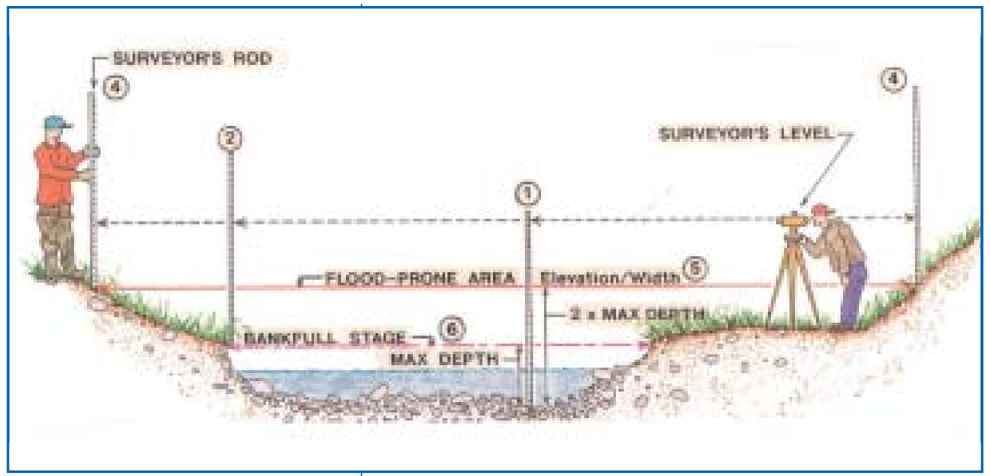


Figure 3.4

Measurement technique for flood-prone area and entrenchment ratio
Rosgen, 1996, 5-20

average depth is the cross-sectional area (A_{bkf}) divided by the bankfull width (W_{bkf}). The primary break between various stream types in the Rosgen classification system is 12, meaning that the bankfull width is 12 times greater than the mean bankfull depth. Stream types with width-to-depth ratios greater than 12 are "B," "C" and "F." Stream types less than 12 are "A," "E" and "G." The "D" stream types have a width-to-depth ratio greater than 40, and the "DA" stream types have less than 40.

Step 4. Determine sinuosity *(see section 2.5).*

Step 5. Measure water-surface slope. Measure the water surface from the top of one riffle to the top of another at least 20 bankfull widths downstream. This can be done using the data collected from the longitudinal-profile survey *(Section 2.6).* The channel slope is calculated by dividing the difference in elevation between the water surface at the most upstream head-of-riffle and the most downstream head-of-riffle by the length of the channel between the two riffles, as measured along the thalweg. This is considered the average slope. "A" and "B" stream types have the steepest slopes, and "E" and "DA" stream types have the lowest. However, slope varies greatly among stream types.

Step 6. Determine median size of the bed material. A pebble count is used to determine the median particle size, or d_{50}, of the bed material. The d_{50} means that 50 percent of the material is smaller and 50 percent is larger. First, conduct a reachwide pebble count by collecting 100 pebbles from a stream reach with a minimum of 20 bankfull widths *(see Section 2.7).* A cumulative frequency plot of the particle-size distribution will provide the d_{50}. The d_{50} will provide the Level II classification as shown in Table 3.1.

Material	Classification	Size Range (mm)
Bedrock	1	>2,048
Boulder	2	256-2,048
Cobble	3	64-256
Gravel	4	2-64
Sand	5	0.062-2
Silt/Clay	6	<0.062

Table 3.1 Substrate Material Classification

3.3 LEVEL III

Restoration projects often fail because the designers did not incorporate the existing and future channel morphologies into the design. As mentioned in Chapter 2, data and information collected from the existing-condition survey are used to determine the stability of the project stream reach, the need for restoration and the potential for restoration (if needed). Therefore, it is imperative that the designer complete morphological analyses upstream and downstream of the project reach. Data collected during the existing-condition survey are used to determine if the stream is moving toward stability or instability and if the cause of instability is localized or streamwide.

Watershed-Scale Instability

Various factors can disrupt the equilibrium of a watershed. In North Carolina, modification of the channel (channelization) and development of the watershed are the most common causes of watershed-scale instability. The designer must address these factors before installing bank-stabilization or habitat-improvement structures. During watershed-scale adjustments, channel evolution usually progresses from downstream to upstream. For example, an incised stream might have a downstream reach that is developing a new floodplain at a lower elevation. The rate of bank erosion decreases as the channel dimension, pattern and profile become stable for the given slope and drainage area. However, the disturbance can have effects that move upstream (in the form of a head-cut), causing degradation, widening and deposition.

Local (Reach)Instability

Local, or reach, instability refers to erosion and deposition processes not caused by instability in the watershed. Perhaps the most common form of local instability is erosion along the outside bank in a meander bend. Local instability also can occur in isolated locations as the result of channel constriction, flow obstructions (ice, debris, structures, etc.), trampling by livestock or geotechnical instability (high banks, loss of riparian vegetation, soil structure, etc.). Local instability problems usually respond to local bank-protection measures, but stabilization treatment should begin and end at stable riffles.

Channel Stability Assessment

Rosgen's stream-channel assessment methodology includes a field assessment of the following variables:

- Stream-channel condition or "state" categories
- Vertical stability—degradation/aggradation
- Lateral stability
- Channel pattern
- River profile and bed features
- Channel dimension relations
- Stream channel scour/deposition potential (sediment competence)
- Dimensionless ratio sediment-rating curves
- Channel evolution

For more information, see Rosgen, 2001b (Section 13.1), available for download at www.wildlandhydrology.com.

Channel Evolution

A common sequence of physical adjustments happens in many streams following a disturbance. This adjustment process is often referred to as channel evolution. Disturbance can result from channelization, urbanization, removal of streamside vegetation or other changes that negatively affect stream stability. Several models have been used to describe this process of physical adjustment. Two models *(Schumm et al., 1984 and Simon, 1989, 1995)* are most widely accepted *(Figure 3.5 and Table 3.2).*

According to Simon's channel-evolution model, the channel evolution process is initiated once a stable, well-vegetated stream that frequently interacts with its floodplain is disturbed. Disturbance commonly results in an increase in stream power that causes degradation, often referred to as channel incision. Incision eventually leads to oversteepening of banks; when critical bank heights are exceeded, the banks begin to fail and mass wasting of soil and rock leads to channel widening. Incision and widening continue upstream. Eventually the mass wasting slows and the stream begins to aggrade. A new low-flow channel begins to form in the sediment deposits. By the end of the evolutionary process, a stable stream with a dimension, pattern and profile similar to those of undisturbed channels forms in the deposited alluvium. The new channel is at a lower elevation than its original form with a new floodplain constructed of alluvial material. The old floodplain has now become a dry terrace *(FISRWG, 1998)*.

Channel-evolution models can illustrate the current trends in a disturbed or constructed channel and show the direction in which they are moving *(Figure 3.6)*. Evaluate the current stage of evolution for the project stream before selecting the appropriate restoration actions.

Streambank Erosion

Streambanks can be eroded by collapse or by moving water. Collapse or mass failure occurs when the bank is too weak to resist gravitational forces. Banks that are collapsing or about to collapse are referred to as being geotechnically unstable. The physical properties of the streambank should be evaluated to determine potential stability problems and to identify the dominant sources of bank instability. Factors to consider include bank height, bank angle, surface protection, soil material and soil stratigraphy. Whenever possible, the streambank-stabilization measure should reconstruct the bank so that bankfull is the top of the bank. This often means building a bankfull bench *(Figure 3.8).*

Shear stress is a measure of the force of water against the channel boundary (i.e., bed and banks) of the stream. Determining mean shear stress and critical dimensionless shear stress provides a means for evaluating the stress required to entrain and move sediment in a stream. Changes to the stream that increase slope or water depth can increase shear stress, thus increasing erosion of the banks and bed. Evaluation of shear stress and sediment transport are discussed in Section 7.2. Whether streambank erosion is a localized problem or part of a larger restoration project, restoring the proper dimension, pattern and profile and installing root wads and rock vanes can stabilize the streambanks. The role of in-stream structures is discussed further in Chapter 8.

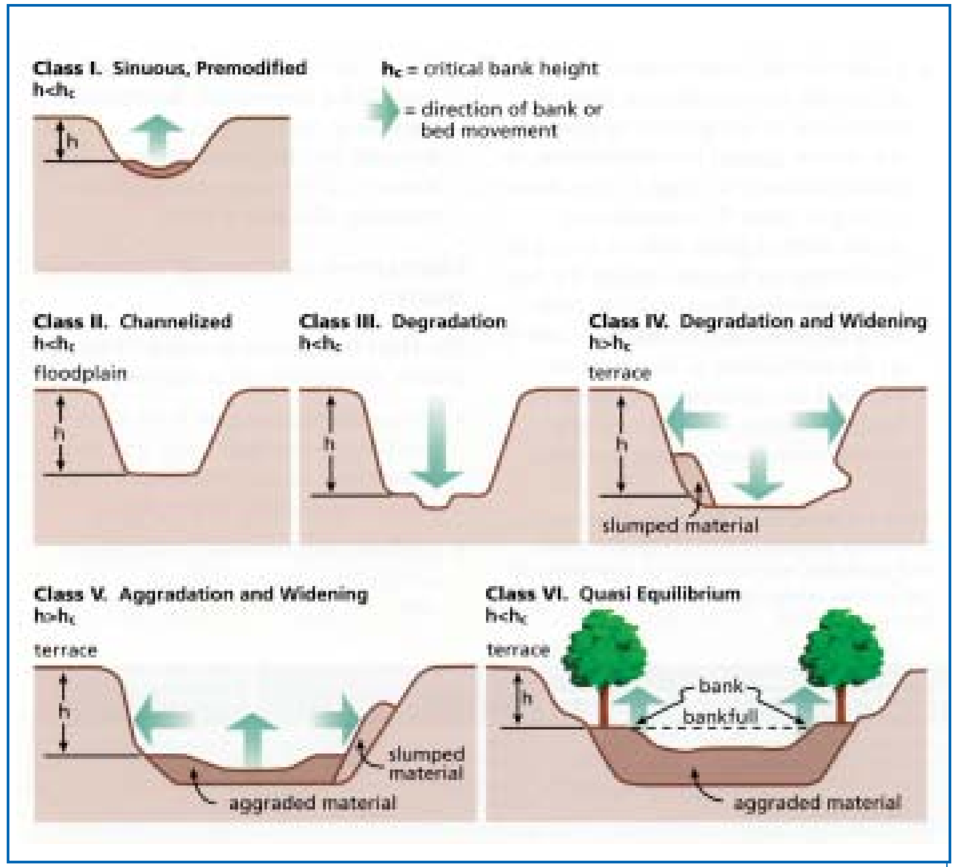


Figure 3.5

Channel-evolution model
FISRWG, 1998, 7-35
(based on Simon, 1989)

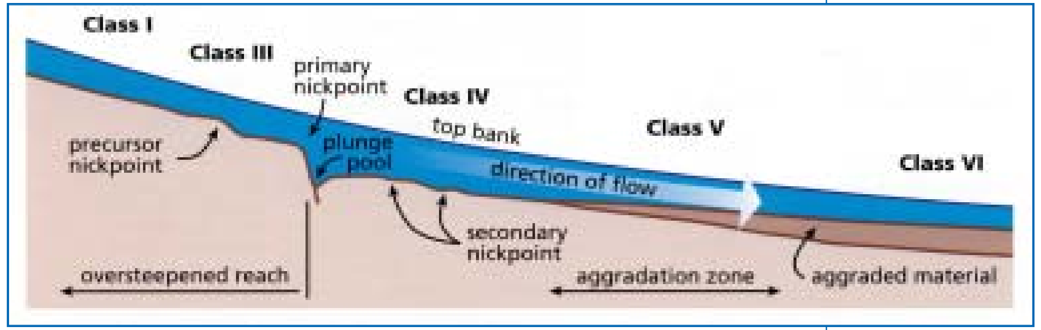


Figure 3.6

Channel-evolution model
FISRWG, 1998, 7-35
(based on Simon, 1989)

Estimates of streambank erosion rates are valuable for evaluating stream impairment and the need for restoration *(FISRWG, 1998; Rosgen, 1996)*. Techniques for estimating streambank erosion rates include cross-section surveys, bank-erosion pins, photography and photoelectronic systems. Recent studies in Wyoming *(Troendle et al., 2001)* and Oklahoma *(Harmel et al., 1999)* showed correlation between bank erosion rates and various field-measured erodibility factors. By taking relatively simple field measurements, one can use these relationships to predict annual erosion rates for stream reaches. By conducting these measurements at many locations, one can estimate the expected annual sediment load due to streambank erosion for a watershed. This information is valuable in prioritizing restoration projects and targeting resources.

Class		Dominant Process		Characteristic Forms	Geobotanical Evidence
No.	Name	Fluvial	Hillslope		
I	Premodified	Sediment transport—mild aggradation; basal erosion on outside bends; deposition on inside bends		Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering	Vegetated banks to flow line
II	Constructed (Channelized)			Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank	Removal of vegetation
III	Degradation	Degradation; basal erosion on banks	Pop-out failures	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank	Riparian vegetation high relative to flow line and may lean toward channel
IV	Threshold (Degradation and Widening)	Degradation; basal erosion on banks	Slab, rotational and pop-out failures	Large scallops and bank retreat; vertical face and upper-bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank	Riparian vegetation high relative to flow line and may lean toward channel
V	Aggradation and Widening	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks	Slab, rotational and pop-out failures; low-angle slides of previously failed material	Large scallops and bank retreat; vertical face, upper bank and slough line; flattening of bank angles; flow line low relative to top bank; development of new floodplain	Tilted and fallen riparian vegetation; re-establishing vegetation on slough line; deposition of material above root collars of slough-line vegetation
VI	Restabilization (Quasi-equilibrium)	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition on floodplain and bank surfaces	Low-angle slides; some pop-out failures near flow line	Stable, alternate channel bars; convex-short vertical face on top bank; flattening of bank angles; development of new floodplain; flow line high relative to top bank	Re-establishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough-line and upper-bank vegetation; some vegetation establishing on bars

Table 3.2. Channel-evolution model description

Simon, 1989, 24, and FISRWG, 1998, 7-36

(photographic examples of each of the six evolutionary stages are provided in Figure 3.7)

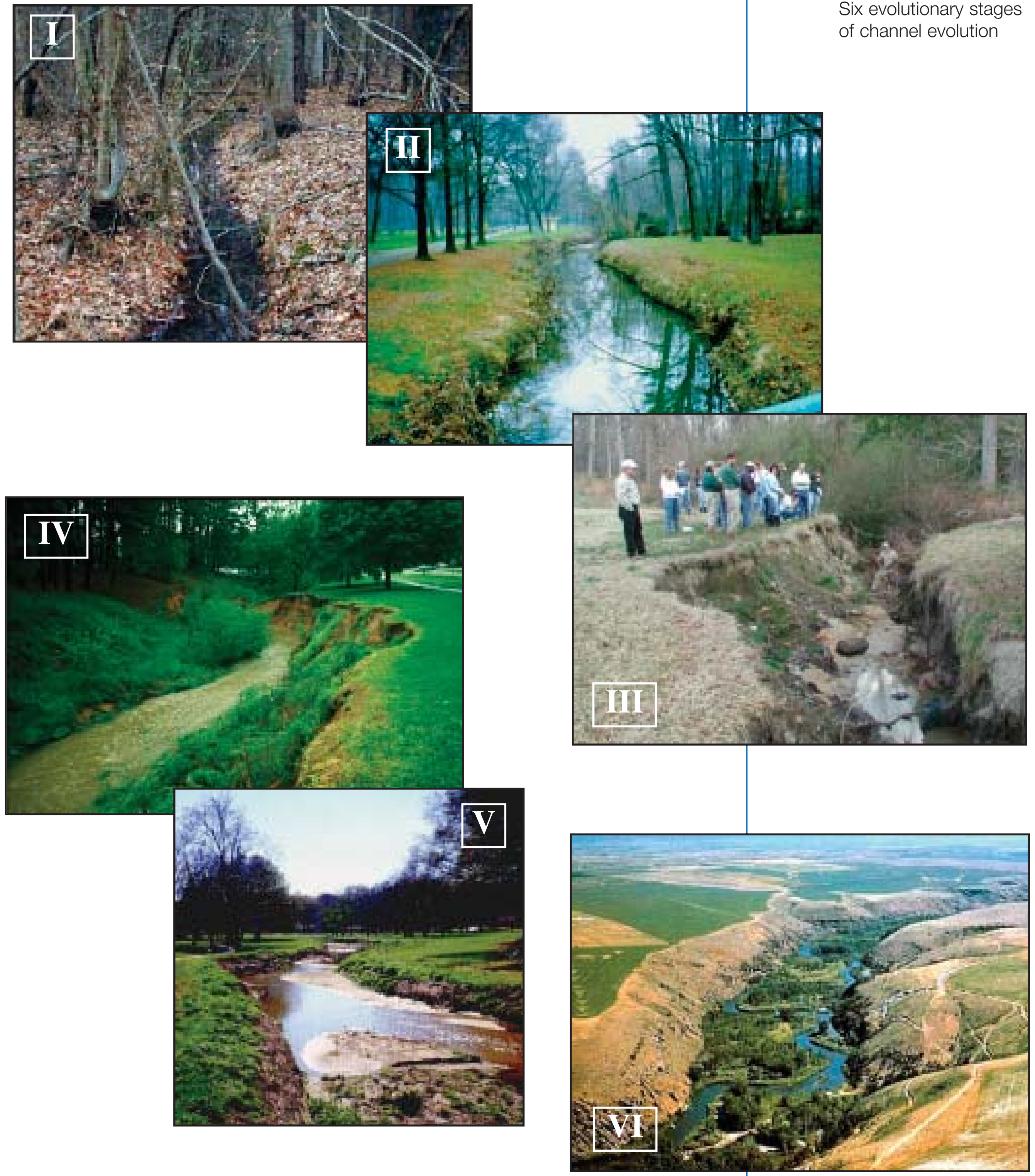


Fig. 3.7

Six evolutionary stages of channel evolution

Figure 3.8

Bankfull bench on restoration site

Stability Assessment Procedures

Bank Erodibility Hazard Index

Rosgen (1996) developed the Bank Erodibility Hazard Index (BEHI) as a quick way to estimate the potential for bank erosion along a stream reach. The BEHI assessment requires field-determination of five factors: (1) the ratio of bank height to bankfull height, (2) the ratio of vegetative-rooting depth to bank height, (3) the density of roots, (4) the streambank angle and (5) the vegetative bank protection. Convert the data to a BEHI index and adjust depending on the bank materials and the stratification of the bank (see Table 3.2).

For a general indication of BEHI ratings for various streambank conditions, see Figure 3.9. BEHI data sheets are in Appendix B. If the banks are made of bedrock or boulders, the BEHI rating in most cases should be "very low" and "low," respectively, in spite of the lack of vegetative surface protection and root mass. Therefore, the numerical index may need to be reduced substantially to reflect this situation. Similarly, cobble banks with less than 50 percent sand would also be resistant to erosion; subtract 10 points from the total numerical index. In contrast, gravel, sand and gravel-and-sand mixed banks would be much more likely to erode and require a higher numerical index. The presence and position of stratified layers can affect bank erodibility also. Many layers focused near the bankfull elevation, where the highest shear stress occurs, would create the most erodible bank, requiring an increase in the numerical index. In contrast, fewer layers located at the bottom or top of the bank away from bankfull would necessitate a smaller increase to the index. The BEHI rating requires visual evaluation of the streambanks, and so it is subjective. Use consistent rating procedures from site to site. Two different assessors likely would report a different numerical index, but probably would report the same overall rating.

Permanent Cross Sections

Establish three to six permanent cross sections at each reach perpendicular to the direction of flow at points that represent varying degrees of erosion in straight reaches and bends. Install left and right survey pins well beyond the top of the bank to ensure that the pins will not erode with the streambank. Survey each cross section to identify the channel thalweg, edge of water, bankfull stage, top of bank and permanent survey pins. Collect data from enough stations to accurately characterize the shape of the channel. Repeat cross-section surveys after major storm events and at least once per year. Plot and overlay the survey data to determine the amount of erosion over time. Calculate streambank erosion rates using changes in cross-section area over time. See Figure 3.10 for an example of how to monitor bank erosion using a permanent cross section.

Adjective Hazard or Risk Rating Categories		Bank Height/ Bankfull Height	Root Depth/ Bank Height	Root Density %	Bank Angle (Degrees)	Surface Protection %	Totals
VERY LOW	Value	1.0-1.1	1.0-0.9	100-80	0-20	100-80	
	Index	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	5-9.5
LOW	Value	1.11-1.19	0.89-0.5	79-55	21-60	79-55	
	Index	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	10-19.5
MODERATE	Value	1.2-1.5	0.49-0.3	54-30	61-80	54-30	
	Index	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	20-29.5
HIGH	Value	1.6-2.0	0.29-0.15	29-15	81-90	29-15	
	Index	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	30-39.5
VERY HIGH	Value	2.1-2.8	0.14-0.05	14-5.0	91-119	14-10	
	Index	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	40-45
EXTREME	Value	>2.8	<0.05	<5	>119	<10	
	Index	10	10	10	10	10	46-50

Adjust points with respect to the specific nature of bank materials and stratification, as follows:
Bank Materials: bedrock (very low rating), boulders (low rating), cobble (subtract 10 points unless gravel/sand >50 percent, then no adjustment), gravel (add 5-10 points depending on percentage sand), sand (add 10 points), silt/clay (no adjustment).
Stratification: Add 5-10 points depending on the number and position of layers.

Table 3.2 Bank Erodibility Hazard Index (BEHI) rating guide
Rosgen, 2001a

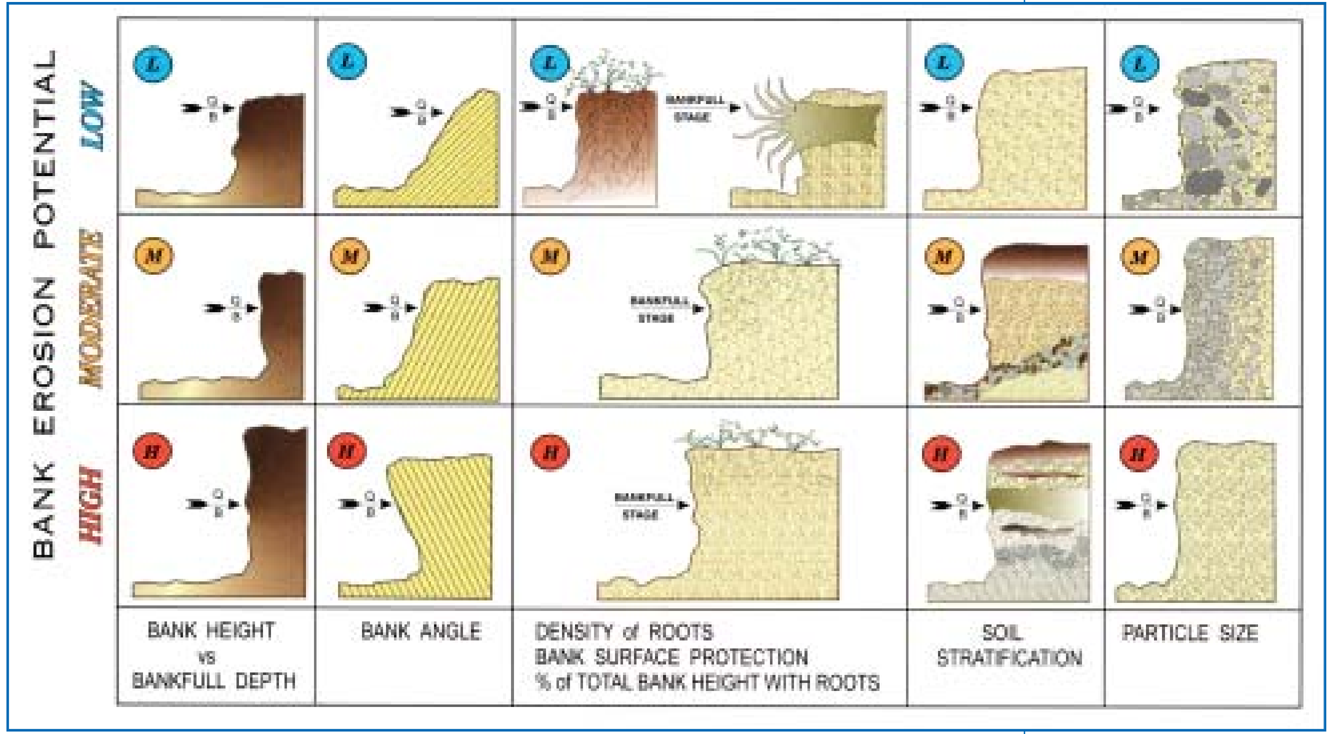


Fig. 3.9

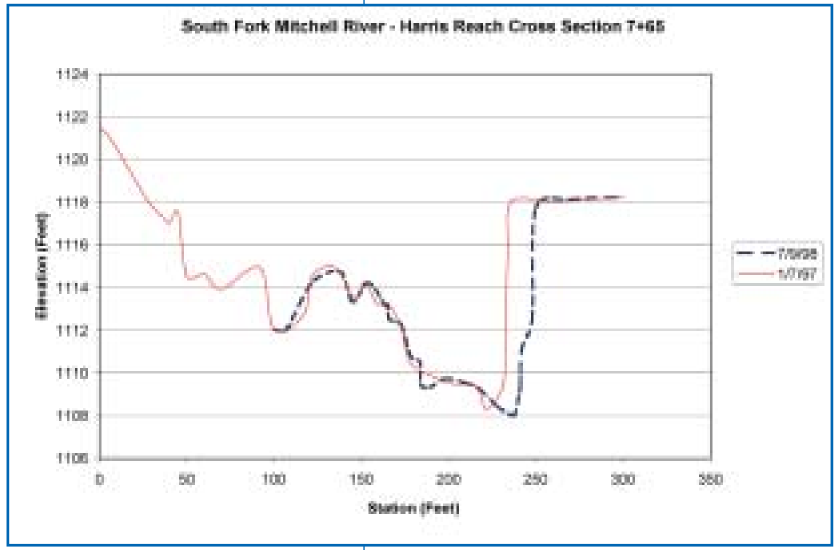
Streambank erodibility factors
Rosgen 1996, 6-40

Bank Pins and Bank Profile

Where possible, install toe pins vertically into the bed of the channel at the location of each permanent cross-section. Locate the pins close to the bank to enable multiple bank-profile surveys in the same location. Depending on the bank height, install two to five bank pins with a vertical spacing of 1 to 2 feet into the outside bank most prone to erosion. If it is not possible to install a toe pin in the channel bed, install a pin at the top of the bank. Place the pin far enough from the top edge of the bank that the pin won't be lost if the bank erodes. Drive half-inch steel rods (3.5 to 7 feet long) horizontally into the bank, leaving 1 to 2 inches exposed. To calculate the bank profile, place the survey rod on top of the toe pin to take vertical measurements. Place a second surveying rod perpendicular to that rod beginning at the toe pin *(Figure 3.11).* Record both vertical and horizontal measurements each time the horizontal rod is moved to another feature on the bank. Be sure to take measurements often to obtain a detailed characterization of the streambank. Calculate streambank erosion rates using changes in cross-section area over time and changes in bank-pin extensions. An example of bank-erosion monitoring using bank profile is shown in Figure 3.12.

Figure 3.10

Permanent cross-section monitoring results



3.4 LEVEL IV

Sediment Transport

Natural-channel designs are based on the premise that a stable stream maintains its dimension, pattern and profile and does not degrade or aggrade over a long period. All natural channel designs are based on the bankfull discharge and corresponding floodplain elevation. Bankfull discharge is assumed to be the effective discharge, which is the flow that transports the bulk of the sediment over a long period. Effective discharge is calculated as the product of the flow-duration curve and the sediment-transport rating curve. Because sediment-rating curves are lacking in the southeastern United States, designers rely on the bankfull stage and corresponding discharge; sediment-transport competency; and capacity calculations to ensure that channels do not aggrade or degrade. These calculations are used to predict the size-class and quantity of bedload transport.

Bedload, combined with suspended load, makes up the stream's total sediment load. Bedload is defined as those particles that slide, roll and saltate (hop) along the streambed during storm flows; such material does not start moving until the discharge amount is at least 40 percent of bankfull discharge. Suspended sediment includes the sediment particles that are transported in the water column; it is an important water-quality parameter. Bedload forms the bed features within the channel and is thus more important in channel formation and natural channel design.

Figure 3.11

Students monitor bank profile on Rocky Branch, Raleigh, N.C.

The ability of the stream to transport its total sediment load is quantified through two measures: sediment-transport competency and sediment-transport capacity. Competency is a stream's ability to move particles of a given size; it is a measurement of force, often expressed as units of lbs/ft^2. Sediment-transport capacity is a stream's ability to move a given quantity of sediment; it is a measurement of stream power, often expressed as units of lbs/ ft•sec. Sediment-transport capacity is also calculated as a sediment-transport rating curve, which provides an estimate of the quantity of total sediment load transported through a cross section per unit time. The curve is provided as a sediment-transport rate in lbs/sec versus discharge or stream power.

Sediment-transport studies are needed in North Carolina and the rest of the Southeast. Many designers now rely on equations and data produced by Andrews (1983) and Shield *(Leopold, 1994)* to validate sediment-transport competency of streams *(see Chapter 7).* However, this data has never been validated for the Southeast. Validation would require both the establishment of gage stations to monitor discharge and long-term sampling of bedload at several reference-reach streams with similar bed material. This monitoring could help generate sediment-capacity curves, which could be used to develop dimensionless sediment-transport curves *(Troendle et al., 2001).*

If long-term study is possible, a designer can develop a sediment-rating curve for a stream and validate models used to predict sediment transport or to predict changes in sediment load due to changes in watershed land-use. For instance, clear-cutting or urbanization in the watershed may increase the proportion of suspended sediment to total sediment load. To develop a sediment-rating curve for either bedload or sediment load, obtain field measurements of material transported in the stream during different flow events. Several devices and methods are available for collecting samples of suspended sediment and bedload. *For more information, see Edwards and Glysson (1999) in Section 13.3. This publication can be viewed online at http://water.usgs.gov/pubs/twri/twri3-c2/.*

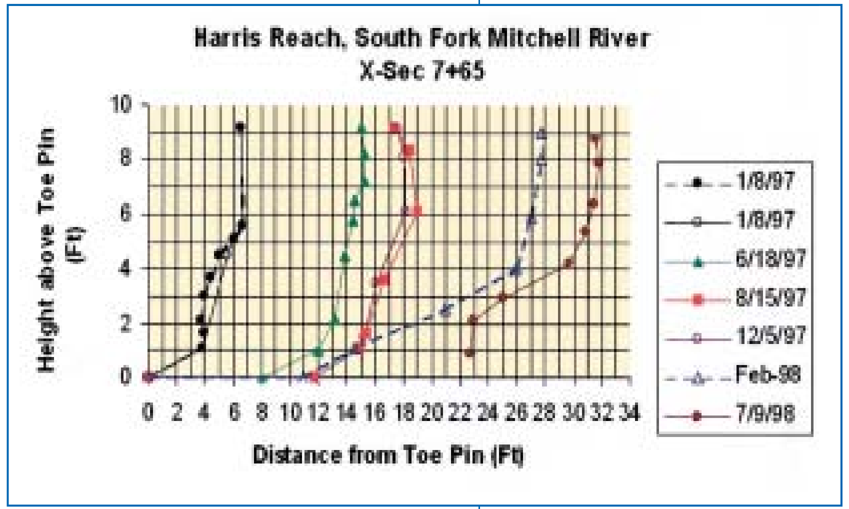


Figure 3.12

Results of bank-profile monitoring on the South Fork of the Mitchell River

Stream Stability Validation

In 1998, NC State University initiated a study to develop relationships between bank erosion rates and field-measured erodibility

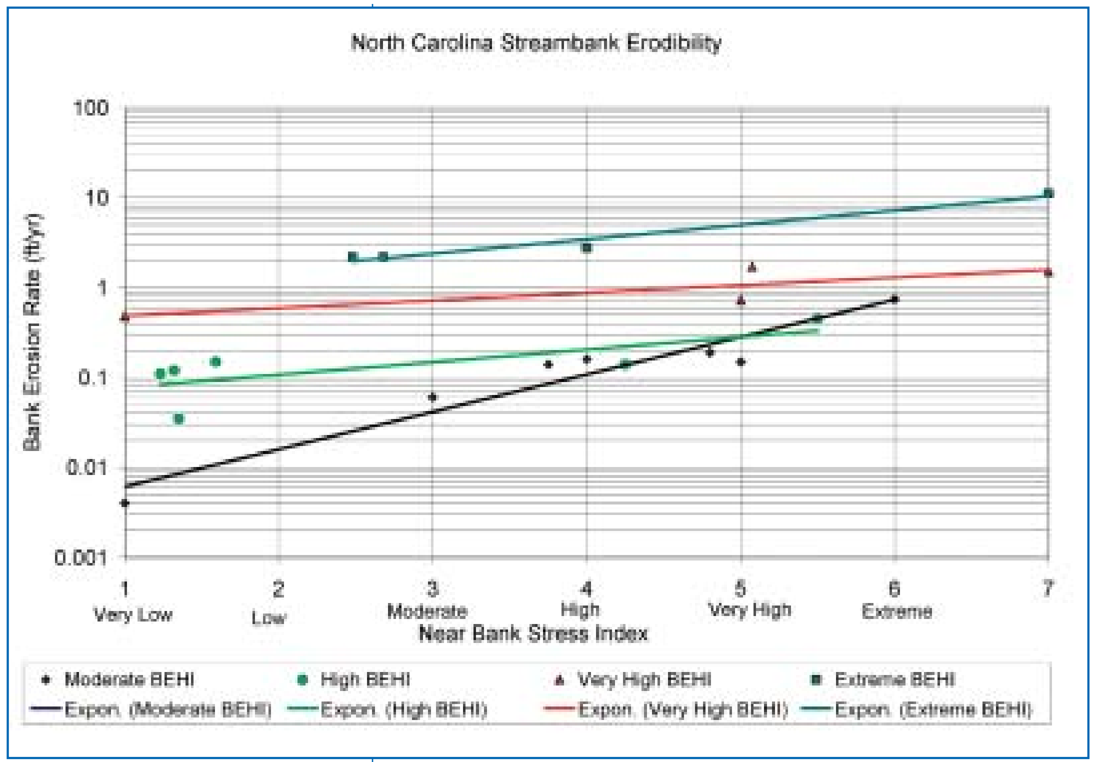


Figure 3.13

Measured streambank erosion rates in relation to near-bank stress and BEHI score
Source: Natural Resource Conservation Service, NC State University and NC Division of Soil and Water Conservation.

factors in the Piedmont and mountains of North Carolina *(Patterson et al., 1999).* Bank-erosion pins were established at 27 cross sections along seven stream reaches representing various land uses. The NRCS and the N.C. Division of Soil and Water Conservation monitored and validated the bank erosion at three of the university's study reaches (14 cross sections) and established six cross sections at three new study sites (*Jessup, 2002*). Figure 3.13 shows the results of the follow-up study. Sites with moderate BEHI ratings exhibited bank erosion rates ranging from 0.04 to 0.74 ft/yr; sites with high BEHI ratings exhibited 0.11 to 0.45 ft/yr of erosion; sites with very high BEHI ratings exhibited 0.48 to 1.7 ft/yr; and sites with extremely high BEHI ratings exhibited 2.19 to 11.15 ft/yr. Additional bank erosion monitoring is needed to expand the data set and increase the length of the sampling period to accommodate potential climatic influences.

Bankfull Verification and Gage Station Analyses

Chapter 4

Chapter 4: **Bankfull Verification and Gage Station Analyses**

Whether assessing the existing condition of a stream or developing a restoration design, it is important to validate the bankfull stage for the stream channel. River Course Fact Sheet Number 3 *(Appendix A)* explains how to find the bankfull stage in North Carolina. The easiest way to validate bankfull is through a gage station reading. However, stations rarely exist along project reaches. Therefore, it is important to develop a relationship of bankfull area and discharge (i.e., hydraulic geometry) to watershed area in the region. These hydraulic geometry relationships are often referred to as regional curves. Developing a regional curve requires a survey of streams and analysis of gage data for several gage stations within the same hydrophysiographic region. It is recommended that the gage station have a minimum of 10 years of record. Use the gage station survey procedure described here to develop regional curves and establish the return period of the flows that shape and maintain the channel. This information is critical when designing a stream where stream flow records are not available. Because hydraulic geometry relationships for streams vary with hydrology, soils and extent of development within a watershed, it is necessary to develop curves for various levels of development in each hydrophysiographic region. Regional curves for various hydrophysiographic regions of North Carolina are provided in Appendix D.

On gaged streams, determine the bankfull discharge and return period by matching the field-determined bankfull indicators to the corresponding USGS stage elevation at the gage *(see Appendix C)*. Then determine the bankfull discharge that corresponds to the bankfull stage by using the USGS stage-discharge rating table. Determine the return period by applying a Log-Pearson Type III distribution to the annual peak discharges recorded for the period that the gage has been in operation *(USGS, 1982)*. Calculate the annual exceedence probability as the inverse of the recurrence interval. On log-probability paper, plot the exceedence probabilities as functions of corresponding calculated discharge measurements. Fit a regression line to the data. Then determine the bankfull discharge recurrence interval from the graph, using the steps in this section.

It is often necessary to supplement data from gaged streams with data from non-gaged, stable streams. Stable streams have little or no bank erosion, and bankfull stage is located at the top of the streambank. For non-gaged streams, calculate bankfull discharge using Manning's equation *(Chow, 1959)*. Determine cross-sectional area from cross section survey data using the average-end area method *(see River Course Fact Sheet Number 3, Appendix A.)* Estimate a roughness coefficient using Manning's equation or by using the d_{84} particle size of the bankfull channel-bed material with the method described by Rosgen, 1998b. The d_{84} is defined as the particle size in which 84 percent of the material from the pebble count is finer than this particle. A reachwide pebble count should be used to determine the d_{84} particle size *(Section 2.7)*.

When identifying bankfull or developing regional curves in urban areas, quantify the level of development in each watershed using land-use maps or data. Use impervious-cover percentage or NRCS runoff-curve numbers. See NRCS, 1986 *(available for download at http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr55.html)* for the method to calculate the curve number. Streams with similar levels of development within the same hydrophysiographic region can be grouped together for a single regional curve.

Stream Gage Survey Procedure: (From Leopold, 1994)

Note: Sample USGS station data is provided in Appendix C.

Step 1. Obtain the following information from the stream gage:
- **a.** Location (including location of current meter measurement sites)
- **b.** Drainage area (in square miles)
- **c.** Stage/discharge curve (gage height/discharge rating table) Call USGS at (919) 571-4000 or visit the Web site www.usgs.gov.
- **d.** Stream discharge notes (9-207 forms) for the previous 10 years or widest range of measured discharge (data for depth, width, velocity and cross-sectional area/discharge)
- **e.** Flood-frequency data (Log-Pearson III) if previously published (If not, obtain the listing of highest momentary maximum flows for period of record and ranking of flood peaks, highest to lowest. Then calculate (m/N+1) x 100, where m = rank, N = total number of years of record. This calculation gives exceedence probability for a respective flood peak, which allows a determination of return period of the various peak flows.)

Step 2. Travel to gage site and observe bankfull indicators along the stream reach. Measure a longitudinal profile upstream of the gage, locating elevations of thalweg, water surface and bankfull stage. Mark bankfull stages along profile with temporary flags, then measure this stage at the gage-height staff reference at the stream-gage cross section. Record the gage height (staff plate) reading that corresponds with the bankfull elevation.

Step 3. Read discharge from the stage-discharge rating table for the stream gage corresponding to the gage height of the field-estimated bankfull stage.

Step 4. Determine exceedence probability associated with field-determined bankfull discharge *(from Step 1e)*. To convert exceedence probability (P) to return period in years, inverse P and multiply by 100 (1/P x 100).

Step 5. If the return period of the field-determined bankfull discharge is between one and two years, the bankfull indicators are within the range of acceptability for use.

Step 6. Plot bankfull discharge versus drainage area for the appropriate hydrophysiographic province associated with the stream gage. All North Carolina regional curve information is located in Appendix D.

Step 7. Plot bankfull values of depth, width and cross-sectional

Step 8. Calculate Manning’s roughness coefficient *n* or other resistance equations from actual velocity for bankfull stage and/or other flows.

Step 9. Obtain the following information to classify the stream at the gage site:

- **Description**

1. *Describe valley type, landform/land type.*
2. *Photograph upstream/downstream.*
3. *Delineate watershed using topographic map.*
4. *Determine drainage area in square miles (usually provided by USGS).*
5. *Evaluate watershed land use/land cover and compute percentage of watershed that is impervious.*
6. *Calculate bankfull-discharge return period in years.*

- **Riffle Cross-Section Dimension**

1. *Bankfull width* (W_{bkf})
2. *Bankfull mean depth* (D_{bkf})
3. *Bankfull maximum depth* (D_{max})
4. *Width-to-depth ratio* (W_{bkf}/D_{bkf})
5. *Bankfull cross-sectional area* (A_{bkf})
6. *Width of flood-prone area* (W_{fpa})
7. *Entrenchment ratio* (W_{fpa}/W_{bkf})
8. *Bank height* (D_{TOB})
9. *Bank height ratio* (D_{TOB}/D_{max})
10. *Bankfull velocity* (V_{bkf})
11. *Bankfull discharge* (Q_{bkf})

- **Plan View (Pattern)**

Measure sinuosity. (K=stream length/valley length)

- **Longitudinal-Profile Survey**

1. *Measure average water-surface slope from the head of one riffle to the head of a downstream riffle (or from max pool to max pool) at a distance of at least 20 times the bankfull width.*
2. *Locate bankfull stage along the longitudinal profile.*

   Note: The elevation difference between bankfull and the water surface at various locations in the reach should not vary more than 6 inches.

- **Materials**

1. *Particle size of channel material (riffles and pools) (Reachwide pebble-count frequency distribution): d15, d35, d50, d84, d95.*

Chapter 5

Priority Options for Restoring Incised Streams

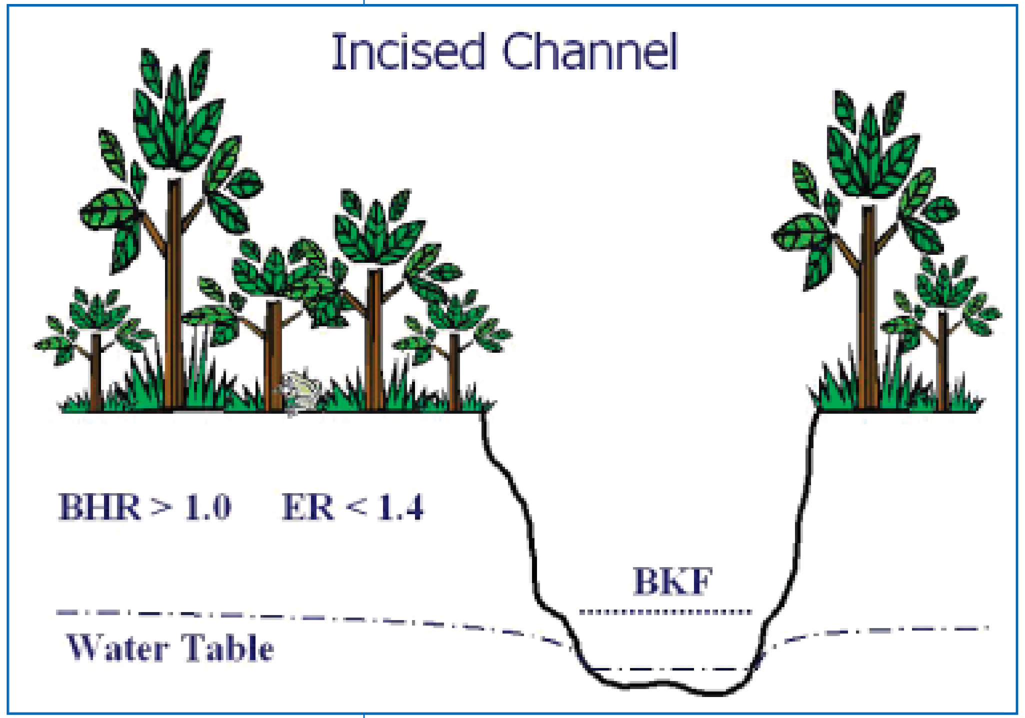
Chapter 5: **Priority Options for Restoring Incised Streams**

Incision of stream channels is caused by straightening of channels, loss of riparian buffers, changes in watershed land-use or changes in sediment supply. Because incised streams typically are unstable and function poorly, they are good candidates for stream-restoration projects. Rosgen (1997) presents four priority options for restoring incised channels. This chapter describes those four options—with the first priority being the most preferred and the last being the least optimal.

An incised stream has a bank height ratio greater than 1.0 ft/ft, meaning that the bankfull stage is at a lower elevation than the top of either streambank (*Figure 5.1*). Severely incised streams with bank height ratios greater than 1.8 ft/ft are usually classified as Rosgen stream types G or F. Shear stress at high flows in these streams may become very high, increasing the potential for streambank erosion and/or streambed downcutting. Moderately incised streams with bank height ratios between 1.4 and 1.8 ft/ft may be classified as Rosgen stream types E, C or B, but they are at increased risk of instability. Slightly incised streams with bank height ratios between 1.1 and 1.3 ft/ft are often stable; however, they may become unstable if land use in the watershed changes or riparian buffers disappear.

Figure 5.1

Cross section of an incised channel



Designers should consider each restoration option in priority order before settling on a final design. The options are described in the following sections and compared in Table 5.1. This chapter also discusses several recent North Carolina case studies that illustrate the application of these restoration approaches.

5.1 Priority 1:
Establish Bankfull Stage at the Historical Floodplain Elevation.

The objective of a Priority 1 project is to replace the incised channel with a new, stable stream at a higher elevation. This is accomplished by excavating a new channel with the appropriate dimension, pattern and profile (based on reference-reach data) to fit the watershed and valley type (*Figure 5.2*). The new channel is typically an E or C stream with bankfull stage located at the ground surface of the original floodplain. The increase in streambed elevation also will raise the water table, in many cases restoring or enhancing wetland conditions in the floodplain.

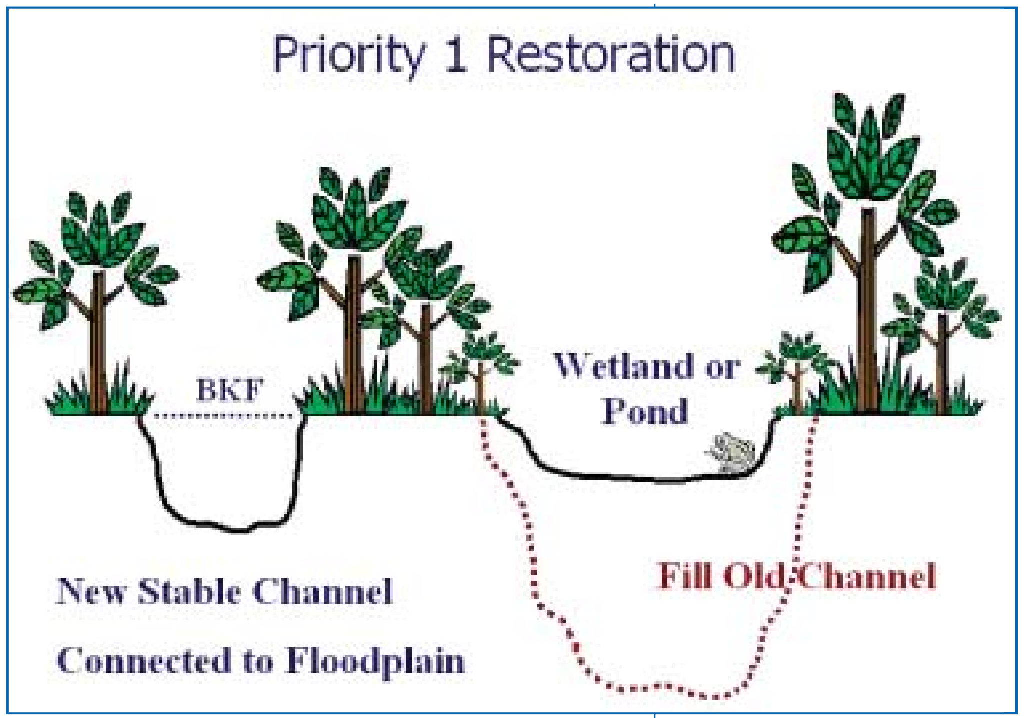


Figure 5.2

Cross section of a Priority 1 restoration project

If designed and constructed properly, a Priority 1 project produces the most long-term stable stream system. It may also be the least expensive and simplest to construct depending on surrounding land-use constraints. Priority 1 projects usually can be constructed in dry conditions while stream flow continues in its original incised channel. The new channel can be stabilized with structures and bank vegetation before water is directed into the new stream. A special consideration with Priority 1 projects is the unbalanced cut/fill requirements. Typically, the amount of soil excavated in constructing the new channel will be much less than that required to completely fill the existing incised channel. The designer has the option of bringing additional fill to the site or creating floodplain ponds and/or wetlands to support habitat and recreation.

Surrounding land uses can limit the use of a Priority 1 approach if there are concerns about increased flooding or widening of the stream corridor. Most Priority 1 projects will result in higher flood stages above bankfull discharge in the immediate vicinity of the project and possibly downstream. The Priority 1 approach also requires sufficient land area on one or both sides of the existing incised stream to construct the new meandering channel on the floodplain. It also may be necessary to raise the existing channel at the beginning of the project reach and/or lower the new channel at the end of the project reach to connect with the existing channel.

5.2 Priority 2:
Create a New Floodplain and Stream Pattern with the Stream Bed Remaining at the Present Elevation.

The objective of a Priority 2 project is to create a new, stable stream and floodplain at the existing channel-bed elevation. This is accomplished by excavating a new floodplain and stream channel at the elevation of the existing incised stream (*Figure 5.3*). The new channel is designed with the appropriate dimension, pattern and profile (based on reference-reach data) to fit the

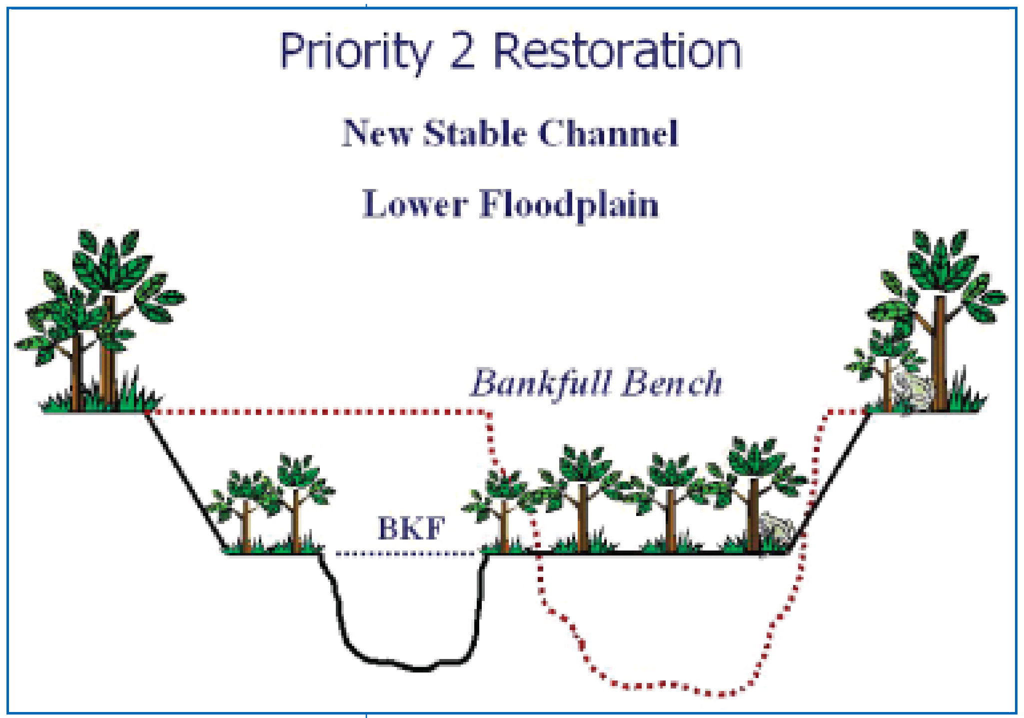


Figure 5.3

Cross section of a Priority 2 restoration project

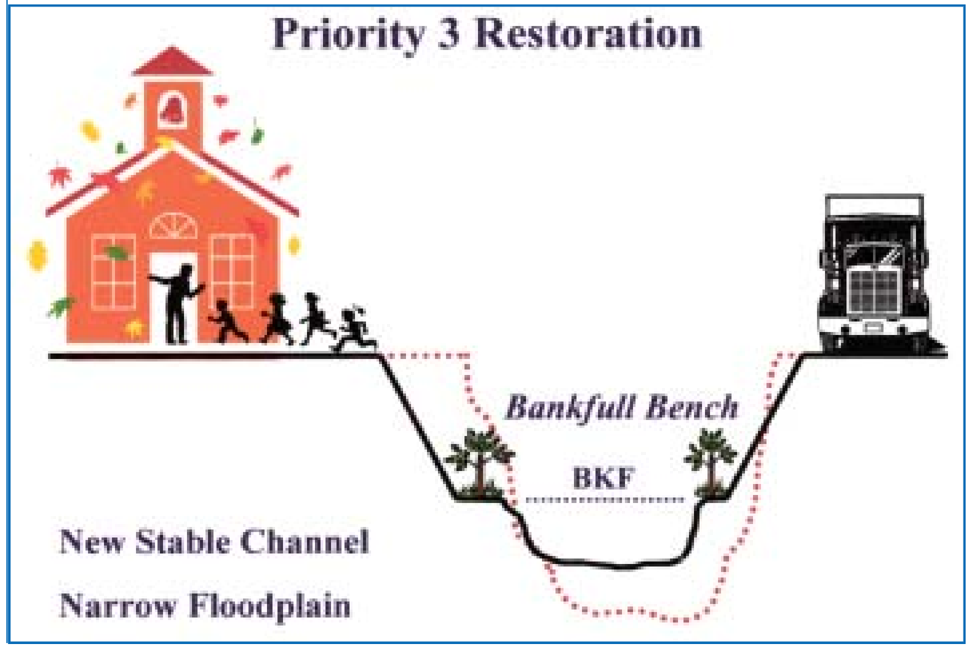
watershed. The new channel is typically an E or C stream with bankfull stage located at the elevation of the newly excavated floodplain.

A Priority 2 project can produce a stream system with long-term stability if designed and constructed properly. It may be more expensive and complex to construct than a Priority 1 project, depending on valley conditions. Priority 2 projects usually can be constructed in dry conditions while stream flow continues in its original channel or is diverted around the construction site. Typically, water is diverted into the new channel as soon as all or part of it is constructed and stabilized with structures and temporary bank-protection measures. Because the new floodplain is excavated at a lower elevation, Priority 2 projects do not increase—and may decrease—the potential for flooding. Also, the stream corridor created by the excavated floodplain may enhance riparian wetlands.

Unlike Priority 1 projects, which are normally short on material to fill the old channel, Priority 2 projects typically produce a surplus of cut material. Designers must consider the expense and logistics of managing extra soil material excavated from the floodplain. The designer may elect to raise the bed of the stream slightly in an attempt to balance cut and fill. Further, surrounding land uses can limit the use of a Priority 2 approach if there are concerns about widening of the stream corridor. This approach requires sufficient land area on one or both sides of the existing incised stream to construct the new floodplain and meandering channel.

Figure 5.4

Cross section of a Priority 3 restoration project



5.3 Priority 3: Widen the Floodplain at the Existing Bankfull Elevation.

Priority 3 is similar to Priority 2 in its objective to widen the floodplain at the existing channel elevation to reduce shear stress. This is accomplished by excavating a floodplain bench on one or both sides of the existing stream channel at the elevation of the existing bankfull stage *(Figure 5.4).* The existing channel may be modified to enhance its dimension and profile based on reference-reach data. The resulting channel is typically a B or Bc (low slope) stream with bankfull stage located at the elevation of the newly widened floodplain. Priority 3 projects typically do not increase sinuosity to a large extent because of land constraints.

A Priority 3 project can produce a stream system with long-term stability if it is designed and constructed properly. But it may require more structural measures and maintenance than Priority 1 or 2 projects. It may be more expensive and complex to construct, depending on valley conditions and structure requirements. Priority 3 projects are constructed in wet conditions unless stream flow is diverted around the construction site. These projects typically have little impact on flooding potential unless there are large changes in channel dimension. Priority 3 projects typically do not produce large quantities of extra cut material or require extensive changes to surrounding land uses. They also do not typically affect riparian wetlands or elevation of the water table.

In-stream structures are important to the success of Priority 3 projects. In many projects, a channelized stream must remain in its current location because of surrounding land uses or utilities. The resulting stream may be classified as a B or Bc channel even though the valley conditions support a more meandering E or C channel. In this case, boulder cross-vane structures should be used to protect streambanks, provide grade control and support scour pools for habitat *(see Chapter 8).*

Section 5.4 Priority 4: Stabilize Existing Streambanks in Place.

Priority 4 projects use various stabilization techniques to armor the bank in place. These projects do not attempt to correct problems with dimension, pattern or profile. Priority 4 projects often use typical engineering practices to harden (armor) one or more streambanks. Projects may use riprap, concrete, gabions, bio-engineering or combinations of structures to protect streambanks. Both the upstream and downstream impacts of the project should be carefully evaluated. Because these projects do not correct dimension, pattern and profile, they are likely to continue being susceptible to extreme shear stress, which can erode streambanks in spite of armoring.

A Priority 4 project can stabilize streambanks if designed and constructed properly, but inspection and maintenance may be necessary to ensure long-term success. For these reasons, the long-term cost may be more. Priority 4 projects are constructed in wet conditions unless stream flow is diverted around the construction site. These projects typically have no impact on flooding potential and do not require changes to surrounding land uses. They also do not typically affect riparian wetlands or elevation of the water table.

Option	Advantages	Disadvantages
1	Results in long-term stable stream Restores optimal habitat values Enhances wetlands by raising water table Minimal excavation required	Increases flooding potential Requires wide stream corridor Unbalanced cut/fill May disturb existing vegetation
2	Results in long-term stable stream Improves habitat values Enhances wetlands in stream corridor. May decrease flooding potential	Requires wide stream corridor Requires extensive excavation May disturb existing vegetation Possible imbalance in cut/fill
3	Results in moderately stable stream Improves habitat values May decrease flooding potential Maintains narrow stream corridor	May disturb existing vegetation Does not enhance riparian wetlands Requires structural stabilization measures May require maintenance
4	May stabilize streambanks Maintains narrow stream corridor May not disturb existing vegetation	Does not reduce shear stress May not improve habitat values May require costly structural measures May require maintenance

Table 5.1 Advantages and disadvantages of restoration options for incised streams

5.5 Priority 1 Case Study: Yates Mill Pond Tributary

The Yates Mill Pond Tributary project is located in a rural watershed in Wake County just south of Raleigh. The existing intermittent stream was incised due to historic straightening and removal of riparian vegetation. The upstream end of the
each was not incised, meaning that the new channel could be connected with the existing channel at its current eleva-
eam end of the first phase of construction in 2000, the existing channel was six feet below the new streambed
op-structure connected the new and old channels until the second phase of construction was completed in 2002.

Parameter	Existing	Design
Watershed Area (sq mi)	0.12	0.12
Stream Classification	E6-G5	C5
Bankfull Cross-Sec Area (sq ft)	8	8
Width/Depth Ratio (ft/ft)	5-12	14
Entrenchment Ratio (ft/ft)	0.6-4.0	15
Bank Height Ratio (ft/ft)	1.0-3.7	1.0
Length (ft)	750	800
Sinuosity (ft/ft)	1.1	1.2
Riparian Buffer Width (ft)	5-10	50-80

Table 5.2. Parameters of Yates Mill Pond tributary-restoration project

Table 5.2 lists physical parameters for the existing and new stream channels. A cross-section survey depicting the existing and as-built stream channels is shown in Figure 5.5. Before and after photos of the project
e shown in Figures 5.6 and 5.7. The project design called for constructing a new, stable C5 stream on the floodplain west of the existing channel. All of the construction was completed in dry conditions before water was turned into the new channel. Because the excavated soil didn't completely fill the existing incised channel, several small ponds were created to provide habitat. To help stabilize the new channel, several log vanes and log weirs were installed along the streambank in addition to root wads, transplants and erosion matting.

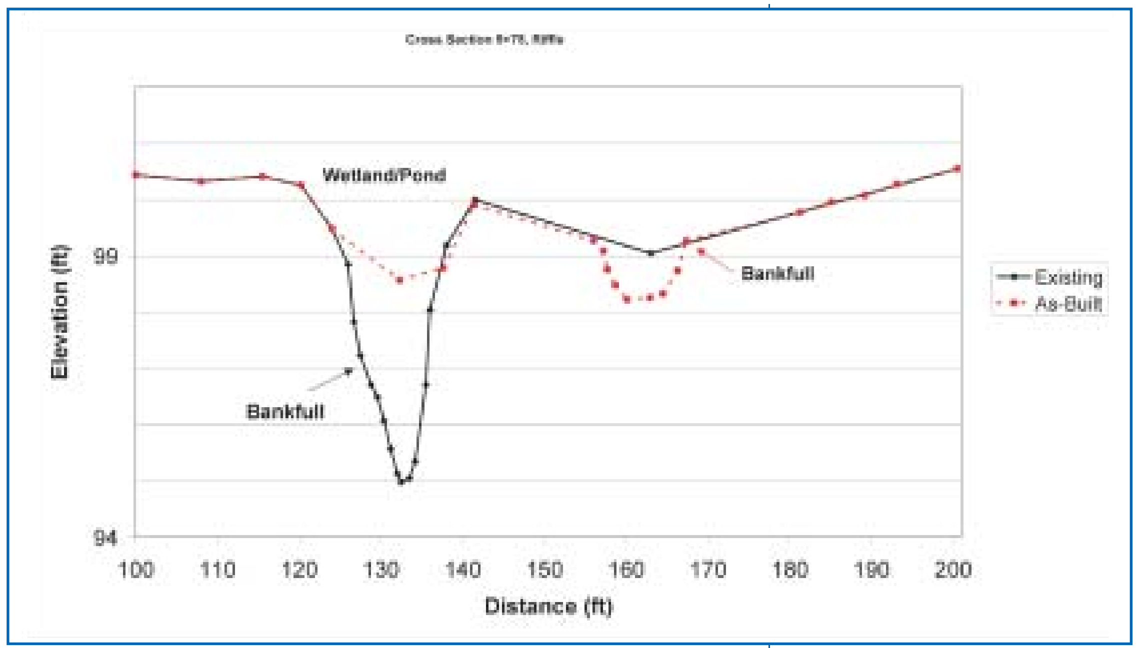


Figure 5.5

Cross-section survey of Yates Mill Pond tributary-restoration project

Figure 5.6

Yates Mill Pond tributary-restoration project before construction

Figure 5.7

Yates Mill Pond tributary-restoration project after construction

5.6 Priority 2 Case Study: Pine Valley Golf Course Tributary

The Pine Valley Golf Course tributary project is located in an urban watershed in New Hanover County in Wilmington. The existing perennial stream was incised due to historic ditching and draining for construction of the golf course and surrounding residential community. The upstream end of the project reach was a drainage culvert that prevented a Priority 1 approach. Project constraints included a sewer line along the left streambank, two permanent golf-cart bridges, two irrigation-line crossings and vegetation concerns at three golf holes crossing the stream reach.

Parameter	Existing	Design
Watershed Area (sq mi)	0.5	0.5
Stream Classification	F	E
Bankfull Cross-Sec Area (sq ft)	10	10
Width/Depth Ratio (ft/ft)	15	10
Entrenchment Ratio (ft/ft)	1.5	5
Bank Height Ratio (ft/ft)	2	1
Length (ft)	789	906
Sinuosity (ft/ft)	1.04	1.2
Riparian Buffer Width (ft)	10	50

Table 5.3 Parameters of Pine Valley Golf Course restoration project

Table 5.3 lists physical parameters for the existing and design stream channels. A cross-section survey depicting the existing and as-built stream channels is shown in Figure 5.8. Before and after photos of the project are shown in figures 5.9 and 5.10. The project design called for constructing a new, stable E5 stream and floodplain at the elevation of the existing channel. Stream flow was diverted through a pump during construction, after which water was turned into the new channel. Because the excavated soil exceeded the amount needed to fill the existing channel, excess soil was hauled to a stockpile area on the golf course property. To help stabilize the new channel, several log cross-vanes and log weirs were installed along the streambank in addition to root wads, transplants and erosion mats.

Figure 5.8

Cross-section survey of Pine Valley Golf Course restoration project

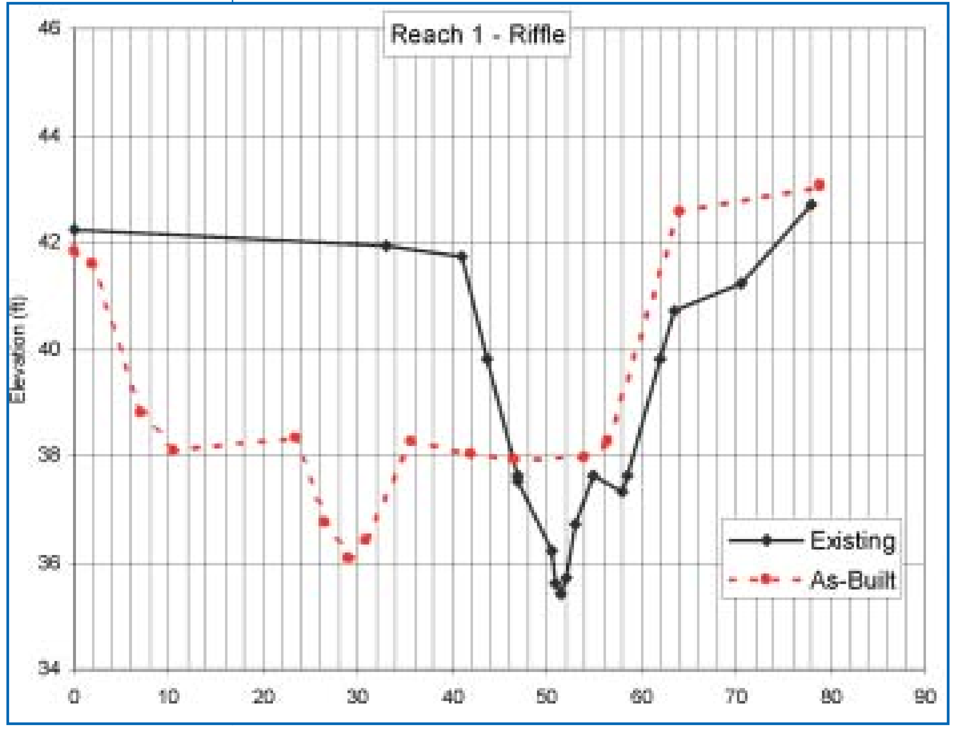


Figure 5.9

Pine Valley Golf Course restoration project before construction

Figure 5.10

Pine Valley Golf Course restoration project after construction

5.7 Priority 3 Case Study: Cove Creek

The Cove Creek project is located in a rural watershed in Watauga County, west of Boone. The existing perennial stream was incised due to a head-cut advancing from a downstream mill dam that was removed in 1989. The upstream end of the project reach was a bridge that prevented a Priority 1 approach. Adjacent landowners were not able to provide sufficient property to construct a new meandering stream, which ruled out a Priority 2 approach. The resulting project goals were to change stream types from F4 to B4c by excavating floodplain benches and to enhance habitat using in-stream structures.

Table 5.4 lists physical parameters for the existing and design stream channels. A cross-section survey depicting the existing and as-built stream channels is shown in Figure 5.11. Before and after photos of the project are shown in figures 5.12 and 5.13. The project design called for constructing floodplain benches at the bankfull elevation of the existing channel and installing boulder cross-vanes. Construction was completed during low flow. Cross vanes, root wads, transplants and erosion mats were used along the streambank to help stabilize the channel and floodplain.

Parameter	Existing	Design
Watershed Area (sq mi)	15	15
Stream Classification	F4	B4c
Bankfull Cross-Sec Area (sq ft)	175	164
Width/Depth Ratio (ft/ft)	16	15
Entrenchment Ratio (ft/ft)	1.1	1.7
Bank Height Ratio (ft/ft)	2.0-2.2	1.0
Length (ft)	1200	1200
Sinuosity (ft/ft)	1.1	1.1
Riparian Buffer Width (ft)	5-10	25-40

Table 5.4. Parameters of Cove Creek restoration project

5.8 Priority 4 Examples

Examples of Priority 4 stabilization and armoring projects are shown in figures 5.14-5.17.

Figure 5.11

Cross-section survey of Cove Creek restoration project

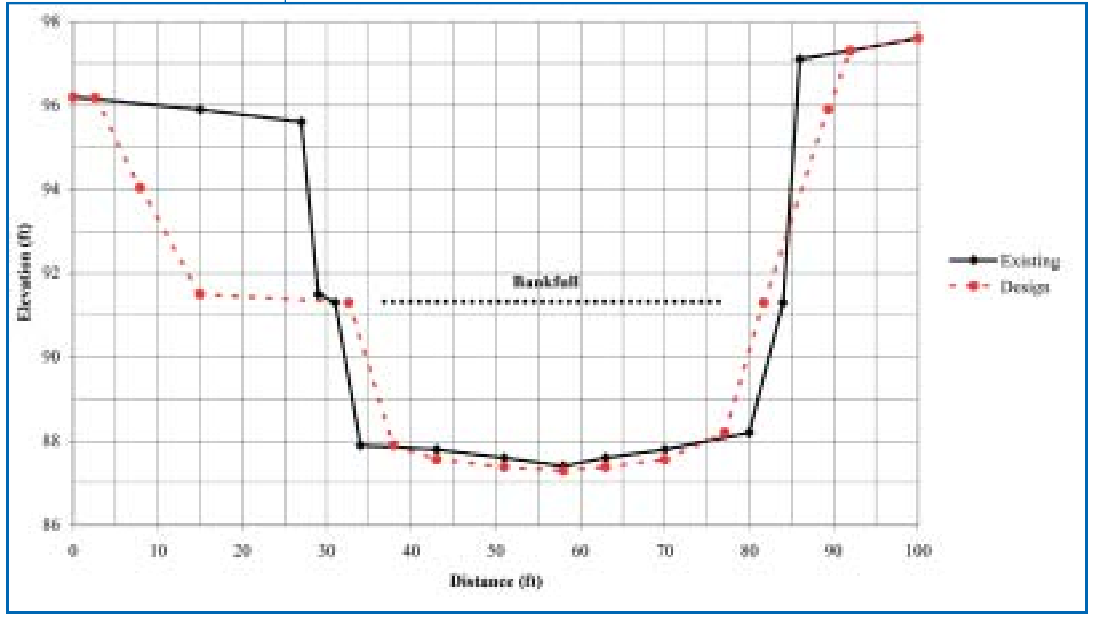


Figure 5.12

Cove Creek restoration project before construction

Figure 5.13

Cove Creek restoration project at bankfull flow after construction

Figure 5.14

Streambank stabilization using riprap at the toe of the bank and bioengineering on the slopes

Figure 5.15

Channel armoring using riprap at the toe of the streambank

Figure 5.16

Streambank armoring using gabion baskets

Figure 5.17

Armoring of streambank using log-crib wall

Notes:

Reference Reach Survey

Chapter 6

Chapter 6: **Reference Reach Survey**

Successful stream restoration requires an understanding of the causes of degradation; specific knowledge of the stream's current state; and an understanding of the stream's most stable dimension, pattern and profile based on its present valley type and flow regime. In addition, quantitative knowledge of stable streams is necessary to determine the stable dimension, pattern and profile that can be applied in a restoration design. A reference reach is a stable river segment that represents a stable channel within a particular valley morphology *(Rosgen, 1998a)*. Reference reaches provide the numerical template that can be applied to unstable reaches. Morphology relationships for reference stream channels are valuable tools for stream-restoration professionals. Designers and reviewers should use reference reaches to determine appropriate stream-channel dimension, pattern and profile for various stream types and watershed conditions.

The reference stream is not necessarily pristine (completely unimpaired). It instead is a reach that characterizes a stable morphology within its setting. Factors that affect reference reach selection include watershed land-use, valley and stream morphology, and flow regime. Reference reach streams should have stable watersheds without significant land-use changes within the past five years; a channel with bankfull stage at the top of bank and without apparent signs of incision or head-cutting; stable, well-vegetated, gently sloping streambanks; and well-defined and properly located bed features. Channels that should not be used as reference reaches include streams with changing or recently modified watershed land-use; active streambank erosion and undercutting; leaning trees with undermined root systems; channel incision; and poorly functioning or improperly located channel features (i.e., no pools or riffles located in the meander bends). For each restoration design, survey at least one stream of the appropriate type; same hydrophysiographic region; and similar valley type, watershed type and size, and bed-material distribution. This will supply morphologic relationships that can be applied in the design. A body of data from several reference reach channels is preferable. Once a reference reach has been identified, follow the field and office procedures described here.

Field Procedures

6.1. Bankfull Identification

Follow the procedures outlined in Section 2.3.

6.2. Longitudinal Profile

Follow the procedures outlined in Section 2.6.

6.3. Pool and Riffle Cross-Section Survey

Follow the procedures outlined in Section 2.4.

6.4 Pebble Count

Conduct a reachwide pebble count. Follow the procedures outlined in Section 2.7.

6.5 Rosgen Stream Classification

Classify the stream using the procedures outlined in Section 3.2.

6.6 Plan-Form Measurements

Measure radius of curvature, R_c, meander wavelength, L_m, and belt width, W_{blt}, at several meander bends in the reference channel *(see Section 2.5 and Figure 6.1)*. Measure sinuosity, K, for the reference reach *(see Section 2.5)*. Draw a schematic map of the reference reach. Show plan view of stream, bed forms, large woody debris, cross sections, valley width, plan-form measurement locations, landmarks, benchmark, etc.

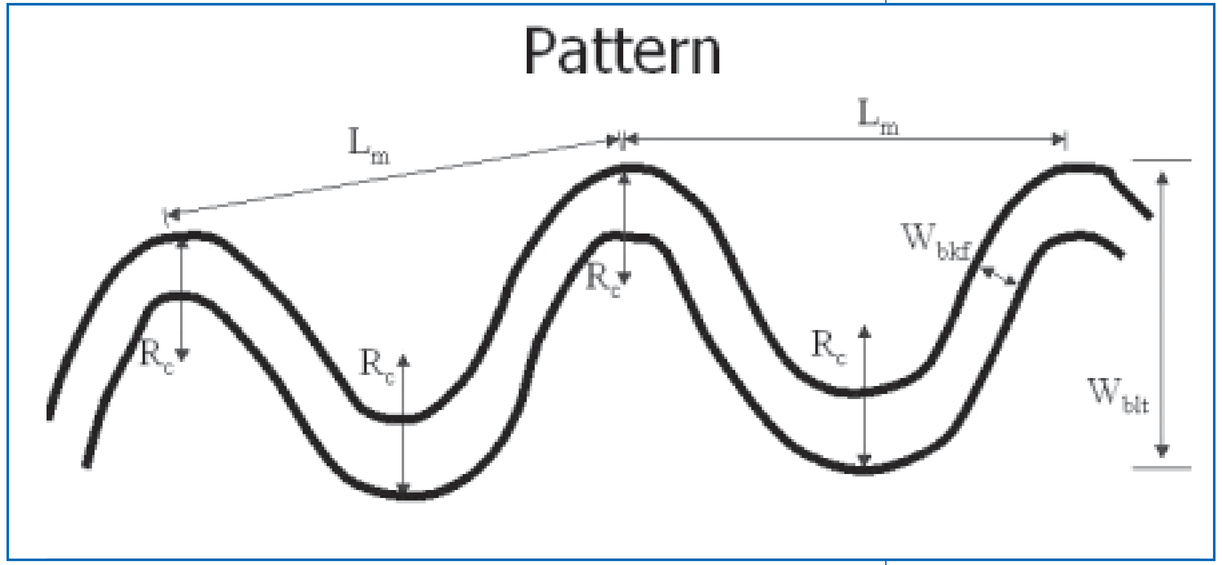


Figure 6.1

Plan-form measurements and dimensionless ratios

meander length ratio=L_m/W_{bkf};

meander width ratio=W_{blt}/W_{bkf};

radius of curvature ratio=R_c/W_{bkf}

Office Procedures

6.7 Profile Data Summary

Step 1: Plot the longitudinal profile with the longitudinal station on the horizontal axis and thalweg, water surface, inner berm, bankfull and top of bank on the vertical axis.

Step 2: Calculate the length and slopes for the following bed-form features: riffles, runs, pools and glides. Length is calculated using the longitudinal thalweg station from the head of the feature (i.e., riffle, run, pool or glide) to the head of the next downstream feature. Slope is then calculated as the length of the feature divided by the water-surface elevation change over the thalweg distance for that feature. Pool-to-pool spacing (p-p) should also be calculated as the distance from max pool to max pool thalweg stations *(see Figure 6.2)*.

6.8 Dimension Data Summary

Step 1: Plot riffle-and-pool cross sections with the cross-section stations on the horizontal axis and the elevation on the vertical axis.

Step 2: Calculate bankfull cross-sectional area for all riffles (A_{bkf}) and pools (A_{pool}) using the procedures outlined in River Course Fact Sheet Number 3 *(see Appendix A)*.

Step 3: Calculate bankfull width, W_{bkf}, for all riffles (W_{bkf}) and pools (W_{pool}) as the horizontal distance between the left and right bankfull stations *(Figure 6.3)*.

Step 4: Calculate mean depth, $D_{bkf}=A_{bkf}/W_{bkf}$, for all pools and riffles *(Figure 6.3)*.

Step 5: Calculate max depth, D_{max}, for all riffle cross-sections and D_{pool} for all pool cross-sections as the vertical distance between bankfull elevation and thalweg elevation *(Figure 6.3)*.

Step 6: Calculate the bank height ratio, BHR, at all riffle cross sections. Divide the difference in elevation between the top of the low bank and the thalweg by the difference in elevation between the bankfull elevation and the thalweg ($BHR=D_{TOB}/D_{max}$). If bankfull is the top of the bank, then the BHR is 1 *(Figure 6.3)*.

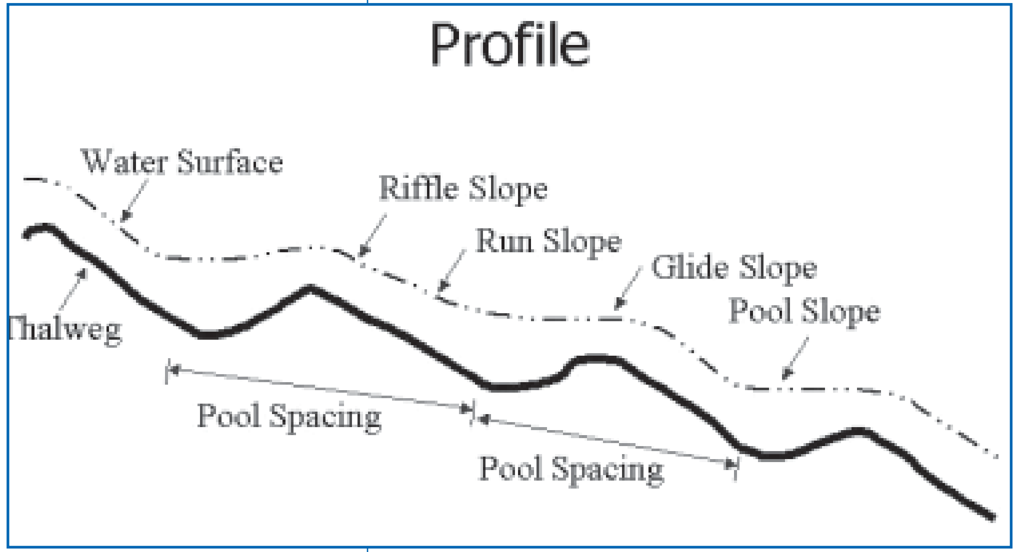


Figure 6.2

Stream profile features and dimensionless ratios

riffle slope ratio=S_{rif}/S_{avg};
run slope ratio=S_{run}/S_{avg};
pool spacing ratio=pool spacing/W_{bkf};
pool slope ratio=S_{pool}/S_{avg};
glide slope ratio=S_{glide}/S_{avg}

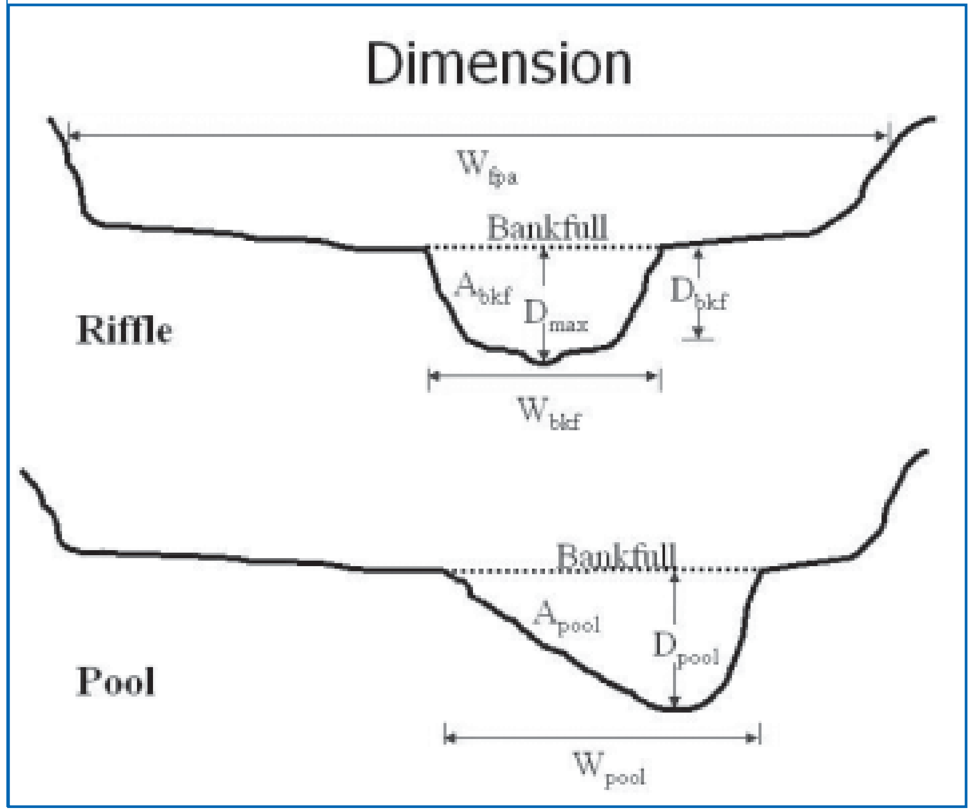


Figure 6.3

Riffle and pool cross-sections and dimensionless ratios

bankfull mean depth (D_{bkf})=A_{bkf}/W_{bkf};
entrenchment ratio (ER)=W_{fpa}/W_{bkf};
width to depth ratio=W_{bkf}/D_{bkf};
max depth ratio=D_{max}/D_{bkf};
bank height ratio (BHR)=D_{TOB}/D_{max};
pool max depth ratio=D_{pool}/D_{bkf};
pool area ratio=A_{pool}/A_{bkf};
pool width ratio=W_{pool}/W_{bkf}

6.9 Pattern Data Summary

Consolidate the pattern data—including sinuosity, radius of curvature, meander wavelength and belt width. Record the minimum, maximum and mean values for radius of curvature, meander wavelength and belt width.

6.10 Reference Reach Summary Table

Summarize the reference reach data and record in the summary table *(Table 7.1, Chapter 7).* Report the maximum, minimum and mean values for each parameter.

6.11 Dimensionless Ratio Calculation

Dimensionless ratios are design parameters that are tools for scaling the data from the reference stream to the design stream, which may have a different bankfull dimension and discharge. The measured reference reach data are divided by a bankfull dimension, W_{bkf}, D_{bkf} or A_{bkf}, to create the dimensionless ratios. Ratios should be calculated for the maximum, minimum and mean values for each morphologic parameter. After ratios are calculated, record them in the summary table *(Table 7.1).*

6.12 Vegetation Reference Reach

Riparian and floodplain restoration should be based on a reference area found within close proximity of the project site. This should be chosen based on the initial riparian assessment of the project site, if possible. Choose a site that has topographic and vegetative characteristics similar to the project site. Reference sites should be as pristine as possible. Ideal areas will not have been disturbed recently and will be free of exotic vegetation *(see Figure 6.4).* If the project site has no native riparian characteristics (i.e., it is urbanized or farmed), look upstream or downstream of the project site to determine the stream's riparian characteristics.

Once the riparian reference site has been chosen, follow the riparian assessment process for describing topography, soil and vegetation as discussed in Section 2.10.

6.13 North Carolina Reference Reach Data

NC State University conducted a study of reference reach streams *(Clinton et al., 1999)* that included detailed morphologic surveys of 14 streams from the Blue-Ridge/Piedmont physiographic regions of North Carolina *(Table 6.1).* The reference reaches included in the study were stable streams with: consistent land use over the past 60 years, no channelization, and no severe bank erosion. The bankfull width of the channels ranged from 8.7 to 69 feet. The data from the stream reaches were analyzed to develop channel pattern and profile relationships. These relationships are described in Table 6.2 and figures 6.5-6.10. Williams (1986), Leopold and Wolman (1960) and Rinaldi and Johnson

Figure 6.4

Example of a reference reach for vegetation

(1997) also developed interrelationships for river meander and channel size. Their data are presented in Table 6.2 for comparison.

Channel-pattern relationships from stable reference reaches are important in designing naturally stable, meandering streams that will replace previously straightened streams. The relationships for belt width, radius of curvature and meander wavelength as functions of bankfull channel width are shown in Table 6.2 and figures 6.5-6.7. All three data sets indicate high variability with the best regression fit occurring for belt width and worst for radius of curvature. The relationship for pool-to-pool spacing as a function of bankfull channel width is shown in Figure 6.8.

Channel-profile relationships are described in figures 6.9 and 6.10. These relationships are important in designing stable streams that dissipate energy through changing bed features and provide stable aquatic habitat. They also can be used to estimate maximum depth of riffles and maximum depth of pools for a given stream-type and watershed condition. Regression relationships *(figures 6.9 and 6.10)* provide a good fit to the measured data for both of these parameters.

Channel-morphology relationships on reference streams are valuable tools for engineers, hydrologists and biologists involved in stream restoration and protection. They also can help evaluate the relative stability of a stream channel. This study created a good fit for most regression equations, indicating strong correlation between morphology relationships in reference stream channels in the rural Piedmont of North Carolina. However, users must consider the natural variability represented by these relationships. The data and relationships from the NC State University study can be useful for comparing additional reference reach data collected in North Carolina's Piedmont region. However, the availability of this data does not replace the need for a reference reach survey that is specific to each individual restoration project.

Table 6.1 Reference Reach Survey Data
Clinton et al., 1999

STREAM NAME	Stream Type	Drainage Area (sq mi)	Bankfull X-Sectional Area (sq. ft.)	Bankfull Width (ft.)	Bankfull Mean Depth (ft.)	Water Surface Slope (ft/ft)	d50/ d84 (mm)	Width to Depth Ratio (ft/ft)	Entrenchment Ratio (ft/ft)	Reach Sinuosity (ft/ft)
Stackrock Creek	B3a	1.1	27.8	24.6	1.1	0.055	100/380	21.8	2.1	1.1
Lost Cove (Upstream)	B3c	7.9	68.5	39.1	1.8	0.019	100/370	22.3	1.9	1.1
Steels Creek	B3c	9.2	95.1	54.0	1.8	0.016	135/512	30.7	1.4	1.2
Craig Creek	B4	1.8	33.0	28.8	1.1	0.033	33/370	25.1	1.3	1.1
Mitchell River Headwaters	B4c	6.5	68.8	35.0	2.0	0.010	40/210	17.8	1.3	1.1
Lost Cove (at Edgemont)	C3	24.8	218.0	64.9	3.4	0.009	144/512	19.3	3.1	1.2
North Fork of the New River	C3	29.0	168.8	52.3	3.2	0.005	75/362	16.3	3.4	1.5
Richland Creek	C4	1	15.5	16.7	0.9	0.013	45/145	18.0	3.0	1.2
Basin Creek	C4	6.8	57.4	30.7	1.9	0.014	38/130	16.4	2.8	1.02
Barnes Creek	C4	23	199.0	69.0	2.9	0.004	45/400	23.8	3.2	1.2
Sal's Branch	E4	0.2	10.4	8.7	1.2	0.011	9.5/30	7.3	18.7	1.1
Spencer Creek	E4	0.5	10.6	8.7	1.2	0.013	8.6/77	7.1	26.3	1.1
Mill Creek	E4	4.7	28.3	13.7	2.1	0.008	40/110	6.6	30.3	1.7
Big Branch	E4	1.9	42.8	21.5	2.0	0.009	45/125	10.8	6.0	1.1

Table 6.2 Reference-reach relationships
Clinton et al., 1999

	Meander Wavelength as a function of Channel Width	Meander Beltwidth as a function of Channel Width	Radius of Curvature as a function of Channel Width
North Carolina	$L_m=1.8W^{1.54}$ Applicable Range: $8.7 \le W \le 69$ ft	$W_{blt}=0.57W^{1.49}$ Applicable Range: $8.7 \le W \le 69$ ft	$R_c=2.4W^{0.94}$ Applicable Range: $8.7 \le W \le 69$ ft
Williams (1986)	$L_m=6.5W^{1.12}$ Applicable Range: $4.9 \le W \le 13{,}000$ ft	$W_{blt}=4.4W^{1.12}$ Applicable Range: $4.9 \le W \le 7{,}000$ ft	$R_c=1.3W^{1.12}$ Applicable Range: $4.9 \le W \le 7{,}000$ ft
Leopold and Wolman (1960)	$L_m=9.7W^{1.1}$ Applicable Range: n/a		$R_c=2.5W^{1.02}$ Applicable Range: n/a
Rinaldi and Johnson (1997)	$L_m=2.86W^{1.13}$ Applicable Range: $9.8 \le W \le 14.8$ ft		

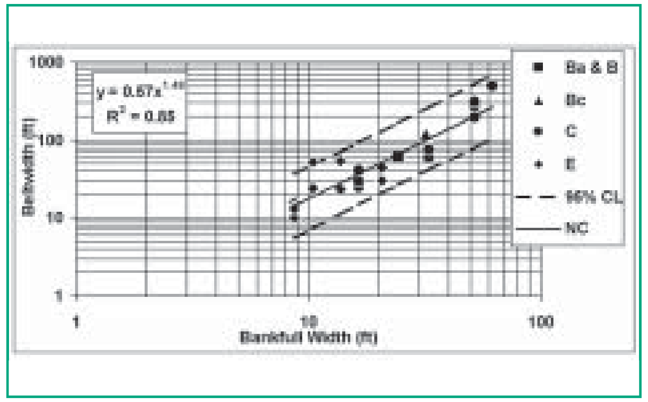


Figure 6.5

Belt width as a function of bankfull width
Clinton et al., 1999

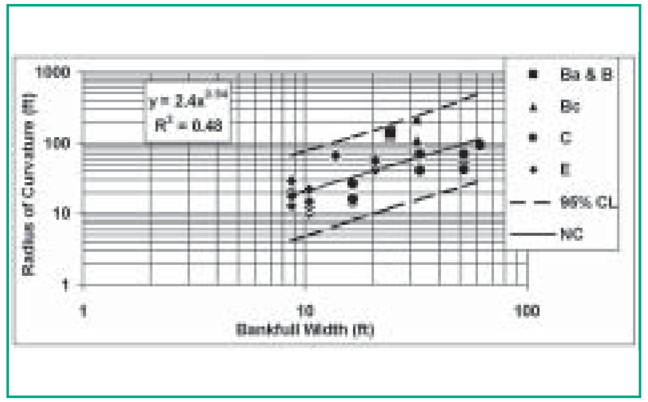


Figure 6.6

Radius of curvature as a function of bankfull width
Clinton et al., 1999

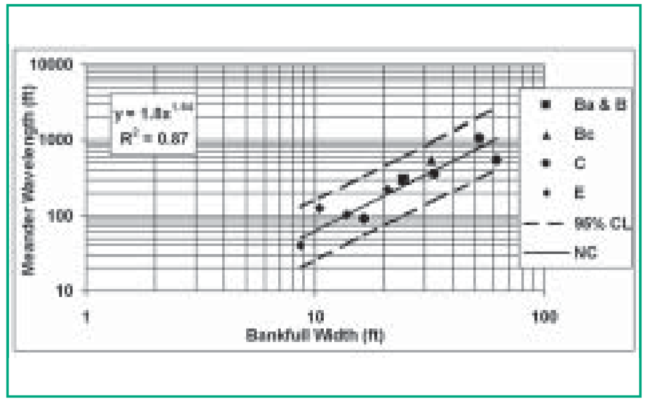


Figure 6.7

Meander wavelength as a function of bankfull width
Clinton et al., 1999

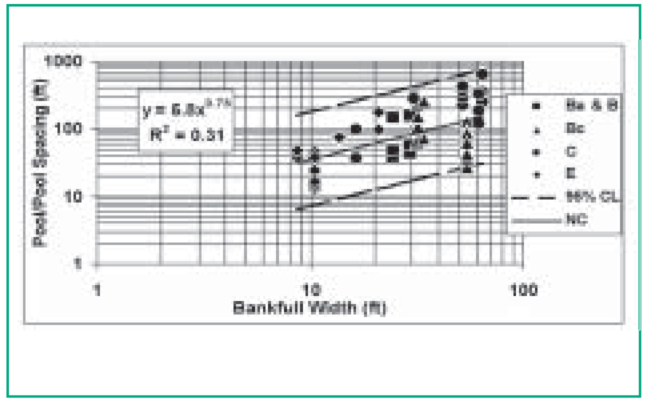


Figure 6.8

Pool-to-pool spacing as a function of bankfull width
Clinton et al., 1999

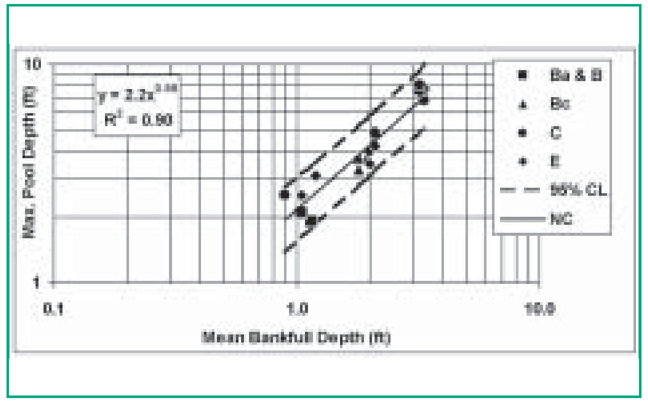


Figure 6.9

Max pool depth as a function of riffle mean bankfull depth
Clinton et al., 1999

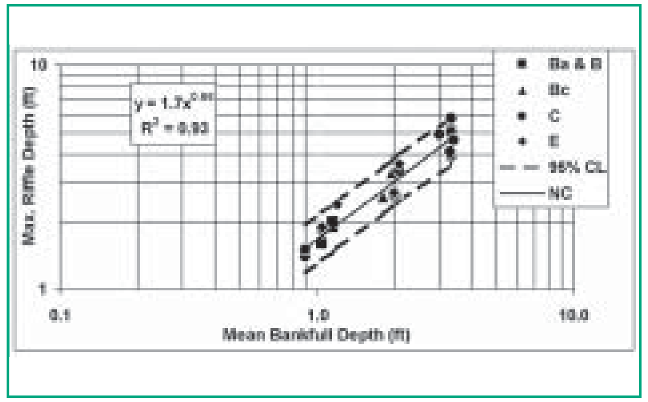


Figure 6.10

Max riffle depth as a function of mean bankfull depth
Clinton et al., 1999

Notes:

Chapter 7

Design Procedures

Chapter 7: **Design Procedures**

7.1 Design Steps

The design process may begin after completion of the existing-condition survey *(Chapter 2)*; validation of bankfull *(Chapter 4)*; determination of restoration goals and selection of stream type to be built *(Chapter 5)*; and identification and survey of a reference reach stream *(Chapter 6)*. The natural channel design process is an iterative approach to fitting proper dimension, pattern and profile to the stream based on reference reach data, restoration goals and the existing site constraints. The reference reach data have been converted into dimensionless ratios so that they can be applied to the stream even if the watershed area and associated channel size are different. Reference reach data should be collected from a stream that is stable, in the same hydrophysiographic region and similar in watershed size (*see Chapter 6).*

Three key steps in the natural channel design process include determining the new dimension, repatterning the stream and developing the longitudinal profile. Complete these steps in order. Afterward, evaluate shear stress and flood studies as a design check. These checks will ensure that the design causes neither erosion, excessive deposition of sediment nor flooding of nearby homes, businesses or roads.

Design Steps *(Adapted from Rosgen, 1998c)*

Note: Values in bold typeface within brackets represent the dimensionless ratios obtained from the reference reach.

Step 1. Select A_{bkf} and Q_{bkf} based on existing-condition survey, regional curve, build-out scenarios and reference reach information. If the river is regulated by a storage reservoir or diversion, obtain the operational hydrology of the installation. Compare the hydrograph with the field evidence of bankfull discharge. Using morphological evidence, back-calculate the stream flow from the cross-sectional area of the bankfull channel. Verify that the estimated bankfull discharge is appropriate for the watershed size. The reservoir or diversion may cause a reduction in bankfull discharge.

Step 2. Select a width-to-depth ratio for the design, considering the width-to-depth ratio **[W/D]** of the reference reach. Do not select an extremely low ratio that will result in very steep streambanks; these are difficult to build and may erode during the early stages of the project when vegetation is immature and rootmass is insubstantial. As a rule of thumb, don't design a width-to-depth ratio of less than 9 unless bank soils are cohesive and consolidated.

Step 3. Calculate proposed bankfull width, $W_{bkf}=\sqrt{(A_{bkf}) \times [W/D]}$.

Step 4. Calculate proposed bankfull mean depth, $D_{bkf}=W_{bkf}/[W/D]$, or A_{bkf}/W_{bkf}.

Step 5. Select the design stream's target sinuosity, K, based on the sinuosity of the project's reference reach and valley. Consider such constraints as large trees, utilities, buildings and other infrastructure.

Step 6. Calculate average slope. ($S_{ave}=S_{val}/K$) based on the sinuosity hoped to be achieved with the design.

Step 7. Validate whether the design will sufficiently transport its sediment load *(see Section 7.2).* Validation may require adjustment of the width-to-depth ratio and/or the sinuosity. If width-to-depth ratio must be adjusted, return to Step 2.

Step 8. Calculate mean bankfull velocity, $V_{bkf}=Qbkf/A_{bkf}$.

Step 9. Calculate bankfull max depth at the riffle ($D_{max}=[D_{max}/D_{bkf}] \times D_{bkf}$). Obtain the max depth ratio, $[D_{max}/D_{bkf}]$, from the reference reach information *(Table 7.1).*

Step 10. Calculate flood-prone area width (from cross section of stream and valley), W_{fpa}=width of the valley at an elevation of 2 x D_{max} *(see Figure 3.4).*

Step 11. When flooding is a concern or the project is subject to FEMA requirements, compute the flood-stage levels with HEC 2 or HEC-RAS procedures *(see Chapter 11).* These procedures provide only an approximate flood-stage level; they are not intended as substitutes for the FEMA procedures. At gage stations, it is necessary to plot various return-period floods and their corresponding depths on the flood-prone area.

Step 12. Calculate meander wavelength ($L_m=[L_m/W_{bkf}] \times W_{bkf}$). Obtain the meander length ratio, $[L_m/W_{bkf}]$, from the reference reach data *(Table 7.1).*

Step 13. Calculate radius of curvature ($R_c=[R_c/W_{bkf}] \times W_{bkf}$). Obtain the radius-of-curvature ratio, $[R_c/W_{bkf}]$, from the reference reach information *(Table 7.1).*

Step 14. Calculate belt width, ($W_{blt}=[W_{blt}/W_{bkf}] \times W_{bkf}$). $[W_{blt}/W_{bkf}]$ is the meander width ratio (MWR) from the reference reach. If the river is confined, use available belt width for the design stream and back-calculate meander width ratio ($MWR=W_{blt}/W_{bkf}$). Make sure MWR is within the acceptable range for the design stream type.

Step 15. Sketch or draw the proposed stream alignment (plan view) over the existing aerial photo or channel map with the appropriate bankfull width; pool width; and appropriate range of values for meander wavelength, radius of curvature and belt width. Adjust pattern to account for existing vegetation and landform changes and to avoid high banks such as terraces or alluvial fans. Vary the stream alignment to simulate natural variability, avoiding a symmetrical layout. Measure stream length by delineating a thalweg in the new channel; measure valley length along the fall line of the valley. Calculate sinuosity. Sinuosity (K)=stream length/valley length.

Step 16. Calculate average slope ($S_{ave}=S_{val}/K$).

Step 17. If the actual sinuosity and associated average slope are not equal to the targeted values determined in Steps 5 and 6, validate that the design stream is competent to transport its sediment load *(see Section 7.2)*. This validation may require adjustment of the width-to-depth ratio and/or the sinuosity. If width-to-depth ratio must be adjusted, return to Step 2. If sinuosity must be adjusted, return to Step 15.

Step 18. Calculate riffle slope, ($S_{rif}=[S_{rif}/S_{ave}] \times S_{ave}$), where $[S_{rif}/S_{ave}]$ is the riffle-slope ratio from the reference reach *(Table 7.1).*

Step 19. Calculate pool slope, (S_{pool} = [S_{pool} / S_{ave}] x S_{ave}), where [S_{pool} / S_{ave}] is the pool-slope ratio from the reference reach *(Table 7.1).*

Step 20. Calculate pool area, (A_{pool} = [A_{pool} / A_{bkf}] x A_{bkf}), where [A_{pool} / A_{bkf}] is the pool-area ratio from the reference reach *(Table 7.1).*

Step 21. Calculate max pool depth, (D_{pool} = [D_{pool} / D_{bkf}] x D_{bkf}), where [D_{pool} / D_{bkf}] is the pool-depth ratio from the reference reach *(Table 7.1).*

Step 22. Calculate pool width, (W_{pool} = [W_{pool} / W_{bkf}] x W_{bkf}), where [W_{pool} / W_{bkf}] is the pool-width ratio from the reference reach *(Table 7.1).*

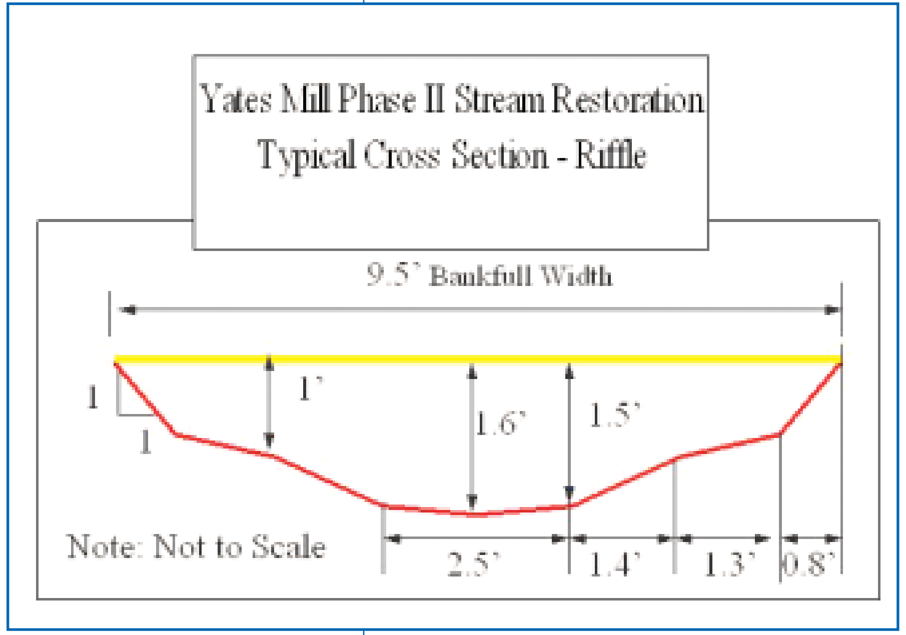
Step 23. Calculate pool length, (L_{pool} = [L_{pool} / W_{bkf}] x W_{bkf}), where [L_{pool} / W_{bkf}] is the pool-length ratio from the reference reach *(Table 7.1).*

Step 24. Calculate sequence of pool-to-pool spacing, (p-p = [p-p/W_{bkf}] x W_{bkf}), where [p-p/W_{bkf}] is the pool spacing ratio from the reference reach *(Table 7.1)*) for riffle-pool or step-pool stream types.

Step 25. Plot typical cross sections for riffles, pools, steps, glides or other features. Scale the dimensions properly and show point-bar slopes (C channels only), entrenchment ratio and side-slope gradients *(figures 7.1 and 7.2).*

Figure 7.1

Riffle cross-section dimension detail

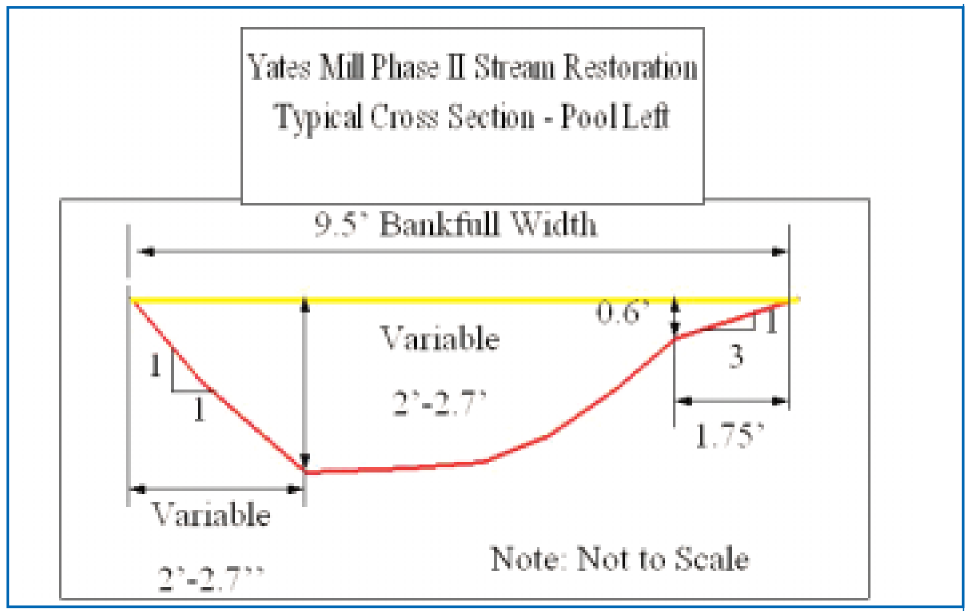


Step 26. Establish stations along the thalweg of the new stream channel alignment. Locate the position for each riffle, run, pool and glide along the new thalweg, remembering that pools are located on the outside of the meander bends. Determine the station for the head of each riffle, run, pool and glide and the max pool. When establishing the stations for these features, refer to the appropriate pool, riffle, run and glide lengths and pool-to-pool spacing established from the reference reach data *(Table 7.1).* Then plot the new longitudinal profile for the proposed stream alignment, including the thalweg and bankfull elevation using the feature stations. When constructing the new profile, first set the bankfull elevation using pool riffle, run and glide slopes from the reference reach data *(Table 7.1).* Then set the thalweg elevation using the maximum depths for riffles, runs, pools and glides determined from the reference reach data *(Table 7.1).* Overlay the new longitudinal profile with the existing profile for comparison *(Figure 7.3).*

Step 27. Calculate earthwork (cut-and-fill) volumes from the cross sections, and use stream length that is appropriate for the persistence of a particular cross section. Plot proposed cross sections overtop the existing channel cross sections.

Figure 7.2

Pool cross-section dimension detail



Step 28. Select specific stabilization devices such as grade-control structures, streambank revetment and riparian vegetation. Locate these features on the plan, profile and section views.

Step 29. Develop detailed design drawings for such specific stabilizing features as cross-vanes for grade control and bank stabilization *(see Chapter 8)*. Develop a plan, profile and section view for each stabilization feature. In the design details and specifications, show all dimensions and describe the materials and installation procedures *(see River Course Fact Sheet Number 4, Appendix A)*.

Step 30. Develop a planting plan for the project reach *(see Chapter 9)*.

Step 31. Develop a construction sequence and erosion-control plan *(see Chapter 10)*.

Step 32. If flooding is a concern or the project is in a FEMA-mapped area, produce hydraulic models to determine changes in flooding *(see Chapter 11)*.

Figure 7.3

Existing versus proposed longitudinal profile

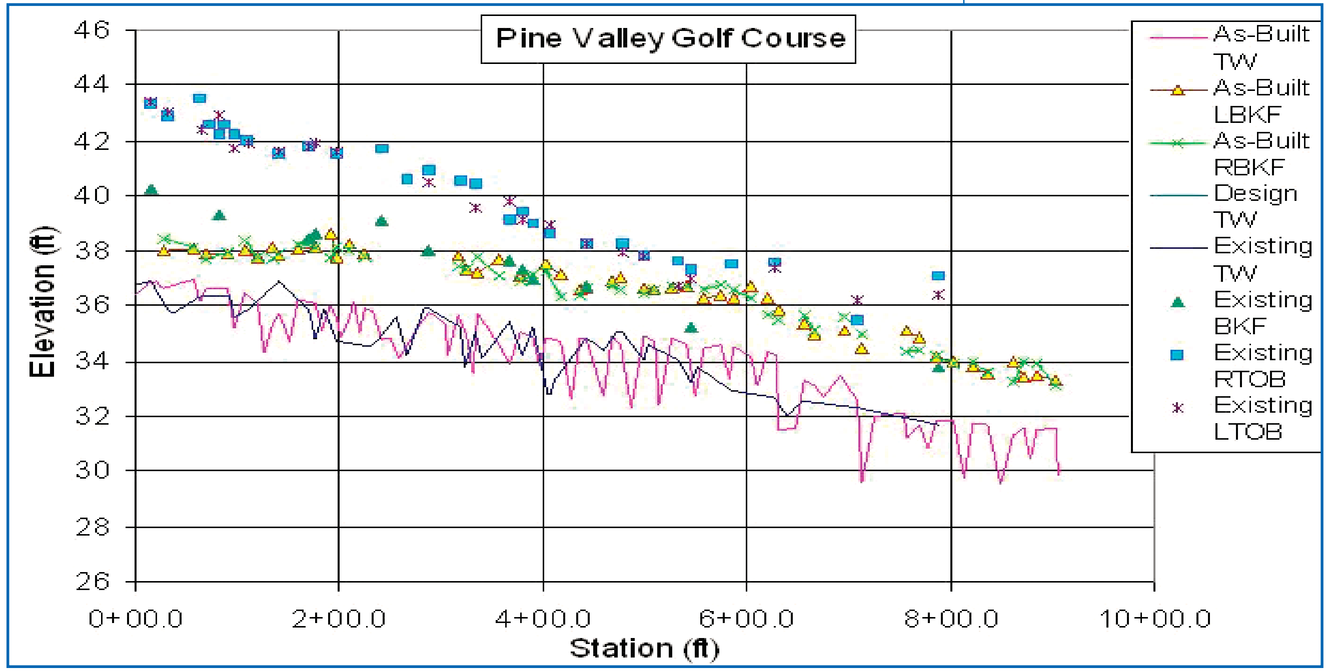


Table 7.1 Design, reference and existing-condition information

Modified from Rosgen, 1998c

	Existing Stream			Reference Reach				Design Stream		
Parameter	MIN	MAX	MEDIAN	MIN	MAX	MEDIAN		MIN	MAX	MEDIAN
Drainage area (sq mi)										
Stream type (Rosgen)										
Bankfull XSEC area, A_{bkf} (sq ft)										
Bankfull width, W_{bkf} (ft)										
Bankfull mean depth, D_{bkf} (ft)										
Width-to-depth ratio, W_{bkf}/D_{bkf}										
Width flood-prone area, W_{fpa} (ft)										
Entrenchment ratio, W_{fpa}/W_{bkf}										
Bankfull velocity (v_{bkf})										
Bankfull discharge (Q_{bkf})										
Max depth @ bkf, D_{max} (ft)										
Max depth ratio, D_{max}/D_{bkf}										
Bank height, D_{TOB} (ft)										
Bank height ratio (BHR), D_{TOB}/D_{max}										
Meander length, L_m (ft)										
Meander length ratio (BHR) , L_m/W_{bkf}										
Radius of curvature, R_c (ft)										
Radius-of-curvature ratio, R_c/W_{bkf}										
Belt width, W_{blt} (ft)										
Meander width ratio, W_{blt}/W_{bkf} (ft)										
Sinuosity, K										
Valley slope, S_{val} (ft/ft)										
Channel slope, S_{ave} (ft/ft)										
Riffle length, L_{rif} (ft)										
Riffle length ratio, L_{rif}/W_{bkf}										
Riffle slope, S_{rif} (ft/ft)										
Riffle slope ratio, S_{rif}/S_{ave}										
Pool slope, S_{pool} (ft/ft)										
Pool slope ratio, S_{pool}/S_{ave}										
Run slope, S_{run} (ft/ft)										
Run slope ratio, S_{run}/S_{ave}										
Glide slope, S_{glide} (ft/ft)										
Glide slope ratio, S_{glide}/S_{ave}										
Pool max depth, D_{pool} (ft)										
Pool max depth ratio, D_{pool}/D_{bkf}										
Pool area, A_{pool} (sq ft)										
Pool area ratio, A_{pool}/A_{bkf}										
Pool width, W_{pool} (ft)										
Pool width ratio, W_{pool}/W_{bkf}										
Pool length, L_{pool} (ft)										
Pool length ratio, L_{pool}/W_{bkf}										
Pool-pool spacing, p-p (ft)										
Pool-pool spacing ratio, p-p/W_{bkf}										
Reach-wide pebble count:										
d16 (mm)										
d35 (mm)										
d50 (mm)										
d84 (mm)										
d95 (mm)										

7.2 Sediment Transport

A stable stream has the capacity to move its sediment load without aggrading or degrading. The total load of sediment can be divided into bedload and suspended load. Suspended load is normally composed of fine sands, silts and clay and transported in suspension. Bedload moves by rolling, sliding or hopping (saltating) along the bed. At higher discharges, some portion of the bedload can be suspended, especially if it contains sand. The movement of particles depends on their physical properties—notably size, shape and density. Grain size directly influences the mobility of a given particle.

Gravel Bed Streams (d_{50} > 2 millimeters):

Sediment transport in streams with gravel and/or cobble beds is usually analyzed by estimating the shear stress or the competency of the stream to move a particular-size particle. Critical dimensionless shear stress τ^*_{ci} is a measure of the force required to mobilize and transport a given-size particle resting on the channel bed. It can be calculated using a bar sample and a wetted-perimeter cross-section pebble count or the pavement and subpavement particle sample from a representative riffle in the reach *(see Section 2.7-2.8 for pebble count, pavement, subpavement and bar sampling methods).*

Step 1: Collect bar samples from several key points along the stream reach that is being restored and the reference reaches. Key points include anywhere there are changes in stream type, bed-material composition or stability. For example, two or more samples may be needed to represent a 1,000-foot reach of stream. Collect pavement and subpavement samples from any areas of the design channel and reference reaches at which a bar sample is not possible. Also collect a wetted-perimeter cross-section substrate analysis (pebble count) for both the design channel and the reference reaches. See the substrate sampling procedures in sections 2.7 and 2.8 for methods of collecting bar, pavement, subpavement and wetted-perimeter pebble counts.

Step 2: Calculate the existing and proposed average bankfull slopes for the design reach from the longitudinal profile.

Step 3: Calculate critical dimensionless-shear-stress, τ^*_{ci}

a. Calculate the ratio $d_{50}/\hat{d}_{50}$, where d_{50}=median diameter of the riffle bed (from 100 count in the riffle or the pavement sample) and $\hat{d}_{50}$=median diameter of the bar sample (or subpavement sample). If the ratio $d_{50}/\hat{d}_{50}$ is between the values of 3.0 and 7.0, calculate τ^*_{ci} using Equation 1 *(Andrews, 1983)*.

$$\tau^*_{ci}=0.0834\left(\frac{d_{50}}{\hat{d}_{50}}\right)^{-0.872} \quad \textit{(Equation 1)}$$

b. If the ratio $d_{50}/\hat{d}_{50}$ is not between the values of 3.0 and 7.0, then calculate the ratio of d_i/d_{50}, where: d_i =largest particle from the bar sample (or from the subpavement sample) and d_{50}=median diameter of the riffle bed (from 100 count in the riffle or the pavement sample). If the ratio d_i/d_{50} is between the values of 1.3 and 3.0, then calculate τ^*_{ci}, using Equation 2 *(Andrews, 1983)*.

$$\tau^*_{ci}=0.0384\left(\frac{d_i}{d_{50}}\right)^{-0.887} \quad \textit{(Equation 2)}$$

Step 4. Once τ^*_{ci} is determined, calculate the minimum bankfull-mean-depth required for entrainment of the largest particle in the bar sample (or subpavement sample) and the bankfull water-surface-slope required for entrainment of the largest particle using equations 3 and 4, respectively.

$$D_r=\left(\frac{1.65\,\tau^*_{ci}\,d_i}{S_e}\right) \quad \textit{(Equation 3)}$$

$$S_r=\left(\frac{1.65\,\tau^*_{ci}\,d_i}{D_e}\right) \quad \textit{(Equation 4)}$$

Where: D_r=bankfull mean depth required (ft)
1.65=sediment density (submerged specific weight)= density of sediment (2.65g/c^3)–density of water (1.0g/c^3)
τ^*_{ci}=critical dimensionless shear stress
d_i=largest particle from bar sample (or subpavement sample) (ft)
S_e=existing bankfull water surface slope (ft/ft)
S_r=bankfull water surface slope required (ft/ft)
D_e=existing or design mean bankfull depth (ft)

If the design mean-riffle-depth is significantly larger or smaller than the depth needed to move the largest particle, the width-to-depth ratio may need to be adjusted up or down, respectively, to correct the depth.

Step 5. Check the bankfull shear stress at the riffle using Shield's curve *(Figure 7.4)* to ensure sediment-transport competence using Equation 5 (for wetted perimeter equations and information on calculating hydraulic radius, see Section 2.9). The shear stress placed on the sediment particles is the force that entrains and moves the particles, given by:

$$\tau=\gamma RS \quad \textit{(Equation 5)}$$

Where: τ=shear stress (lb/ft^2)
γ=density of water (62.4 lb/ft3)
R=hydraulic radius of the riffle cross-section at bankfull stage (ft)
s=average stream slope (ft/ft)

If Shield's curve reveals that the shear stress can move a particle size that is significantly larger or smaller than the d_i of the bar or subpavement sample, the sinuosity may need to be increased or decreased, respectively. Decreasing the sinuosity would increase the average channel slope, thus increasing the shear stress. Increasing the sinuosity would decrease the average channel slope, thus decreasing the shear stress. It is important to note that in field studies of rivers in Colorado, Rosgen reported transport of larger particles than Shield's tested at the upper range of shear stress *(Rosgen, 2002)*.

Sand and Silt/Clay Bed Streams

In the case of sand-bed streams, evaluate sediment-transport capacity, including stream power and sediment discharge. This type of analysis ensures that the stream has the ability to move the total sediment load through a cross section. Unit stream

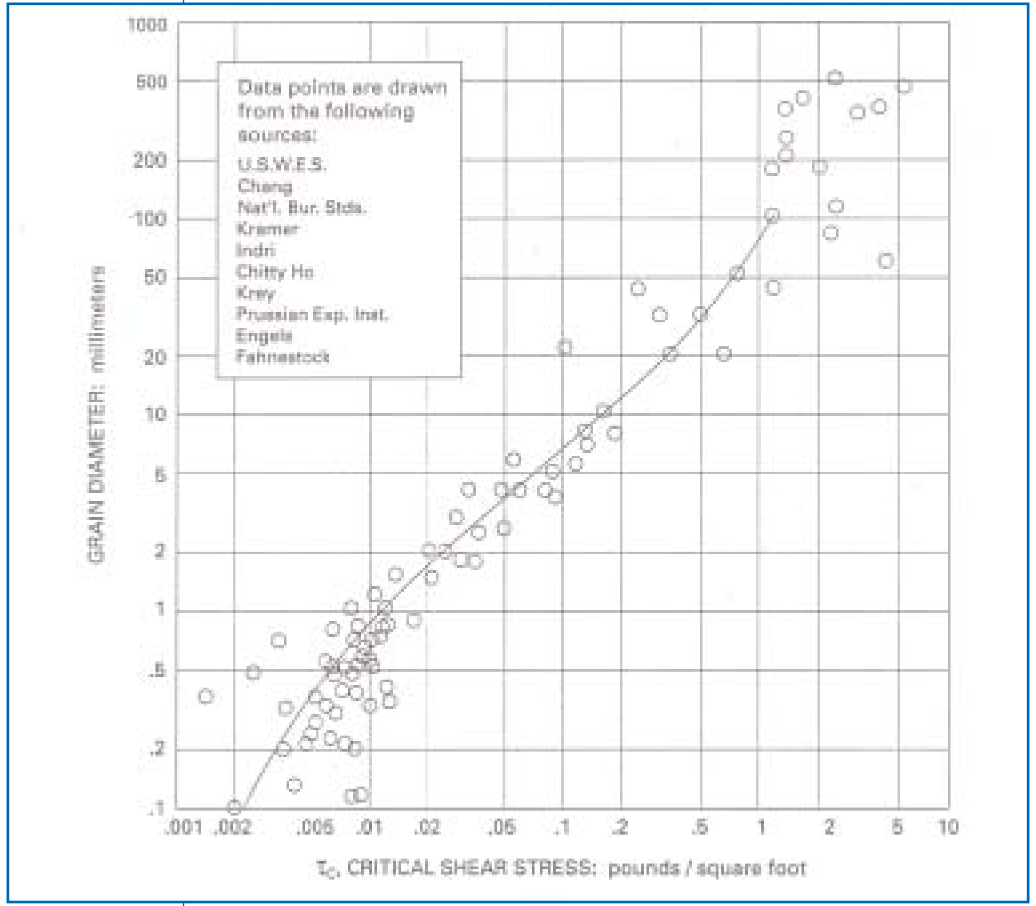


Figure 7.4

Shield's Diagram
Leopold, 1994, 194

power and/or a sediment-transport model, such as HEC 6 or SAM, can be used to model the design channel and compare the sediment-discharge rates to a section of reference stream, preferably upstream and downstream of the restoration reach. In this way, a sediment budget can be created in which the inflow of sediment is equal to the outflow. In addition, individual stream sections can be modeled to show localized competency and capacity. The same procedure can be applied to streams whose beds are sand/silt. In a stream with a cohesive-clay bed, little bed load transport would be expected. Clay-bed streams are typically stable or erode at very low rates; however, bed load could move through a stream reach. For example, sand and silt may pass through the stream reach as a result of low cohesion between sand and clay.

Structures

Chapter 8

Chapter 8: **Structures**

Selecting the methods for stabilizing a streambank is one of the last steps in designing a natural channel. This chapter provides natural channel designers with specifications and suggestions for installing rock and log structures (some structures and methods for stabilizing streambanks are not presented here). River Course Fact Sheet Number 4 *(Appendix A)* and Appendix E provide additional information and some design diagrams for structures. The designer must complete a thorough morphological assessment of the stream reach and watershed before using these techniques. Designers are encouraged to use a variety of techniques, depending on site conditions and the supply of native materials. Materials native to the region vary, so the materials chosen also will vary. Boulders are appropriate for streams with substrate of gravel and larger rocks; log structures are more appropriate for the low-sloping Coastal Plain sand-bed streams, where woody debris plays a significant role.

In-stream structures in restoration projects control the grade and protect the bank. Rock and log structures force the flow of water away from vulnerable streambanks that lack vegetation or have high bank-height ratios. Log vanes, root wads and similar structures add woody debris to the stream, enhancing habitat. Rosgen (2001c) has published helpful information on placement considerations, rock sizing, specifications and applications. Rosgen also has noted that in-stream structures should achieve the following goals:

ALL SITES:

- Maintain stable width-to-depth ratio
- Maintain enough shear stress to move the large particles (competence)
- Decrease near-bank velocity, shear stress or stream power
- Maintain channel capacity
- Maintain fish passage at all flows

SITE-SPECIFIC:

- Provide safe passage for or enhance recreational boating
- Improve fish habitat
- Be visibly compatible with natural channels
- Cost less than traditional structures
- Create maintenance-free diversion
- Reduce bridge pier/footer scour
- Reduce road-fill erosion and prevent sediment deposition.

Rosgen also notes that when sizing and choosing placement for in-stream structures, the project designer must:

- Base the rock size on bankfull shear-stress
- Use footers, in the absence of bedrock, to the depth of scour
- Consider using and locating these structures after completing the proper design of the dimension, pattern and profile for the restored channel
- Ensure stability of structure during high flows (floods)

See Rosgen, 2001c (available for download at http://www.wildlandhydrology.com).

8.1. Root Wads

A root wad is the root mass or root ball of a tree, including a portion of the trunk. Root wads armor a streambank by deflecting stream flows away from the bank. They also support the streambank structurally, provide habitat for fish and other aquatic animals and supply food for aquatic insects. A few examples of root wads are shown in figures 8.1 and 8.2.

Figure 8.1

Root wad placed on outside of meander bend

Figure 8.2

Track hoe with hydraulic thumb inserting root wad into streambank

Design Criteria

Ideally, the trunk of the tree above the root wad should have a 10- to 24-inch basal diameter. Root wads with larger diameters are more expensive to install and disturb more soil and vegetation. Regardless of diameter, the trunk length should be 10 to 15 feet. Install root wads where the primary flow vectors intercept the bank at acute angles. It generally is not necessary to place root wads against each other for the entire length of a meander bend. Install root wads at the toe of the bank, as low as possible. Generally, one-third to one-half of the root wad is placed below the base-flow elevation. Where scour depths are high, install footer logs below the root wads. Where bank heights are low—1 to 1 1/2 times bankfull height—place boulders at least 1 ton or heavier behind the root wad. If banks are high and have plenty of vegetation and root mass, footer logs and boulders may not be needed (*Figure 8.1*). Boulders and transplants prevent back-eddy scour that may be caused by the root wad during high flow. In North Carolina, root wads are most successful on the outside of gentle meanders (high ratio of radius-of-curvature to bankfull width) and upstream of streambank vegetation, where they will help prevent erosion from any back eddies that occur during high flow.

Installation

Root wads are installed by either the drive-point method or trenching methods. The drive-point method is preferred because it disturbs the least amount of soil and adjacent vegetation and is more cost-effective. The drive-point method uses a track hoe with a hydraulic thumb to insert the root wad directly into the bank *(Figure 8.2)*. Sharpen the end of the log with a chainsaw before driving it into the bank. A loader or second track hoe may be used to hold the root wad in place while the track hoe with the hydraulic thumb grasps the root fan and drives the trunk into the bank. To prevent destruction of the root fan, don't ram the track-hoe bucket into the root wad excessively (if the streambank is resistant to the root wad and trunk, consider the trenching method or substitute another structure). If vegetation exists on the streambanks, avoid destroying these plants during installation. Orient root wads upstream so that the stream flow meets the root wad at a 90-degree angle, deflecting water away from the bank (*Figure 8.1*). If a back eddy is formed by the structure, place a transplant or boulder on the downstream side of the root wad.

If the root wad cannot be driven into the bank or the bank needs reconstruction, use the trenching method. For this method, excavate a trench for the log portion and install a footer log underneath the root wad. Place the footer log in a trench excavated parallel to the bank and well below the streambed. Place the root wad on top of the footer. Keep at least one-third of the root wad below normal base-flow conditions. Once the root wad is installed, backfill the trench and rebuild the bank with transplants or sod mats. Grade the upper bank or terrace scarp to a maximum slope of 1.5:1, seed it with a rye grain or other native seed material, and cover it with an erosion-control fabric.

8.2. Vanes

Vanes come in four types: single vane, J-hook vane, cross vane and W-weir. Vanes can be constructed from large tree trunks or boulders, but most are built using boulders. Single and J-hook vanes protect the streambank by redirecting the thalweg away from the streambank and toward the center of the channel. They also improve in-stream habitat by creating scour pools and providing oxygen and cover. Cross vanes serve a similar purpose and also may control the grade in both meandering and step-pool streams.

Design Criteria

All four vanes are oriented upstream at 20- to 30-degree angles off the bank. Single and J-hook vanes are located just downstream of where the stream flow encounters the streambank at acute angles. Vanes should be highest next to the bank, generally starting at or slightly below bankfull. Rock vanes along the outside of a meander bend are shown in Figure 8.3. If the potential for bank erosion is not too high, start the structures between bankfull and the inner berm. In either case, slope the structures downward, pointing them upstream. The size of rock will depend on the size of the stream, the dominant bed material and the depth of scour in the channel at high flow. In streams with substrate of gravel or larger rock, the boulders should be generally 1 to 2 tons. Flat rocks are preferable. In a newly created channel (i.e., Priority 1 restoration), consider using sills on the vane structures. Sills extend into the bank where the highest rock meets the streambank. The purpose of the sill is to prevent water from cutting around the boulders next to the bank during high flow. This is especially important on newly excavated channels that may have unconsolidated materials on the banks and little or no vegetation for a while. All structures (diagrams) shown in this section include sills.

The length of a single-vane structure may span up to one-half of the base-flow channel width. The slope of the structures may range from 2 to 20 percent; the longer and flatter the structures, the more streambank protected and habitat enhanced. The rocks in all three structures (except the last two rocks of a J-hook) must touch each other, and footer rocks must be placed at

Figure 8.3

Rock vanes on outside of meander bend immediately after installation (looking upstream) the depth of scour. One to two rocks underneath and downstream of the top rock usually will suffice. To prevent the structure from toppling into a scour hole, place the footer rock downstream of the top rock.

J-hook vanes are built like single vanes except for the last two to three rocks. Space these rocks apart about one-half the diameter of the rock to create flow-convergence *(figures 8.4 and 8.6)*. This flow-convergence creates a large scour hole to dissipate energy and provide aquatic habitat.

Figure 8.4

Looking downstream at a J-hook vane

Cross vanes provide grade control, keep the thalweg in the center of the channel and protect streambanks from erosion. A cross vane has three components: two rock vanes and one center structure placed perpendicular to the flow. The center structure sets the grade of the streambed. Installed cross vanes are shown in figures 8.7 and 8.8. Since a cross vane raises or holds the bed elevation, it is often placed within the glide or at the head of the riffle. This placement sets the elevation of the upstream pool and holds the elevation of the downstream riffle. A cross vane at the head of a riffle is typical in small streams that have a short distance between features. In larger streams, the cross vane is placed in the glide *(Figure 8.9)*.

Figure 8.5

Rock vane and J-hook vane (looking upstream)

With cross vanes and log structures, geotextile material is used on the upstream side of the boulders or logs. Footers help prevent movement of the structure during high flow, but spaces between the boulders can allow material to move through, creating a "hole" in the cross vane. Even if the rocks are touching, these holes still may appear *(Figure 8.10)*. If the hole is large enough, the majority, if not all, of the flow at base-flow level may move through it. If the channel has a variety of substrate sizes (small gravel to cobble), back-filling on the upstream side of the structure may close these gaps. But if the material is too uniform or the gaps too large, the structure may eventually be compromised. To prevent this, place geotextile fabric on the upstream side of the structure during construction and bury it to the depth of the footers (this is strongly recommended for structures that provide critical grade-control on a project). The fabric will help to prevent water from piping between or underneath the rocks or logs. Once the backfill material is placed upstream of this, no material should move through at all. Figure 8.11 shows fabric being used on a log vane. To ensure stability of important grade-control structures, such as in a step-pool system, minimize the drop in elevation for each structure. The larger the difference in elevation from immediately upstream to downstream of the structure, the more stress is placed on the structure itself. In this case, grade control may fail and jeopardize the entire project.

The W-weir structure is very similar to the cross vane, in that it maintains the grade of the streambed and provides excellent aquatic habitat. W-weirs can be used only on large rivers

Figure 8.6

J-hook placement in meander bend

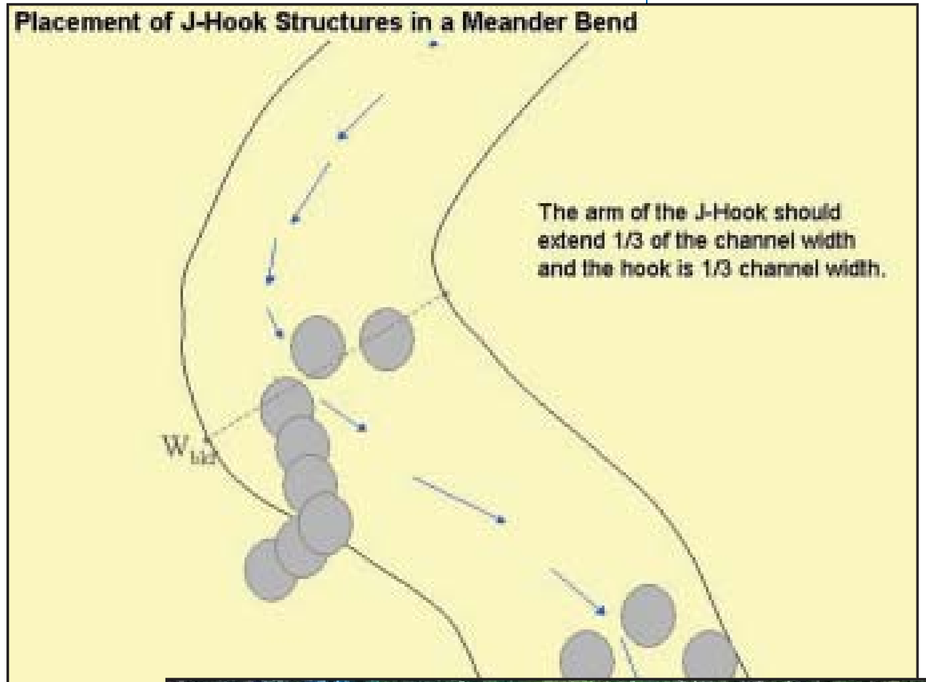


Figure 8.7

Cross-vane structure with woody debris for habitat enhancement

Figure 8.8

Cross vane showing placement and measurements
* The lowest slope is most desirable, but in small streams a narrow channel may necessitate higher slopes (10 to 20 percent).

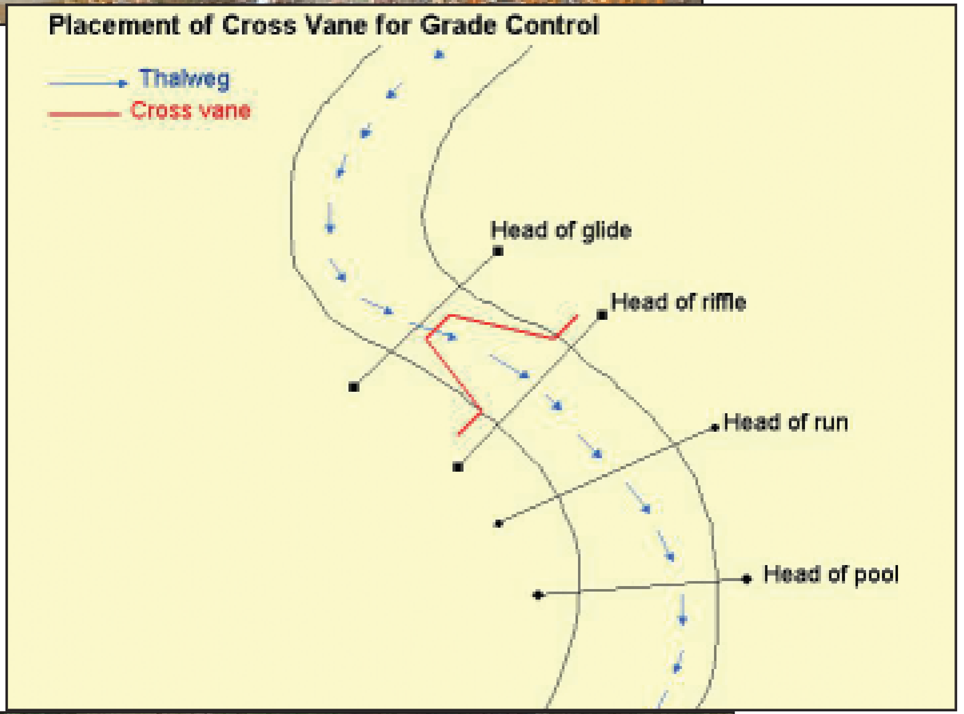


Figure 8.9

Placement of cross-vane structure in a meandering stream

Figure 8.10

Hole formed on cross vane due to gap in structure

because they span a significant distance across the channel. Their design is described as a W formation in the downstream direction. From the plan-view perspective, the weir is similar to two cross-vanes joined in the center of the channel. Figure 8.12 shows a schematic of the W-weir. Due to the double cross-vane effect of the W-weir, two thalwegs are created. This design helps to enhance fish habitat. The W-weir also can be designed to maintain recreational boating, stabilize streambanks, facilitate irrigation diversions, reduce scour of a bridge's center pier and foundation, and increase sediment transport at bridge crossings. Two W-weirs may be constructed together on very wide rivers and/or where two bridge center piers (three cells) require protection *(Rosgen, 2001c)*.

Figure 8.11

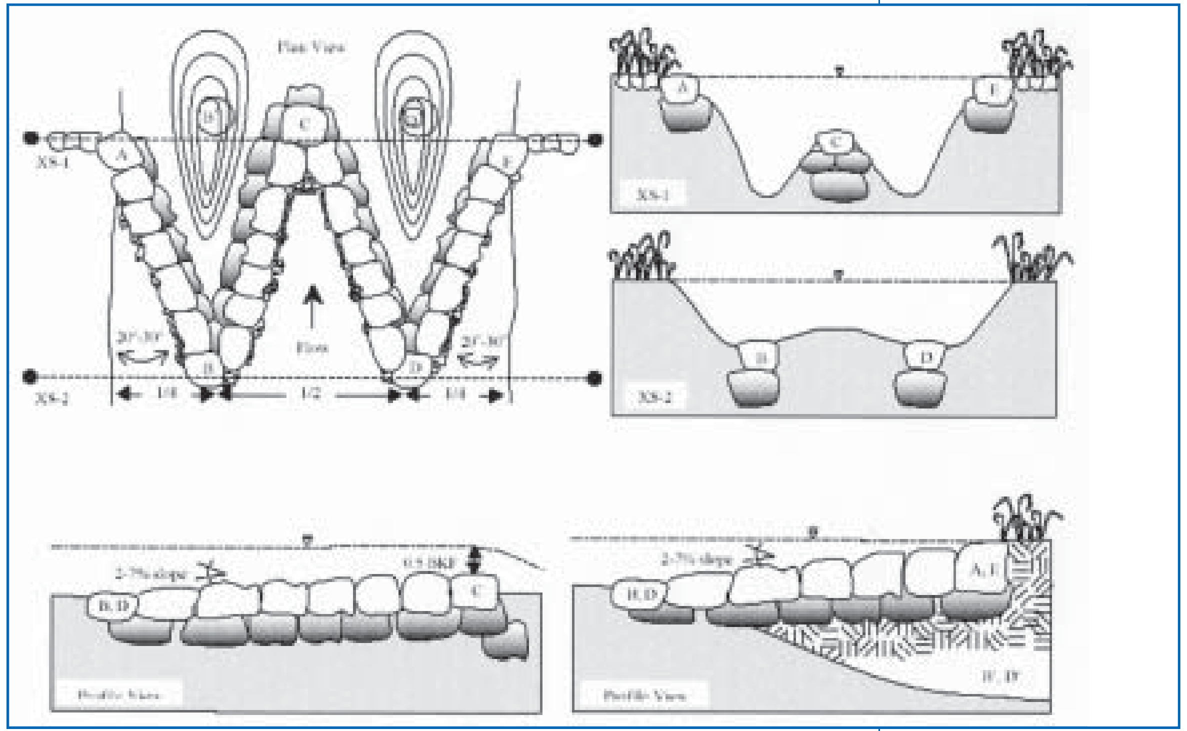
Use of geotextile fabric on the upstream side of log structure

8.3 Stream Crossings

Design road crossings to minimize negative impacts on stream stability, sediment transport, aquatic habitat and fish passage while meeting prescribed hydraulic and structural criteria. The ultimate goal is to construct a stable stream system that neither

Figure 8.12

Plan, cross section and profile views of the W-weir
Rosgen 2001c



scours nor aggrades. This approach includes maintaining the consistency of dimension, pattern and profile of the stream with particular attention to maintaining bankfull width and width-to-depth ratio. Where feasible, use bridges or arch culverts to minimize floodplain restrictions. For culvert systems, use floodplain culverts, where appropriate, to relieve the hydraulic load on the main-channel culvert; this will limit downstream scour and erosion *(see Figure 8.13).*

Figure 8.13

Floodplain culverts on Rocky Branch, NC State University

Specific design recommendations are:

1. Maintain the natural stream-gradient and meander-pattern. Avoid overly steep or perched culverts that will block fish passage.
2. Cross the stream at a perpendicular angle.
3. Size the main culvert to match the natural channel bankfull width. Provide for the unobstructed flow of the bankfull storm-event in the main culvert without changing velocity.
4. Design the culvert openings to maintain base flow at its normal width, depth and velocity. This may require low weirs or multiple openings to carry base flow and avoid sediment buildup in the system.
5. Use bankfull culvert openings on the floodplain to carry flows exceeding bankfull discharge.
6. Where appropriate, use boulder cross-vanes upstream and downstream of the culvert to maintain desired flow direction and grade, improve sediment transport through culverts, and improve habitat.

8.4 Structures and Design Features for Habitat Enhancement

Stream restoration work historically has concentrated on redesigning the dimension, pattern and profile of impacted stream reaches. Designs often are patterned after reference-reach streams and focus on reducing bank erosion and providing effective sediment transport. Restoration and enhancement projects generally also address the restoration of the riparian buffer. However, the restoration of in-stream habitat has not been addressed as thoroughly as channel stability and riparian vegetation. Many benthic organisms prefer one type of microhabitat, depending on season. For example, certain species of caddisflies are typically found only in riffles, which are the most productive habitat for many benthic (bottom-dwelling) organisms. Successful restoration projects should therefore provide proper riffle/pool sequences to ensure recolonization. Different fish species require different habitat types. Good in-stream habitat is structurally complex and is composed of both inorganic (i.e., boulder, cobble, fine sediment particles) and organic components. Pools and riffles of varying sizes and placements are important too. Additional important habitat features that can be included in a stream restoration design are listed below.

Overhanging woody vegetation provides food, shade and cover for aquatic organisms. Installing transplants and live stakes of alder, silky dogwoods and willows around rootwads will help to establish overhanging vegetation quickly.

Erratic rocks with ledges and shelves provide cover and habitat. Use that "odd" rock that won't fit into a structure as part of a boulder cluster. Stacking rocks can be used to create a "cubbyhole" feature.

Boulder clusters create multiple points of flow-convergence and eddies. Upwelling from subsurface flows around boulders pulls material into the water column. Fish can hold behind the clusters in eddies and feed in the upwelling. Currents also cleanse the substrate and provide better spawning habitat. Boulder clusters and other structures (such as large woody debris) can catch and hold limbs and debris that will snag leaf-packs. Leaf-packs accumulate in streams and provide habitat and food for a number of benthic insects. Therefore, adding large woody debris can enhance the habitat of boulder clusters.

Large woody debris placed in pools or lodged under boulders, combined with other structures, can provide "snag" habitat for fish and will help trap leaf-packs, which are important to productivity. Logjams between vane structures can be incorporated to improve pool habitat. Logs should not be incorporated into a vane structure because it may create a gap in the structure that could cause a failure. Large woody debris can be placed in the floodplain and will later be available to the stream during high flows. However, too much large woody debris in the floodplain could cause a downstream debris jam and extensive bank erosion.

Deep pools provide great cover and holding areas (places with little or no current) for fish. Large woody debris anchored in the pool also will provide snag habitat. Designers are often reluctant to dig the thalweg at the outermost edge of the meander bend for fear that the bank might collapse. However, installation of root wads, live stakes or fabric anchors in the meander bend should prevent instability.

Floodplain pools provide excellent habitat not only for amphibians but also for certain species of insects such as dragonflies and damselflies. To ensure that these pools continue to provide good amphibian habitat, it is important to design and build them so that they dry out every two to three years. This prevents a large population of predators (i.e., fish) from becoming established in the pool. Amphibian organisms are adapted to periods of drought—adults can burrow in the substrate for protection, and many eggs and small larvae also can survive.

Coarse substrate harvested from the existing stream channel can be reintroduced into newly constructed riffles to speed habitat development. Substrate harvesting can be particularly beneficial in Priority 1 stream-restoration projects that involve constructing a new channel and abandoning the existing stream channel.

Other microhabitats, which presumably will develop over time, often are not specifically considered as part of a restoration project. Although these habitat components are hard to construct, project monitors should note their development or lack thereof. Some examples of these complementary habitats are described as follows:

Fine particulate organic material: Over time, fine particulate organic matter collects in the interstitial spaces between the dominant substrate material. This material is food for many benthic organisms. All collector-gatherer organisms will feed on this type of organic material at some point in their life cycle. The increase in habitat heterogeneity should also improve the streambed/hyporheic zone connection and movement of animals between zones under different flow conditions.

Aquatic plants: Very little consideration has been given to how important aquatic plants (including macrophytes and attached algae) are to the benthic fauna of restoration reaches. Many benthic insects are collected only in this type of habitat. Caddisflies *(Micrasema, Brachycentrus)*, mayflies *(Ephemerellidae)* and chironomids are commonly collected in aquatic macrophytes (specifically *Podostemum,* commonly known as river weed, in North Carolina). Living plants provide structural habitat. When they die, they are colonized by bacteria and fungi, becoming food for aquatic macroinvertebrates.

Fine streambank root material: Rootwads provide habitat for fish and stabilize eroding streambanks. However, most of them do not mimic streambank plants, which usually extend fine roots into the current along the outside bends in a stable stream. Many leptocerid caddisflies *(Triaenodes, Oecetis)* and odonata (dragonflies and damselflies) are found primarily in this habitat.

Vegetation Stabilization and Riparian-Buffer Re-establishment

Chapter 9

Chapter 9: **Vegetation Stabilization and Riparian-Buffer Re-establishment**

A combination of planting methods improves the chances for successfully fulfilling the restoration objectives of bank stabilization, flood attenuation and habitat enhancement. Appendix F lists appropriate species from the three physiographic regions of North Carolina to incorporate into restoration plans.

9.1. Salvaging On-Site Vegetation

Potential transplants may include small trees up to 3 inches in diameter. Sycamores are an easily salvaged species. Prune these trees to about 6 feet and scoop the entire root mass with the bucket of a track hoe. Keep the root balls and surrounding soil intact. Don't rip limbs or bark from the transplants. Such native shrubs as alder *(Alnus* spp.*),* elderberry *(Sambucus canadensis)* and spicebush *(Lindera benzoin)* also are good transplants. Prune shrubs to 3 or 4 feet and harvest like the trees. Herbaceous plants can be salvaged as well. Rushes *(Juncus* spp.*),* sedges *(Carex* spp.*)* and other tender plants can be harvested and placed at the toe slope along the water's edge, where woody vegetation is not appropriate.

If salvaged vegetation cannot be installed immediately, stockpile it in a relatively moist area or keep it continually moist. This is especially important during summer.

Place woody transplants at bankfull elevation or above. If soil is compacted in the planting area, loosen it to a depth of at least 1 foot. Plant transplants the same depth at which they were originally growing. Replace soil around the transplants and tamp it down to eliminate air pockets. Spacing will depend on availability of material. If transplants are limited, start in critical areas, such as along meander bends or near in-stream structures.

Figure 9.1

Salvaging vegetation at construction site

Figure 9.2

Successfully planted black-willow stake

9.2. Live Staking

As with transplants, it may be possible to harvest stake material from the site. Stakes are branches or small limbs cut from a larger tree or shrub. If material is not available on-site, check with surrounding landowners or nurseries. Silky dogwood *(Cornus amomum)* and willow *(Salix* spp.*)* are good candidates for staking. Some species of shrubs and trees can be propagated from cuttings and root stems, although this technique is labor-intensive. Stakes should range from one-half inch to 2 inches in diameter with an average length of 3 feet. Cut stakes with an angle on the bottom and flush on tops, with buds oriented upward. Trim all side branches cleanly so the cutting is one stem. Keep stakes cool and moist to keep them alive and dormant. Plant stakes in late fall to early spring while they are dormant. Install stakes in areas where erosive forces are greatest, such as along meander bends and behind in-stream structures. Stakes usually are installed 2 to 4 feet apart using triangular spacing along the streambanks. Different sites may require slightly different spacing. Drive stakes into the ground with a rubber hammer, or make a hole using a metal bar and slip the stake into it. Tamp each stake in at a right angle to the slope, keeping one-half to four-fifths of the stake below the ground surface. At least two buds (lateral and/or terminal) should remain above the ground surface. Pack the soil firmly around the hole afterward. Do not use split stakes.

9.3. Bare-Root Plantings

Bare-root material is recommended on large restoration sites requiring many trees. Bare-root plantings are more economical than container plants, although survival rates may be lower. Choose plants from local nurseries or growers that offer plants suited to the site. Refer to Appendix F for a list of appropriate species to plant in North Carolina.

Late fall to early spring is the best time for planting. Early fall planting allows more time for root establishment. If bare-root plants can't be installed right away, heel them into moist soil or sawdust, according to general horticultural practice. Use wet canvas, burlap, straw or other suitable material at all times to prevent drying. The method selected should be appropriate to the weather conditions and the length of time the roots will remain out of the ground.

Figure 9.3

Demonstration of bare-root seedling installation with dibble bar

Loosen soil in the planting area to a depth of at least 5 inches. Make planting holes with a mattock, dibble, planting bar, shovel or other appropriate tool. Plant rootstock in a vertical position with the root collar about one-half inch below the soil surface. Make sure the planting trench or hole is deep and wide enough to permit the roots to spread out and down. Keep the plant stem upright. Replace soil and tamp firmly around each transplant to eliminate air pockets. See Appendix F for an installation diagram. Spacing guidelines for rooted shrubs and trees are provided in Table 9.1.

Type	Spacing	# Per 1,000 sq ft
Shrubs and trees (10-25 ft)	6-8 ft	15-25
Trees (>25 ft)	8-15 ft	4-15

Table 9.1. Spacing guidelines for shrubs and trees

9.4. Container Plant Material

Some projects may require container, or potted, plants. These come in many different sizes and shapes. Check with local nurseries and growers for availability. When installing potted plants, dig a hole that is twice the diameter of the pot. Remove the plant from the container and tease roots apart if the plant is root-bound. Place plant in hole, making sure the root collar is even with the ground surface and the stem is upright. Back-fill with potting soil or fill from the hole. Make sure the fill is free of clods and stones, loose and evenly distributed around the plant. Tamp firmly around the plant to eliminate air pockets. Add mulch to retain moisture. Refer to Section 9.3 for installation techniques and spacing requirements. Appendix F lists appropriate species for North Carolina.

Figure 9.4

Installing potted plants

9.5. Permanent Seeding

For maximum habitat diversity and ground cover, include seeds among the planted material. Permanent (perennial) seeding mixtures are available from nurseries and can vary widely. A site-specific combination of herbaceous species and grasses based on surrounding native flora is recommended. Site conditions and project requirements will determine the vegetation needs and installation methods. Appendix F lists appropriate herbaceous species for North Carolina. Follow nursery recommendations for appropriate planting times and methods. Before planting the permanent seed mix, see the site-preparation and soil-amendment procedures in Section 10.2.

Figure 9.5

Example of permanent seed mix

Notes:

Erosion and Sediment Control Plan

Chapter 10

Chapter 10: **Erosion and Sediment Control Plan**

10.1. Pollution Control: Construction Sequence and Structures

All restoration work should comply with the requirements of the North Carolina Sedimentation Pollution Control Act and the federal Clean Water Act. During construction, measures must be taken to control erosion and minimize the production of sediment and other pollutants of water and air.

Construction Sequence

The construction sequence is a critical component of the erosion and sediment control plan for a stream-restoration project. First, it is important to divide the stream into segments or reaches for construction. Each segment can be completed and stabilized before moving on to the next. This will minimize the exposed soil that is vulnerable to erosion at any given time during the project. Schedule the excavation and moving of soil materials so areas will be unprotected from erosion for the shortest time feasible. Stockpile any soil excavated from the new channel in locations shown on construction plans/drawings. Install silt fences around all stockpiles.

Three basic approaches can be used to address potential sediment and erosion associated with stream restoration: 1) construct the new channel in the dry (absent of stream flow), 2) pump or divert the water around each project stream reach, or 3) work in the active channel. Constructing a new channel in the dry is preferred, and it is often possible in many Priority 1 and some Priority 2 *(see Chapter 5)* stream-restoration projects. Because water continues to flow in the old channel, this approach allows the new channel to be built and stabilized on dry ground before it is exposed to stream flow. Pumping or diverting the water around the active construction project is feasible in small watersheds with low to moderate base flow; it generally is not feasible in streams with large base flow. Even in smaller streams, pumping usually cannot be maintained during storm flows, so precautions must be taken to minimize exposed soil and associated erosion. The least-preferred option is working in the active stream channel, though it is necessary in many cases. When working in the active channel, it is important to start and finish each element of the project in a single day. For example, if construction of a boulder cross-vane begins in the morning, the vane should be completed and erosion-control matting installed on disturbed streambanks the same day. Sediment-control measures should be taken below the construction project to prevent sediment from traveling downstream. Such measures might include check dams and various sediment-trapping fabrics as described in the North Carolina Erosion and Sediment Control Planning and Design Manual *(available from the North Carolina Division of Land Resources, http://www.dlr.enr.state.nc.us/eropubs.html).*

Following are examples of temporary measures commonly used in stream-restoration projects to reduce sedimentation and erosion. All pollution-control measures and works must be kept functional as long as needed during the construction operation. Remove all temporary measures and restore the site as closely as possible to original conditions *(see the N.C. Sedimentation and Erosion-Control Manual).*

Diversions – Diversion structures divert water away and collect runoff from work areas for treatment by sediment traps, such as check dams. If possible, diversions should be constructed along a contour so that they have a near-flat slope. Diversions should be seeded and lined with erosion-control fabric, if necessary, or otherwise stabilized so they do not erode.

Stream Crossings – Equipment should cross streams at fords or temporary culverts. To construct a ford, grade a ramp into the stream channel on both banks. These ramps should be 5:1 or flatter and lined with stone. Install filter fabric combined with stone in the bed of the stream. Any temporary culvert should be sized to carry at least the bankfull discharge. Place stone on the upstream and downstream sides of the culvert to prevent erosion of the streambanks, and fill soil around the culverts. Also, place stone on top of the fill on which heavy equipment will be driven.

Sediment Filters – Geotextile sediment fences will trap sediment from areas with limited runoff (never use them in areas of concentrated flow). Install these fences on the contour along the entire downstream perimeter of the area being disturbed. To effectively trap sediment, these filters should be trenched into the ground and properly anchored. Make sure support stakes are properly spaced; if heavy-duty filter fabric is not being used, install wire support behind the filter.

Waterways – Waterways can be used for the safe disposal of runoff from fields, diversions and other structures. Stabilize waterways with grass, erosion-control fabric or stone, depending on the slope of the waterway. Make sure the outlet for the water-

Figure 10.1

Properly installed erosion-control blanket way is stable and equipped with stone or other material that will dissipate the energy of water being discharged.

Coconut/Straw-Fiber Blanket – Coconut/straw-fiber blankets should be used only on streambanks with little or no established vegetation at the time the stream flow is directed into the newly constructed channel. Project specifications will determine the type of erosion-control blanket to use. For wildlife and habitat purposes, it is best to use completely biodegradable blankets. Blankets with plastic components often trap animals. Lay the coconut/straw-fiber blanket when grading is complete. Provide a smooth soil surface free of stones, clods or other debris that will prevent the contact of the blanket with the soil. Apply fertilizer, seed and lime prior to installing blankets. Follow manufacturer's guidelines for installation. The engineer/ project manager may need to adjust the trenching or stapling requirements to fit individual site conditions.

Other – Additional erosion-control measures may be required by the federal, state or local government agency that is responsible for reviewing and inspecting the site's erosion-control plan.

10.2. Pollution Control: Seeding

Seed any disturbed areas, including streambanks, access areas and stockpile locations. Immediately after construction activities are completed, plant seeds of both permanent and temporary vegetation. This work includes preparing the area; furnishing and placing the seed, mulch, fertilizer and soil amendments; and anchoring mulch.

1. Seedbed Preparation – On sites where equipment can be operated safely, loosen the seed bed mechanically. Compacted soil may require disking. Steep banks may require roughening, either by hand-scarifying or equipment. The engineer/ project manager should determine the condition needs on-site. If seeding is done immediately after construction, seedbed preparation may not be necessary. Exceptions would be in compacted, polished or freshly cut areas.

2. Fertilizing/Liming – In disturbed areas, fertilizer and lime will help seeds establish more quickly. If possible, test the soil's fertility. The N.C. Department of Agriculture tests soil samples at no charge. These tests help determine proper distribution rates for fertilizer and lime in the sampled area. See Appendix F for the department's Soil Sample Information Sheet and contact information. Distribute fertilizer and lime evenly over the area to be seeded. Mix the fertilizer and lime uniformly into the top 3 inches of soil; if the bed is gravelly or cobbled, incorporation is not necessary. Fertilizer and lime should be applied at the following rates:

10-10-10 Fertilizer: 10 lbs per 1,000 sq ft **or** 435 lbs per acre

Lime: 50 lbs per 1,000 sq ft **or** 2,200 lbs per acre

3. Temporary Seeding – Temporary seeding is useful for erosion-control when permanent vegetation cannot be established due to planting season and where temporary ground cover is needed to allow time for native or woody vegetation to become established. Choose an annual seed that will not outcompete native vegetation. Apply the following vegetation at the listed rates.

Fall, Winter, Spring Seeding:
Rye grain/winter wheat mix, winter wheat or barley
3 lbs per 1,000 sq ft or 130 lbs per acre.

Summer Seeding:
Browntop millet, Sudan grass
1 lb per 1,000 sq ft **or** 45 lbs per acre

4. Mulching – Mulch temporarily protects soil from erosion. Apply mulch within 48 hours of seeding. Apply straw mulch on seeded areas at a rate of 3 bales per 1,000 sq ft (130 bales per acre). Apply mulch uniformly. Anchor with biodegradable netting.

Notes:

Chapter 11

Flood Studies

Chapter 11: **Flood Studies**

11.1. Introduction

The regulations administered by the Federal Emergency Management Agency (FEMA) are applicable to projects in areas that have been mapped by FEMA. FEMA's National Flood Insurance Program (NFIP) promotes sound land-use practices within the floodplain. The NFIP limits the impact of flooding by restricting development, buying property and using flood-control structures in the floodplain. One of the most important functions of the NFIP is establishing flood insurance rates through the use of risk data.

Section 60.3(d)(3) of the National Flood Insurance Program (NFIP) regulations states that a community shall "*prohibit encroachments, including fill, new construction, substantial improvements, and other development within the adopted regulatory floodway unless it has been demonstrated through hydrologic and hydraulic analyses performed in accordance with standard engineering practice that the proposed encroachment would not result in any increase in flood levels within the community during the occurrence of the base (100-year) flood discharge.*"

Figure 11.1

Flooding from Hurricane Floyd

Photograph courtesy of J. Jordan, U.S. Army Corps of Engineers

When a new project is proposed, the designer must consider two potential impacts. The first potential impact is the change in flood levels. During flood flows, flooding may occur in areas that have never flooded. The second impact is any change in the floodway. A floodway is the area around a stream in which development is prohibited *(Figure 11.2)*. Increasing the floodway could have significant impacts on the insurance rates for any affected property owner(s) and decrease the amount of developable property. Contact the local FEMA administrator early in the process to ensure that the project is acceptable to the community.

11.2. FEMA Maps and Nomenclature

When a project will change the existing floodway and 100-year flood elevations, an application must be submitted to FEMA containing the modeling results from the proposed project and the proposed map revisions. If approved, FEMA will issue a "conditional letter of map revision" (also known as a CLOMR). Once the project is completed, new cross sections must be generated from the "as-built" survey information. The new cross sections are then used to develop a new hydraulic model. The new maps and modeling results generated from the as-built information are then submitted to FEMA. Once these are approved by FEMA, a "letter of map revision" (LOMR) is issued. One of the most important aspects of a map revision is the change in the floodway *(Figure 11.2)*.

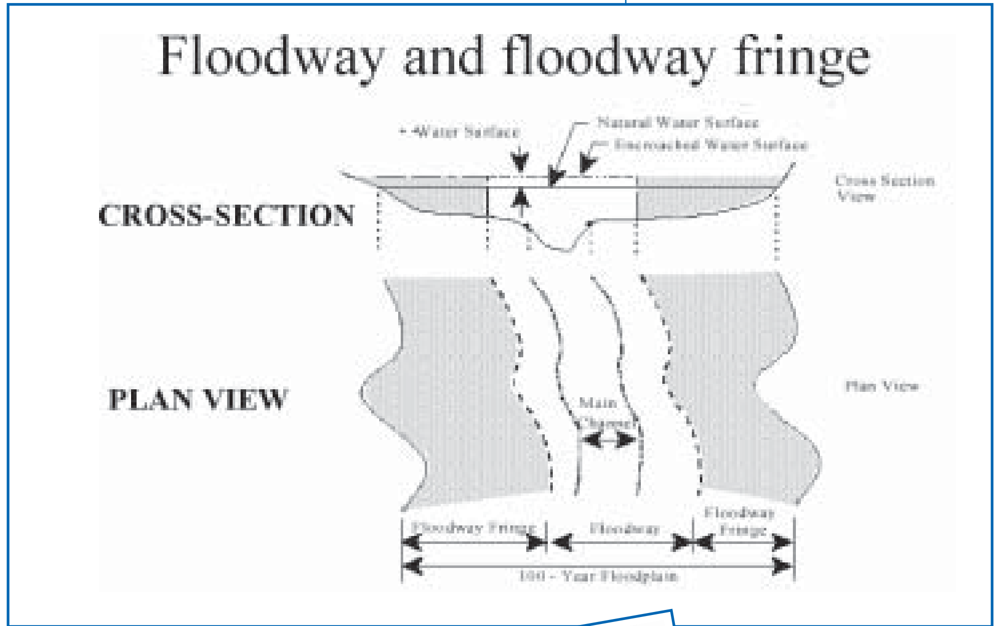


Figure 11.2

Illustration of floodway and floodway fringe

U.S. Army Corps of Engineers, HEC-RAS User Manual documentation

FEMA offers NFIP flood maps that show the extent of flooding for a 100-year flood *(Figure 11.3).* Reports called "Flood Insurance Studies," which contain data and results, accompany the flood maps. Flood maps provide the community name, community number (six-digit number) and effective date in the lower right corner of the map. This information is required for ordering a hydraulic model and completing the MT-2 form for a CLOMR.

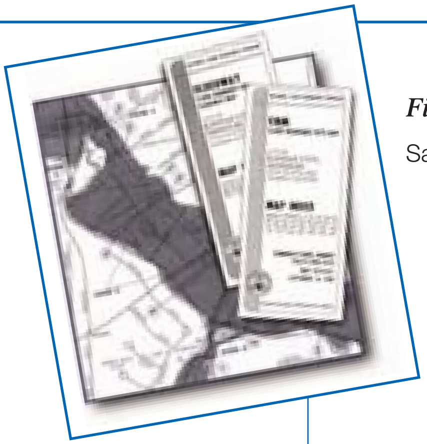


Figure 11.3

Sample FEMA map

A FEMA map (or plate as it is sometimes called) depicts several zones that indicate flood boundaries and shows whether they were derived from modeling or from approximate methods. Zones A and AE indicate the 100-year floodplain using approximate methods and modeling, respectively. Zones V and VE indicate the 100-year floodplain plus hazards from storm waves (for coastal projects) using approximate methods and modeling,

Figure 11.4

Sample excerpt from FEMA map

respectively. FEMA Zone X has multiple meanings, including but not limited to: outside the 500-year floodplain (not regulated); within the 500-year floodplain (not regulated); within the 100-year floodplain with flood depth less than 1 foot; and areas protected from the 100-year flood by dikes. Zone D indicates areas where flood studies haven't been conducted but are possible. The floodway is indicated by the crosshatched areas over the stream channel *(Figure 11.4)*.

11.3. FEMA Requirements and Flood Modeling

If the project is not in a FEMA-mapped area, no federal requirements apply. The only requirements may be those of local authorities (city, town or county). It is the designer's responsibility to comply with any local regulations. If the area floods after a project is built, the designer may be required to prove the flooding was not a result of the new project.

If the project is in a FEMA-mapped area, there are two options: (1) submit a no-impact certification or (2) submit the necessary application for a map revision. A no-impact certification is commonly granted for sewer-line installation. Sewer-line installation takes place inside the floodway, although the impact of the new sewer line is usually negligible on flood elevations. A no-impact certification for a proposed stream-restoration project is unlikely to be approved and would have to be handled on a case-by-case basis by the local FEMA administrator. *FEMA Region IV's procedures for no-rise certification for proposed developments in regulatory floodways are available for download at http://www.msema.org/forms/nfip/No-Rise_certification.pdf.*

A map revision is needed if a no-impact certification is not applicable and the project is in a FEMA-mapped area. There are two types of FEMA-mapped areas: detailed study areas and those mapped using approximate methods. Detailed study areas are those that have a mapped floodway; approximate areas do not have a mapped floodway. Hydraulic modeling is required when a proposed project exists in either area.

If the proposed project is in a FEMA-mapped area, give serious thought before proposing a Priority 1 stream restoration, especially if there are structures in the floodplain. In a Priority 1 project, the channel is raised and reconnected to the floodplain, which results in increased water-surface elevations and potential damage to existing structures. A Priority 2 or Priority 3 restoration may be more appropriate if structures are located in the floodplain. A project is not allowed to cause an increase in predicted flood elevations for existing structures.

To determine if the project site is in a mapped area, contact the local city/county planning office. The local planning office may have the Flood Insurance Rate Map (FIRM) needed for the project site; otherwise it can be ordered from FEMA. FEMA does not map drainage areas less than 1 square mile. Internet resources for FEMA maps and information are:

http://www.fema.gov/maps/ *(maps)*
http://www.fema.gov/about/regoff.htm *(regional and state offices)*
http://msc.fema.gov/MSC/toc.htm *(index for map data and user guides)*

Many stream-restoration projects may increase water-surface elevations at low to moderate discharges but have little or no impact on flood flows. This is because at 100-year flows, there usually isn't much difference between pre- and post-restoration water levels. However, water-surface elevation (and therefore flood extent) is difficult to predict because it varies depending on the geometry, roughness and vegetation in the channel or floodplain and conditions and structures downstream. This is why flood studies incorporate a hydraulic model.

If a no-impact certification is possible, it will almost always require hydraulic modeling. Hydraulic modeling must be undertaken if a map revision is needed. A hydraulic model will generate data to show the impact the project will have on the new floodway and floodplain. The hydraulic model currently used to calculate flood elevations is the U.S. Army Corps of Engineers Hydrologic Engineering Center's HEC-2 hydraulic model. A Windows-interfaced version of this model called HEC-RAS (River Analysis System) also is available.

The basic modeling steps include:

Step 1. Obtain the FEMA map for the project area *(http://www.fema.gov/maps/)*. From the FEMA map, obtain the community name, community number (six-digit number) and effective date (all in the lower right corner of the front cover of the map).

Step 2. Obtain the HEC-2 model. Call 1-(877) 336-2627 or 1-(877) FEMA MAP.

Step 3. Obtain the forms needed to document modeling. For the CLOMR, visit the Web site http://www.fema.gov/mit/tsd/ dl_mt-2.htm. For a no-impact certification form, contact the local FEMA administrator directly.

Step 4. Develop a series of models in the following order:

a. Duplicate Effective Model – Take the model that was provided, get it running, and make sure the output matches the original output used to generate the FEMA map.

b. Corrected Effective Model – Add any new topographic data to the model. The model must not reflect any man-made changes that have occurred since the date of the original model (check results with original and look for any errors associated with the model).

c. Existing or Pre-Project Model—Add any new changes (man-made) within the floodplain made after the date of the original model (not including the proposed project). Insert new cross sections at this stage.

d. Revised or Post-Project Conditions Model—Change the pre-project model to reflect the proposed project. These changes will include modification of cross sections and possibly channel roughness.

Figure 11.5

Cove Creek prior to restoration

11.4. Case Study

The Cove Creek restoration project illustrates several important aspects of FEMA requirements for stream-restoration projects. Cove Creek is located in Watauga County within a FEMA-mapped area. A Priority 3 restoration project was completed at this site; therefore, pattern was not changed and structures were installed to create a step-pool system. The cross-sectional area of the channel below bankfull stage remained unchanged, although the cross-sectional area above bankfull stage was increased. The project was modeled using HEC-RAS, and the results along with a project description were submitted to the local FEMA administrator. Based on hydraulic modeling results and description of the project, the local FEMA administrator determined that a map revision was not necessary. Figures 11.5 and 11.6 show before and after photographs of the channel cross section at the project location.

Figure 11.6

Cove Creek after restoration

Notes:

Restoration Evaluation and Monitoring

Chapter 12

Chapter 12: **Restoration Evaluation and Monitoring**

Monitoring and evaluation help determine whether the design objectives have been met. They also reveal the need for adjustments to design parameters, installation procedures and/or stabilization methods. Information collected should be made available to other restoration professionals to ensure continued improvement in the field of stream restoration, design and construction.

Each stream-restoration design should have a monitoring plan to:

a. Determine if stabilization and grade-control structures are functioning properly.
b. Check channel stability by measuring dimension, pattern and profile; particle-size distribution of channel materials; sediment transport; and streambank erosion rates.
c. Determine biological response (i.e., vegetation, macroinvertebrates and fish).
d. Determine if the specific objectives of the restoration have been met.

12.1 Methodology

A monitoring plan should include items presented in levels III *(Section 3.3)* and IV *(Section 3.4)* of Rosgen's stream hierarchy that predicts and validates natural channel stability *(Figure 3.1)*. Classify the geomorphology of the stream using the Rosgen (1996) system; assess it using the results of the survey data. Current agency stream-mitigation monitoring requirements include morphology, photo-documentation and vegetation. Monitor these parameters at least once a year for five years after construction. In addition, it may be useful to monitor shading and temperature; fish and invertebrates; and/or stream stability. Prepare a monitoring report that organizes data in a format that is easy to replicate annually.

12.2 Morphology

Complete a geomorphic survey. Include in the monitoring plan an assessment of streambank stability as well as stream morphology. During field reconnaissance, establish permanent cross-sections at riffles and pools, survey the longitudinal profile and conduct pebble counts. Select distinctive areas (upstream to downstream) along the stream corridor as individual sections or reaches for reference; survey and monitor them. Denote these areas on the plan-view drawings.

For all of the following, collect data once a year for at least five years after construction. Plot cross sections over those of previous years for comparison and evaluation.

Cross-Section Geometry

For monitoring purposes, establish permanent cross sections in each of the reaches along the restored stream corridor. Survey at least one riffle and one pool cross section for each reach. Note the location of each cross section to establish the exact transect location along the longitudinal profile.

Use rebar to mark each cross section. Install left and right bank-pins to mark the location of each cross section surveyed. Drive each pin (left and right) vertically all the way into the ground on each side of bank to establish the outer limits of each surveyed cross section. Place wooden stakes (wrapped with surveyor's tape) adjacent to the rebar marker to aid in locating the cross sections in the field. Show the locations of all cross sections on the plan-view drawings. Use as much detail as possible, as it is very difficult to find the markers once vegetation becomes established.

Complete the following steps to ensure successful replication of cross section location and survey parameters. Also, see Section 2.4 for cross section survey instructions.

General procedure for permanent cross-section survey:

- Locate cross section on plan-view drawing and in field.
- Locate end points on banks and mark them with rebar.
- Pull a survey tape from left bank to right bank looking downstream at the cross-section location between the two rebar endpins. The zero end of the tape should be directly over the left rebar stake.
- Set up level/surveying equipment in location with the fewest visual obstacles.
- Survey any permanent/temporary benchmarks (refer to plan-view drawings).
- Survey from left to right bank.
- Survey distinctive points (i.e., top of bank, edge of water, bankfull features, thalweg) and any other breaks in slope.

Survey elevations in the area can be based on any of the rebar pins (benchmark) set in the field. The relative elevation at each pin is located on the cross section survey data.

Measure all significant breaks in slope that occur across the channel. Outside the channel, measure important features, including the active floodplain and terraces.

Longitudinal Profile

The longitudinal profile measures points along the thalweg of the stream channel. The profile indicates the elevations of water surface, channel bed, floodplain (bankfull) and terraces. The elevations and positions of channel-defining indicators and in-stream structures also can be monitored with this profile.

Take longitudinal profiles for each reach of the project along the corridor of the restored stream. Survey the longitudinal profile and cross sections at the same time. Place the beginning of the longitudinal-profile tape at the established station-zero point (STA 0) and continue downstream to the end of the restored stream reach. At each station along the profile, survey the thalweg, water surface, bankfull and, if appropriate, top of low bank. The start and end points of each longitudinal profile should be located on the plan-view drawings. Extend each profile from upstream to downstream along the entire length of the restored channel. Also, see Section 2.6 for longitudinal-profile survey instructions.

Pebble-Count Data

The composition of the stream bed and banks is a good indicator of changes in stream character, channel form, hydraulics, erosion rates and sediment supply. A pebble count gives a quantitative description of the bed material. Pebble counts should be performed at permanent cross sections within each reach of the project. Each count should include 100 pebbles collected from left bankfull to right bankfull. Follow the procedures for cross-section analysis of the substrate outlined in Section 2.7. Perform a pebble count at each of the reaches along the stream channel. Record the count on a tally sheet and plot the data by size-class and frequency *(see Figure 2.10).*

12.2.1 Success Criteria

Using this data to judge success or failure of restoration activities is somewhat subjective. There likely will be minimal changes in the cross sections, profile and/or substrate composition. Evaluate changes that occur during the monitoring period to determine if they represent a movement toward a more unstable condition. When analyzing monitoring results, physical parameters of particular concern include: width-to-depth ratio, entrenchment ratio, bank height ratio, radius-of-curvature ratio, feature slopes and substrate composition. Deviations from the design values on these parameters may lead to significant channel instability. For example, analysis of changes in the width-to-depth ratio and/or channel slope may determine if any changes will lead to problems with sediment transport. In a stable condition, the monitoring results should show only a slight adjustment in width-to-depth ratio, which is expected as vegetation and the associated root mass create a narrowing of the channel. With regard to the substrate material and expected adjustments during the monitoring period, a coarsening of the bed is normal because fine material moves downstream and is not replaced. The stabilization of eroding banks, for example, decreases the amount of fine material in the stream. Profile measurements consist of the facet slopes for each of the features in the channel (riffle, run, pool and glide). Stability of the channel depends on maintaining these slopes, especially the riffle slopes. Significant adjustments to the facet slopes may indicate such processes as channel down-cutting and increased channel slope. Because each restoration project will have its own critical values, the values that determine the geomorphic threshold for a particular stream must be determined on a case-by-case basis. Adjustments that do not exceed the critical values may be attributed to changes within or along the channel that signal increased stability, such as added vegetation on the banks.

12.3 Photo Documentation

Establish photographic points at distinguishing locations along the stream, including in-stream structures.

Take photos at points along the stream corridor (i.e., standing upstream, looking downstream). Mark each photo point in the field with a wooden stake, or reference it by cross section or stream feature/structure (i.e., rock vane). Place all photo-point locations on the plan-view drawings for future reference.

Take photographs standing at the approximate location of the established photo-point, cross-section location, and/or referenced stream feature/structure. Take photographs throughout the monitoring period at the same locations. Compare to photos from previous years to evaluate vegetative growth and channel stability.

Use photographs to subjectively evaluate channel aggradation or degradation, bank erosion, success of riparian vegetation and effectiveness of in-stream structures and erosion-control measures. Photos will indicate the presence or absence of developing bars within the channel or an excessive alteration in channel depth or width. Photos also will indicate the presence of any excessive bank erosion or continuing degradation of the bank. The series of photos over time should indicate successional maturation of riparian vegetation.

12.4 Vegetation

Survival of vegetation should be evaluated using survival plots and/or direct counts along the entire corridor of the restored stream.

Survival of vegetation inside the riparian buffer may be documented for the monitoring period through stem-counts and photographic documentation of the entire length of the buffered corridor. Document the data from stem-counts and photographs at pre-established stations/plot areas. If the initial (year-one) survey doesn't show 80 percent survival, plant supplemental vegetation the next winter.

12.4.1 Plot Locations

Locate plots adjacent to the stream and survey them for future replication. Plots should be located in areas large enough to obtain a representative sample of the planted population. Ideally, a sample size of 10 percent of the planted area should be surveyed. In some cases, plots will be located in areas such as outside meander bends or atop bankfull benches and extended into the riparian buffer.

12.4.2 Plot Size

Two different types of plots need to be established to determine survivorship of stakes and bare-root seedlings. Sizes and numbers of plots will depend on site conditions, particularly buffer width and project size. Ideally, rectangular plots as large as 100 square meters will be used in determining survivability for bare-root trees. These should be linear and parallel to the stream channel. Count stakes from beginning to end of outside meander bends if this is the sole location of stakes. If stakes are planted along runs, riffles or glides, use rectangular plots as with the bare-root trees. Plot size will depend on site conditions and project size. Herbaceous plants are neither stakes nor bare-root trees. If development of herbaceous cover is desired, include counts of this material (establish subplots) in either the stake or bare-root tree plot counts. The plot size for herbaceous cover should be no more than 1 square meter.

12.4.3 Timing

Sample vegetation during the growing season. Ideally, this would be mid-summer in June or July. The growing season ends between Aug. 1 and Oct. 31 depending on location.

12.5 Additional Monitoring Opportunities

12.5.1 Bank Stability Monitoring

The newly constructed or repaired streambanks can be monitored and assessed for their stability. This monitoring can be accomplished through BEHI rating, bank pins, bank profile and permanent cross section. See Section 3.3 for instructions. Post-restoration stability assessment and bank-erosion monitoring results can be compared to preconstruction data to determine if the restoration work has improved the stability and thereby lessened streambank erosion.

12.5.2 Shading and Temperature

Monitoring of water and air temperatures will show how well the planted vegetation is providing thermal stability in the riparian zones. Water temperature may be sampled using recording thermometers such as the *StowAway, XTI* made by Onset Computer Corporation or a similar device. These thermometers may be placed in the stream at the beginning and end of each site and set to record the water temperature every hour. Water temperature recording can continue each year until the desired stream-shading is accomplished. Evaluate shading effects on air temperature by recording air temperature along each reference transect established for lateral photo reference (upstream and downstream of the photo points to the extent of the photographs). Record air temperature at each location in which the shading effect is measured; measure 1 meter above the ground or water surface. Determine temperature stability by measuring air temperature in the shade for seven consecutive days. This temperature stability measurement may be done within the easement or buffer area at the top of the streambank as well as outside of the easement, both along one of the established photo-point transect lines.

Comparisons of air temperature and shading along each transect (from edge of buffer to midstream) should indicate a lower temperature and increased shading. Water temperature should decrease or at least be constant as it moves through the restoration site. Decreased temperature might not be observed until riparian vegetation grows enough to shade the stream and riparian zone. Temperature stability data should indicate that the riparian zone has a more stable (less varied) temperature regime than a site outside of the vegetated buffer. Reference data from existing riparian zones in excellent condition need to be developed to provide targets for shading and thermal buffering.

12.5.3 Fish and Invertebrate Data

Information on fish and aquatic macroinvertebrate populations (density and diversity) may be used to guide decision-making in the restoration planning and monitoring process. These populations can provide insights on the overall health of the stream and the need for habitat improvement. When restoration work can be done throughout the watershed, these populations are a valuable tool for assessing the success of the work. When populations can be evaluated on a watershed basis and at the restoration site, a marked difference at the site might indicate that local conditions are limiting populations. In this case, on-site work may improve the populations, and monitoring of important populations may be warranted.

When sampling fish and invertebrate populations, use standard procedures so that results can be compared with other studies. Quantitative fish-population samples can be evaluated using the 3-pass depletion method that the N.C. Wildlife Resources Commission uses to evaluate trout populations *(Armour et al., 1983).* Population estimates can be computed using Microfish 3.0 *(Deventer and Platts, 1989)*. Population estimates and biomass estimates can then be easily converted to densities and standing crops. The Index of Biotic Integrity used by the N.C. Division of Water Quality (Department of Environment and Natural Resources) is a good method for qualitative fish-population sampling. Invertebrate sampling should follow the methods prescribed by the Division of Water Quality *(available for download at http://h2o.enr.state.nc.us/ncwetlands/dave.pdf)*. Monitoring reports should explain the need for the fish and invertebrate data and how they will be used to evaluate any restoration work.

Notes:

Chapter 13

References and Resources

Chapter 13: **References and Resources**

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http://h2o.enr.state.nc.us/ncwetlands/dave.pdf
N.C. Division of Water Quality, Wetlands/401 Certification Unit
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North Carolina Stream Restoration Institute
http://www.ncsu.edu/sri/

Stream Systems Technology Center
http://www.stream.fs.fed.us/

U.S. Army Corps of Engineers, Wilmington District Regulatory Division
http://www.saw.usace.army.mil/wetlands/regtour.htm

U.S. Environmental Protection Agency, Office of Water, River Corridor and Wetland Restoration
http://www.epa.gov/owow/wetlands/restore/

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Notes:

Appendices

Appendices

River Course Fact Sheets

Appendix A

Fact Sheet Number 1

Natural Stream Processes

River Course

River Course is a fact sheet series developed to provide information and technologies related to the use of natural channel design in restoring impaired streams.

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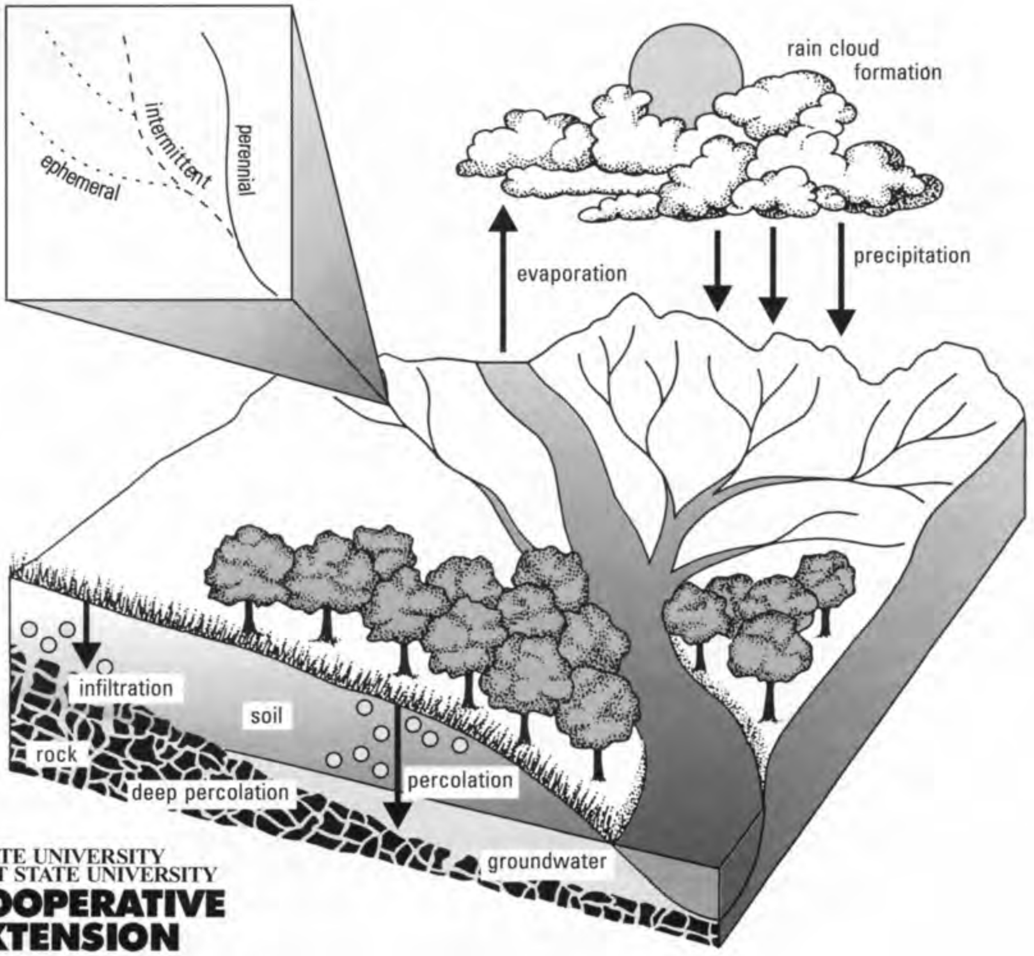
Streams and rivers are integral parts of the landscape that carry water and sediment from high elevations to downstream lakes, estuaries, and oceans. The land area draining to a stream or river is defined as its **watershed**. When rain falls in a watershed, it either runs off the land surface, infiltrates into the soil, or evaporates (Figure 1). As surface runoff moves downslope, it concentrates in low areas and forms small stream channels. These are referred to as **ephemeral channels** that only carry water during rainfall runoff. Downstream from ephemeral channels are **intermittent streams**, which carry water during wet times of the year. These streams are partially supplied by groundwater rising to the surface as **stream baseflow**. They dry up when groundwater levels drop. Further downstream where baseflow is large enough to sustain stream flow throughout the year, **perennial streams** are formed. The size and flow of a stream are directly related to its watershed area. Other factors which affect channel size and stream flow are land use, soil types, topography, and climate. The **morphology**, or size and shape, of the channel reflect all of these factors.

While streams and rivers vary greatly in size, shape, slope, and bed materials, all streams share common characteristics. Streams have left and right streambanks (looking downstream) and streambeds consisting of mixtures of bedrock,

Figure 1. Hydrologic cycle showing rainfall, runoff, infiltration, groundwater flow, and stream network.



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boulders, cobble, gravel, sand, or silt/clay. Other physical characteristics shared by some stream types include pools, riffles, steps, point bars, meanders, flood plains, and terraces. All of these characteristics are related to the interactions among climate, geology, topography, vegetation and land use of the watershed. (Each of these characteristics will be defined in this fact sheet.) The study of these interactions and the resulting streams and rivers is called **fluvial geomorphology**.

In addition to transporting water and sediment, natural streams also provide the habitat for many aquatic organisms including fish, amphibians, insects, mollusks, and plants. Trees and shrubs along the banks provide a food source and regulate water temperatures. Channel features like pools, riffles, steps, and undercut banks provide diversity of habitat, oxygenation, and cover. For these reasons natural resource managers increasingly use natural channel designs to restore impaired streams.

Bankfull Stage and Discharge

The most important stream process in defining channel form is the **bankfull discharge**, which is sometimes referred to as the effective discharge, or dominant discharge. Bankfull discharge is the flow that transports the majority of a stream's sediment load over time and thereby forms the channel. The bankfull stage, during bankfull flow is the point at which flooding occurs on the floodplain. This may or may not be the top of the streambank. If the stream has downcut due to changes in the watershed or streamside vegetation, the floodplain stage may be a small bench or scour line on the streambank (Figure 2a). In this case, the top of the bank, which was formerly the floodplain, is called a **terrace**. A stream with terraces close to the top of the banks is an **incised**, or **entrenched stream**. If the stream is not entrenched, then bankfull is near the top of the bank (Figure 2b). On average, bankfull discharge occurs approximately every 1.5 years. In other words, each year there is about a 67 percent chance of having a bankfull streamflow event. The Rosgen stream classification system uses bankfull stage as the basis for measuring the **width/depth ratio** and **entrenchment ratio**, two of the most important delineative criteria. Therefore, it is critical to correctly identify bankfull stage when classifying streams and designing stream restoration measures. The Rosgen stream classification is discussed in detail in **River Course 2:** *Application of the Rosgen Stream Classification in North Carolina.*

Natural Channel Stability

A naturally stable stream channel maintains its dimension, pattern, and profile over time so that the stream does not **degrade** or **aggrade**. Stable streams migrate across the landscape slowly over long periods of time while maintaining their form and function. Naturally stable streams must be able to transport the sediment load supplied by the watershed. Instability occurs when scouring causes the channel to incise (degrade) or excessive deposition causes the channel bed to rise (aggrade). A generalized relationship of stream stability is shown as a schematic drawing in Figure 3. The drawing shows that the product of sediment load and sediment size is proportional to the product of stream slope and discharge or stream power. A change in any one of these variables causes a rapid physical adjustment in the stream channel.

Channel Dimension

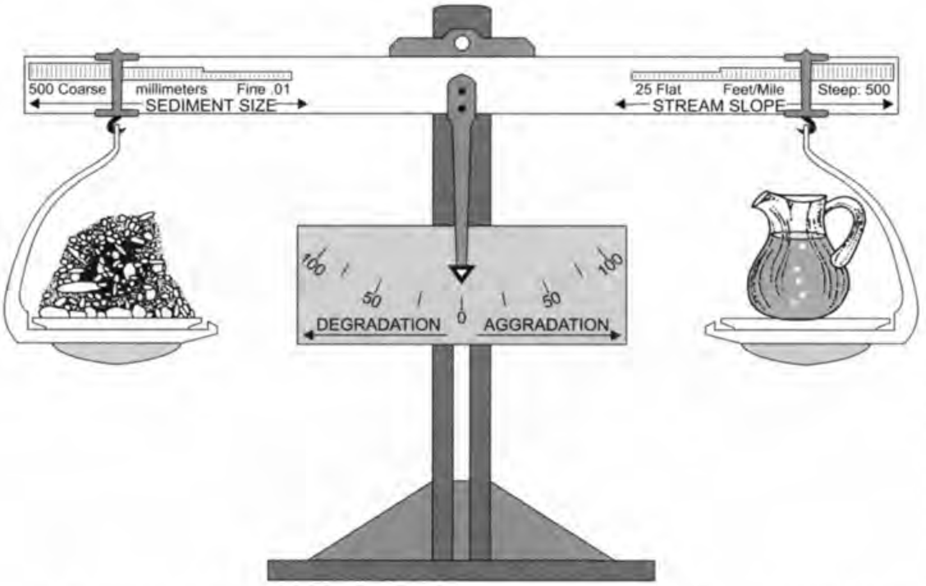
The **dimension** of a stream is its cross-sectional area (width multiplied by mean depth). The width of a stream generally increases in the downstream direction in proportion to the square root of discharge. Stream width is a function of discharge (occurrence and magnitude), sediment transport (size and type), and the stream bed and bank materials. North Carolina has a humid subtropical climate with an abundance of vegetation and rainfall throughout the year. Vegetation along the streambanks provides resistance to erosion so our streams are often narrower than streams in more arid regions. The mean depth of a stream varies greatly from reach to reach depending on channel slope and riffle/pool or step/pool spacing.

Figure 2a (top). Photograph of an incised stream showing bankfull stage, developing floodplain, and terrace.

Figure 2b (above). Photograph of a stream showing bankfull as the top of the bank.

Stream Pattern

Stream **pattern** describes the "plan view" of a channel as seen from above. Streams are rarely straight. They tend to follow a sinuous path across a floodplain. The sinuosity of a stream is defined as the channel length following the deepest



(Sediment LOAD) x (Sediment SIZE) ∝ (Stream SLOPE) x (Stream DISCHARGE)

Figure 3. Schematic drawing showing stream stability. (after Lane and Silvey)

point in the channel (the thalweg) divided by the valley length. A meander increases resistance and reduces channel gradient relative to a straight reach. The meander geometry and spacing of riffles and pools adjust so that the stream performs minimal work. Stream pattern is qualitatively described as straight, meandering, or braided. Braided channels are less sinuous than meandering streams and possess three or more channels. Quantitatively, stream pattern can be defined through the following measurements shown in Figure 4: meander wavelength, radius of curvature, amplitude, and belt width.

Stream Profile

The **profile** of a stream refers to its longitudinal slope. At the watershed scale, channel slope generally decreases in the downstream direction. The size of the bed material also decreases in the downstream direction. Channel slope is inversely related to sinuosity. This means that steep streams have low sinuosities and flat streams have high sinuosities. The profile of the streambed can be irregular because of variations in bed material size and shape, riffle/pool spacing, and other variables. The water surface profile mimics the bed profile at low flows. As water rises in a channel during storms, the water surface profile becomes more uniform as illustrated in Figure 5a.

Channel Features

Natural streams have sequences of riffles and pools or steps and pools that maintain channel slope and stability. These features are shown in Figure 5b. The riffle is a bed feature with gravel or larger size particles. The water depth is relatively shallow and the slope is steeper than the average slope of the channel. At low flows, water moves faster over riffles, which provides oxygen to the stream. Riffles are found entering and exiting meanders and control the streambed elevation. Pools are located on the outside bends of meanders between riffles. The pool has a flat slope and is much deeper than the average depth. At low flows, pools are depositional features and riffles are scour features. At high flows, however, the pool scours and bed material deposits on the riffle. This occurs because a force, called **shear stress**, applied to the streambed increases with depth and slope. Slope and depth increase rapidly over the pools during large storms, increasing shear stress and causing scour. The inside of the meander bend is a depositional feature called a **point bar,** which also helps maintain channel form.

Step/pool sequences are found in high gradient streams. Steps are vertical drops often formed by large boulders, bedrock knickpoints, downed trees, etc. Deep pools are found at the bottom of each step. The step provides grade control and the pool dissipates energy. The spacing of step pools gets closer as the channel slope increases.

Conclusions

A stream and its floodplain comprise a dynamic environment where the floodplain, channel, and bedforms evolve through natural processes that erode, transport, sort, and deposit alluvial materials. The result is a dynamic equilibrium, where the stream maintains its dimension pattern and profile over time, neither degrading nor aggrading. Land use changes in the watershed and channelization can upset this balance. A new equilibrium may eventually result,

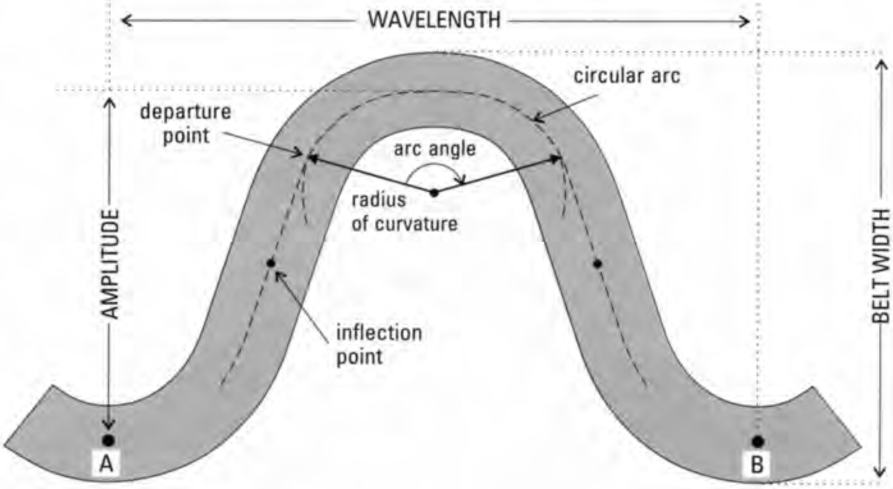
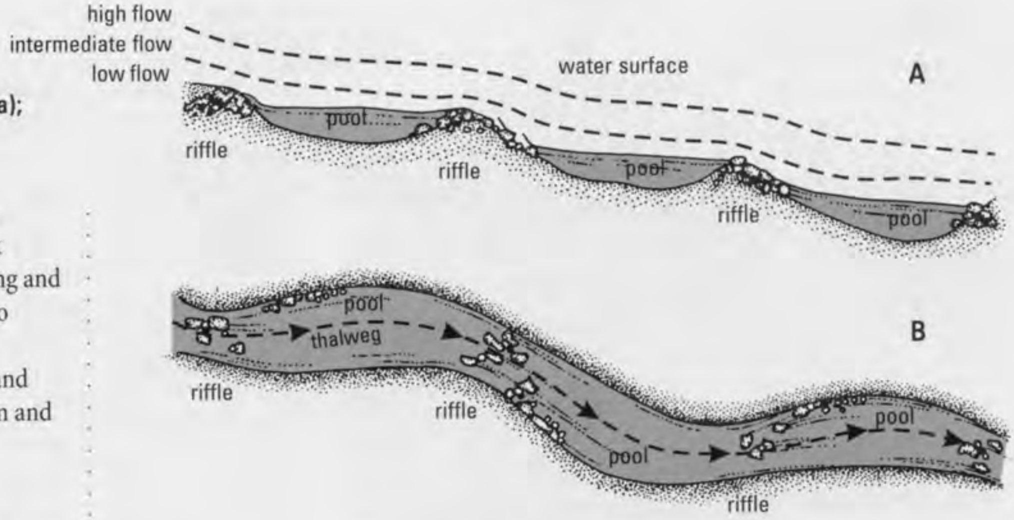


Figure 4. Stream pattern measurements.

Figure 5. Bed and water surface slope at baseflow and stormflow (a); riffle/pool sequence (b).



but not before large adjustments in channel form, such as extreme bank erosion or incision. By understanding and applying natural stream processes to stream restoration projects, a self-sustaining stream can be designed and implemented that maximizes stream and biological potential.

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GLOSSARY

Aggradation – The rising of a stream bed due to sediment deposition.

Alluvial features – Landforms created by rivers, such as floodplains. Sediments are typically round and smooth from water erosion.

Bankfull discharge – The flow that over time maintains the form of the channel by transporting the majority of the sediment load. For the purpose of this fact sheet, it is synonymous with effective and dominant discharge.

Bankfull stage – The elevation at which flooding occurs on a floodplain.

Colluvial features – Landforms that are not well developed by the river. Sediments are typically angular and jagged.

Degradation – The lowering of the streambed by scour and erosion. Opposite of aggradation.

Entrenchment – A vertical description of the stream. Flood flows in an entrenched stream are contained within the streambanks or adjacent terraces. Flood flows in a stream that is not entrenched are spread out over a floodplain. For the purpose of this fact sheet, entrenchment and incision are synonymous. Entrenchment is further discussed in River Course # 2.

Floodplain – A relatively flat alluvial feature adjacent to the stream channel that is formed during the present climate and receives flood flows.

Incision –See entrenchment.

Knickpoint – A bedrock outcrop that creates an abrupt change in the longitudinal profile of a stream and controls the streambed elevation.

Meander – A bend or curve in the stream that often resembles a sine-generated curve.

Point bar – A cresent-shaped depositional feature with coarse material located on the inside bend of a meander.

Pool – Located on the outside of a meander bend or the bottom of a step, pools are deep flat areas in the stream created by scour. Pools generally contain fine-grained bed materials, such as sand and silt.

Reach – A relatively short defined length of stream.

Return interval – The expected frequency of occurrence for a given discharge, i.e. 1.5 years.

Riffle – Gravel size or larger bed sediment where the stream is shallow and swift at low flows. Riffles are produced during high flows by the accumulation of large bed materials.

Ripples, dunes, and antidunes – Bed forms found in sand bed streams with little or no gravel. Ripples form under low shear stress conditions, whereas, dunes and antidunes form under moderate and high shear stresses, respectively. Dunes are the most common bed forms found in sand bed streams.

Scour – Erosive action of water in streams by excavating and transporting bed and bank materials downstream.

Shear stress – The force exerted by flowing water on the bed or banks of a stream. Shear stress may be estimated as the product of mean flow depth or hydraulic radius, channel slope, and the density of water.

Step – A vertical drop formed by boulders, bedrock, or downed trees. Serves as grade control in high gradient streams.

Thalweg – Literally means "valley way" and is the deepest point of a cross section. It is the low flow channel of the stream.

Watershed – The land area that drains water to a given stream, lake, estuary, or ocean.

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Fact Sheet Number 2

River Course

River Course is a fact sheet series developed to provide information and technologies related to the use of natural channel design in restoring impaired streams.

Application of the **Rosgen Stream Classification System** to North Carolina

nc stream restoration institute

Restoration of impaired streams begins with an understanding of the watershed's current condition and stream potential. Stream classification offers a way to categorize streams based on channel morphology. This fact sheet focuses on a classification system popular with hydrologists, engineers, and biologists—the Rosgen stream classification system.

Stream Classification

The classification of natural streams is not new. Over the past 100 years, there have been about 20 published stream classification systems. The first recognized classification was by Davis in 1899. Davis classified streams in terms of age (youthful, mature, and old age). The classification systems devised between 1899 and1970 were largely qualitative descriptions of stream features and landforms and were difficult to apply universally. In 1994, Rosgen published *A Classification of Natural Rivers*. Because of its usefulness in stream restoration, this classification system has become popular among hydrologists, engineers, geomorphologists, and biologists working to restore the biological function and stability of degraded streams.

Rosgen Stream Classification System

The Rosgen stream classification system categorizes streams based on channel morphology so that consistent, reproducible, and quantitative descriptions can be made. Through field measurements, variations in stream processes are grouped into distinct stream types. Rosgen lists the specific objectives of stream classification as follows:

1. Predict a river's behavior from its appearance.
2. Develop specific hydraulic and sediment relationships for a given stream type.
3. Provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics.
4. Provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties.

The Rosgen stream classification consists of four levels of detail ranging from broad qualitative descriptions to detailed quantitative assessments. Figure 1 shows the hierarchy (Levels I through IV) of the Rosgen classification inventory and assessment. Level I is a geomorphic characterization that categorizes streams as "A," "B," "C," "D," "DA," "E," "F," or "G." Level II is called the morphological description and requires field measurements. Level II assigns a number (1 through 6) to each stream type describing the dominant bed material. Level III is an evaluation of the stream condition and it's stability. This requires an assessment and prediction of channel erosion, riparian condition, channel modification, and other characteristics. Level IV is verification of predictions made in Level III and consists of sediment transport, stream flow, and stability measurements.

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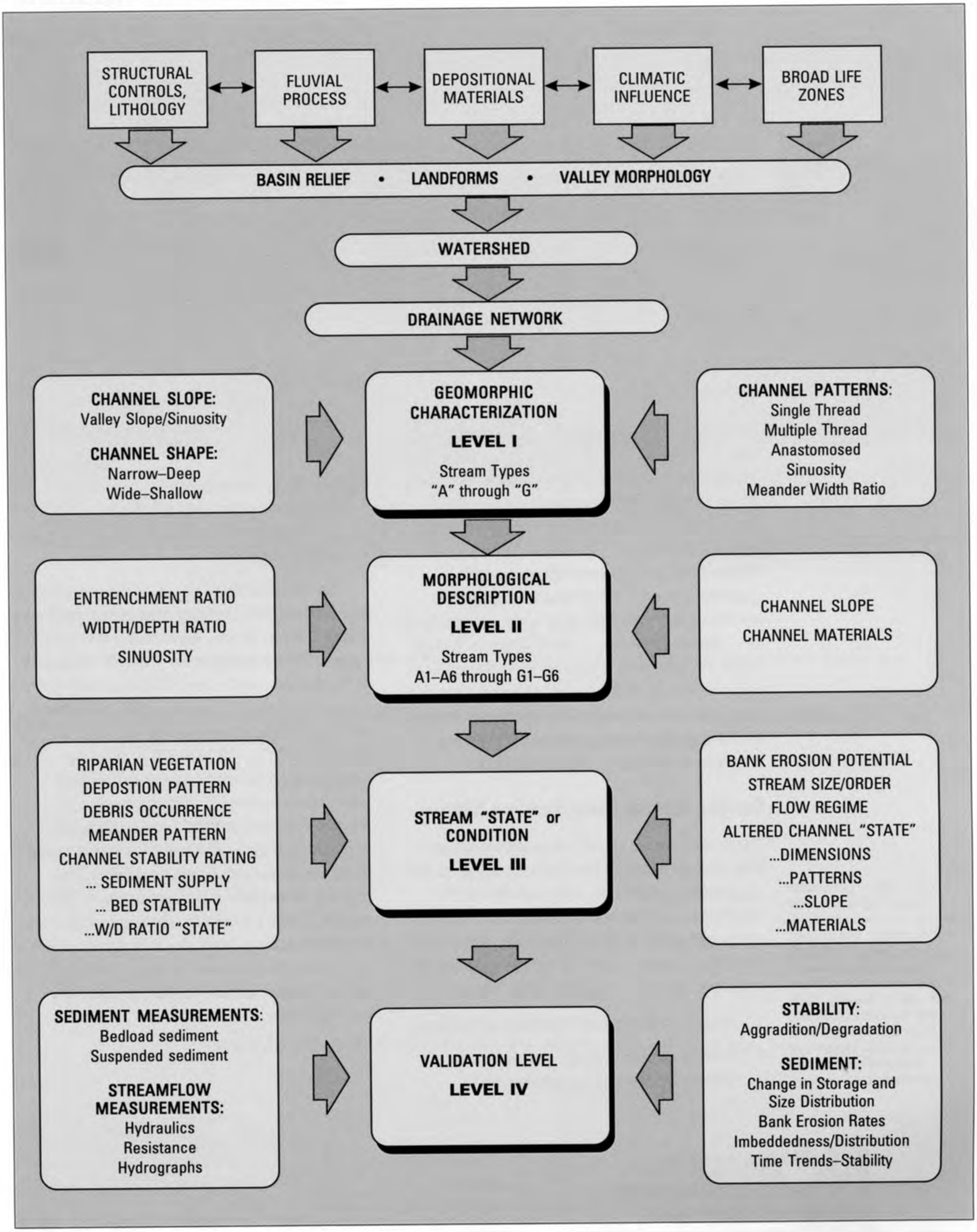
Figure 1. Rosgen Stream Classification Levels.



Bankfull Stage

The width/depth and entrenchment ratios used in the classification are measured at the bankfull stage. By definition, bankfull stage is the elevation of the floodplain adjacent to the active channel. If the stream is entrenched, bankfull stage is identified as a scour line, bench, or top of the point bar. If the stream is not entrenched, then bankfull is near or at the top of the bank. Relationships of bankfull cross sectional area as a function of watershed size help identify bankfull stage in the field. Bankfull stage and natural stream process terminology are further discussed in *River Course 1: Natural Stream Processes*, AG-590-1. Field techniques for identifying bankfull stage are provided in *River Course 3*, AG-590-3.

Application of the Rosgen Stream Classification System

A hierarchical key to the Rosgen stream classification system is shown in Figure 3 on page 4. The criteria and measurements used to classify the stream are discussed below.

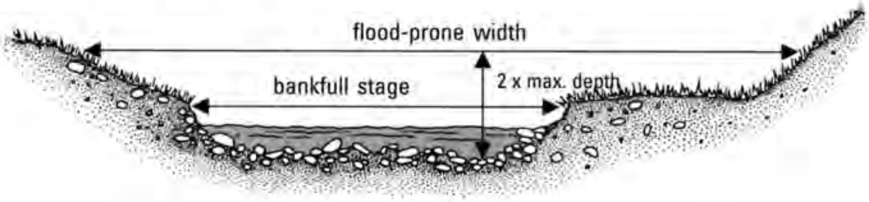


Figure 2. The entrenchment ratio measures the degree of channel incision as the flood-prone width divided by the bankfull width.

Single or Braided Channel Determination — A braided channel consists of three or more distinct channels. Anything less is considered a single channel. The only stream types for braided channels are "D" and "DA." Single or braided channel determination can be made from aerial photograph or field observation.

Entrenchment Ratio —The entrenchment ratio is a field measurement of channel incision. Specifically, it is the flood-prone width divided by the bankfull width. The flood-prone width is measured at the elevation of twice the maximum depth at bankfull. Lower entrenchment ratios indicate channel inclusion. Large entrenchment ratios mean that there is a well-developed floodplain. An example of this measurement is shown in Figure 2. The following stream types are entrenched: "A," "F," and "G."

Width to Depth Ratio —The width to depth ratio is a field measurement of the bankfull width divided by the mean bankfull depth. The break between single channel classifications is 12, meaning that the bankfull width is 12 times greater than the mean bankfull depth. Stream types with width/depth ratios greater than 12 are "B," "C," and "F." Stream types less than 12 are "A," "E," and "G." The "D" stream types have a width/depth ratio greater than 40 and the "DA" stream types are less than 40.

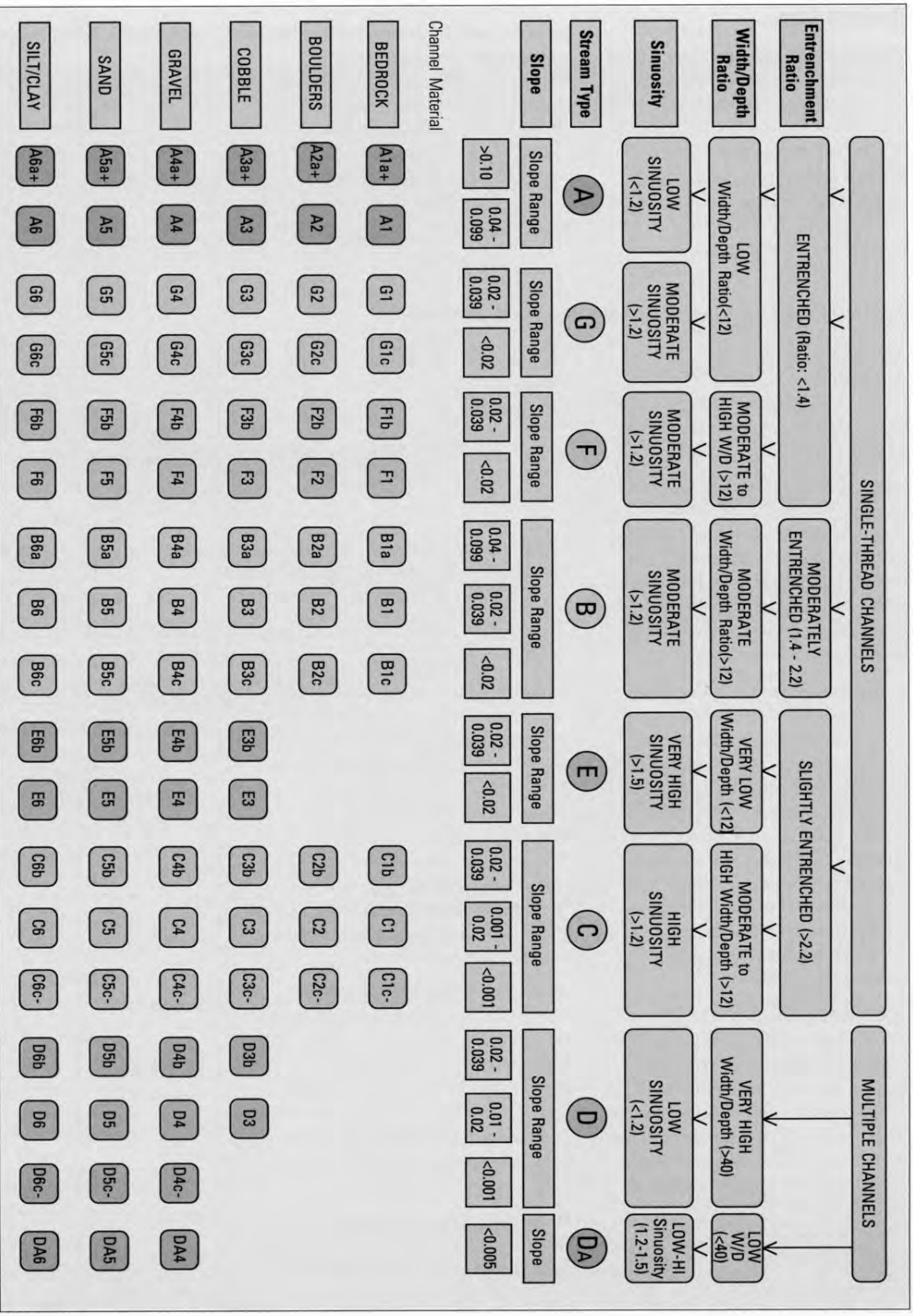
Sinuosity —Sinuosity is a measure of a stream's "crookedness." Specifically, it is the channel length divided by a straight-line valley length. The greater the number, the higher the sinuosity. Sinuosity is related to slope. Natural streams with steep slopes have low sinuosities, and streams with low slopes typically have high sinuosities. Sinuosity can be measured from large scale aerial photographs but should not be measured from 1:24,000 or smaller scale topographic maps.

Water Surface Slope — The water surface slope is a field measurement from the top of a riffle to the top of another riffle at least 20 bankfull widths downstream. This is considered the average slope. "A" and "B" stream types have the steepest slopes and "E" and "DA" stream types have the lowest. However, slope varies greatly among stream types.

Median Size of the Bed Material — A pebble count procedure is used to determine the D50 of the bed material. The D50 is the median particle size, meaning that 50 percent of the material is smaller and 50 percent is larger. A stream reach of 20 bankfull widths is sampled. The reach is divided into pool and riffle sub-reaches. One hundred samples are taken from pools and riffles according to their percentage of the total length. For example, if 60 percent of the reach is a riffle and 40 percent is a pool, then 60 samples will be taken from the riffles and 40 from the pools. A cumulative frequency plot of the particle size distribution will provide the D50.

The D50 will provide the following "level II" classification.

	Size Range (mm)
Bedrock = 1	>2,048
Boulder = 2	256-2,048
Cobble = 3	64-256
Gravel = 4	2-64
Sand = 5	0.062-2
Silt/Clay = 6	<0.062



Stream Type	A	A	G	G	F	F	B	B	B	E	E	C	C	C	D	D	D	DA
Slope	>0.10	0.04 - 0.099	0.02 - 0.039	<0.02	0.02 - 0.039	<0.02	0.04 - 0.099	0.02 - 0.039	<0.02	0.02 - 0.039	<0.02	0.02 - 0.039	0.001 - 0.02	<0.001	0.02 - 0.039	0.01 - 0.02	<0.001	<0.005
BEDROCK	A1a+	A1	G1	G1c	F1b	F1	B1a	B1	B1c			C1b	C1	C1c-				
BOULDERS	A2a+	A2	G2	G2c	F2b	F2	B2a	B2	B2c			C2b	C2	C2c-				
COBBLE	A3a+	A3	G3	G3c	F3b	F3	B3a	B3	B3c	E3b	E3	C3b	C3	C3c-	D3b	D3		
GRAVEL	A4a+	A4	G4	G4c	F4b	F4	B4a	B4	B4c	E4b	E4	C4b	C4	C4c-	D4b	D4	D4c-	DA4
SAND	A5a+	A5	G5	G5c	F5b	F5	B5a	B5	B5c	E5b	E5	C5b	C5	C5c-	D5b	D5	D5c-	DA5
SILT/CLAY	A6a+	A6	G6	G6c	F6b	F6	B6a	B6	B6c	E6b	E6	C6b	C6	C6c-	D6b	D6	D6c-	DA6

Figure 3. Key to the Rosgen Classification of Natural Rivers. As a function of the "continuum of physical variables" within stream reaches, values of *entrenchment* and *sinuosity* ratios can vary by +/– 0.2 units; while values for width/depth ratios can vary by +/– 2.0 units.

DESCRIPTION OF NORTH CAROLINA STREAM TYPES

Stream Type "A"

Type "A" streams are single thread channels with a width/depth ratio less than 12, meaning they are narrow and moderately deep. They are entrenched, high gradient streams with step/pool bed features. "A" streams with a channel slope greater than 10 percent are classified as "Aa+." "A" streams flow through steep V-shaped valleys, do not have a well-developed floodplain, and are fairly straight.

Basin: Yadkin
Stream Type: A1

Basin: Yadkin
Stream Type: A1a+

Stream Type "B"

Type "B" streams are wider than "A" streams and have a broader valley but not a well-developed flood plain. These single thread streams are moderately entrenched with moderate to steep slopes. Type "B" streams are often rapid dominated streams with step/pool sequences. Bank heights are typically low. The high width/depth ratios and moderate entrenchment ratios make this stream type quite resilient to moderate watershed changes.

Basin: Little Tennessee
Stream Type: B3

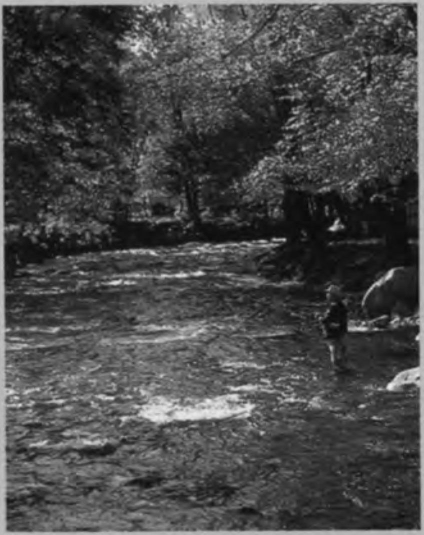
Basin: Catawba
Stream Type: B4c

DESCRIPTION OF NORTH CAROLINA STREAM TYPES *(continued)*

Stream Type "C"

Type "C" streams are riffle/pool streams with a well-developed floodplain, meanders, and point bars. These streams are wide with a width/depth ratio greater than 12. Type "C" streams are moderately entrenched, and therefore, use their floodplain during large storms.

Basin: French Broad
Stream Type: C5



Basin: French Broad
Stream Type: C4

Stream Types "D" and "DA"

Type "D" streams are multi-channel (3 or more) streams. These braided streams are found in well-defined alluvial valleys. Braided channels are characterized by moderate to high bank erosion rates, depositional features such as transverse bars, and frequent shifts in bed forms. The channels are typically on the same gradient as their valley. There are few "D" streams in North Carolina.

The "DA" stream type is a stable braided stream with a low but highly variable width/depth ratio (for braided channels) and low slope (less than 0.5 percent). The DA stream types are found in wide alluvial valleys or deltas exhibiting interconnected channels and an abundance of wetlands. This stream type is often found in the coastal plain of North Carolina.

Basin: Chowan
Stream Type: DA6

Basin: Neuse
Stream Type: DA6

DESCRIPTION OF NORTH CAROLINA STREAM TYPES *(continued)*

Stream Type "E"

For the single thread channels, the "E" stream types are the evolutionary end point for stream morphology and equilibrium. The "E" stream type is slightly entrenched with low width/depth ratios, and moderate to high sinuosities. The bedform features are consistent riffle/pool sequences. Analyses of North Carolina streams determined that many "E" stream types in wide floodplains have been relocated to the edge of the floodplain and straightened. This has resulted in moderate entrenchment ratios and lower sinuosities. Dense vegetation has helped these streams remain as "E" stream types, but they do not function at their biological potential because of disruptions in the riffle/pool sequence. "E" stream types are generally found in wide alluvial valleys, ranging from mountain meadows to the coastal plain.

Basin: Holston (Virginia)
Stream Type: E4

Basin: Neuse
Stream Type: E4

Stream Type "F"

The "F' stream types are deeply entrenched, often meandering streams with a high width/depth ratio (greater than 12). These stream types are typically working to create a new floodplain at a lower elevation and will often evolve into "C" and then "E" stream types. This evolutionary process leads to very high levels of bank erosion, bar development, and sediment transport. The "F" stream types are found in low-relief valleys and gorges.

Basin: Watauga
Stream Type: F4

Basin: Watauga
Stream Type: F4

DESCRIPTION OF NORTH CAROLINA STREAM TYPES *(continued)*

Stream Type "G"

The "G" or gully stream types are similar to the "F" types but with low width/depth ratios. With few exceptions, "G" stream types possess high rates of bank erosion as they try to widen into an "F." "G" stream types are found in a variety of landforms, including meadows, urban areas, and new channels within relic channels.

Basin: Catawba

Stream Type: G5

Basin: Cape Fear

Stream Type: G6

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Fact Sheet Number 3

River Course

Finding Bankfull Stage in North Carolina Streams

River Course is a fact sheet series developed to provide information and technologies related to the use of natural channel design in restoring impaired streams.

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Dominant, Effective, and Bankfull Discharge

Restoring streams to a stable form through natural channel design requires detailed information about surface water hydrology and the interactions between rainfall and overland flow or runoff. The channel-forming or dominant discharge is the most common method for sizing channel dimension if the stream restoration requires re-shaping the channel. Channel dimension is the cross sectional shape of the channel, including channel width, depth, and cross sectional area. **Dominant discharge** is a theoretical discharge that if constantly maintained in an alluvial stream over a long period of time will produce the same channel geometry that is produced by the long-term hydrograph. **Effective discharge** is defined as the discharge that transports the largest percentage of the sediment load over a period of many years. Effective discharge is the peak of a curve obtained by multiplying the flood frequency curve and the sediment discharge rating curve (Figure 1). **Bankfull discharge** is the discharge that fills a stable alluvial channel to the elevation of the active floodplain. This discharge is morphologically significant because it identifies the point where the active channel stops and the floodplain begins. In other words, it represents the breakpoint between the processes of channel formation and floodplain formation.

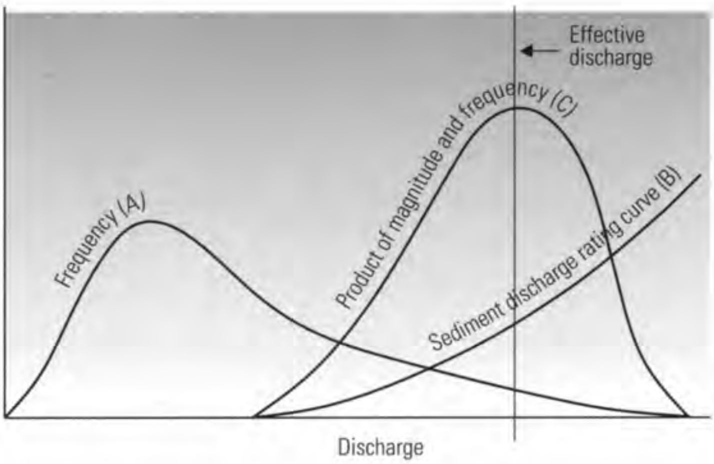

Figure 1. Effective discharge determination from sediment rating and flow duration curves. The peak of curve C marks the discharge that is most effective in transporting sediment. (Wolman and Miller, 1960)

Since bankfull discharge is the only discharge that can be identified in the field using physical indicators, it is the one most commonly used in natural channel design. Most river engineers and hydrologists work under the assumption that dominant, effective, and bankfull discharges are approximately equal. This assumption has not been proven true in the Southeast; however, the differences will probably not significantly affect a natural channel design.

Field Indicators of the Bankfull Stage

The height of water, or stage, during bankfull flow is the point at which flooding occurs on the floodplain. This may or may not be the top of the streambank. If the stream has downcut due to changes in the watershed or streamside vegetation, the floodplain stage indicator may be a small bench or scour line on the streambank. The top of the bank, which was formerly the floodplain, is called a terrace in this case. A stream with a terrace near the top of the banks is an incised, or entrenched, stream. If the stream is not entrenched, then

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bankfull is near the top of the bank. On average, bankfull discharge occurs approximately every 1.5 years. In other words, each year there is about a 67 percent chance of having at least one bankfull streamflow event. The bankfull event can occur any number of times per year.

The Rosgen stream classification system uses bankfull stage as the basis for measuring the width/depth ratio and entrenchment ratio, two of the most important delineative criteria. Therefore, it is critical to correctly identify bankfull stage when classifying streams and designing stream restoration measures. The Rosgen stream classification system is discussed in detail in *Application of the Rosgen Stream Classification System in North Carolina*, AG-590-2.

The most consistent bankfull indicator in North Carolina streams is the uppermost scour line. Other bankfull indicators include the back of a point bar, the upper break in slope of the bank, and occasionally the top of the bank. Often, there is another prominent feature known as the inner berm. The Army Corps of Engineers refers to the inner berm as the mean high water mark. This feature is usually identified as a scour line or small bench halfway between the low flow water surface and the bankfull stage. While this feature is morphologically significant, it is not the dominant discharge and should thus not be used for sizing a channel. Examples of bankfull indicators are included in Figure 2.

Regional Curves

Bankfull hydraulic geometry relationships, also called regional curves, first developed by Dunne and Leopold (1978), related bankfull channel dimensions to drainage area. Gage station analyses throughout the United States have shown that the bankfull discharge has an average return interval of about 1.5 years or 67 percent annual exceedence probability. The primary

Figure 2. Examples of the inner berm and bankfull indicators.

2a. Mills River Gage, Henderson County, C4 stream type. The break in slope at the lower bench is the inner berm (IB). Bankfull (BKF) is the upper scour line.

2b. Rocky Branch, Wake County, G4/F4 stream type. This stream is actively building a new floodplain. The front of the bench is the inner berm and bankfull is the back of the bench.

Figure 2c. South Fork Mitchell River, Surry County, C4/E4 stream type. Bankfull is rarely the top of a point bar. However, in cases where there is an excessive upstream sediment supply, a point bar will build to bankfull as shown in this photograph. The inner berm is the lower bench.

Figure 2d. Hominy Creek, Wilson County, E5 stream type. Bankfull is the break in slope near the top of the bank. Notice the deposition on the floodplain. The inner berm is the lower bench inside the channel.

purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds and to help estimate the bankfull dimension and discharge for natural channel designs. The bankfull cross sectional area vs drainage area regional curve for North Carolina rural piedmont is shown in Figure 3.

Details about the development of regional curves and additional data for the rural piedmont of North Carolina are discussed by Harman et al., (1999). Additional curves for North Carolina physiographic regions will be posted on the web at the following address as they are completed: **http://www.bae.ncsu.edu/bae/programs/extension/wqg/sri.**

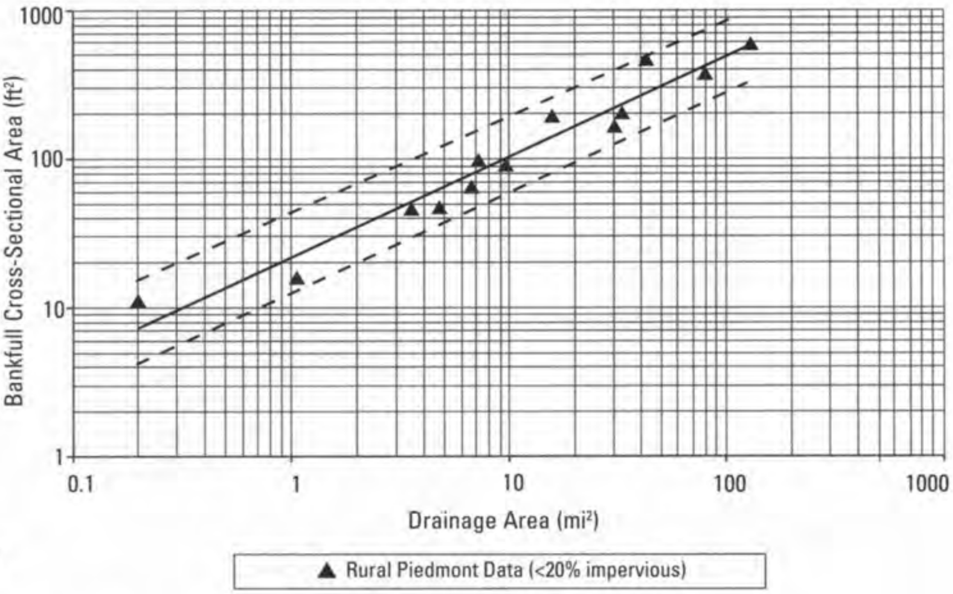


Figure 3. North Carolina rural piedmont curve.

Finding and Verifying Bankfull Stage in the Field

The following steps should be taken for identifying and verifying the bankfull stage in the field **on an un-gaged stream**.

1. Using a USGS quad sheet or similar map, determine the drainage area in miles squared for the watershed/stream section of interest.

2. Calculate the percent of impervious cover for the watershed of interest.

3. Using the indicators listed above, walk upstream and downstream for a distance of at least 20 times the bankfull width and flag the bankfull indicators.

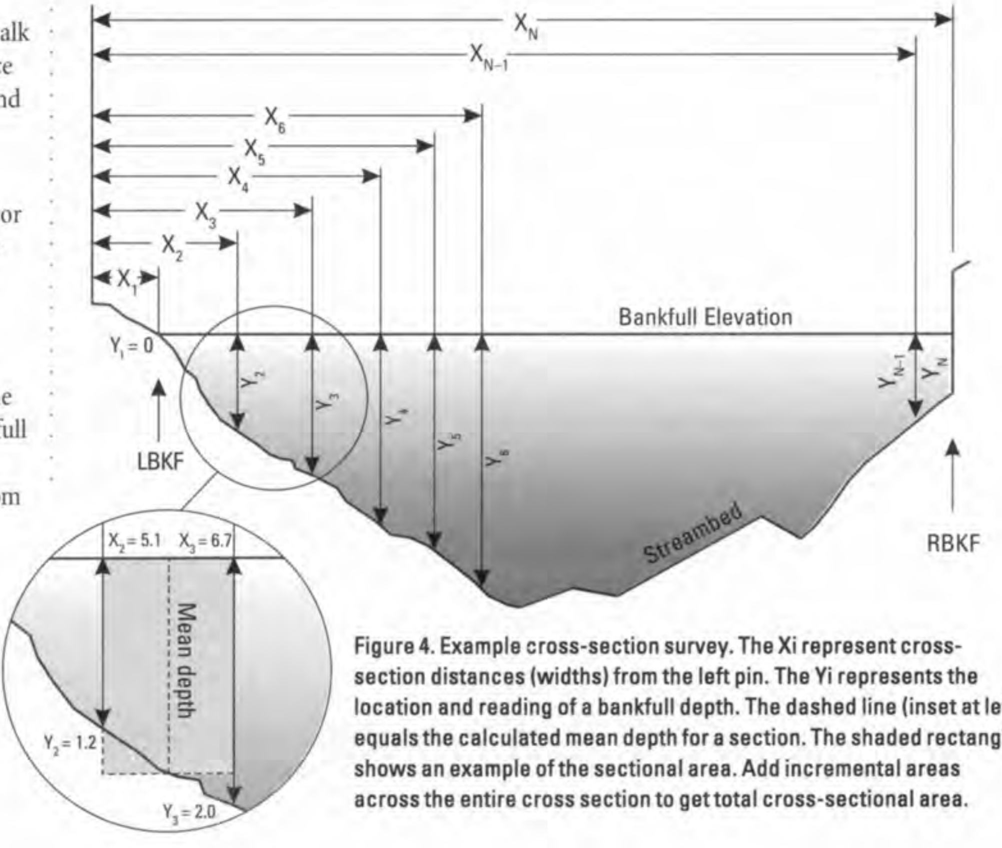
4. Use a survey rod to measure the difference between the bankfull indicator and the current water surface along the study reach. The variability of this difference should not be more than 6 inches.

5. At a riffle or run, pull a tape from the left bankfull indicator to the right bankfull indicator (cross section). Measure the depth to the channel bed/bottom (Yi), from a level line at bankfull or use a survey instrument, at several stations (Xi) along the cross section. Be sure to choose points that correspond to breaks in slope. Spacing between points should not be more than ¼ the width of the channel. An example is provided in Figure 4. Calculate the cross sectional area (A_{bkf}) as follows:

$$A_{bkf} = \Sigma (X_{i+1} - X_i) [(Y_i + Y_{i+1})/2]$$

where, X_i = cross section distances (widths) to successive vertical depths measured from the left bankfull station and Y_i = the vertical depth. The bankfull width (W_{bkf}) is measured as $X_{right\ bkf} - X_{left\ bkf}$.

6. For your watershed area and percent impervious cover, compare the field estimated bankfull cross sectional area to the area on the regional curve for that stream's hydrophysiographic region. If it is



Incremental area between X_2 and X_3

$= (X_3 - X_2) [(Y_2 + Y_3)/2]$

$= (6.7 - 5.1) [(1.2 + 2.0)/2]$

$= 2.56$ ft²

Figure 4. Example cross-section survey. The Xi represent cross-section distances (widths) from the left pin. The Yi represents the location and reading of a bankfull depth. The dashed line (inset at left) equals the calculated mean depth for a section. The shaded rectangle shows an example of the sectional area. Add incremental areas across the entire cross section to get total cross-sectional area.

close to the regression line (between the upper and lower 95 percent confidence limits, dashed lines on Figure 3) **AND** the feature is consistent for 20 bankfull widths, then this feature is (most likely) the bankfull stage.

If the measured bankfull cross sectional area falls outside of the 95 percent confidence limit, the following steps should be taken.

1. Recheck calculations.
2. If the point is below the lower 95 percent confidence limit, make sure that the feature is not the inner berm. Typically, the inner berm has roughly half the cross sectional area as bankfull. Look for other features above the inner berm, such as an upper scour line or break in slope that are consistent for a longer distance upstream and downstream of the cross section.
3. If the point is low, be sure there is not an upstream impoundment.
4. If the point is above the rural curve but below the urban curve, it may be part of a separate relationship for suburban development.
5. Visit a nearby gage station and check the return interval for BKF. It should be between 1 and 2 years.
6. Finally, know your watershed! Factors such as stream type, impervious cover, topography, channel materials, sediment transport, and bank vegetaion all contribute to the size of a bankfull channel.

Conclusion

Successfully identifying bankfull stage is the crux to any stream restoration design. With practice and experience, bankfull can be identified correctly and consistently in stable and moderately unstable streams. Regional curves should be used as an aid in verifying which morphological feature is or is not bankfull. When possible, gage stations near the project site should be surveyed and compared to the regional curve. If a gage station is surveyed, the bankfull stage should be carried through the gage plate to obtain a bankfull discharge from the stage/discharge relationship. Using the bankfull discharge and Log Pearson Type III flood frequency distribution, a return interval or exceedence probability can be obtained. The return interval should be between 1 and 2 years.

If regional curves are used for natural channel design, other methods such as Manning's equation or HEC 2/ HEC RAS should be used to estimate the bankfull discharge for comparison. If a sediment/ discharge relationship and flow duration curve is available for the project, then the effective discharge should be used for the design. In all cases, professional judgment is required to make the final design decisions. Therefore, it is imperative that the designer understands the cause and effect relationships governing the morphology of the channel.

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Fact Sheet Number 4

River Course

Using Root Wads and Rock Vanes for Streambank Stabilization

River Course is a fact sheet series developed to provide information and technologies related to the use of natural channel design in restoring impaired streams.

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This fact sheet provides design information on using root wads and rock vanes for streambank stabilization. Before these structures can be used, the designer must know the cause of the instability and if the problem is local or system wide.

Determining Stream Instability

Watershed-Scale Instability

The equilibrium of a stream corridor can be disrupted by various factors. In North Carolina, direct channel modification (channelization) and development of the watershed are the most common causes of watershed-scale instability. If watershed-scale instability is occurring, the designer must address these changes before bank stabilization or habitat improvement structures are installed. During watershed-scale adjustments, channel evolution usually progresses upstream. For example, an incised stream might have a downstream reach that is developing a new floodplain at a lower elevation. The rate of bank erosion is decreasing as the channel dimension, pattern, and profile become stable for the given slope and drainage area. The disturbance can have effects that move upstream, however, causing degradation, widening, and then deposition.

Reach Instability

Reach or local instability refers to erosion and deposition at a specific place in the watershed and will not have major consequences upstream or downstream of the impaired reach. Perhaps the most common form of local instability is bank erosion along the outside bank in a meander bend. Local instability can also occur in isolated locations as the result of channel constriction, flow obstructions (ice, debris, structures, etc.), or geotechnical instability (high banks, loss of vegetation, soil structure, etc.). Local instability problems are amenable to local bank protection measures. Caution must be exercised if only local treatments on one site are implemented. The stabilization treatment must begin and end at stable riffles.

Streambank Erosion

Streambanks can be eroded by moving water or by collapse. Collapse, or mass failure, occurs when bank materials cannot resist gravitational forces. Banks that are collapsing or about to collapse are referred to as being geotechnically unstable. The physical properties of the streambank should be evaluated to determine potential stability problems and to identify the dominant mechanisms of bank instability. Streambank factors that should be considered include bank height, bank angle, surface protection, soil material, and soil stratigraphy. Whenever possible, the streambank stabilization measure should reconstruct the bank so that bankfull is the top of the bank. This often means building a bankfull bench as shown in Figure 1.

Whether streambank erosion is a localized problem or part of a larger restoration project, root wads and rock vanes, can be used to stabilize the streambanks and improve aquatic habitat.

Root Wads

Root wads include the root mass or root ball of a tree plus a portion of the trunk. Root wads are used to armor a streambank by deflecting stream flows away from the bank. They also provide structural

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Figure 1. Many streams in the North Carolina mountains and piedmont are incised. The potential for erosion increases as streambank height increases. These incised and eroding streambanks should be graded to include a bankfull bench.

support to the streambank, habitat for fish and other aquatic animals, as well as a food source for aquatic insects. An example of a root wad is shown in Figure 2.

Design Criteria

Root wads should have a basal diameter between 10 and 20 inches. Use larger diameter root wads for the trenching method, discussed below. Install root wads where the primary flow vectors intercept the bank at acute or right angles. It is generally not necessary to place root wads against each other for the entire length of a meander bend. It is very important that the root wads are installed at the toe of the bank. Generally, one-third of the root wad should be below the baseflow elevation. In locations where scour depths are high, footer logs should be installed below the root wads. In locations where bank heights are low, 1 to 1.5 times bankfull height, 1 ton or larger boulders should be placed on top of and behind the root wad. If bank heights are high; however, with plenty of vegetation and root mass, footer logs and boulders may not be needed.

Installation

There are two primary ways to install a root wad: 1) the **drive-point method**, and 2) the **trenching method**. If it can be used, the drive-point method is preferred because it disturbs the least amount of soil and is more cost effective to install. The drive-point method inserts the root wad directly into the bank, as shown in Figure 3. It is helpful to sharpen the end of the log with a chainsaw before "driving" it into the bank. Orient root wads upstream so that the stream flow meets the root wad at a 90-degree angle, deflecting the water away from the bank as shown in Figure 4. A transplant or boulder should be placed on the downstream side of the root wad if a back eddy is formed by the root wad.

If the root wad cannot be driven into the bank or the bank needs to be reconstructed, the trenching method should be used. This method requires that a trench be excavated for the log portion of the root wad. In this case, a footer log can be installed underneath the root wad. The footer log should be placed in a trench excavated parallel to the bank and well below the streambed. The root wad is placed on top of the footer as shown in Figure 5. One-third of the root wad should remain below normal base flow conditions. Once the root wad is installed, the trench is backfilled, and the bank rebuilt with transplants or sod mats. The upper bank or terrace scarp should be graded to at most a 1.5-to-1 slope, seeded with an annual grain or native seeds, and covered

Figure 2. Root wads after installation.

Figure 3. Root wad installation using drive-point method.

with an erosion control fabric.

Rock Vanes

The three most common types of vanes are: 1) single vane, 2) J-hook vane, and 3) cross vane. Vanes are most often constructed from boulders. Vanes 1) protect the streambank by redirecting the thalweg away from the streambank and towards the center of the channel, and 2) improve in-stream habitat through scour, oxygenation, and cover.

Design Criteria

All three vanes are oriented upstream with angles off the bank from 20 to 30 degrees. Vanes are located just downstream of the point where the stream flow encounters the streambank at acute angles. The structure is highest next to the bank, generally starting at bankfull. The structures slope down, pointing upstream. The size of rock will depend on the size of the stream, but generally will be heavier than 1 to 2 tons. Flat rocks are preferred. A common rock dimension for a vane is 6 feet by 4 feet by 3 feet for larger streams (bankfull width greater than 20 feet). As a rule of thumb, use the largest rock possible.

The length of a single vane structure can span one-half to two-thirds of the baseflow channel width. The slopes of the structure can range widely, from 2 to 20 percent; however, longer, flatter structures are preferred for maximum length of streambank protection and maximum habitat creation. The rocks in all three structures must touch each other (except last two rocks of J-hook) and have footer rocks to the depth of scour. Generally, one to two rocks underneath and downstream of the top rock will suffice. It is very important to include the footer rock downstream of the top rock to prevent the structure from sinking into a scour hole. Figure 6 shows the design drawing for a single rock vane.

J-hook vanes are built just like rock vanes except for the last two or three

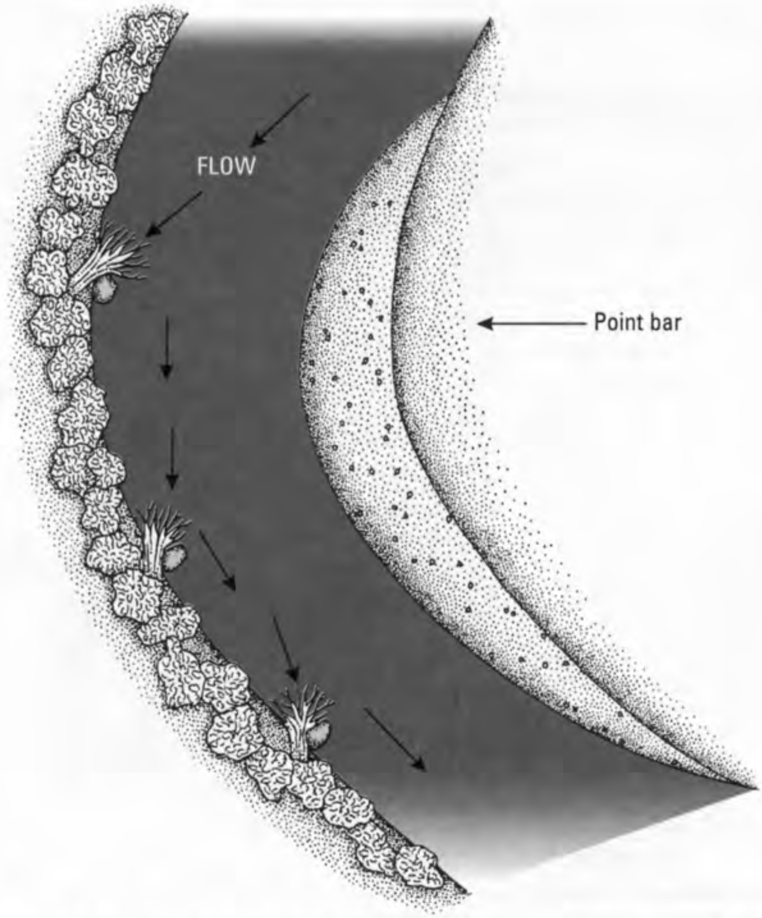
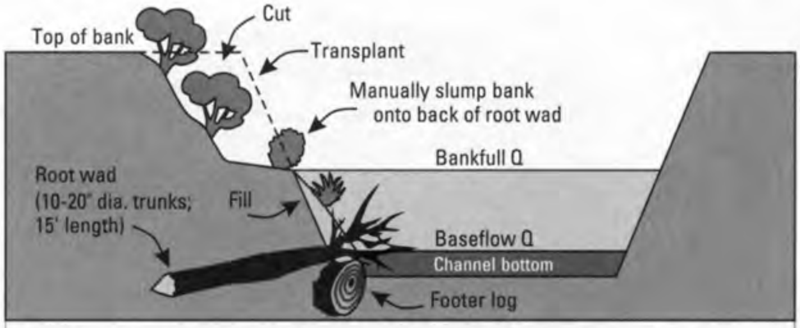


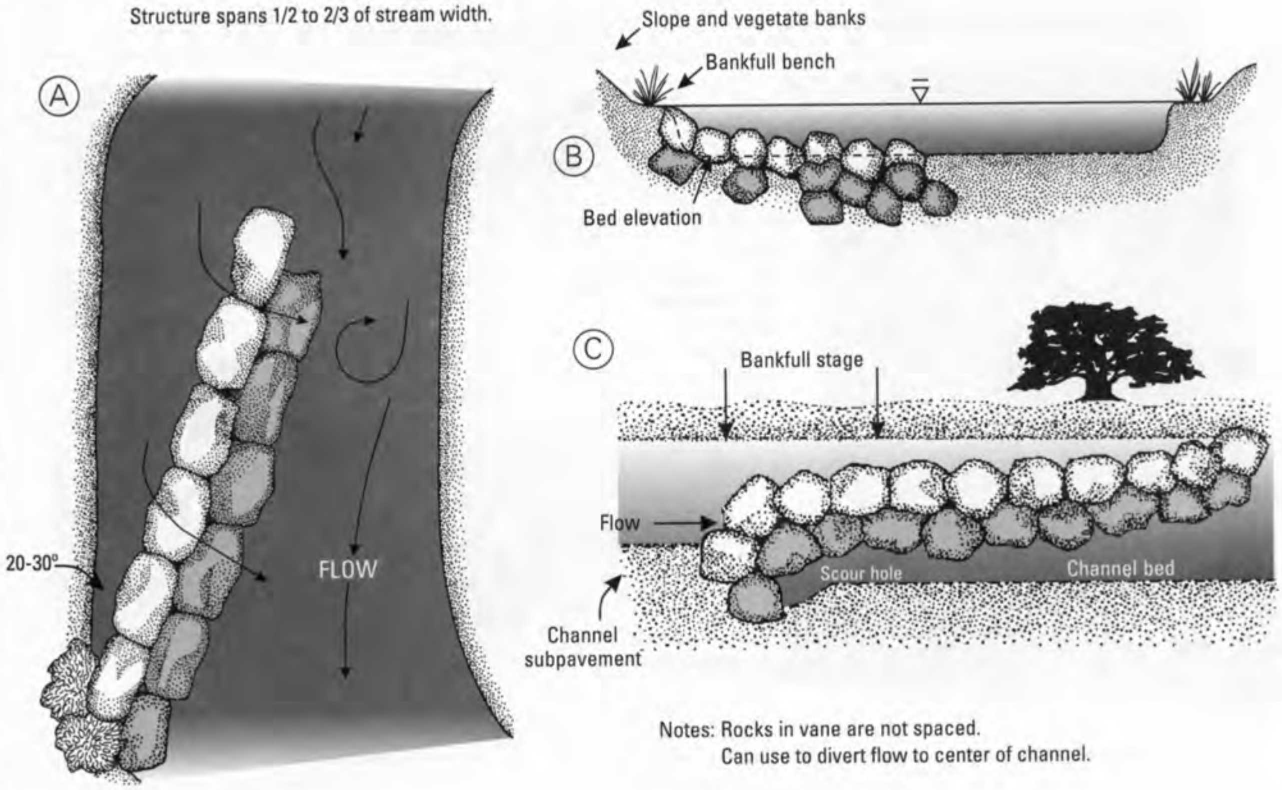
Figure 4. Root wads should be installed on the outside of the meander bend. They should be angled upstream to deflect the stream flow away from the bank.



Notes: 1) May need a boulder or log on top of root wad if bank height is low or non-cohesive soils.
2) Transplant mature trees on back of root wad and up bank.
3) Slope bank from 1.5:1 to 2:1.

Figure 5. Cross-section view of root wad design.

Figure 6. (a) Plan view, (b) cross-section, and (c) profile views of a rock vane.



Notes: Rocks in vane are not spaced.
Can use to divert flow to center of channel.

rocks. These rocks are spaced about one-half of the rock diameter to create flow convergence. The result is a large scour hole for energy dissipation and aquatic habitat. Figure 7 shows the design of a J-hook vane.

Cross vanes are used to provide grade control, to keep the thalweg in the center of the channel, and to protect the bank. A cross vane consists of two rock vanes and one center structure perpendicular to the flow. This center structure sets the invert grade of the streambed. Therefore, this structure can be used to raise the bed and is often used at the head of a riffle to set the elevation of the upstream pool. Figure 8 provides the design specifications for cross vanes.

Examples of vanes are shown at the Stream Restoration Institute Web page at http://www.bae.ncsu.edu/bae/programs/extension/wqg. Click on Stream Restoration Institute.

Conclusion

Before using the design specifications and suggestions in this fact sheet to install root wads and rock vanes, the designer must first complete a thorough morphological assessment of the stream reach and watershed. Selecting methods for stabilizing a streambank is one of the last steps in a natural channel design. The methods in this fact sheet are not "the only methods" for stabilizing streambanks. Designers are encouraged to use a variety of techniques depending on site conditions and supply of native materials. Check the Stream Restoration Institute Web page for other stream restoration-related materials at http://www.bae.ncsu.edu/bae/programs/extension/wqg. Click on Stream Restoration Institute.

Figure 7. (a) Plan view, (b) cross-section, and (c) profile views of J-hook vane.

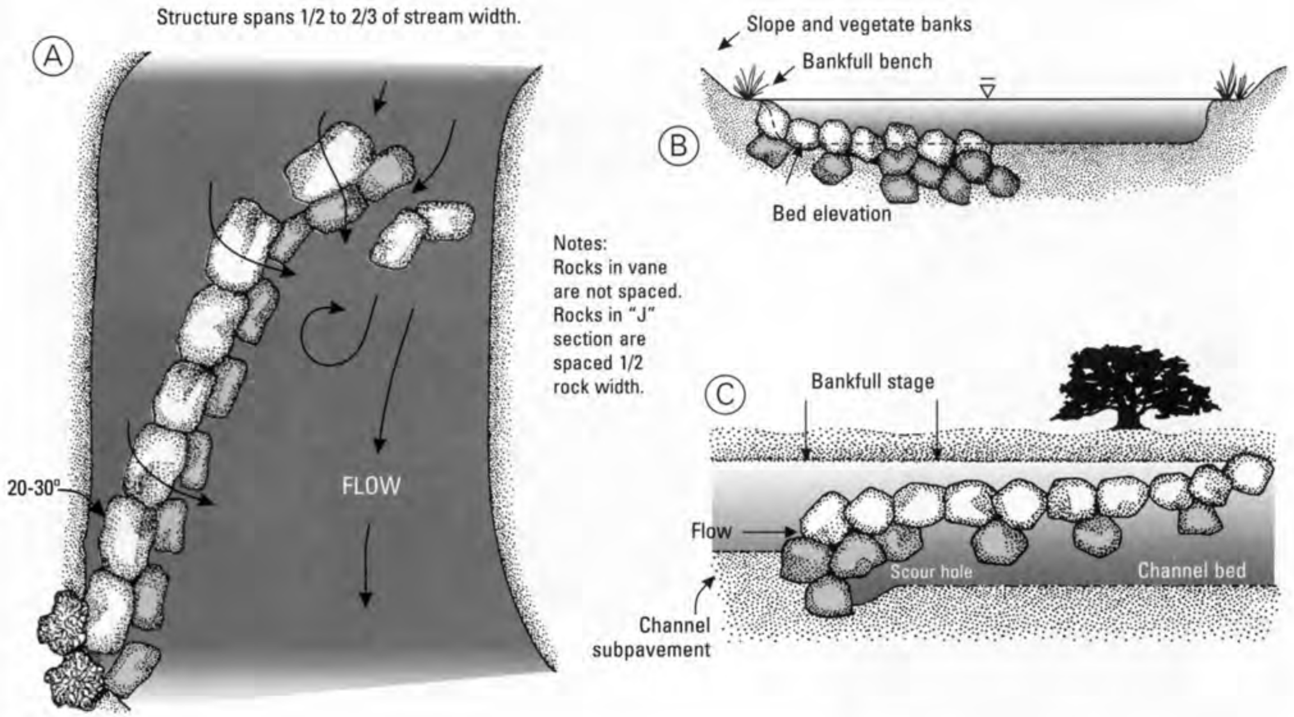
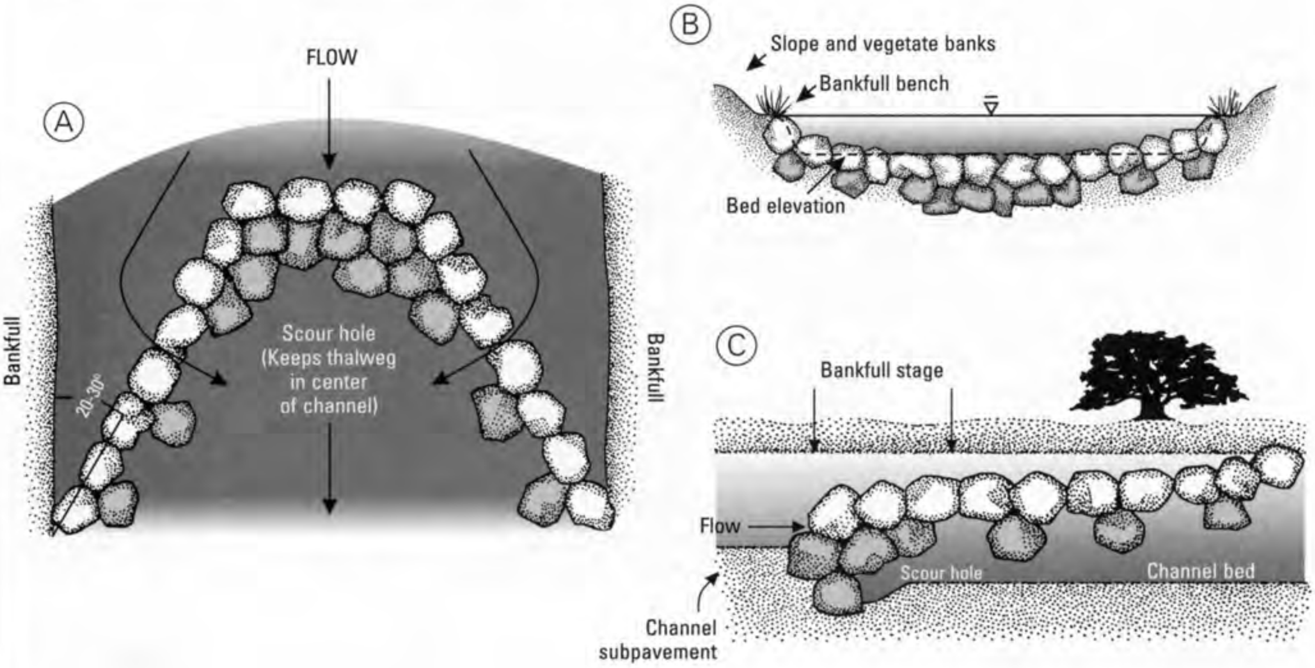


Figure 8. (a) Plan view, (b) cross-section, and (c) profile views of cross vane.



Note: There should be no gaps between the rocks in the cross vane.

References

Federal Interagency Stream Restoration Working Group. 1999. *Stream Corridor Restoration: Principles, Processes, and Practices.* Federal Interagency Stream Restoration Working Group. Washington, D.C.

Rosgen, D.L. 1998. *River Restoration and Natural Channel Design Course Handbook.* Wildland Hydrology. Pagosa Springs, CO.

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(Reprint)

Cross-Section Survey

Site ____ **Date** ____________

Survey Crew ____

Longitudinal Station ____________ **Cross-Section Feature** __________________________

STA	BS	HI	FS	ELEV	NOTE	WIDTH	BKF DEPTH	AVG DEPTH	BKF AREA

BM = Benchmark
LTOB = Left Top of Bank
RTOB = Right Top of Bank
TP = Turning Point
LBKF = Left Bankfull
RBKF = Right Bankfull
TW = Thalweg
LIB = Left Inner Berm
RIB = Right Inner Berm
WS = Water Surface
LEW = Left Edge Water
REW = Right Edge Water

Cross-Section Survey Example

Site ____ **Date** ____________

Survey Crew ____

Longitudinal Station ____________ **Cross-Section Feature** ___________________________

STA	BS	HI	FS	ELEV	NOTE	WIDTH	BKF DEPTH	AVG DEPTH	BKF AREA
BM	4.72	104.72		100.00	BM				
0 + 00		104.72	5.61	99.11					
0 + 20		104.72	5.92	98.80	LTOB	20.0			
0 + 26		104.72	6.15	98.57	LBKF	6.0	0.00		
0 + 29		104.72	8.22	96.50	LEW	3.0	2.07	1.04	3.12
0 + 33		104.72	8.65	96.07		4.0	2.50	2.29	9.16
0 + 35		104.72	9.05	95.67		2.0	2.90	2.70	5.40
0 + 42		104.72	9.25	95.47		7.0	3.10	3.00	21.00
0 + 48		104.72	9.44	95.28	TW	6.0	3.29	3.20	19.20
0 + 52		104.72	9.33	95.39		4.0	3.18	3.24	12.96
0 + 57		104.72	8.89	95.83		5.0	2.74	2.96	14.80
0 + 62		104.72	8.18	96.54	REW	5.0	2.03	2.39	11.95
0 + 67		104.72	6.15	98.57	RBKF	5.0	0.00	1.02	5.10
0 + 74		104.72	5.22	99.50	RTOB	7.0			
1 + 00		104.72	4.15	100.57		26.0			
								Total	102.69

BM = Benchmark
LTOB = Left Top of Bank
RTOB = Right Top of Bank
TP = Turning Point
LBKF = Left Bankfull
RBKF = Right Bankfull
TW = Thalweg
LIB = Left Inner Berm
RIB = Right Inner Berm
WS = Water Surface
LEW = Left Edge Water
REW = Right Edge Water

Longitudinal Profile Survey

Site ____ **Date** __________

Survey Crew ____

STA	BS	HI	FS	ELEV	NOTE

BM = Benchmark
LTOB = Left Top of Bank
RTOB = Right Top of Bank
TP = Turning Point
LBKF = Left Bankfull
RBKF = Right Bankfull
TW = Thalweg
LIB = Left Inner Berm
RIB = Right Inner Berm
WS = Water Surface
LEW = Left Edge Water
REW = Right Edge Water

Stream Survey Data Sheet

Site ____ Date ____________

Survey Crew ____

Riffle Cross-Section:

Area at Bankfull, A_{bkf} (ft^2) _______

Mean Depth at Bankfull, $D_{bkf} = A_{bkf} / W_{bkf}$ (ft) _______

Width at Bankfull, W_{bkf} (ft) _______

Entrenchment Ratio, $ER = W_{fpa} / W_{bkf}$ (ft/ft) _______

Width Flood Prone Area, W_{fpa} (ft) _______

Width to Depth Ratio, $W/D = W_{bkf} / D_{bkf}$ (ft/ft) _______

Maximum Depth Bankfull, D_{max} (ft) _______

Bank Height Ratio, $BHR = D_{TOB} / D_{max}$ (ft/ft) _______

Max Depth Top Low Bank, D_{TOB} (ft) _______

Max Depth Ratio = D_{max} / D_{bkf} (ft/ft) _______

Longitudinal Profile (minimum of 20 X bankfull width):

Length of Channel Thalweg, L_{tw} (ft) _______

Slope of Channel, $S_{ave} = \Delta ELEV / L_{tw}$ (ft/ft) _______

Length of Valley, L_{valley} (ft) _______

Sinuosity, $K = L_{tw} / L_{valley}$ (ft/ft) _______

Elevation Change (head first riffle to head last riffle), ΔELEV (ft) _______

Pool Cross-Section:

Pool Area at Bankfull, $A_{.pool}$ (ft^2) _______

Pool Area Ratio = $A_{.pool} / A_{bkf}$ (ft^2/ft^2) _______

Pool Width at Bankfull, W_{pool} (ft) _______

Pool Width Ratio = W_{pool} / W_{bkf} (ft/ft) _______

Pool Max Depth Bankfull, D_{pool} (ft) _______

Pool Max Depth Ratio = D_{pool} / D_{bkf} (ft/ft) _______

Pattern Survey (minimum of 2 wavelengths, list ranges of measurements):

Meander Wavelength, L_m (ft) ____________

Meander Wavelength Ratio = L_m / W_{bkf} (ft/ft) ____________

Meander Belt Width, W_{blt} (ft) ____________

Meander Width Ratio = W_{blt} / W_{bkf} (ft/ft) _____________

Radius of Curvature, R_c (ft) ____________

Radius of Curvature Ratio = R_c / W_{bkf} (ft/ft) _____________

Pebble Count Results (reachwide):

Median Particle Size, d50 (mm) ____________

Pebble Count

Site ____ **Date** ____________

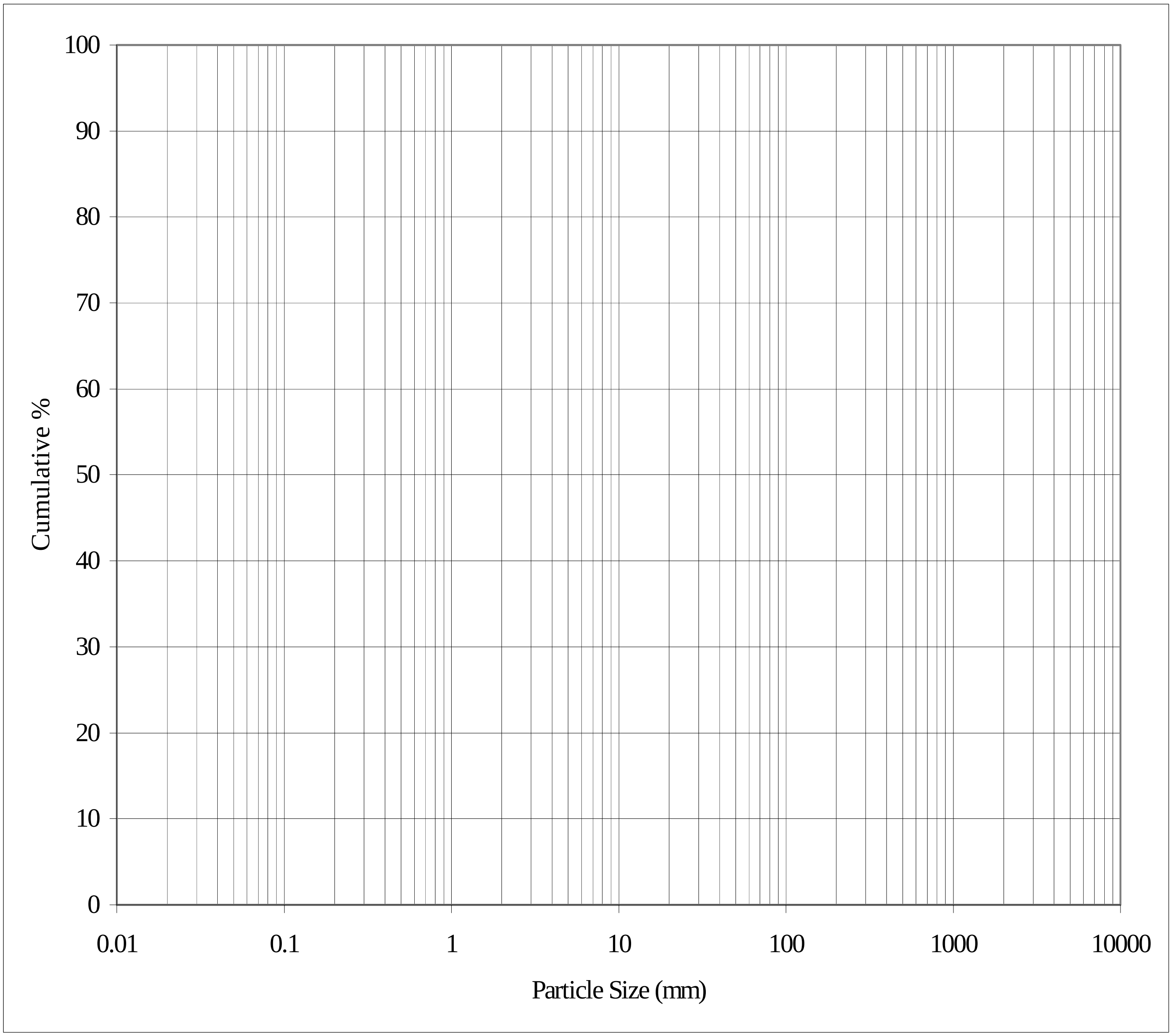
Survey Crew ____

Particle	**Description**	**Size (mm)**	**Particle Count**				**%**	**Cum %**
			Riffle	**Pool**	**Other**	**Total**		
Silt/Clay	**Silt/Clay**	**< 0.062**						
Sand	**Very Fine**	**0.062 – 0.125**						
	Fine	**0.125 – 0.25**						
	Medium	**0.25 – 0.5**						
	Coarse	**0.5 – 1.0**						
	Very Coarse	**1.0 – 2.0**						
Gravel	**Very Fine**	**2.0 – 4.0**						
	Fine	**4.0 – 5.7**						
	Fine	**5.7 – 8.0**						
	Medium	**8.0 – 11.3**						
	Medium	**11.3 – 16.0**						
	Coarse	**16.0 – 22.6**						
	Coarse	**22.6 – 32**						
	Very Coarse	**32 – 45**						
	Very Coarse	**45 – 64**						
Cobble	**Small**	**64 – 90**						
	Small	**90 – 128**						
	Large	**128 – 180**						
	Large	**180 – 256**						
Boulder	**Small**	**256 – 362**						
	Small	**362 – 512**						
	Medium	**512 – 1024**						
	Large	**1024 – 2048**						
Bedrock	**Bedrock**	**> 2048**						
Total								

Pebble Count

Site ____ **Date** __________

Survey Crew ____



Bank Erosion Hazard Index

Site ____ **Date** ____________

Survey Crew ____

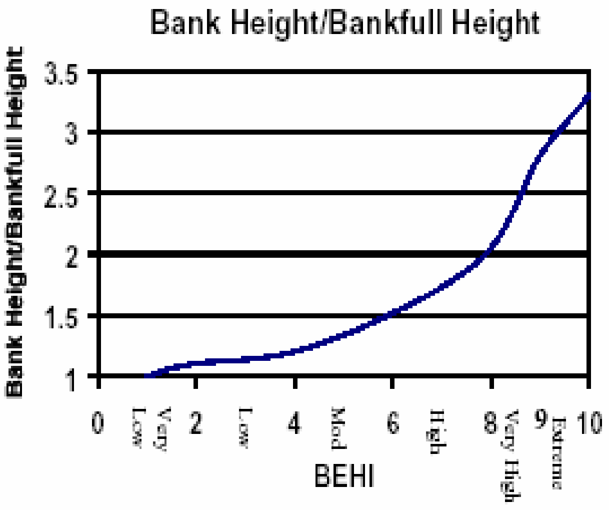
Category		**Bank Ht Ratio (ft/ft)**	**Root Depth Ratio (%)**	**Root Density (%)**	**Bank Angle (degrees)**	**Surface Protection (%)**	**Total Index**
Very Low	**Value**	1.0 – 1.1	100 – 80	100 – 80	0 – 20	100 – 90	
	Index	1 – 2	1 – 2	1 – 2	1 – 2	1 – 2	< 10
Low	**Value**	1.1 – 1.2	80 – 55	80 – 55	20 – 60	90 – 50	
	Index	2 – 4	2 – 4	2 – 4	2 – 4	2 – 4	10 – 20
Moderate	**Value**	1.2 – 1.5	55 – 30	55 – 30	60 – 80	50 – 30	
	Index	4 – 6	4 – 6	4 – 6	4 – 6	4 – 6	20 – 30
High	**Value**	1.5 – 2.0	30 – 15	30 – 15	80 – 90	30 – 15	
	Index	6 – 8	6 – 8	6 – 8	6 – 8	6 – 8	30 – 40
Very High	**Value**	2.0 – 2.8	15 – 5	15 – 5	90 – 120	15 – 5	
	Index	8 – 9	8 – 9	8 – 9	8 – 9	8 – 9	40 – 45
Extreme	**Value**	> 2.8	< 5	< 5	> 120	< 5	
	Index	10	10	10	10	10	> 45
Field Measure	**Value**						
	Index						

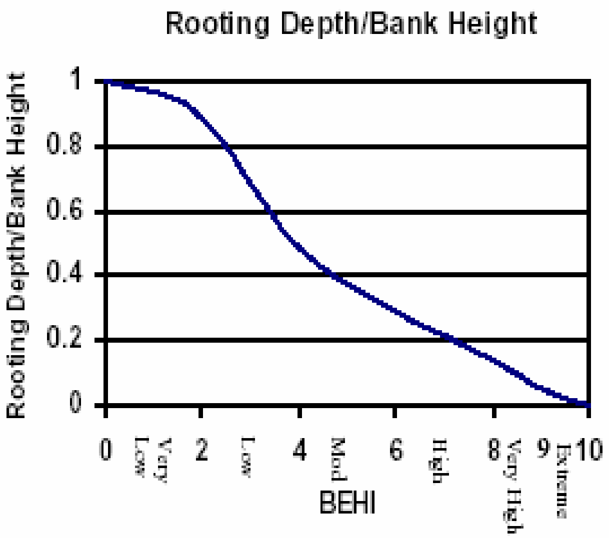
Total Field Index _______

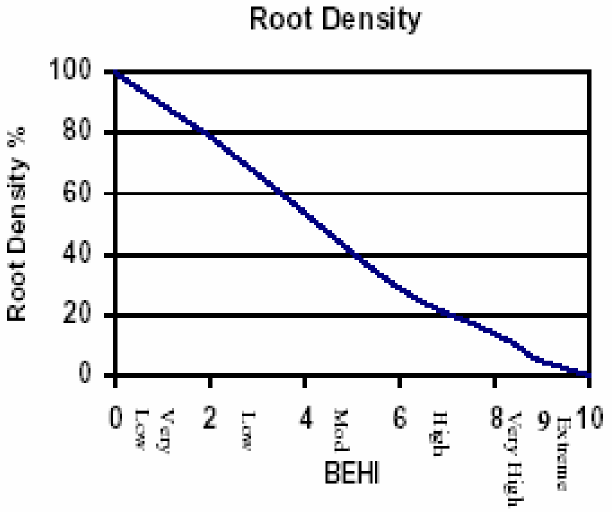
Numerical Adjustments _______

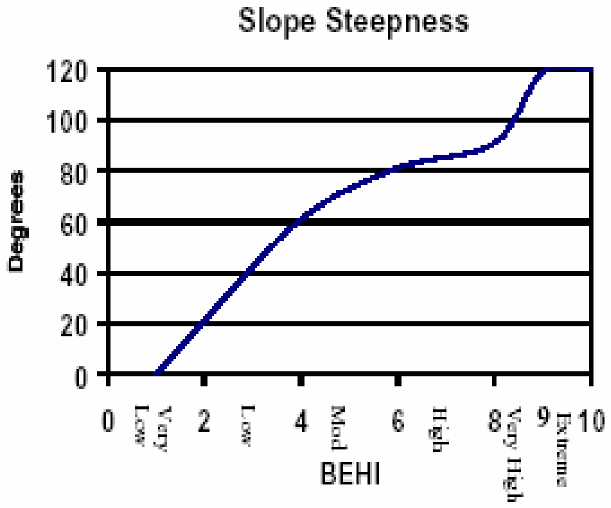
Bedrock:	BEHI Very Low
Boulders:	BEHI Low
Cobble:	Decrease by one category if gravel/sand less than 50%
Gravel:	Adjust Index up 5 – 10 points depending on sand %
Sand:	Adjust Index up 10 points
Silt/Clay:	No Adjustment
Stratification:	Adjust Index up 5 – 10 points depending on position of unstable layers in relation to bankfull stage

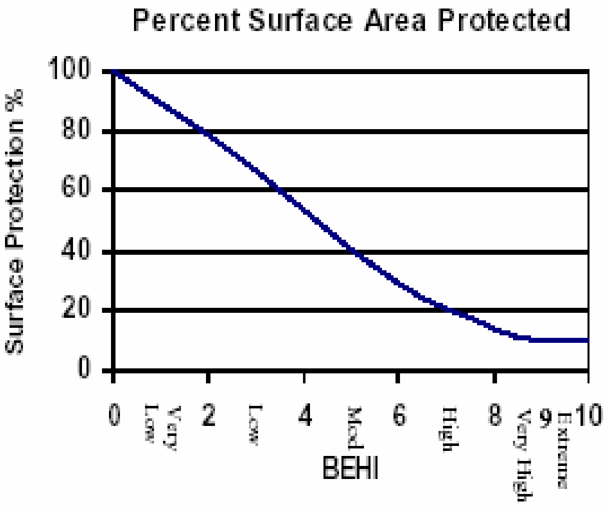
Adjusted BEHI ________


Bank Height/Bankfull Height


Rooting Depth/Bank Height


Root Density


Slope Steepness


Percent Surface Area Protected

Gage Station Data

Appendix C

UNITED STATES DEPARTMENT OF INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION
EXPANDED RATING TABLE
TYPE: LOG
DATE PROCESSED: 09-10-1998 @ 12:48 BY dwalters

02114450
LITTLE YADKIN RIVER AT DALTON, N. C.
OFFSET: .00

DD: 2 TYPE: 001 RATING NO: 11.0
START DATE/TIME: 10-01-96 (0015)

GAGE HEIGHT (FEET)	DISCHARGE IN CUBIC FEET PER SECOND					(EXPANDED PRECISION)					DIFF IN Q PER TENTH FT
	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	
4.10	1197	1201	1206	1210	1214	1218	1223	1227	1231	1235	43.00
4.20	1240	1244	1248	1252	1257	1261	1265	1270	1274	1278	43.00
4.30	1283	1287	1291	1296	1300	1304	1309	1313	1317	1322	43.00
4.40	1326	1330	1335	1339	1344	1348	1352	1357	1361	1366	44.00
4.50	1370*	1374	1378	1383	1387	1391	1395	1400	1404	1408	42.00
4.60	1412	1417	1421	1425	1429	1434	1438	1442	1446	1451	43.00
4.70	1455	1459	1464	1468	1472	1476	1481	1485	1489	1494	43.00
4.80	1498	1502	1507	1511	1515	1520	1524	1528	1533	1537	43.00
4.90	1541	1546	1550	1554	1559	1563	1567	1572	1576	1581	44.00
5.00	1585*	1589	1593	1598	1602	1606	1610	1615	1619	1623	42.00
5.10	1627	1632	1636	1640	1645	1649	1653	1657	1662	1666	43.00
5.20	1670	1674	1679	1683	1687	1692	1696	1700	1705	1709	43.00
5.30	1713	1717	1722	1726	1730	1735	1739	1743	1748	1752	43.00
5.40	1756	1761	1765	1769	1774	1778	1783	1787	1791	1796	44.00
5.50	1800*	1804	1808	1812	1817	1821	1825	1829	1833	1837	41.00
5.60	1841	1846	1850	1854	1858	1862	1866	1871	1875	1879	42.00
5.70	1883	1887	1891	1896	1900	1904	1908	1912	1917	1921	42.00
5.80	1925	1929	1933	1938	1942	1946	1950	1954	1959	1963	42.00
5.90	1967	1971	1975	1980	1984	1988	1992	1997	2001	2005	42.00
6.00	2009	2013	2018	2022	2026	2030	2035	2039	2043	2047	43.00
6.10	2052	2056	2060	2064	2069	2073	2077	2081	2086	2090	42.00
6.20	2094	2098	2103	2107	2111	2116	2120	2124	2128	2133	43.00
6.30	2137	2141	2146	2150	2154	2158	2163	2167	2171	2176	43.00
6.40	2180	2184	2189	2193	2197	2201	2206	2210	2214	2219	43.00
6.50	2223	2227	2232	2236	2240	2245	2249	2253	2258	2262	43.00
6.60	2266	2271	2275	2279	2284	2288	2292	2297	2301	2306	44.00
6.70	2310	2314	2319	2323	2327	2332	2336	2340	2345	2349	44.00
6.80	2354	2358	2362	2367	2371	2375	2380	2384	2389	2393	43.00
6.90	2397	2402	2406	2411	2415	2419	2424	2428	2433	2437	44.00
7.00	2441	2446	2450	2455	2459	2463	2468	2472	2477	2481	44.00
7.10	2485	2490	2494	2499	2503	2508	2512	2516	2521	2525	45.00
7.20	2530	2534	2539	2543	2548	2552	2556	2561	2565	2570	44.00
7.30	2574	2579	2583	2588	2592	2597	2601	2606	2610	2614	45.00
7.40	2619	2623	2628	2632	2637	2641	2646	2650	2655	2659	45.00
7.50	2664	2668	2673	2677	2682	2686	2691	2695	2700	2704	45.00
7.60	2709	2713	2718	2722	2727	2731	2736	2740	2745	2749	45.00
7.70	2754	2758	2763	2767	2772	2776	2781	2785	2790	2795	45.00
7.80	2799	2804	2808	2813	2817	2822	2826	2831	2835	2840	46.00

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                  UNITED STATES DEPARTMENT OF INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION                PAGE  1
                                                 EXPANDED RATING TABLE                                            TYPE: LOG
02114450                                         DATE PROCESSED: 09-10-1998 @ 12:48 BY dwalters
LITTLE YADKIN RIVER AT DALTON, N. C.                                                 DD:    2    TYPE: 001    RATING NO: 11.0
OFFSET: .00                                                                          START DATE/TIME: 10-01-96  (0015)

BASED ON _______ DISCHARGE MEASUREMENTS, NOS ________, AND ________, AND IS ______ WELL DEFINED BETWEEN ______ AND ______ CFS
                                                                   COMP BY _____ DATE ________     CHK. BY _____ DATE ________

  GAGE                                                                                                            DIFF IN Q
 HEIGHT                        DISCHARGE IN CUBIC FEET PER SECOND            (EXPANDED PRECISION)                     PER
 (FEET)      .00       .01       .02       .03       .04       .05       .06       .07       .08       .09       TENTH FT

   .40      4.000*    4.308     4.630     4.969     5.324     5.695     6.083     6.489     6.912     7.353       3.812

   .50      7.812     8.291     8.788     9.305     9.841     10.40     10.98     11.57     12.19     12.84       5.688
   .60      13.50*    14.19     14.90     15.63     16.38     17.16     17.97     18.80     19.65     20.53       7.940
   .70      21.44     22.37     23.33     24.31     25.33     26.37     27.44     28.53     29.66     30.81       10.56
   .80      32.00*    33.17     34.37     35.60     36.85     38.14     39.45     40.79     42.17     43.57       13.00
   .90      45.00*    46.46     47.95     49.47     51.02     52.60     54.22     55.86     57.54     59.26       16.00

  1.00      61.00*    62.53     64.08     65.65     67.25     68.87     70.51     72.18     73.87     75.58       16.32
  1.10    - 77.32     79.08     80.86     82.67     84.50     86.36     88.24     90.14     92.07     94.02       18.68
  1.20      96.00*    97.82     99.65     101.5     103.4     105.3     107.2     109.1     111.1     113.0       19.00
  1.30      115.0     117.0     119.1     121.1     123.2     125.3     127.4     129.5     131.6     133.8       21.00
  1.40      136.0*    138.2     140.4     142.7     145.0     147.2     149.6     151.9     154.2     156.6       23.00

  1.50      159.0*    161.3     163.7     166.0     168.4     170.8     173.2     175.6     178.1     180.5       24.00
  1.60      183.0*    185.7     188.3     191.0     193.8     196.5     199.3     202.1     204.9     207.7       27.60
  1.70      210.6     213.5     216.4     219.3     222.2     225.2     228.2     231.2     234.2     237.3       29.80
  1.80      240.4     243.5     246.6     249.8     252.9     256.1     259.3     262.6     265.8     269.1       32.00
  1.90      272.4     275.8     279.1     282.5     285.9     289.3     292.8     296.2     299.7     303.2       34.40

  2.00      306.8     310.3     313.9     317.5     321.2     324.8     328.5     332.2     335.9     339.7       36.70
  2.10      343.5     347.3     351.1     354.9     358.8     362.7     366.6     370.6     374.5     378.5       39.00
  2.20      382.5     386.6     390.6     394.7     398.8     403.0     407.1     411.3     415.5     419.7       41.50
  2.30      424.0*    428.1     432.2     436.4     440.5     444.7     448.9     453.2     457.4     461.7       42.00
  2.40      466.0*    470.2     474.4     478.7     483.0     487.2     491.6     495.9     500.2     504.6       43.00

  2.50      509.0*    512.9     516.9     520.9     524.9     528.9     532.9     536.9     540.9     545.0       40.10
  2.60      549.1     553.2     557.3     561.4     565.5     569.7     573.8     578.0     582.2     586.4       41.50
  2.70      590.6     594.9     599.1     603.4     607.6     611.9     616.3     620.6     624.9     629.3       43.00
  2.80      633.6     638.0     642.4     646.8     651.2     655.7     660.1     664.6     669.1     673.6       44.50
  2.90      678.1     682.6     687.2     691.7     696.3     700.9     705.5     710.1     714.7     719.3       45.90

  3.00      724.0*    728.1     732.2     736.3     740.4     744.6     748.7     752.8     757.0     761.2       41.30
  3.10      765.3     769.5     773.7     777.9     782.1     786.4     790.6     794.8     799.1     803.4       42.30
  3.20      807.6     811.9     816.2     820.5     824.8     829.1     833.4     837.8     842.1     846.5       43.20
  3.30      850.8     855.2     859.6     864.0     868.4     872.8     877.2     881.6     886.1     890.5       44.20
  3.40      895.0     899.4     903.9     908.4     912.9     917.4     921.9     926.4     930.9     935.5       45.00

  3.50      940.0*    944.1     948.3     952.5     956.6     960.8     965.0     969.2     973.3     977.5       41.70
  3.60      981.7     986.0     990.2     994.4     998.6     1003      1007      1011      1016      1020        42.30
  3.70      1024      1028      1033      1037      1041      1046      1050      1054      1058      1063        43.00
  3.80      1067      1071      1076      1080      1085      1089      1093      1098      1102      1106        44.00
  3.90      1111      1115      1120      1124      1128      1133      1137      1142      1146      1151        44.00

  4.00      1155*     1159      1163      1168      1172      1176      1180      1184      1189      1193        42.00
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                         UNITED STATES DEPARTMENT OF INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION
                                                SUMMARY OF DISCHARGE MEASUREMENT DATA
02114450                                                                                              DATE PROCESSED: 19-Aug-98 13:33
LITTLE YADKIN RIVER AT DALTON, N. C.

**************************************************************************************************************************************
  NO.   * DATE   * MADE BY * WIDTH *  AREA  * MEAN *  GAGE   * DISCHARGE * SHIFT *  PCT. *  NO.  * GHT. * TIME * RATED *   CONTROL
        * TIME   *                          * VEL. * HEIGHT *     CFS    * ADJ. * DIFF. * SECT. * CHG. *
**************************************************************************************************************************************
                                                                          RATING NO.  9.0
  300  1983/09/19    IJF      22.0     11.6    0.59      0.58     6.89     -0.06   +3.6     26     0.00    0.9     G     LGT DEBRIS
                       REMARKS: LEAVES ON CONTROL

  301  1983/10/05    IJF      22.5     12.5    0.65      0.61     8.14     -0.06   -1.3     28     0.00    0.9     G     LGT DEBRIS
                       REMARKS: LEAVES ON CONTROL

  302  1983/11/14    CLH      30.0     10.6    1.25      0.69     13.3     -0.06   +1.5     26     0.00    1.5     G     LGT DEBRIS
                       REMARKS: LEAVES ON CONTROL

  303  1984/01/10    CMR      31.0     29.8    1.14      0.85     34.1             -0.6     23     0.00    2.0     G     CLEAR
                       REMARKS: CONTROL CLEAR. WATER MUDDY - NO LEAVES VISIBLE.

  304  1984/04/23    CMR      28.5     27.5    1.57      0.89     43.1              0.0     26     0.00    1.0     G     CLEAR
                       REMARKS: 0

  305  1984/05/29    CMR      55.0     173.    3.41      2.60     590              +5.4     18    -0.04    0.5     G     CLEAR
                       REMARKS: 0

  306  1984/06/26    CMR      14.5     15.9    1.26      0.72     20.0              0.0     25     0.00    0.5     G     CLEAR
                       REMARKS: 0

  307  1984/10/05    CMR      17.0     17.6    0.91      0.67     16.1             +0.6     28     0.00    0.5     G     CLEAR
                       REMARKS: 0

  308  1985/01/16    CMR      18.0     22.4    1.30      0.81     29.1             -1.0     29     0.00    1.3     G     CLEAR
                       REMARKS: CONTROL CLEAR. NO ICE ON CONTROL.

  309  1985/04/08    CMR      16.0     16.9    1.20      0.71     20.2             +4.6     22     0.00    1.0     G     CLEAR

  310  1985/05/15    CMR      13.2     8.19    1.67      0.63     13.7             +4.6     27     0.00    1.0     G     CLEAR

  311  1985/09/16    CMR      15.0     9.92    1.26      0.62     12.5             +0.8     29     0.00    1.0     G     CLEAR

  312  1985/12/03    IJF      49.0     35.6    1.37      0.93     48.8     +0.03            27     0.00    1.0     G     CLEAR

  313  1986/03/04    IJF      48.5     21.7    1.35      0.74     29.2     +0.04            24     0.00    1.0     G     CLEAR

  314  1986/04/18    IJF      20.0     19.4    1.00      0.70     19.4     +0.01            26     0.00    0.5     G     CLEAR

  315  1986/06/09    IJF      16.2     15.9    0.54      0.58     8.60     -0.02            27     0.00    0.6     F     LGT DEBRIS
                       REMARKS: LIGHT LIMBS,TWIGS AND LEAVES ON CONTROL.

  316  1986/07/17    IJF      12.0     11.3    0.22      0.44     2.50                      23     0.00    1.0     F     LGT DEBRIS
           1212
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                    UNITED STATES DEPARTMENT OF INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION
                                          SUMMARY OF DISCHARGE MEASUREMENT DATA
02114450                                                                                           DATE PROCESSED: 19-Aug-98 13:33
LITTLE YADKIN RIVER AT DALTON, N. C.

*************************************************************************************************************************************
 NO.   * DATE  * MADE BY * WIDTH *  AREA  * MEAN *  GAGE  * DISCHARGE * SHIFT *  PCT. *  NO.  * GHT. * TIME * RATED *   CONTROL
       * TIME  *                          * VEL. * HEIGHT *    CFS    *  ADJ. * DIFF. * SECT. * CHG. *
*************************************************************************************************************************************

 317  1986/08/27    IJF     23.0    14.2   0.29     0.47     4.18                        23     0.00    0.5     G     LGT DEBRIS
          1230

 318  1986/10/06    CMR     7.60    5.52   1.60     0.46     3.28                        26     0.00    0.5     F     LGT DEBRIS
          1215

 319  1986/11/14    CMR     16.5                    0.68     12.7                        24     0.00    0.6     G     HVY DEBRIS
          1430      REMARKS: REMOVED INSTALLED 12241 7609H1532M58

 320  1987/01/07  RCP/SCS   31.0    46.5   0.48     0.74     22.2                        31     0.00    2.0     G     CLEAR
          1430

 321  1987/02/24  RCP/SCS   37.0    51.4   1.64     1.18     84.1               -2.0     26    -0.01    1.5     G     CLEAR
          0915

 322  1987/04/02    SCS     44.5    91.3   0.68     1.04     61.8               +0.1     34     0.00    2.0     F     CLEAR
          1110

 323  1987/08/27  SCS/RCP   26.0    12.8   0.81     0.60     10.4               -6.7     33     0.00    0.9     F     CLEAR
          1011      REMARKS: NO "GOOD" SECTION FOUND, "FAIR" ONE USED.  HANDRAILS PLACED ON GAGEHOUSE PLATFORM.

 324  1987/10/02    SCS     24.4    18.6   0.81     0.67     15.0               -6.2     33     0.00    0.7     G     LGT DEBRIS
          0937

 325  1987/11/20    SCS     25.0    22.9   0.91     0.74     20.8      -0.01    -5.8     31    -0.01    1.0     F     CLEAR
          0824

 326  1988/01/06    SCS     26.1    23.2   1.06     0.77     24.7      -0.01    -5.4     31    +0.05    2.0     G     SHORE ICE
          1030

 327  1988/02/11    RCP     35.0    20.7   1.43     0.80     29.5      +0.01    +4.2     29     0.00    1.5     G     CLEAR
          0817

 328  1988/05/23    SCS     25.0    19.5   1.00     0.69     19.4      +0.03    +10      22     0.00    0.6     G     CLEAR
          1157

 329  1988/06/16    RCP     24.0    11.0   0.82     0.58     9.06      -0.01    -8.4     23    -0.01    1.0     G     CLEAR
          0754      REMARKS: BATTERY CHECKED 12.5 VOLTS

 330  1988/06/27    SCS     24.5    18.7   0.91     0.70     17.1      +0.02    +6.5     33    -0.01    0.5     G     MOD DEBRIS
          1029      REMARKS: CONTROL CLEARED OF MODERATE DEBRIS AFTER MEASUREMENT , -0.03GAGE HEIGHT CHANGE. HEAVY THUNDERSTORM E

 331  1988/07/28    JFR     26.0    25.6   1.10     0.78     28.3      +0.02    +8.4     33     0.00    0.5     G     CLEAR
          1245      REMARKS: EXCHANGED BATTERIES. CABLEWAY OK. MARKINGS NEED TOUCHING UP.

 332  1988/08/26  MDC/SCS   20.7    10.8   0.33     0.48     3.57      -0.04    -26      40     0.00    1.0     F     MOD DEBRIS
          1030      REMARKS: INSPECTED CABLE. LB A FRAME HANDRAIL NEEDS REPAIR, O                               OTHERWISE OK.

 333  1988/10/11    MDC     25.5    22.7   0.66     0.63     14.9      +0.04    +21      29    +0.01    1.0     G     HVY DEBRIS
          1230      REMARKS: BATTS. OK. SMALL LIMB HANGING ON CABLE ABOUT HALFWAY DOWN, COULDN'T SHAKE IT OFF.
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STATION 02114450 LITTLE YADKIN RIVER AT DALTON, N. C.

AGENCY: USGS
STATE: 37
COUNTY: 169
DISTRICT: 37

STATION LOCATOR
LAT. LONG.
-
361756 0802553

DRAINAGE AREA: 42.80 SQ MI
CONTRIBUTING
DRAINAGE AREA: SQ MI
GAGE DATUM: 813.70 (NGVD)
BASE DISCHARGE: 1700.00 CFS

WATER YEAR	DATE	PEAK DISCHARGE (CFS)	DISCHARGE CODES	GAGE HEIGHT (FT)	GAGE HT CODES	HIGHEST SINCE	MAX GAGE HEIGHT (FT)	DATE	GAGE HT CODES	NUMBER OF PARTIAL PEAKS
1961	03/08/61	2630.00		7.75						2
	02/23/61	2320.00		6.76						
	06/22/61	2060.00		6.02						
1962	06/12/62	7740.00		17.86						3
	12/12/61	2070.00		6.31						
	04/08/62	1880.00		5.77						
	06/02/62	1960.00		6.02						
1963	03/12/63	4850.00		12.66						2
	12/04/62	2040.00		6.16						
	03/06/63	1960.00		6.02						
1964	01/25/64	2860.00		8.28						3
	04/07/64	2170.00		6.54						
	07/20/64	1770.00		5.50						
	08/31/64	2550.00		7.51						
1965	10/16/64	4560.00		12.12						3
	11/25/64	2560.00		7.52						
	02/07/65	1730.00		5.41						
	03/26/65	3220.00		9.17						
1966	02/13/66	2410.00		7.16						1
	02/28/66	1780.00		5.53						
1967	01/27/67	698.00		2.87						0
1968	03/12/68	1710.00		5.32						0
1969	10/19/68	3780.00		10.39						1
	07/02/69	2530.00		7.44						
1970	08/10/70	3540.00		9.87						3
	06/25/70	2130.00		6.45						
	07/23/70	2020.00		6.16						
	08/06/70	2350.00		6.99						
1971	10/30/70	3800.00		10.44						2
	02/22/71	3770.00		10.38						
	05/13/71	1890.00		5.82						
1972	06/21/72	8290.00		18.81						6
	10/25/71	4300.00		11.57						
	01/13/72	1790.00		5.54						
	05/04/72	2090.00		6.34						
	05/14/72	3600.00		10.00						
	05/15/72	1920.00		5.90						
	09/30/72	2330.00		6.94						
1973	02/02/73	3530.00		9.84						5
	11/14/72	2550.00		7.51						
	12/15/72	2140.00		6.47						
	03/17/73	1950.00		5.98						
	06/17/73	2090.00		6.35						
	06/24/73	2340.00		6.97						
1974	01/21/74	3790.00		10.43						5
	12/21/73	2620.00		7.68						

	04/04/74	3620.00	10.05	
	08/04/74	2780.00	8.08	
	08/06/74	3710.00	10.25	
	09/06/74	3100.00	8.88	
1975	03/30/75	8880.00	19.60	2
	03/14/75	3460.00	9.70	
	06/01/75	2720.00	7.93	
1976	10/17/75	1620.00	5.10	0
1977	10/09/76	2390.00	7.10	2
	12/07/76	1820.00	5.62	
	04/05/77	2100.00	6.38	
1978	07/03/78	6190.00	15.25	3
	10/26/77	2890.00	8.34	
	01/26/78	4110.00	11.15	
	07/16/78	2700.00	7.87	
1979	09/22/79	9400.00	20.29	5
	01/02/79	2180.00	6.58	
	01/21/79	3020.00	8.66	
	02/24/79	2750.00	7.99	
	02/25/79	2010.00	6.13	
	03/05/79	5680.00	14.33	
1980	10/02/79	3180.00	9.03	4
	03/21/80	3150.00	8.96	
	04/09/80	2760.00	8.03	
	07/18/80	2010.00	6.14	
	07/23/80	1760.00	5.48	
1981	09/07/81	2570.00	7.56	0
1982	10/27/81	1780.00	5.53	0
1983	04/10/83	2390.00	7.11	1
	12/16/82	2130.00	6.44	
1984	05/28/84	8780.00	19.39	1
	02/23/84	2320.00	6.92	
1985	08/18/85	4100.00	11.13	0
1986	11/04/85	1410.00	4.56	0
1987	03/01/87	4650.00	12.29	5
	04/15/87	2490.00	7.35	
	04/24/87	3370.00	9.49	
	04/25/87	4620.00	12.22	
	07/02/87	4010.00	10.92	
	09/07/87	3880.00	10.63	
1988	07/23/88	481.00	2.40	0
1989	05/05/89	3010.00	8.64	0
1990	03/17/90	6240.00	15.33	0
1991	10/22/90	4520.00	12.01	0

Regional Hydraulic Geometry Relationships

Appendix D

BANKFULL HYDRAULIC GEOMETRY RELATIONSHIPS FOR NORTH CAROLINA STREAMS

William A. Harman[1], Gregory D. Jennings[1], Jan M. Patterson[1],
Dan R. Clinton[1], Louise O. Slate[1], Angela G. Jessup[2],
J. Richard Everhart[2] and Rachel E. Smith[1]

ABSTRACT

Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull stream channel dimensions to watershed drainage area. This paper describes results of bankfull hydraulic geometry relationships developed for North Carolina Piedmont streams. Gage stations were selected with a minimum of 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and less than 20% impervious cover in the watershed. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also included in the study. Cross-sectional and longitudinal surveys were measured at each study reach to determine channel dimension, pattern, and profile information. Log-Pearson Type III distributions were used to analyze annual peak discharge data for USGS gage station sites. Power function relationships were developed using regression analyses for bankfull discharge, channel cross-sectional area, mean depth, and width as functions of watershed drainage area. The bankfull return interval for the gaged watersheds ranged from 1.1 to 1.8, with a mean of 1.4 years. Continuing work will expand this database for the North Carolina Mountains, Piedmont, and Coastal Plain physiographic provinces.

Key Words: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses

INTRODUCTION

Stream channel hydraulic geometry theory developed by Leopold and Maddock (1953) describes the interrelations between dependent variables such as width, depth and area as functions of independent variables such as watershed area or discharge. These relationships can be developed at a single cross section (at-a-station) or across many stations along a reach (Merigliano, 1997). Hydraulic geometry relationships are empirically derived and can be developed for a

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[2] Respectively, Civil Engineer and District Conservationist, USDA-Natural Resources Conservation Service.

specific river or watershed in the same physiographic region with similar rainfall/runoff relationships (FISRWG, 1998).

Hydraulic geometry relationships are often used to predict channel morphology features and their corresponding dimensions. This paper describes the process used in North Carolina to develop hydraulic geometry relationships at the bankfull stage. Results for the rural Piedmont physiographic region are presented. Bankfull hydraulic geometry relationships, also called regional curves, were first developed by Dunne and Leopold (1978) and related bankfull channel dimensions to drainage area. Gage station analyses throughout the United States has shown that the bankfull discharge has an average return interval of 1.5 years or 66.7% annual exceedence probability (Dunne and Leopold, 1978; Leopold, 1994). A primary purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds and to help estimate the bankfull dimension and discharge for natural channel designs (Rosgen, 1994).

FIELD INDICATORS OF BANKFULL STAGE

The correct identification of the bankfull stage in the field can be difficult and subjective (Williams, 1978; Knighton, 1984; and Johnson and Heil, 1996). Numerous definitions exist of bankfull stage and methods for its identification in the field (Wolman and Leopold, 1957; Nixon, 1959; Schumm, 1960; Kilpatrick and Barnes, 1964; and Williams 1978). The identification of bankfull stage in the humid Southeast is especially difficult because of dense understory vegetation and long history of channel modification and subsequent adjustment in channel morphology. It is generally accepted that bankfull stage corresponds with the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel forming agent that maintains channel dimension and transports the bulk of sediment over time. Field indicators include the back of point bars, significant breaks in slope, changes in vegetation, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for streams in the rural Piedmont of North Carolina are the highest scour line and the back of the point bar. It is rarely the top of the bank or the lowest scour or bench.

STUDY AREA

North Carolina contains three major physiographic provinces: Mountains, Piedmont, and Coastal Plain. Because rainfall/runoff relationships vary by province and land cover, separate bankfull hydraulic geometry relationships are being developed for rural, suburban, and urban areas for each physiographic region (total of 9 regional curves). It may be necessary to further stratify the data for unique areas such as high rainfall areas in the Mountains and the Sandhills bordering the Piedmont and Coastal Plain. To date, data collection efforts have focused on the rural Piedmont and Mountains.

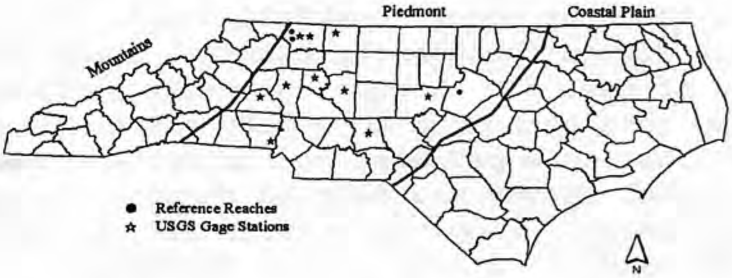

Figure 1: North Carolina map showing physiographic provinces with gaged and un-gaged study reaches.

USGS gage stations were identified with at least 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and less than 20% impervious cover over the watershed area. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also selected for data collection using the same criteria. Figure 1 shows the relative locations of gaged and un-gaged study reaches.

METHODOLOGY

Data Collection

The following gage station records were obtained from the United States Geological Survey: 9-207 forms, stage/discharge rating tables, annual peak discharges, and established reference marks. At the gage, bankfull stage was flagged upstream and downstream of the gage station using the field indicators listed above. Once a consistent indicator was found, a cross-sectional survey was completed at a riffle or run near the gage plate. Temporary pins were installed in the left and right banks, looking downstream. The elevations from the survey were related to the elevation of a gage station reference mark. Each cross section survey started at or beyond the top of the left bank. Moving left to right, morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994; U.S.

Geological Survey, 1969). From the survey data, at-a-station bankfull hydraulic geometry was calculated.

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

Data Analyses

Log-Pearson Type III distributions were used to analyze annual peak discharge data for the USGS gage station sites. Procedures outlined in USGS Bulletin #17B Guidelines for Determining Flood Flow Frequency were followed (U.S. Geological Survey, 1982). USGS recommends Log-Pearson distributions because the log transformation removes positive skew from the data. Generalized skew coefficients and corresponding mean square errors for the Blue Ridge/Piedmont and Coastal Plain are 0.195 and 0.038, respectively (Pope, 1999). For this study, a range of exceedance probabilities from 0.9950 to 0.0100 was chosen. This range represents recurrence intervals between 1.005 and 100 years, with focus between the 1 and 2 year recurrence interval. The annual exceedance probability was calculated as the inverse of the recurrence interval. Exceedance probabilities were plotted as functions of corresponding calculated discharge measurements on log-probability paper, and a regression line was fit to the data. The bankfull discharge recurrence interval was then estimated from the graph.

Ungaged stream reaches were also surveyed to provide points in watersheds with relatively small drainage areas. To obtain a bankfull discharge (Q) estimate, at the stable ungaged watersheds, Manning's equation was used as:

$$Q = 1.4865\ AR^{2/3}\ S^{1/2} / n \qquad (1)$$

where R = hydraulic radius, A = cross sectional area, S = average channel slope or energy slope, and n = roughness coefficient estimated using the bankfull mean depth and channel bed materials. Flood frequency analyses were not completed on ungaged streams.

RESULTS AND DISCUSSION

The at-a-station hydraulic geometry relationships for bankfull discharge, cross-sectional area, width, and mean depth as functions of watershed area for the rural Piedmont of North Carolina are shown in Figures 3a-d. These relationships represent 10 USGS gage stations and 3 un-gaged reaches ranging in watershed area from 0.2 to 128 mi^2. The best-fit regression equations and upper and lower 95% confidence limits are shown for each relationship. The power function regression equations and corresponding coefficients of determination are:

$$Q_{bkf} = 66.57\ A_w^{0.89}\ ;\ (R^2 = 0.97) \qquad (2)$$

$$A_{bkf} = 21.43\ A_w^{0.68}\ ;\ (R^2 = 0.95) \qquad (3)$$

$$W_{bkf} = 11.89\ A_w^{0.43}\ ;\ (R^2 = 0.81) \qquad (4)$$

$$D_{bkf} = 1.50\ A_w^{0.32}\ ;\ (R^2 = 0.88) \qquad (5)$$

where, Q_{bkf} = bankfull discharge (cfs), A_w = watershed drainage area ($mi^{2)}$, A_{bkf} = bankfull cross sectional area (ft^2), W_{bkf} = bankfull width(ft), and D_{bkf} = bankfull mean depth (ft). Table 1 summarizes field measurements, hydraulic geometry, gage station analyses, and flood frequency analyses. The high coefficients of determination indicate good agreement between the measured data and the best-fit relationships. However, the wide range of the values included within the 95% confidence limits indicates the need for caution when using these relationships. For example, the bankfull cross-sectional area for a 10-mi^2 watershed ranges from approximately 60 to 180 ft^2 with a predicted value of 103 ft^2. The range of variability increases with increasing watershed area. This natural variability results from variations in average annual runoff, stream type (Rosgen, 1994), land use, and the natural variability of stream hydrology (Leopold, 1994). The bankfull return interval ranged from 1.09 to 1.80, with an average of 1.4 years. Dunne and Leoplod (1978) reported a bankfull return interval of 1.5 years from a national study.

The relationships described in equations 2-5 represent data collected only in rural Piedmont streams in North Carolina. Ongoing work is being done in urbanized Piedmont watersheds and in streams throughout the Mountain and Coastal Plain provinces to compare with the existing relationships. Continuing data collection will ultimately result in a set of relationships for each physiographic province and sub-region, stratified by rainfall/runoff relationships.

CONCLUSION

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They can also be used to help evaluate the relative stability of a stream channel. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the rural Piedmont of North Carolina. However, users must be careful to consider the natural variability represented by the 95% confidence limits for these relationships. Further work is necessary to develop reliable relationships for other regions and rainfall/runoff conditions.

ACKNOWLEDGEMENTS

The NC Interagency Stream Restoration Task Force is developing bankfull hydraulic geometry relationships for all three physiographic regions in North Carolina. Special thanks go to task force members, Dani Wise, Ben Pope, Ray Riley, Sherman Biggerstaff, Jean Spooner, Carolyn Mojonnier, Rachel Smith, Mark Cantrell, Alan Walker, and Neil Woerner. The authors acknowledge the AWRA reviewers for their thorough review of this manuscript.

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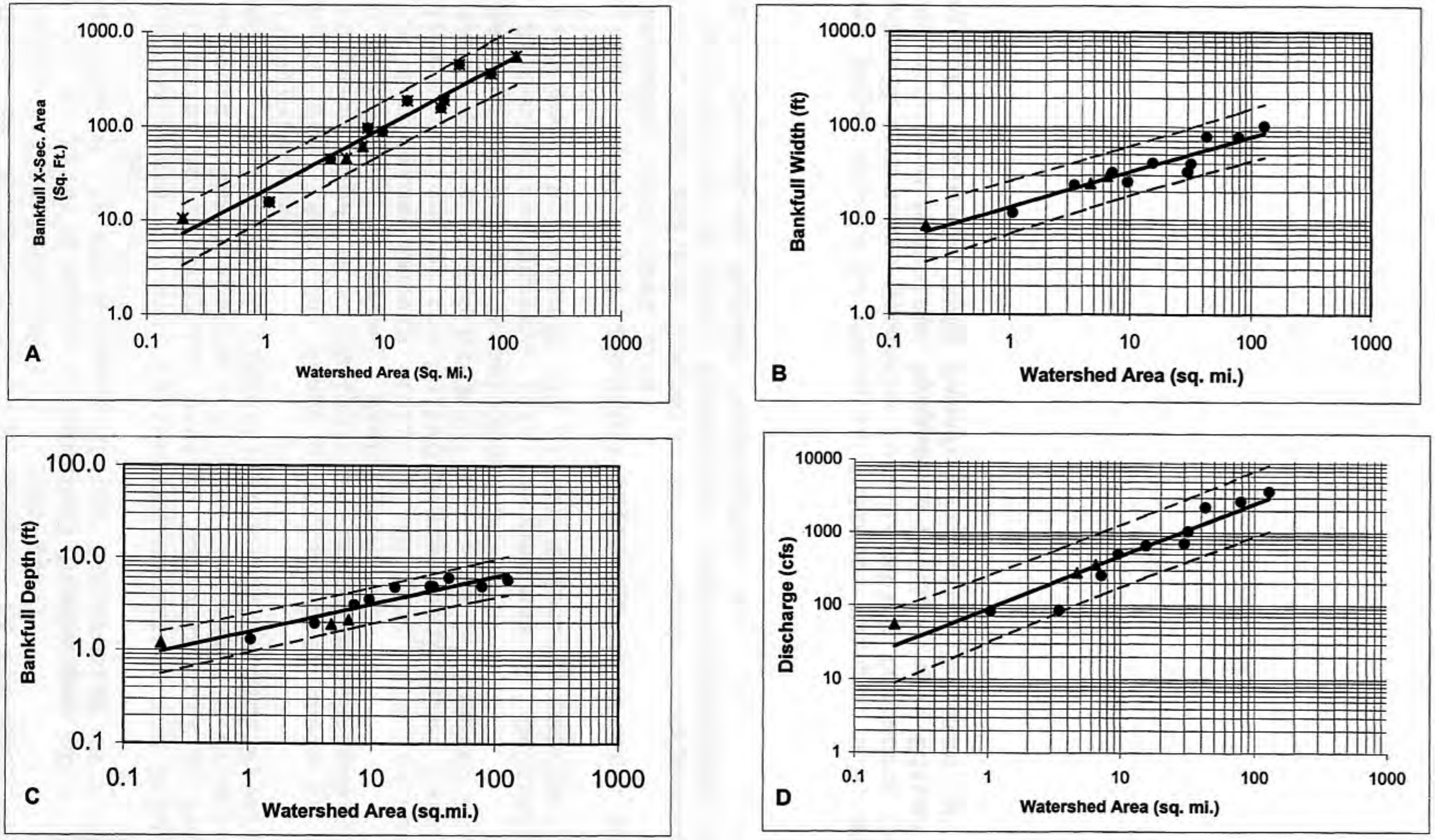

Figure 3: Bankfull hydraulic geometry relationships for rural Piedmont North Carolina Streams. The four graphs represent: a) cross sectional area, b) width, c) depth, and d) discharge. The circles represent gage stations and the triangles represent ungaged streams.

Stream Name	Gage Station ID	Drainage Area (mi^2)	Stream Type (Rosgen)	Bankfull Discharge (cfs)	Bankfull Xsec Area (ft^2)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Water Surface Slope (ft/ft)	Return Interval (Years)	Exceedence Probability (%)
Sal's Branch	Reference Reach	0.2	E4	55.4	10.4	8.7	1.2	0.0109	n/a	n/a
Humpy Creek	02117030	1.05	E5	83.0	15.8	12.0	1.3	0.0060	1.7	59
Dutchmans	02123567	3.44	C5	85.1	45.6	23.5	1.9	0.0170	1	100
Mill Creek	Reference Reach	4.7	E4	277	46.7	24.5	1.9	0.0080	n/a	n/a
Upper Mitchell River	Reference Reach	6.5	B4c	356	62.5	29.2	2.1	0.0095	n/a	n/a
Norwood Creek	0214253830	7.18	E5	253.7	98.8	32.0	3.1	0.0008	1.1	91
North Pott's Creek	02121180	9.6	E5	507.2	89.6	25.4	3.5	0.0012	1.7	59
Tick Creek	02101800	15.5	E	655.3	194	40.5	4.8	0.0005	1.3	77
Moon Creek	02075160	29.9	E5	708.8	162	33.0	4.9	0.0015	1.8	56
Long Creek	02144000	31.8	E5	1041	195	40.0	4.9	0.0010	1.4	71
Little Yadkin River	02114450	42.8	G5	2236	469	77.5	6.1	0.0018	1.4	71
Mitchell River	02112360	78.8	C	2681	377	77.0	4.9	0.0030	1.6	63
Fisher River	02113000	128	C3	3687	578	101	5.7	0.0023	1.4	71

Table 1: Hydraulic geometry, survey summary, and flood frequency analyses for gaged and ungaged stream reaches.

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HYDRAULIC GEOMETRY RELATIONSHIPS FOR URBAN STREAMS THROUGHOUT THE PIEDMONT OF NORTH CAROLINA[1]

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ABSTRACT: Hydraulic geometry relationships, or regional curves, relate bankfull stream channel dimensions to watershed drainage area. Hydraulic geometry relationships for streams throughout North Carolina vary with hydrology, soils, and extent of development within a watershed. An urban curve that is the focus of this study shows the bankfull features of streams in urban and suburban watersheds throughout the North Carolina Piedmont. Seventeen streams were surveyed in watersheds that had greater than 10 percent impervious cover. The watersheds had been developed long enough for the streams to redevelop bankfull features, and they had no major impoundments. The drainage areas for the streams ranged from 0.4 to 110.3 square kilometers. Cross-sectional and longitudinal surveys were conducted to determine the channel dimension, pattern, and profile of each stream and power functions were fitted to the data. Comparisons were made with regional curves developed previously for the rural Piedmont, and enlargement ratios were produced. These enlargement ratios indicated a substantial increase in the hydraulic geometry for the urban streams in comparison to the rural streams. A comparison of flood frequency indicates a slight decrease in the bankfull discharge return interval for the gaged urban streams as compared to the gaged rural streams. The study data were collected by North Carolina State University (NCSU), the University of North Carolina at Charlotte (UNC), and Charlotte Storm Water Services. Urban regional curves are useful tools for applying natural channel design in developed watersheds. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions.

(KEY TERMS: hydraulic geometry; regional curve,; bankfull; flood frequency analyses; urbanization,; urban water management.)

INTRODUCTION

Decades of urban sprawl have degraded large numbers of streams throughout the country. Channelization, loss of riparian vegetation, floodplain restrictions, and changes in hydrology have altered the dimension, pattern, and profile – and thereby the function and habitat of many urban streams. As little as 10 percent impervious cover has been linked to stream degradation, with degradation becoming more severe as impervious cover increases (Schueler, 1995). Hammer (1973) found that the average annual flood, which equaled the 1.78-year storm, was doubled by an increase in population density of 5,500 to 6,000 persons per square mile from a rural condition. In addition, large contiguous impervious areas can significantly increase the size of a stream channel (Hammer, 1972). Hammer (1972) developed stream channel enlargement ratios from a comparison of 50 urban and 28 rural watersheds in the Piedmont of Pennsylvania. His study showed an enlargement ratio for the cross section of urbanized streams ranged from 0.7 to 3.8 for drainage areas ranging from 2.6 to 15.5 square kilometers in size, respectively.

A common sequence of physical adjustments has been observed in many streams following disturbance. This adjustment process is often referred to as channel evolution. Disturbance can result from channelization, increase in runoff, and removal of streamside

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vegetation, as well as other changes that negatively affect stream stability. All of these disturbances are common in the urban environment. Several models have been used to describe this process of physical adjustment for a stream. Simon's channel evolution model (1989) served as a guide for selecting stream reaches to include in this study. Simon's model characterizes evolution in six steps, including: (1) sinuous, premodified, (2) channelized, (3) degradation, (4) degradation and widening, (5) aggradation and widening, and (6) quasi-equilibrium.

The channel evolution process is initiated once a stable, well-vegetated stream that frequently interacts with its floodplain is disturbed. Disturbance commonly results in an increase in stream power that causes degradation, often referred to as channel incision. Incision eventually leads to oversteepening of banks. When critical bank heights are exceeded, the banks begin to fail and mass wasting of soil and rock leads to channel widening. Incision and widening continue moving upstream, commonly known as a head cut. Eventually the mass wasting slows and the stream begins to aggrade. A new low-flow channel begins to form in the sediment deposits. By the end of the evolutionary process, a stable stream with dimension, pattern, and profile similar to those of undisturbed channels forms in the deposited alluvium. The new channel is at a lower elevation than its original form, with a new floodplain constructed of alluvial material. The old floodplain remains a dry terrace (FISRWG, 1998). Most urban streams are at some stage of this evolutionary process. The time period required to reach a state of quasi-equilibrium is highly variable and has not yet been determined.

Channelization and channel incision can result in a loss of the water quality filtration and denitrifying function for the riparian buffers along many stream corridors. This is due to the lowering of the water table and the increase in the ratio of bank height to bankfull height associated with channelization and/or incision. In North Carolina, it was found that nitrogen removal capacity is lost as much of the ground water flow to the stream passes beneath the buffer root system in these deeply incised stream systems (Kunickis, 2000).

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

Hydraulic geometry relationships for streams vary with hydrology, soils, and extent of development within a watershed. Therefore, it is necessary to develop curves for various levels of development in each hydrophysiographic region. There are three primary physiographic regions in North Carolina: Mountains, Piedmont, and Coastal Plain. The Piedmont is located between the Mountains and Coastal Plain and is characterized by rolling hills and wide alluvial valleys. The average annual precipitation is approximately 45 inches. Most Piedmont streams have moderate slopes that are controlled by bedrock outcrops (Horton *et al.,* 1991). Hydraulic geometry data have already been developed for rural Piedmont North Carolina streams (Harman *et al.,* 1999). This study focuses on identifying and comparing bankfull dimension and discharge of streams with urban watersheds to those with rural watersheds in the Piedmont.

Seventeen streams were surveyed in North Carolina Piedmont watersheds that had greater than 10 percent impervious cover. The watersheds had been developed long enough for the streams to redevelop bankfull features, and they had no major impoundments. The majority of the streams included in the study were in the process of recovering from past disturbances, such as channelization or incision resulting from changes in hydrology due to urbanization. The reaches selected for the survey were in or approaching quasi-equilibrium. Streams selected could be described using either Simon's Class I or Class VI stages of evolution (Simon, 1989). Class I streams were those where the bankfull stage remained at the top of bank due to the presence of an immediate downstream grade control that restricted incision, in most cases a culvert. The channel, however, did show enlargement, which likely resulted primarily from a widening process. Other streams could be described as Class VI because they showed stable, alternate channel bars associated with development of a new floodplain.

The drainage areas for the streams ranged from 0.4 to 110.3 square kilometers. The study includes data collected by North Carolina State University, and by the University of North Carolina at Charlotte and the Charlotte Storm Water Services (Wilkerson, 1998). Streams are located in Chapel Hill, Raleigh, Durham, Winston-Salem, and Charlotte. The locations of the survey sites are displayed on the map in Figure 1.

This paper develops hydraulic geometry relationships for urban streams that have reached or are approaching quasi-equilibrium in the channel evolution process. Urban curves for the Piedmont of North Carolina area were developed that compare bankfull cross-sectional area, discharge, width, and depth with drainage area. These relationships are compared to rural curves developed by Harman *et al.* (1999). Enlargement ratios comparing urban to rural curves are calculated to compare the magnitude of increases in the hydraulic geometry associated with urban impacts.

MATERIALS AND METHODS

U.S. Geological Survey (USGS) gaged urban streams were identified. Of the urban gaged streams, only those that met the study criteria were surveyed. The urban study site criteria included: Piedmont streams with greater than 10 percent impervious surface in their drainage area (Schueler, 1995), no major impoundments, exhibiting bankfull indicators, and having a stable riffle or run cross-section. Ten percent impervious cover was selected as the threshold for urban stream designation based on the findings compiled from studies across the nation by Schueler (1995). Additional urban streams were identified through map analysis, local agency contacts, and field reconnaissance. A consistent bankfull indicator was identified along each stream survey reach. Bankfull stage in general corresponds to the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel-forming flow, maintaining channel dimension and transporting the bulk of sediment over time (Leopold, 1994). Field indicators of bankfull stage include the back of point bars, significant breaks in slope along the streambank (cross-sectional perspective), changes in vegetation, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for North Carolina Piedmont streams are the highest scour line and the back of the point bar. The top of the bank or the lowest scour or bench is rarely an indicator of bankfull (Harman *et al.*, 1999).

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

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

For gaged streams, the bankfull discharge and return period were determined using the USGS stage-

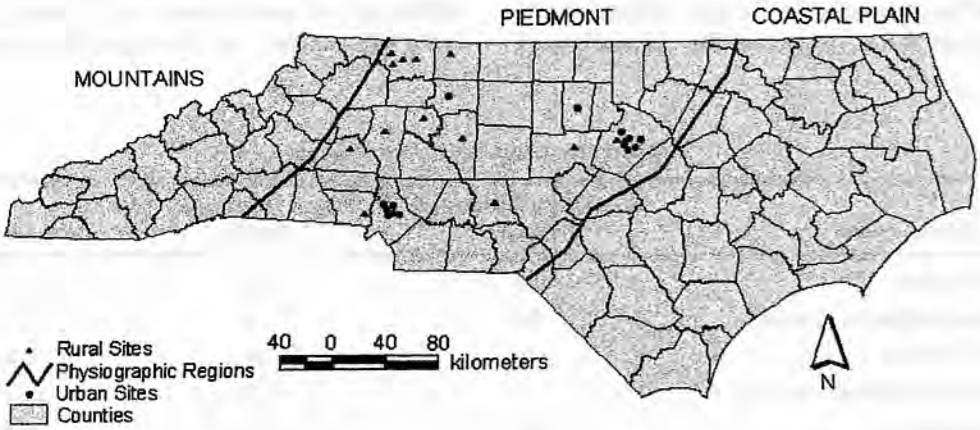

Figure 1. Survey Sites in North Carolina.

discharge rating table and flood-frequency analysis, respectively. At least ten years of USGS gage discharge data, including annual peak flows, were necessary to develop flood frequency relationships. Log-Pearson Type III distributions were used to analyze the annual peak discharge data (USGS, 1982). The generalized skew coefficient presented in the USGS Bulletin 17B was used for the flood frequency analysis (USGS, 1982). The annual exceedence probability was calculated as the inverse of the recurrence interval. Exceedence probabilities were plotted as functions of corresponding calculated discharge measurements. From these flood frequency relationships a specific discharge can then be related to a return interval. In the case of Pigeon House Creek, Bushy Branch, and Marsh Creek at Millbrook, the return interval was provided by a USGS flood frequency study of 32 small urban basins in North Carolina (USGS, 1996). For this study, concurrent records of rainfall and runoff data collected in small urban basins were used to calibrate rainfall-runoff models. Historic rainfall records were used with the calibrated models to synthesize a long-term record of annual peak discharges. The synthesized record of annual peak discharges was then used in a statistical analysis to determine flood frequency distribution. The study reported the discharges for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals. USGS provided the 1.11- and 1.25-year discharges for the three streams included in this study (B. F. Pope, personal communication, February 15, 2000, U.S. Geological Survey, Raleigh, North Carolina).

For nongaged streams, bankfull discharge was calculated using Manning's equation (Chow, 1959). Cross-sectional area and hydraulic radius were calculated using the cross-section survey data, and a roughness coefficient was estimated according to Chow (1959). A sensitivity analysis comparing the discharge calculated using Manning's equation to the discharge produced by the gage data was conducted to validate the discharge method selected. When available, gage discharge data were used for all statistical analyses. The results of the sensitivity analysis are presented in Table 1.

For the streams surveyed by North Carolina State University, existing Environmental Protection Agency (EPA) land use data were then used to estimate the impervious percentage for each stream's watershed. The EPA land use data are categorized by Level 2 in the Anderson Land Use Classification System (Anderson *et al.*, 1976), which includes residential, commercial, industrial, several vegetation types, pasture, cropland, industrial, and other categories (EPA, 1998). Natural Resource Conservation Service (NRCS) guidelines were used to assign an impervious cover percentage to each land use (NRCS, 1986). In the case of the Charlotte streams, Mecklenburg County's land use data were used to determine the impervious percentage. Distinct land use polygons were identified within each study watershed. Each land use area was assigned a land use code, and each land use code was then assigned an average impervious surface percentage using the NRCS guidelines (NRCS, 1986).

For each stream, the bankfull cross-sectional area, discharge, width, and depth were plotted versus drainage area for the urban data. These relationships were found to be linear on a log scale, e.g., a power function was utilized. Confidence intervals (95 percent) on the individual observations and the regression relationships were also calculated. The same regression relationships and confidence intervals were also developed for the rural data presented by Harman *et al.* (1999). The urban curves were then compared to the rural data (Harman *et al.*, 1999). A statistical regression test (analysis of covariance) using the PROC GLM procedure in SAS, was performed to test for homogeneity of slopes, that is, to test for statistical evidence that the slope was different for the urban as compared to the rural curves. If there was no evidence of slope differences, a pooled slope was assumed and parallel regression lines with different intercepts were calculated. Confidence intervals (95 percent) on the regression relations were also

TABLE 1. Discharge Sensitivity Analysis.

Stream Name	Manning's Discharge (cms)	Gage Discharge (cms)	Percent Error
Pigeon House Branch	3	3	0.3
McMullen Creek at Sharon View Rd.	34	28	19.6
Long Creek at Oakdale	34	29	17.2
Irwin Creek Near Billy Graham Pkwy.	73	69	5.0
McAlpine at Sardis Rd.	68	74	-8.4
Little Sugar Creek at Archdale Rd.	130	124	4.5

calculated. If there was evidence of different slopes, the error estimate around the regression lines was pooled and each line was allowed to have a different slope as well as intercept.

From a comparison of the urban and rural regional curves, it is possible to quantify the effect of urbanization by examining different enlargement ratios of a specific drainage area and dimension:

$$Ex = xu/xr \tag{1}$$

where, Ex = enlargement ratio; xu = bankfull dimension of depth (Dbkf), width (Wbkf), cross section (Abkf), or discharge (Qbkf) at a specific drainage area in urban areas; and xr = the same bankfull dimensions at a specific drainage area in rural areas. These enlargement ratios are based on comparing the dimensions obtained from the power functions (regional curves) fitted to the data and not comparison of the specific data. Relating the urban and rural region curves by plotting the enlargement ratios as a function of drainage area gives yet another power function.

RESULTS AND DISCUSSION

Table 2 summarizes field measurements and hydraulic geometry data for the urban streams. The rural regional curve data from Harman *et al.* (1999) are also included in Table 2. The relationships for bankfull discharge, cross-sectional area, width, and mean depth as functions of watershed area for the urban Piedmont of North Carolina are shown in Figure 2. The resulting 95 percent confidence intervals for both the individual observations and the regression relationship also are shown on Figure 2. In comparison, the same hydraulic geometry relationships and associated confidence intervals for the rural Piedmont relationships from Harman *et al.* (1999) are shown in Figure 3. The urban relationships shown in Figure 2 represent nine USGS gage stations and eight ungaged reaches ranging in watershed area from 0.4 to 110.3 square kilometers. The power functions regression equations and corresponding coefficients of determination for the urban curves are:

$$A_{bkf} = 3.02\ A_w^{0.65} \qquad r^2 = 0.95 \tag{2}$$

$$Q_{bkf} = 4.77\ A_w^{0.63} \qquad r^2 = 0.94 \tag{3}$$

$$W_{bkf} = 5.43\ A_w^{0.33} \qquad r^2 = 0.88. \tag{4}$$

$$D_{bkf} = 0.54\ A_w^{0.33} \qquad r^2 = 0.87 \tag{5}$$

where, Q_{bkf} = bankfull discharge in cubic meters per second (cms), A_w = watershed drainage area in square kilometers (sq km), A_{bkf} = bankfull cross-sectional area in square meters (sq m), W_{bkf} = bankfull width in meters (m), and D_{bkf} = bankfull mean depth in meters (m). The regression analyses documented a statistically significant exponent, verifying that as watershed area increases the cross-sectional area, discharge, width, and depth of the bankfull channel also increase. The high coefficients of determination indicate these power functions explain a high percentage of the variability of the four hydraulic geometric variables. Additional sources of variability include natural variations in average annual runoff, stream type (Rosgen, 1994), land use, and stream hydrology (Leopold and Maddock, 1953; Leopold, 1994). The bankfull return interval ranged from 1.1 to 1.5 for the gaged stream stations, with both the average and the median return interval at 1.3. Dunne and Leopold (1978) reported a bankfull return interval of 1.5 years from a national study.

The comparison of the urban data to the rural data to test for slope differences and to determine enlargement is shown on Figure 4. For each of the geometric relationships, there was no statistical evidence that the slopes for the urban and rural curves were different. Therefore, these regression relationships were calculated with the same slopes and different intercepts. In each relationship, there was a statistically significant difference between the intercepts, therefore indicating significant shift or enlargement with the urban streams for similar drainage areas. The best-fit regression equations for the pooled data are shown for each urban and rural relationship (Figure 4). The resulting enlargement ratios are as follows:

$$E_{Abkf} = 2.65 \tag{6}$$

$$E_{Qbkf} = 2.91 \tag{7}$$

$$E_{Wbkf} = 1.66 \tag{8}$$

$$E_{Dbkf} = 1.57 \tag{9}$$

It can be seen from these functions that the urban streams display a substantial increase in hydraulic geometry as compared to the rural counterparts. Since all the streams evaluated in this study were located in the same physiographic region – the Piedmont – it can be assumed that these enlargement ratios are a good representation of the flux in channel size, which can be expected as a rural watershed is developed. The drainage areas of the streams ranged from 0.4 to 110.3 square kilometers. There was no evidence that the enlargement ratios varied with watershed size (determined from the analysis of covariance,

TABLE 2. Hydraulic Geometry and Survey Summary for Gaged and Ungaged Urban and Rural Stream Reaches.

Survey Team*	Stream Name	Gaged Site	D.A. (sq km)	Bkfl Cross-Sectional Area (sq m)	Discharge (cms)	Width (m)	Mean Depth (m)	Return Interval	Stream Type (Rosgen)	Impervious Surface Percentage
NCSU	Bushy Branch at Schaub Drive	No**	0.5	1.4	2	3	0.4	1.5	E	20
NCSU	Bolin Creek Tributary	No	0.4	1.4	3	3	0.4		Eb	36
NCSU	Marsh Creek at Millbrook	No**	0.5	3.7	6	5	0.7	1.1	E	25
NCSU	Pigeon House Branch	Yes	0.7	2.2	3	5	0.5	1.1	E	47
NCSU	Rocky Branch 1	Yes***	1.0	2.9	4	10	0.3		F	80
C	Plaza-Midwood Creek at Masonic Dr.	No	1.4	4.1	5	4	1.0		E	26
NCSU	Brushy Fork Tributary No. 2 (WS)	No	1.4	3.4	6	7	0.5		C	66
NCSU	Rocky Branch 2	Yes***	1.8	4.0	7	8	0.5		F	80
NCSU	Kentwood Park	No	2.1	5.4	9	8	0.6		Bc	54
C	Little Hope Creek at Woodlawn	No	3.0	5.6	8	7	0.8		E	38
C	Little Hope Creek at Seneca Place	Yes	6.8	11.3	21	11	1.0	1.4	E	41
C	McMullen Creek at Sharon View Rd.	Yes	18.0	21.0	28	14	1.5	1.5	E	33
C	McMullen Creek at Quail Hollow Rd.	No	29.8	29.5	59	16	1.8		E	32
C	Long Creek @ Oakdale	Yes	42.5	26.5	29	16	1.7	1.4	E	17
C	Irwin Creek near Billy Graham Pkwy.	Yes	79.5	54.0	69	22	2.4	1.2	E	32
C	McAlpine at Sardis Road	Yes	102.6	55.4	74	23	2.4	1.3	E	24
C	Little Sugar Creek at Archdale Rd.	Yes	110.3	72.7	124	29	2.5	1.2	E	39
Rural	Sal's Branch	No	0.5	1.0	2	3	0.4		E4	<10
Rural	Humpy Creek	Yes	2.7	1.5	2	4	0.4	1.7	E5	<10
Rural	Dutchmans	Yes	8.9	4.2	2	7	0.6	1	C5	<10
Rural	Mill Creek	No	12.2	4.3	8	7	0.6		E4	<10
Rural	Upper Mitchell River	No	16.8	5.8	10	9	0.7		B4c	<10
Rural	Norwood Creek	Yes	18.6	9.2	7	10	0.9	1.1	E5	<10
Rural	North Pott's Creek	Yes	24.9	8.3	14	8	1.1	1.7	E5	<10
Rural	Tick Creek	Yes	40.1	18.0	19	12	1.5	1.3	E	<10
Rural	Moon Creek	Yes	77.4	15.1	20	10	1.5	1.8	E5	<10
Rural	Long Creek	Yes	82.4	18.1	29	12	1.5	1.4	E5	<10
Rural	Little Yadkin River	Yes	110.9	43.6	63	24	1.8	1.4	G5	<10
Rural	Mitchell River	Yes	204.1	35.0	76	23	1.5	1.6	C	<10
Rural	Fisher River	Yes	331.5	53.7	104	31	1.7	1.4	C3	<10

*C = University of North Carolina-Charlotte and Charlotte Storm Water Services; NCSU = North Carolina State University; Rural = from Harman *et al.*, 1999.
**Gage no longer in place. Discharge calculated using Manning's equation.
***Ten years of gage data not available for flood frequency analysis.

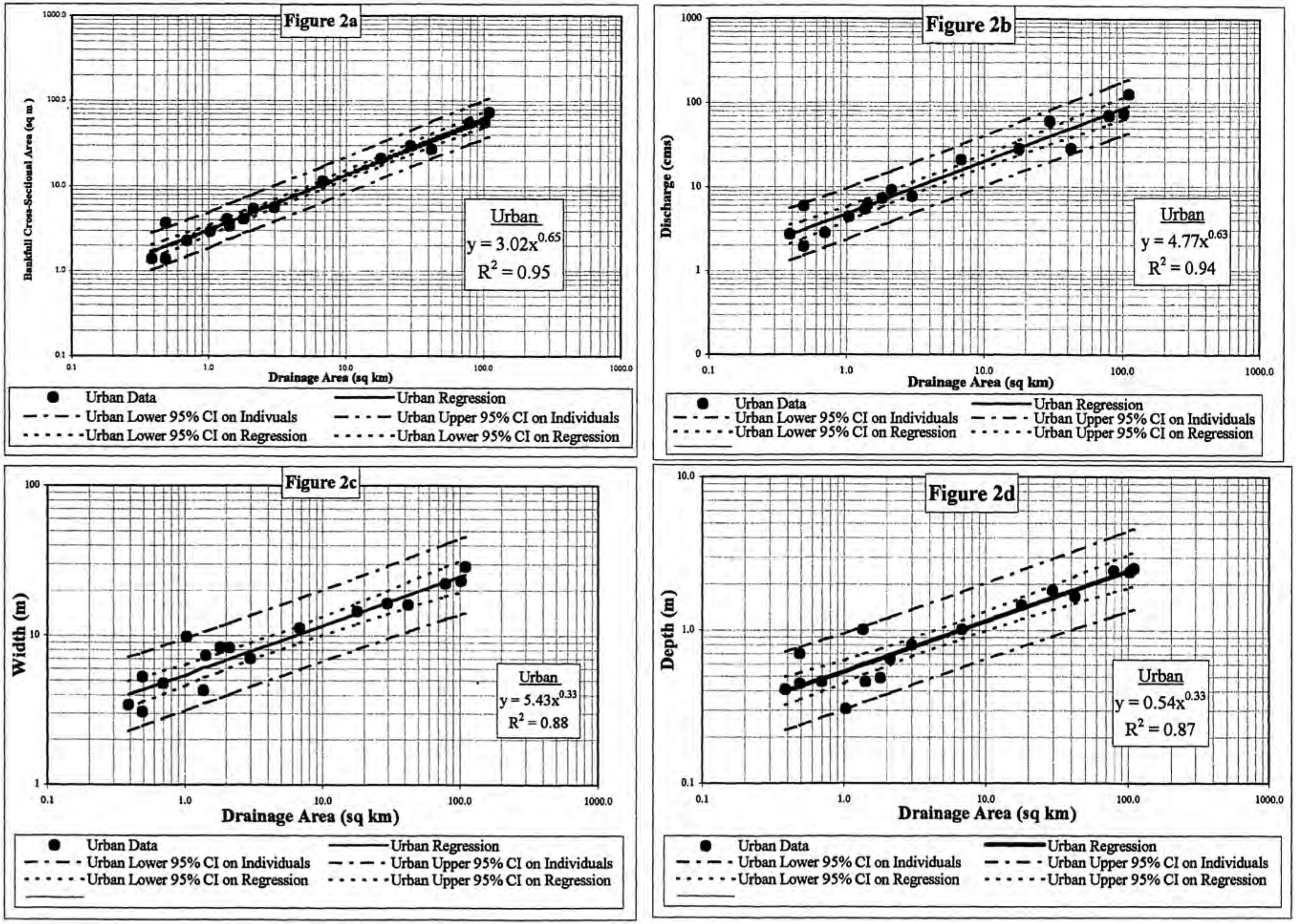

Figure 2. Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Urban Streams in the North Carolina Piedmont.

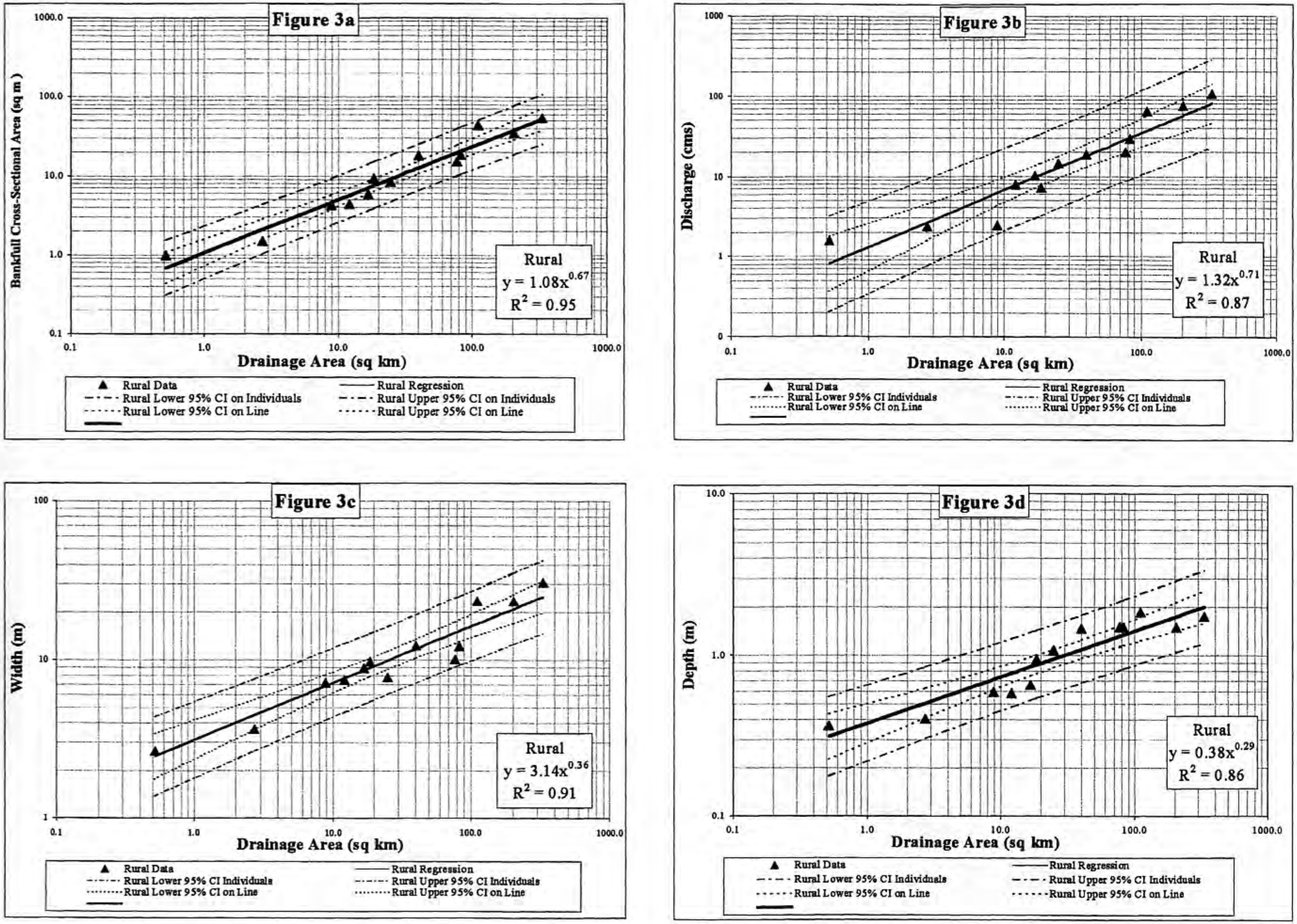

Figure 3. Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Rural Streams in the North Carolina Piedmont from Harman *et al.* (1999).

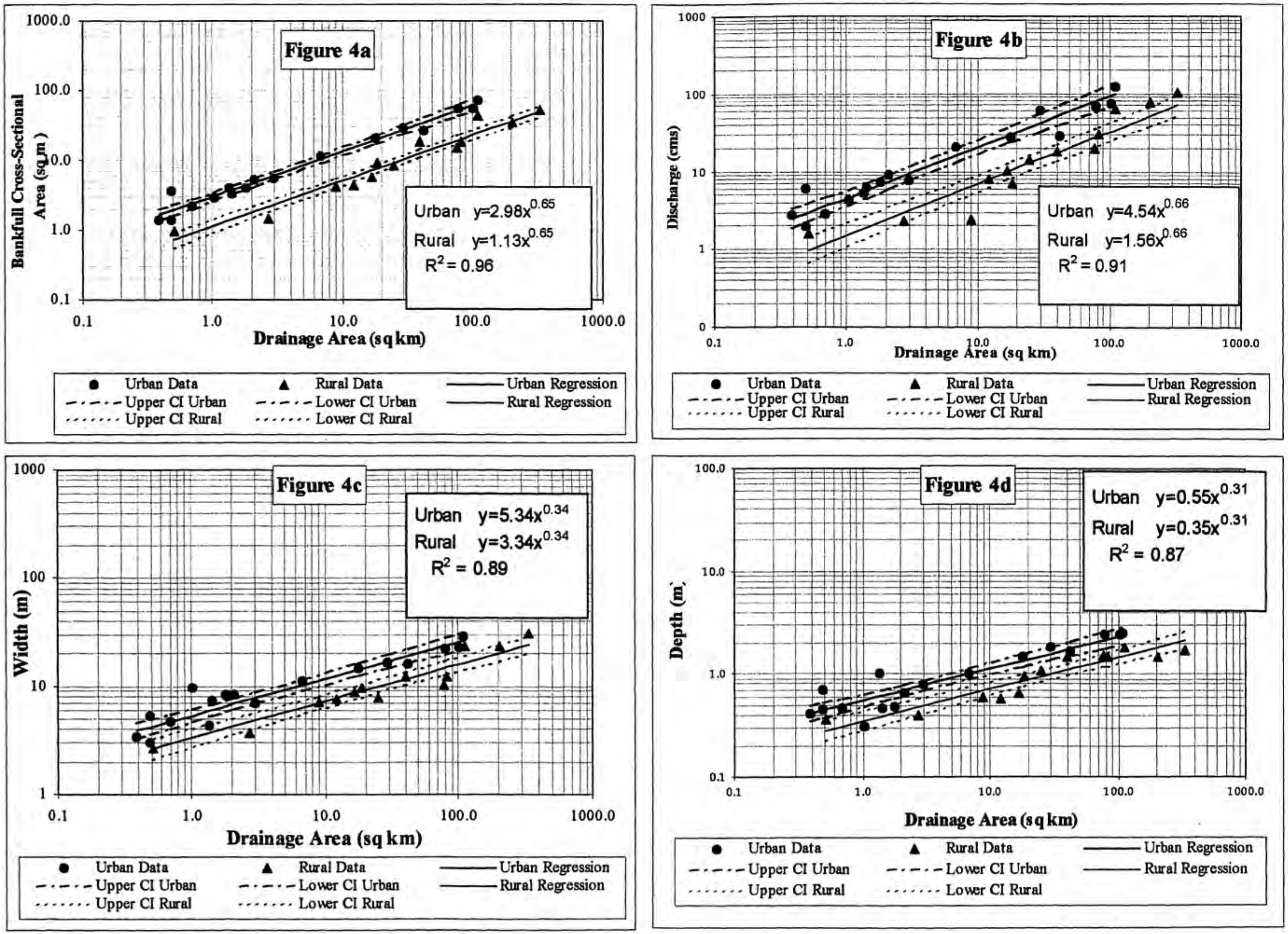

Figure 4. Comparison of Urban Versus Rural Regional Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Streams in the North Carolina Piedmont.

which showed no evidence for different slopes on the log scale between the urban and rural curves). The increase in bankfull cross-sectional area between rural and urban streams is comparable to the increase calculated using Hammer's channel enlargement ratios. This study shows an enlargement ratio of the cross section of urbanized streams of 2.6, which is comparable to Hammer's (1972) enlargement range of 0.7 to 3.8 found in similar sized watersheds.

Despite an increase in the bankfull discharge in the urban streams, the study reveals only a slight variation in flood frequency for bankfull discharge from the Log-Pearson Type III analyses of annual peak discharge from the gage stations included in the study (USGS, 1982). The urban gaged North Carolina Piedmont streams surveyed revealed return intervals ranging from 1.1 to 1.5, with an average bankfull return interval of 1.3 years. This is slightly lower but comparable to that of their rural counterparts, which produced bankfull discharge return intervals ranging from 1.09 to 1.8 with an average of 1.4 years (Harman *et al.*, 1999).

CONCLUSION

This study found enlarged bankfull dimension and discharge for urban streams versus rural streams with the same watershed area in the Piedmont region of North Carolina (see Figure 4). The enlargement in bankfull cross-sectional area between rural and urban streams falls into the upper end of the range found by Hammer (1972) and shows much less variability. The study also shows an increase in bankfull average width and depth with an increase in urbanization. The depth increase, however, does not represent an increase in pools. Rather, the streams surveyed were dominated by riffle and run and lacked good pool habitat. The increase in depth is merely a function of a larger channel that is carrying larger discharges. The study also revealed only a slight reduction in the bankfull discharge return interval for the urban gaged streams surveyed. Urban streams produced an average bankfull return interval of 1.3, compared to the average of 1.4 previously determined for the rural streams (Harman *et al.*, 1999). This indicates no significant change in the flood frequency of bankfull discharge between rural and urban streams in the Piedmont of North Carolina.

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

Further work is necessary to develop reliable relationships for other regions and rainfall-runoff conditions. Additional data are being collected for the urban and suburban curves in Piedmont North Carolina in order to capture a broader range of stream types, drainage area impervious cover percentages, and drainage area sizes throughout the North Carolina Piedmont. Variability in enlargement could be influenced by a number of factors including land use type and its location in the watershed, soil type, wetlands, riparian condition, topography, and channelization or other past channel modifications.

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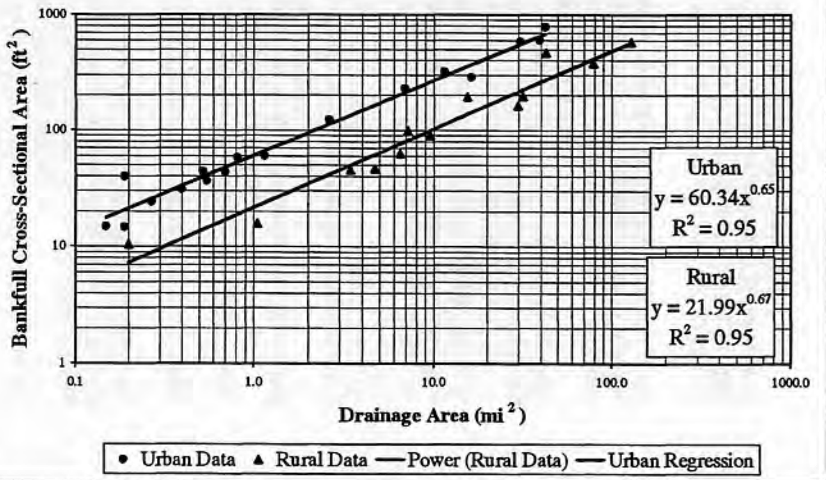
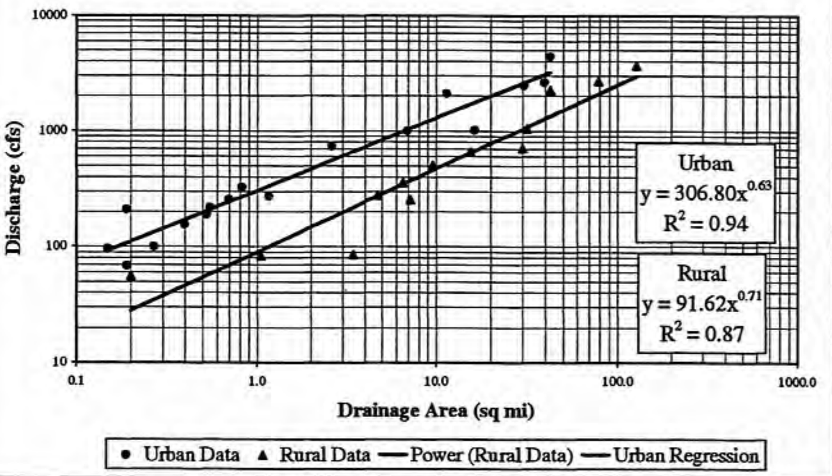
North Carolina Piedmont Regional Curve



North Carolina Piedmont Regional Curve



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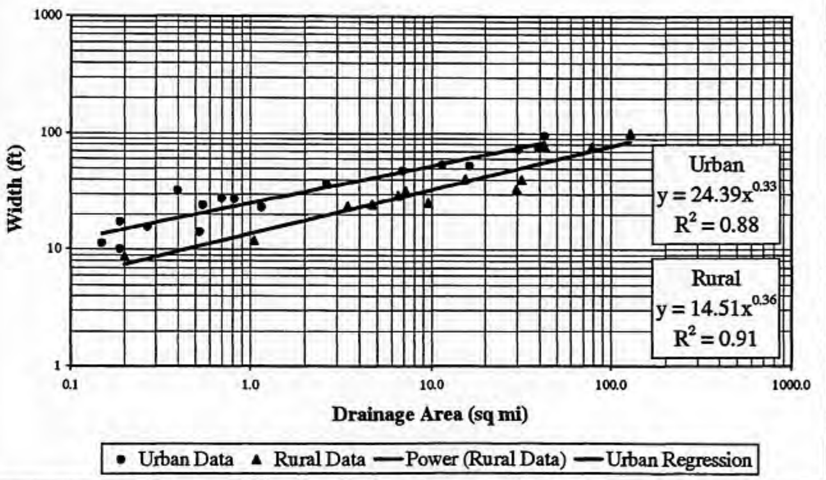

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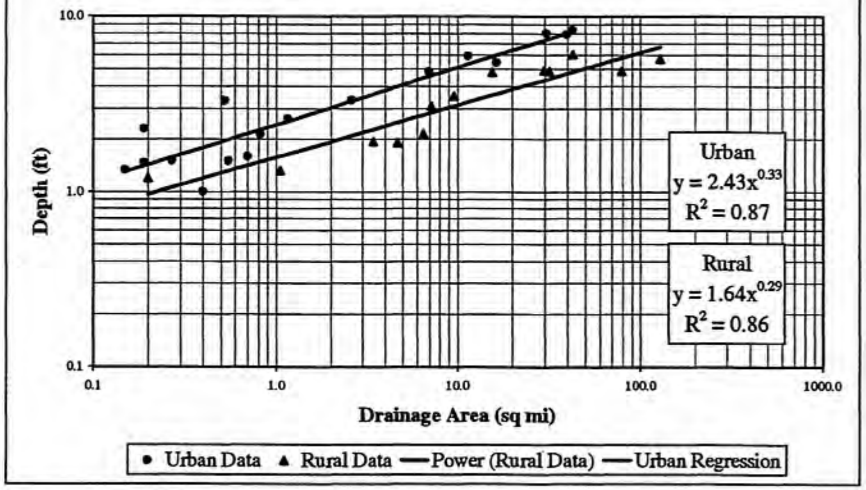

BANKFULL REGIONAL CURVES FOR NORTH CAROLINA MOUNTAIN STREAMS

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ABSTRACT: Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull stream channel dimensions and discharge to watershed drainage area. This paper describes preliminary results of bankfull regional curve relationships developed for North Carolina Mountain streams. Gage stations were selected with a minimum of 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and impervious cover ranges of <20%. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also included in the study. Cross-sectional and longitudinal surveys were measured at each study reach to determine channel dimension, pattern, and profile information. Log-Pearson Type III distributions were used to analyze annual peak discharge data for USGS gage station sites. Power function relationships were developed using regression analyses for bankfull discharge, channel cross-sectional area, mean depth, and width as functions of watershed drainage area. The bankfull return interval for the rural mountain gaged watersheds ranged from 1.1 to 1.7 years, with a mean of 1.3 years. The mean bankfull return interval for rural North Carolina Piedmont gage stations was 1.4 years. Continuing work will expand this database for the North Carolina Mountain Physiographic Region.
KEY TERMS: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses, Mountains

INTRODUCTION

Stream channel hydraulic geometry theory developed by Leopold and Maddock (1953) describes the interrelations between dependent variables such as width, depth and area as functions of independent variables such as discharge. Hydraulic geometry relationships are empirically derived and can be developed for streams in the same physiographic region with similar rainfall/runoff relationships (FISRWG, 1998). Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull channel dimensions to drainage area (Dunne and Leopold, 1978). Gage station analyses throughout the United States have shown that the bankfull discharge has an average return interval of 1.5 years or 67% annual exceedence probability (Dunne and Leopold, 1978; Leopold, 1994). A primary purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds and to help estimate the bankfull dimension and discharge for natural channel designs (Rosgen, 1994). This paper describes the process used in North Carolina to develop hydraulic geometry relationships at the bankfull stage. Preliminary results for rural watersheds in the Blue Ridge Mountain physiographic region are presented.

NORTH CAROLINA MOUNTAIN STUDY AREAS

North Carolina contains three major physiographic provinces: the Mountains, Piedmont, and Coastal Plain. The highest (100 inches) and the lowest (40 inches) mean annual precipitation in the Eastern U.S. is recorded in the North Carolina Mountains, both within the project study area and within 50 miles of each other. The steep mountain topography is also a factor in stream morphology, with the highest peak east of the Rocky Mountains at Mt. Mitchell (6,684 feet). In general, watersheds are more than 50% forested. Land cover dominated by human influences is locally high, but is less than 40% overall. Because rainfall/runoff relationships vary by province and land cover, separate bankfull hydraulic geometry relationships are being developed for rural and urban areas for each physiographic province. It may be necessary to further

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stratify the data for unique areas such as high rainfall areas in the Mountains and the Sandhills bordering the Piedmont and Coastal Plain.

USGS gage stations were identified with at least 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and impervious cover ranges of <20%. A geographic information system was used to analyze Thematic Mapper (TM) 1996 data to select watersheds with less than 20% impervious cover. To supplement data collected in gaged watersheds and provide points in smaller drainage areas, stable reference reaches in un-gaged watersheds were also selected using the same criteria. Project study sites are shown in Figure 1.

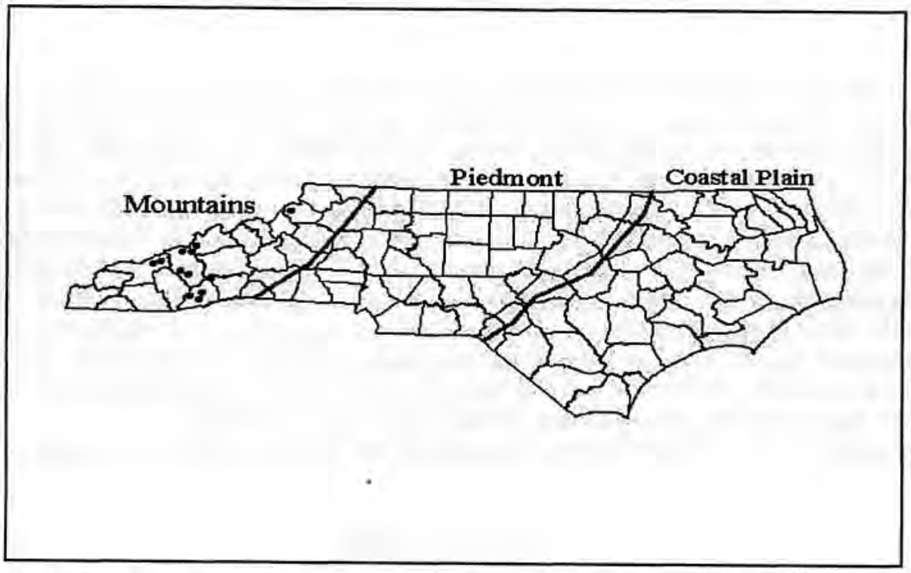

Figure 1: North Carolina map showing physiographic provinces with Mountain study sites shown has dots.

Field Identification of Bankfull

Accurate identification of the bankfull stage in the field can be difficult and subjective (Williams, 1978; Knighton, 1984; and Johnson and Heil, 1996). Numerous definitions exist of bankfull stage and methods for its identification in the field (Wolman and Leopold, 1957; Nixon, 1959; Schumm, 1960; Kilpatrick and Barnes, 1964; and Williams 1978). The identification of bankfull stage in the humid Southeast is especially difficult because of dense understory vegetation and long history of channel modification and subsequent adjustment in channel morphology. It is generally accepted that bankfull stage corresponds with the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel-forming agent that maintains channel dimension and transports the bulk of sediment over time. Field indicators include the back of point bars, other significant breaks in slope, changes in vegetation type, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for streams in North Carolina are the highest scour line and the back of the point bar. It is rarely the top of the bank or the lowest scour or bench.

DATA COLLECTION AND ANALYSES

The following gage station records were obtained from the United States Geological Survey: 9-207 forms, stage/discharge rating tables, annual peak discharges, and established reference marks. Bankfull stage was flagged upstream and downstream of the gage station using the field indicators listed above. Once a consistent indicator was found, a cross-sectional survey was completed at a riffle or run near the gage plate. Temporary pins were installed in the left and right banks, looking downstream. The elevations from the survey were related to the elevation of a gage station reference mark. Each cross section survey started at or beyond the top of the left bank. Moving left to right, morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994). From the survey data, bankfull hydraulic geometry was calculated.

For each reach, a longitudinal survey was completed over a stream length approximately equal to 20 bankfull widths (Leopold, 1994). Longitudinal stations were established at each bed feature (heads of riffles and pools, maximum pool depth, scour holes, etc.). The following channel features were surveyed at each station: thalweg, water surface, low bench or scour, bankfull stage, and top of the low bank. The longitudinal survey was carried through the gage plate to obtain the bankfull stage. Using the current rating table and bankfull stage, the bankfull discharge was determined. Log-Pearson Type III distributions were used to analyze annual peak discharge data for the USGS gage station sites (Harman et al., 1999). Procedures outlined in USGS Bulletin #17B Guidelines for Determining Flood Flow Frequency were followed (U.S. Geological Survey, 1982). The bankfull discharge recurrence interval was then calculated from the flood frequency analyses. The stream was classified using the Rosgen (1994) method.

Ungaged, stable streams were also surveyed to provide points in watersheds with relatively small drainage areas. A stability analyses was completed before the stream was surveyed which included a bank erosion assessment, channel incision measurements, floodplain assessments, and review of historical maps and aerial photographs. To obtain a bankfull discharge (Q) estimate, at the stable ungaged watersheds, Manning's equation was used as:

$$Q = 1.4865\, AR^{2/3}\, S^{1/2} / n \qquad (1)$$

Where, R = hydraulic radius (ft), A = cross sectional area(ft^2), S = average channel slope or energy slope (ft/ft), and n = roughness coefficient estimated using the bankfull mean depth and channel bed materials. Flood frequency analyses was not completed on ungaged streams.

RESULTS AND DISCUSSION

The regional curves for the rural Mountains of North Carolina are shown in Figures 2a, b, c, and d. These relationships represent 9 USGS gage stations and 3 un-gaged reaches ranging in watershed area from 2.0 to 126 mi^2. The power function regression equations and corresponding coefficients of determination for bankfull discharge, cross sectional area, width, and mean depth are shown in Table 1.

Table 1: Power function regression equations for bankfull discharge and dimensions, where Q_{bkf} = bankfull discharge (cfs), A_w = watershed drainage area (mi$^{2)}$, A_{bkf} = bankfull cross sectional area (ft^2), W_{bkf} = bankfull width(ft), and D_{bkf} = bankfull mean depth (ft).

Parameter	**Power Function Equation**	**Coefficient of Determination R^2**
Bankfull Discharge	$Q_{bkf} = 115.7A_w^{0.73}$	0.88
Bankfull Area	$A_{bkf} = 22.1A_w^{0.67}$	0.88
Bankfull Width	$W_{bkf} = 19.9A_w^{0.36}$	0.81
Bankfull Depth	$D_{bkf} = 1.1A_w^{0.31}$	0.79

Table 2 summarizes field measurements and hydraulic geometry. Table 3 summarizes bankfull discharge, flood frequency, and mean annual rainfall analyses. The moderately high coefficients of determination indicate good agreement between the measured data and the best-fit relationships. The vast range in mean annual precipitation (42 inches to 98 inches) explains the large degree of variability. Other sources of variability include the age of the forest, topography, land cover, soil type, runoff patterns, stream type and the natural variability of stream hydrology (Leopold, 1994). The bankfull return interval ranged from 1.1 to 1.9 years, with an average of 1.5 years. The mean bankfull return interval for rural North Carolina Piedmont gage stations was 1.4 years (Harman et al., 1999). Dunne and Leoplod (1978) reported a bankfull return interval of 1.5 years from a national study.

CONCLUSION

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They can also be used to help evaluate the relative stability of a stream channel. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the rural Mountains of North Carolina. Further work is necessary to develop additional data points to further explain the variability.

ACKNOWLEDGEMENTS

The NC Stream Restoration Institute is developing bankfull hydraulic geometry relationships for all three physiographic regions in North Carolina. Special thanks go to Angela Jessup, Richard Everhart, Ben Pope, Ray Riley, Sherman Biggerstaff, Kevin Tweedy, Jean Spooner, Carolyn Buckner, Barbara Doll, Rachel Smith, Louise Slate, and Brent Burgess. The authors acknowledge the AWRA reviewers for their thorough review of this manuscript.

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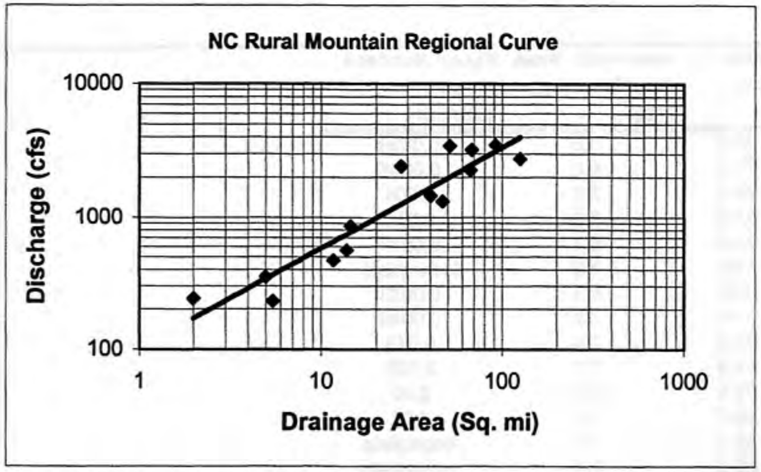

Figure 2a - Bankfull Discharge vs Drainage Area

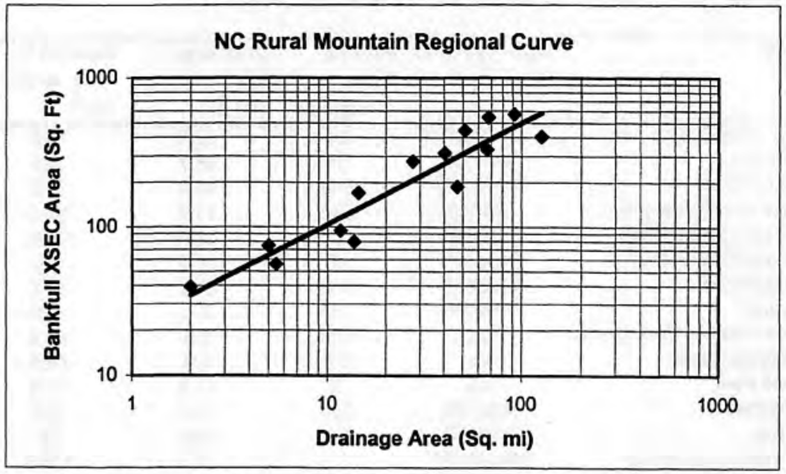

Figure 2b - Bankfull Cross Sectional Area vs Drainage Area

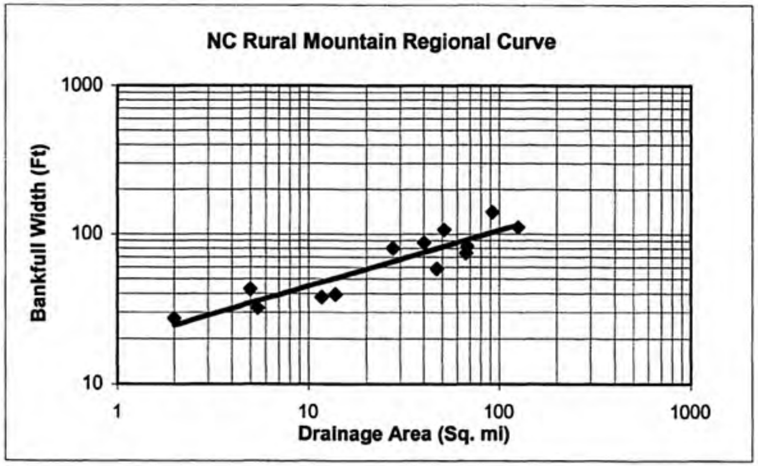

Figure 2c - Bankfull Width vs Drainage Area

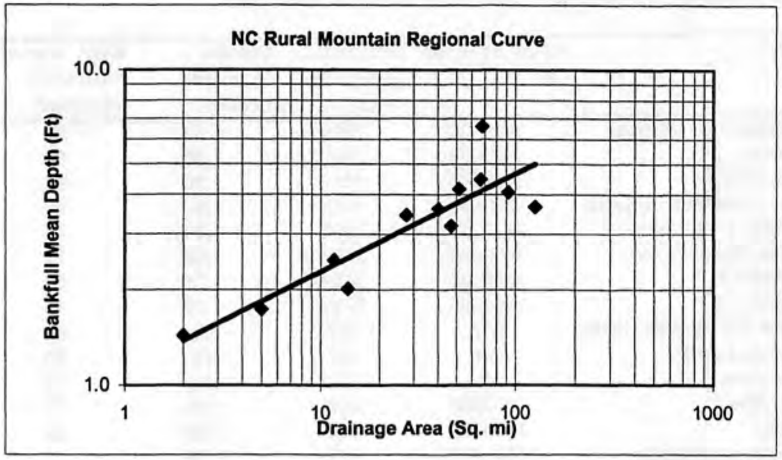

Figure 2d - Bankfull Depth vs Drainage Area

Table 2: Summary of field measurements and hydraulic geometry.

Stream Name	Gage Station ID	Stream Type (Rosgen)	Drainage Area (mi^2)	Bankfull Xsec Area (ft^2)	Bankfull Width (ft)	Bankfull Depth (ft)	Mean Water Surface Slope (ft/ft)
French Broad at Rosman	3439000	E4	67.9	545	82.4	6.6	0.0009
Mills River	3446000	C4	66.7	333	74.3	4.5	0.0035
Davidson River	3441000	B4c	40.4	316	87.6	3.6	0.004
Catheys Creek near Brevard	344000	B4c	11.7	93.1	38.0	2.5	0.013
West Fork of the Pigeon	3456100	B3	27.6	278	80.6	3.4	0.0077
East Fork Pigeon River	3456500	B	51.5	446	107	4.2	Incomplete
Watauga River	3479000	B4c	92.1	572	140	4.1	0.0033
Big Laurel	3454000	B	126	406	111	3.7	0.0045
East Fork Hickey Fork Creek	n/a	B3a	2.0	39.3	27.4	1.4	0.045
Cold Spring Creek	n/a	B4	5.0	74.4	42.9	1.7	0.025
Caldwell Fork	n/a	B	13.8	79.3	39.4	2.0	0.02
Cataloochee	3460000	B3c	46.9	187	58.7	3.2	0.01
Bee Tree	3450000	B3	5.46	56	32.1	1.7	Incomplete
North Fork Swannanoa	344894205	C3	14.5	170.6	69.3	2.5	Incomplete

Table 3: Summary of Discharge, Flood Frequency and Rainfall Data

Stream Name	Gage Station ID	Bankfull Discharge (cfs)	Return Interval (Years)	Mean Annual Rainfall (Inches)
French Broad at Rosman	3439000	3226	1.30	98
Mills River	3446000	2263	1.90	90
Davidson River	3441000	1457	1.10	94
Catheys Creek near Brevard	344000	470	1.67	94
West Fork of the Pigeon	3456100	2430	1.10	70
East Fork Pigeon River	3456500	3450	1.59	70
Watauga River	3479000	3492	1.25	56
Big Laurel	3454000	2763	1.59	42
East Fork Hickey Fork Creek	n/a	242	n/a	48
Cold Spring Creek	n/a	352	n/a	50
Caldwell Fork	n/a	560	n/a	74
Cataloochee	3460000	1320	1.60	74
Bee Tree	3450000	232	1.60	74
North Fork Swannanoa	344894205	856	1.85	