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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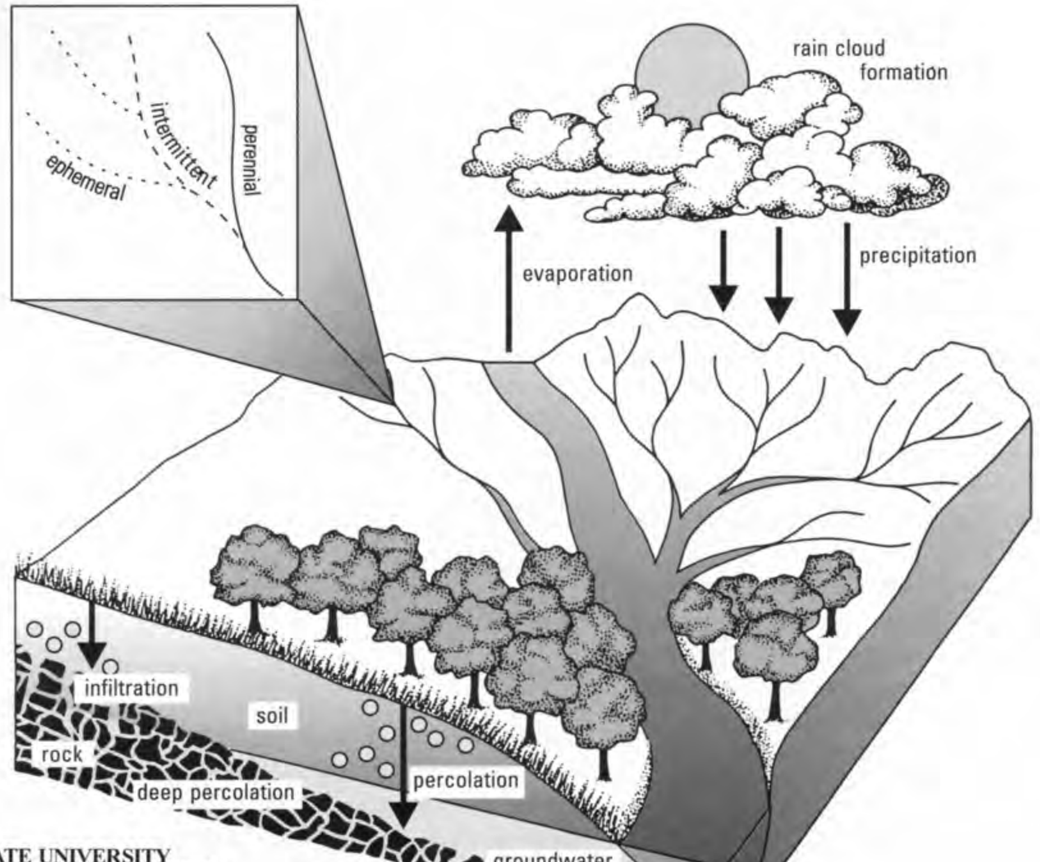
Streams and rivers are integral parts of the landscape that carry water and sediment from high elevations to downstream lakes, estuaries, and oceans. The land area draining to a stream or river is defined as its **watershed**. When rain falls in a watershed, it either runs off the land surface, infiltrates 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.*

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.

Natural Channel Stability

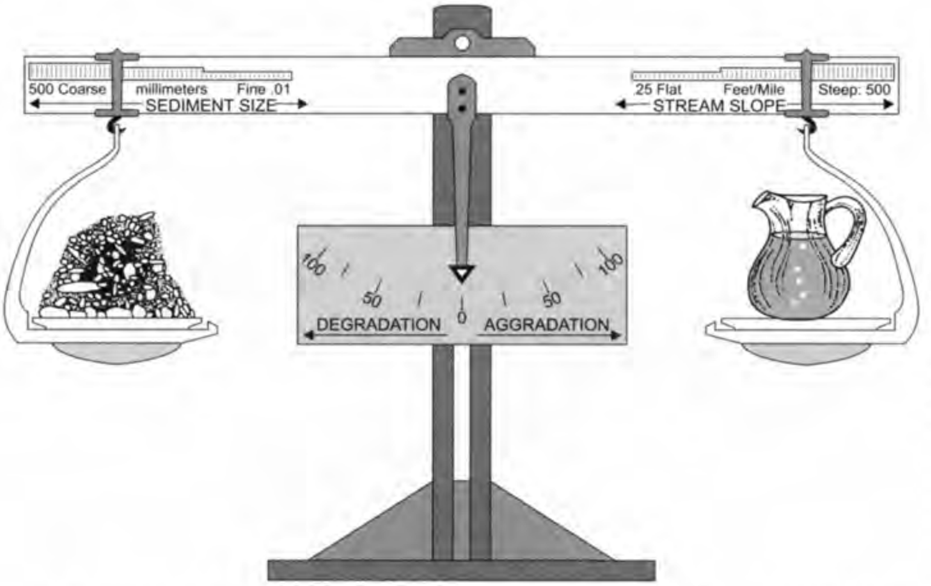
A naturally stable stream channel maintains its dimension, pattern, and profile over time so that the stream does not **degrade** or **aggrade**. Stable streams migrate across the landscape slowly over long periods of time while maintaining their form and function. Naturally stable streams must be able 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.

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



$(\text{Sediment LOAD}) \times (\text{Sediment SIZE}) \propto (\text{Stream SLOPE}) \times (\text{Stream DISCHARGE})$

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,

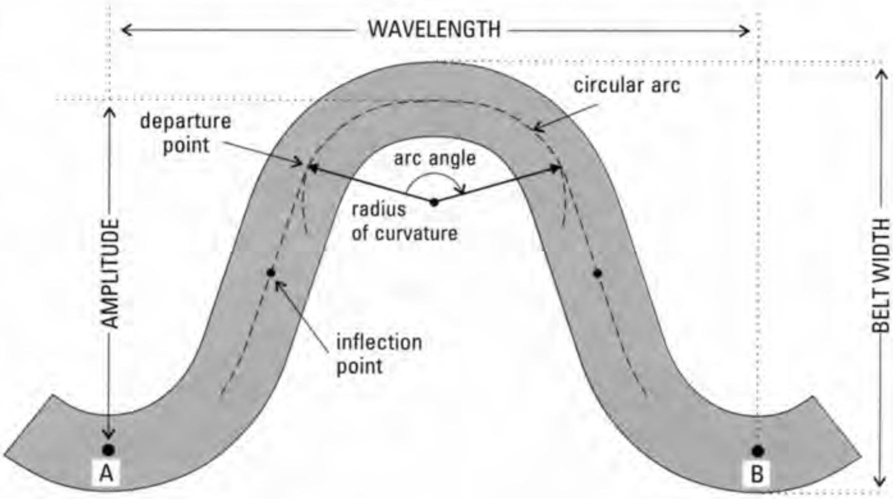
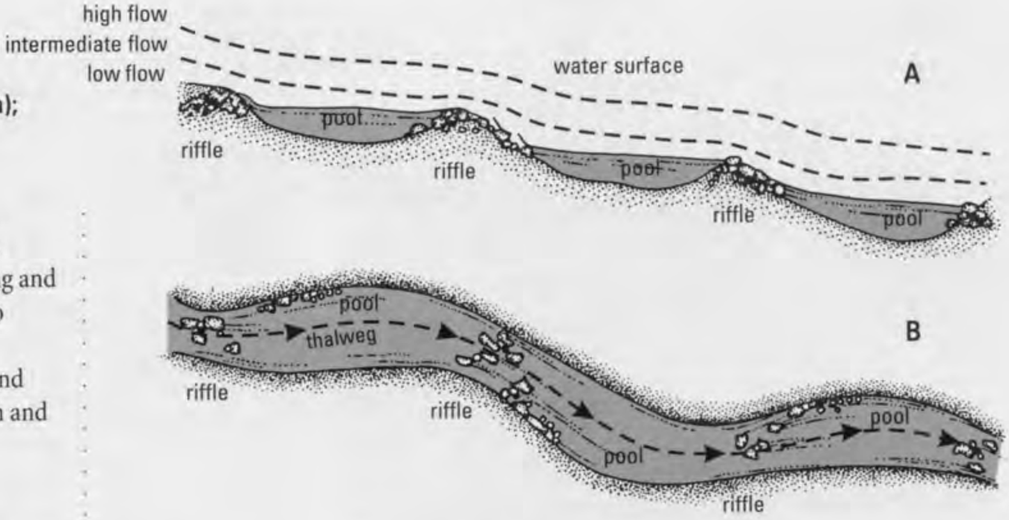


Figure 4. Stream pattern measurements.

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.

References

Knighton, David. 1984. Fluvial Forms and Processes. Rutledge, Chapman and Hall, Inc. New York, NY.

Leopold, Luna. 1994. A View of the River. Harvard University Press. Cambridge, MA

Leopold, Luna B., Wolman, Gordan M., and John P. Miller. 1992. Fluvial Processes in Geomorphology. Dover Publications, Inc. Mineola, NY.

Rosgen, Dave. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Springs, CO.

Thorne, Colin R., Hey, Richard D., and Malcolm D. Newson (Editors). 1997. Applied Fluvial Geomorphology for River Engineering and Management. John Wiley and Sons. New York, NY.

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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

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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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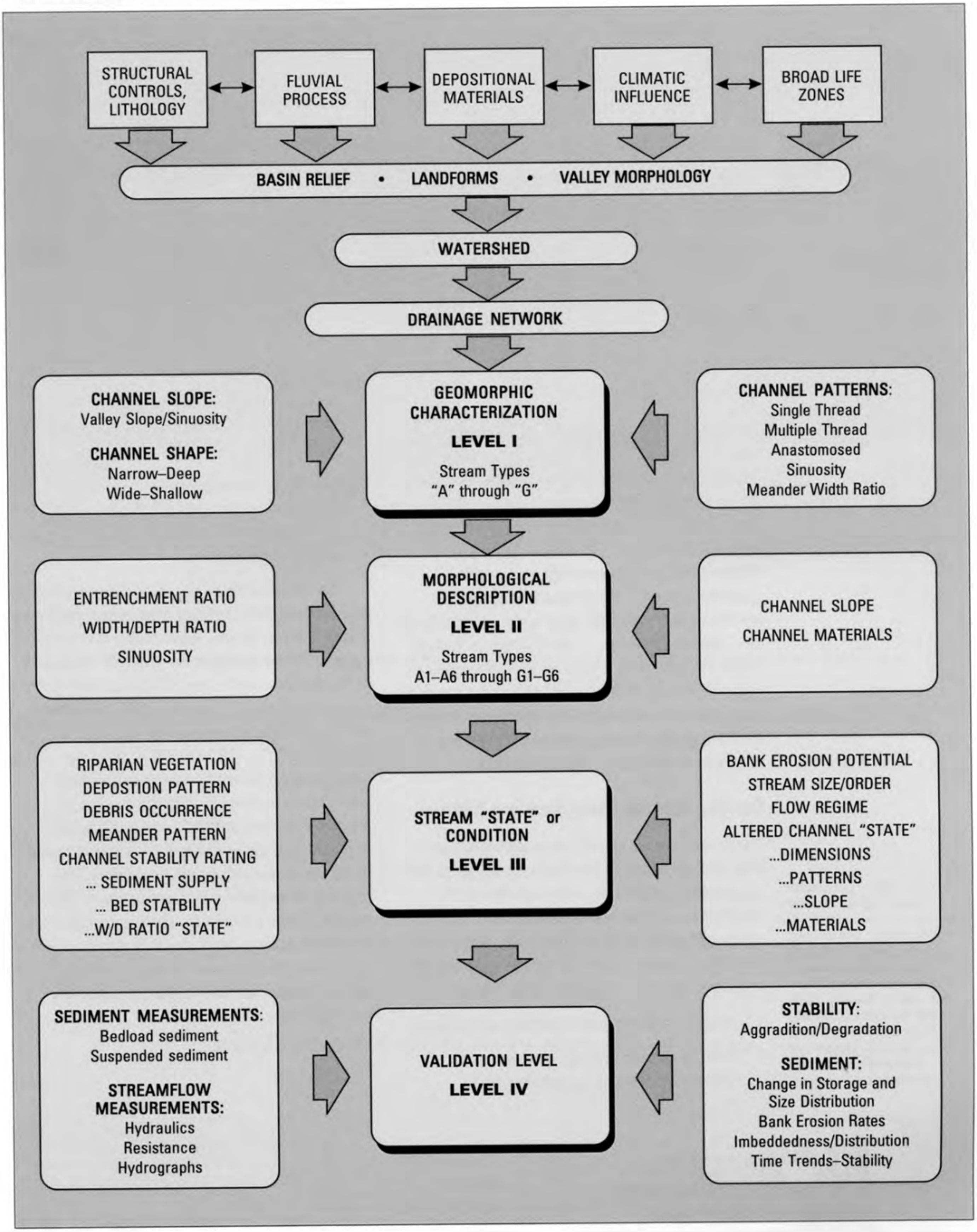
Figure 1. Rosgen Stream Classification Levels.



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.

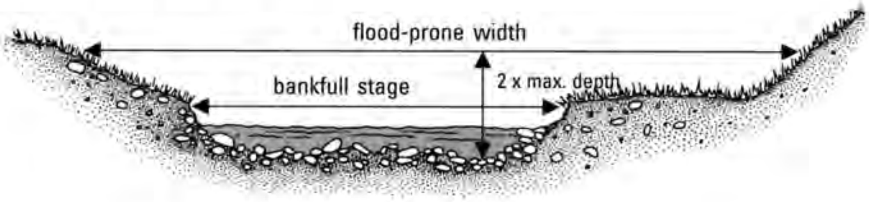


Figure 2. The entrenchment ratio measures the degree of channel incision as the flood-prone width divided by the bankfull width.

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

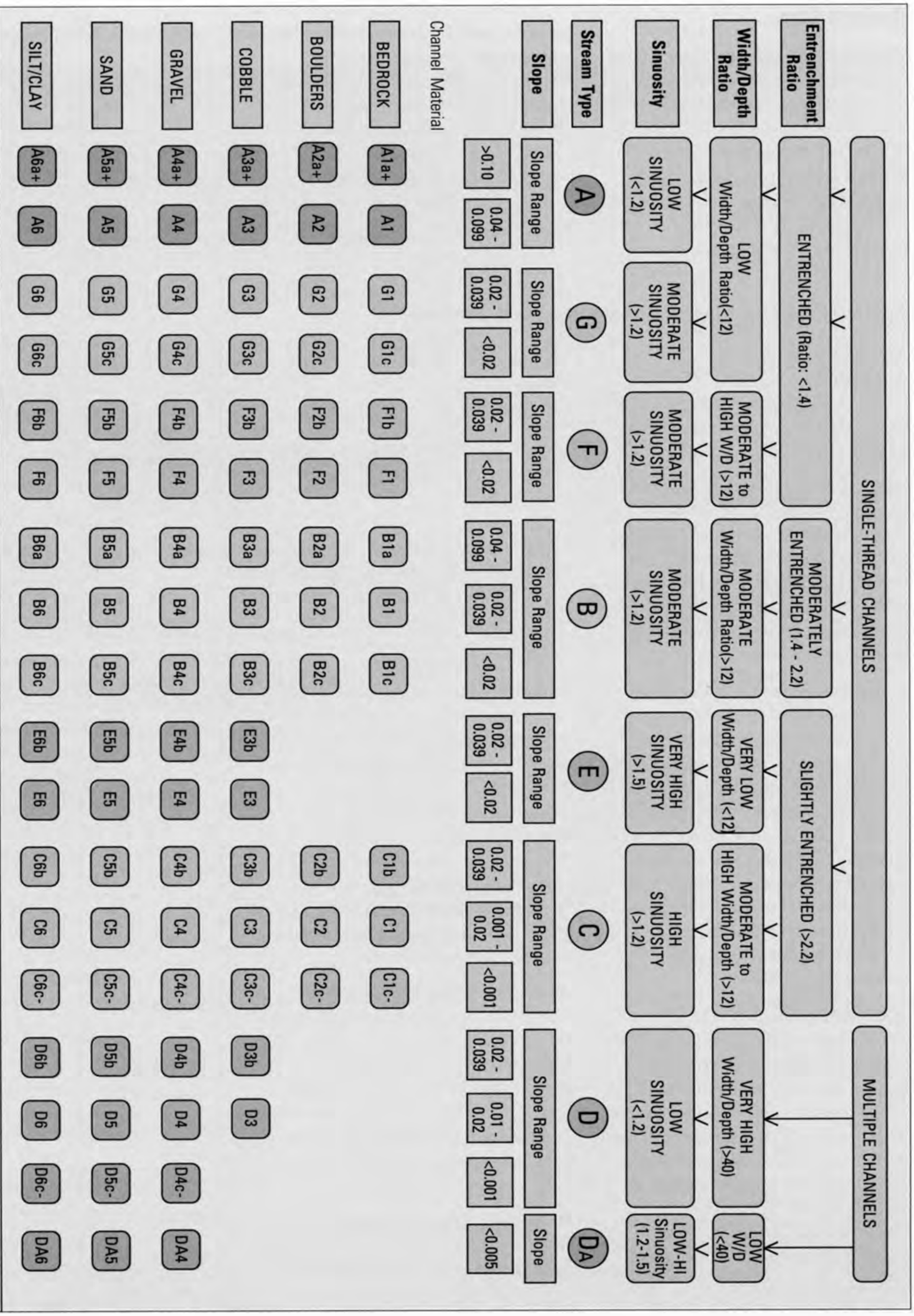


Figure 3. Key to the Rosgen Classification of Natural Rivers. As a function of the "continuum of physical variables" within stream reaches, values of *entrenchment* and *sinuosity* ratios can vary by +/– 0.2 units; while values for width/depth ratios can vary by +/– 2.0 units.

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

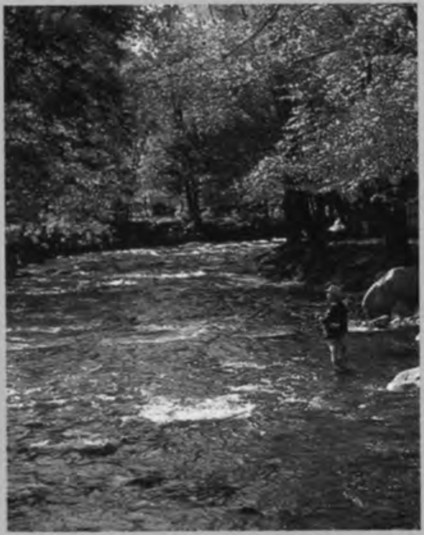
Basin: Catawba
Stream Type: B4c

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

References

Davis, W.M. 1899. The Geographical Cycle. *Geographical Journal* 14: 481-504.

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

Rosgen, D.L. 1994. *A Classification of Natural Rivers.* Catena, vol 22: 169-199. Eisevier Science, B.V. Amsterdam.

Rosgen, D.L. 1998. *Stream Classification Field Guide.* Wildland Hydrology, Pagosa Springs, CO.

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Fact Sheet Number 3

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.

Finding Bankfull Stage in North Carolina 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.

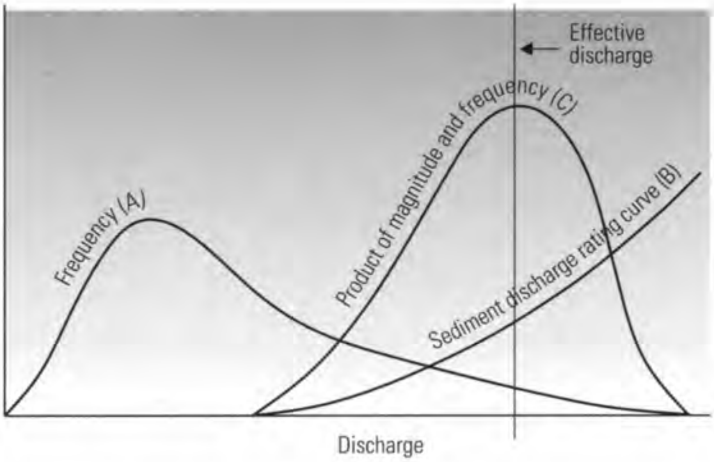

Figure 1. Effective discharge determination from sediment rating and flow duration curves. The peak of curve C marks the discharge that is most effective in transporting sediment. (Wolman and Miller, 1960)

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.

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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 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.**

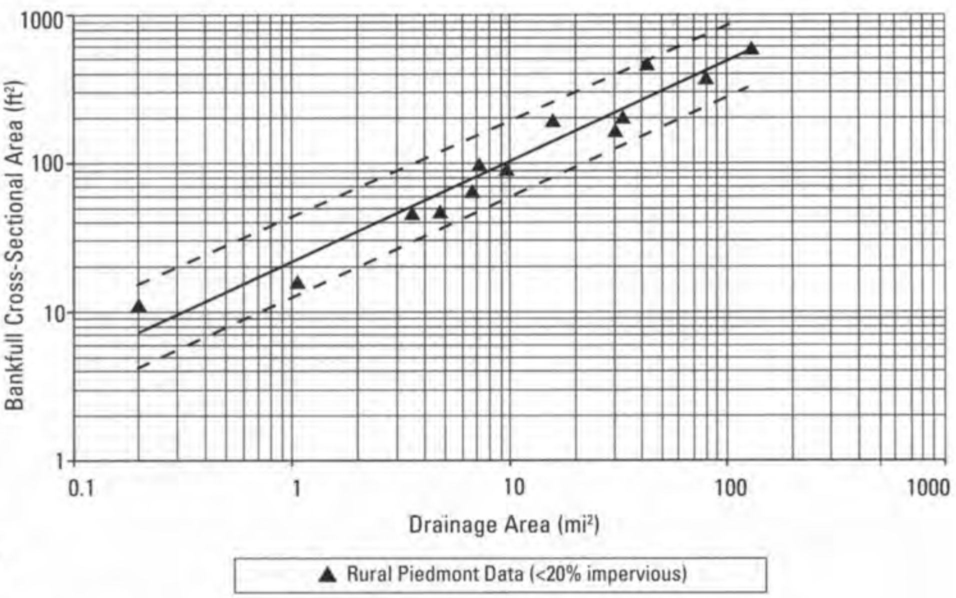


Figure 3. North Carolina rural piedmont curve.

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.

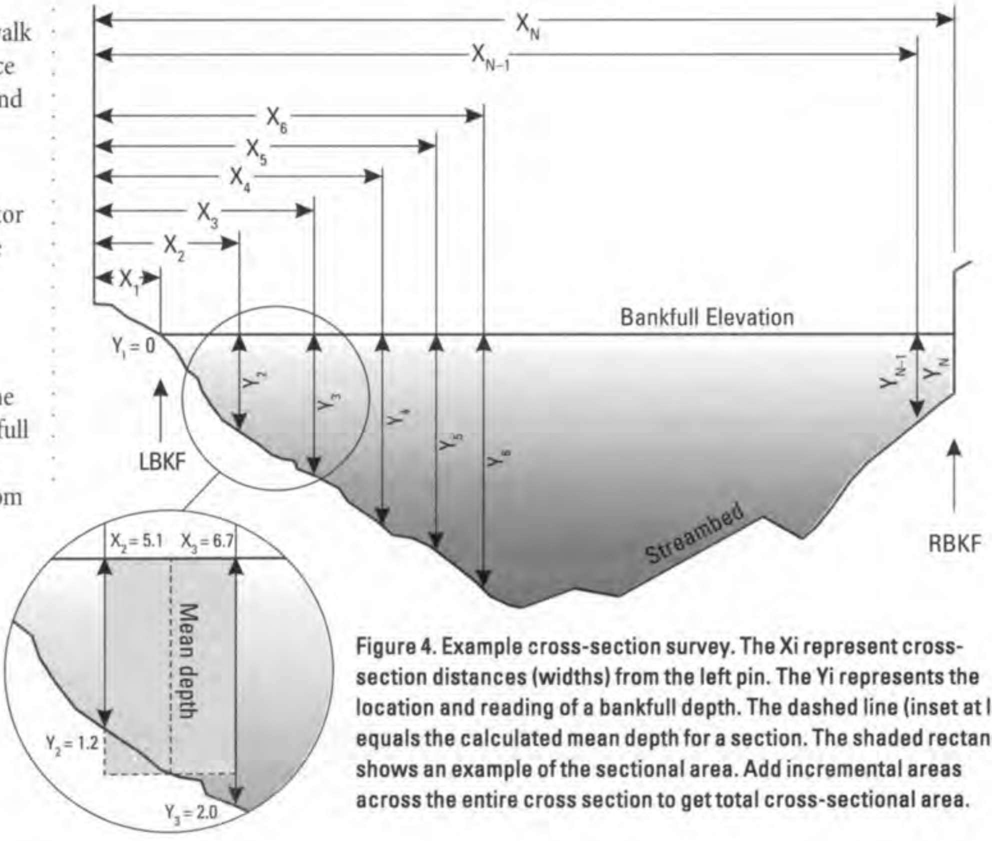
4. Use a survey rod to measure the difference between the bankfull indicator and the current water surface along the study reach. The variability of this difference should not be more than 6 inches.

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.

References

Dingman, L.S. 1994. *Physical Hydrology*. Prentice-Hall, Inc. Upper Saddle River, NJ.

Dunne, T. and L.B. Leopold. 1978. *Water and Environmental Planning*. W.H. Freeman Company. San Francisco, CA.

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

Harman, W.H. et al. 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. *AWRA Wildland Hydrology Proceedings*. AWRA Summer Symposium. Bozeman, MT.

Rosgen, D.L. 1994. *A Classification of Natural Rivers*. Catena, vol 22: 169-199. Eisevier, B.V. Amsterdam.

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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.

nc
stream
restoration institute

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

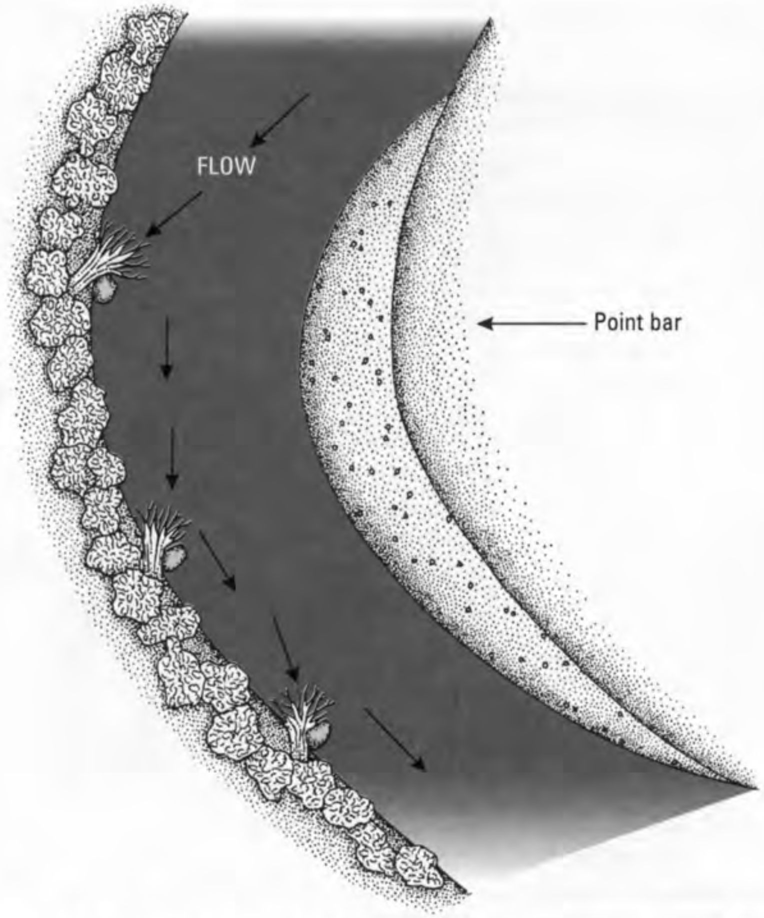
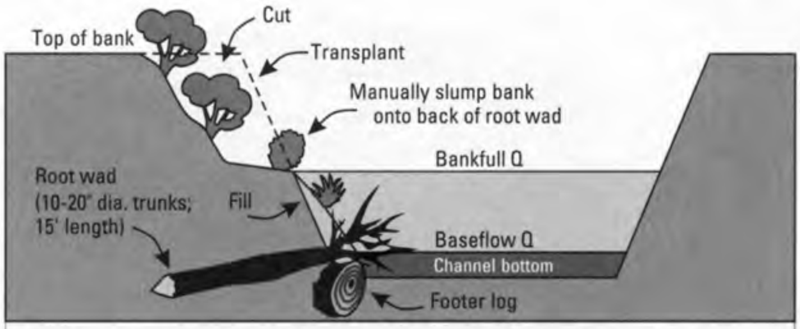


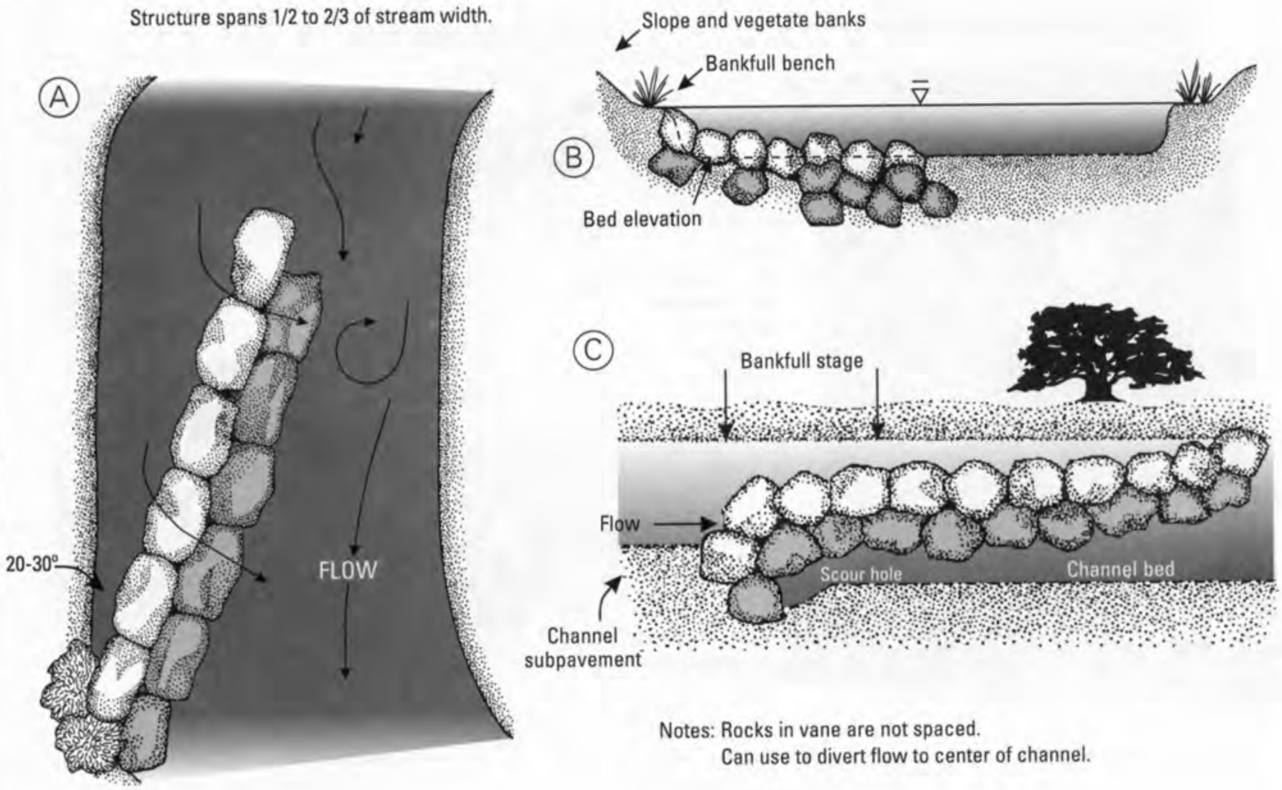
Figure 4. Root wads should be installed on the outside of the meander bend. They should be angled upstream to deflect the stream flow away from the bank.



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.

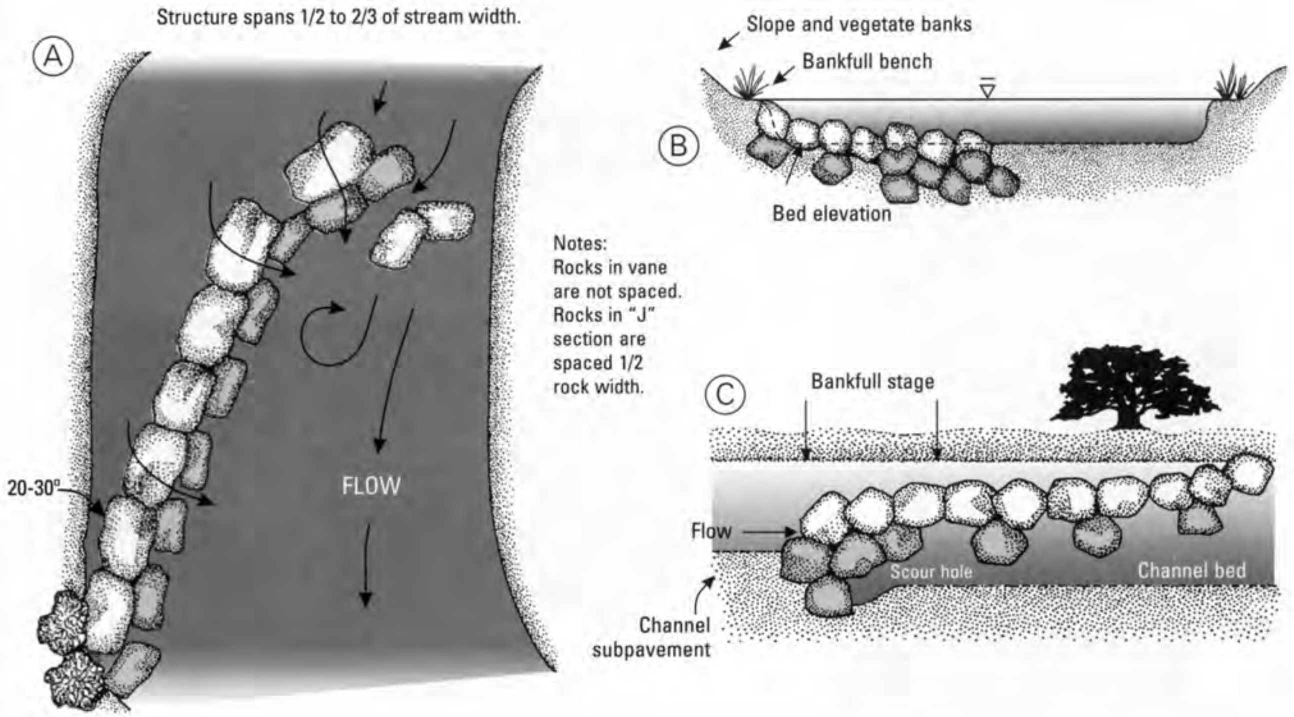
Cross vanes are used to provide grade control, to keep the thalweg in the center of the channel, and to protect the bank. A cross vane consists of two rock vanes and one center structure perpendicular to the flow. This center structure sets the invert grade of the streambed. Therefore, this structure 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

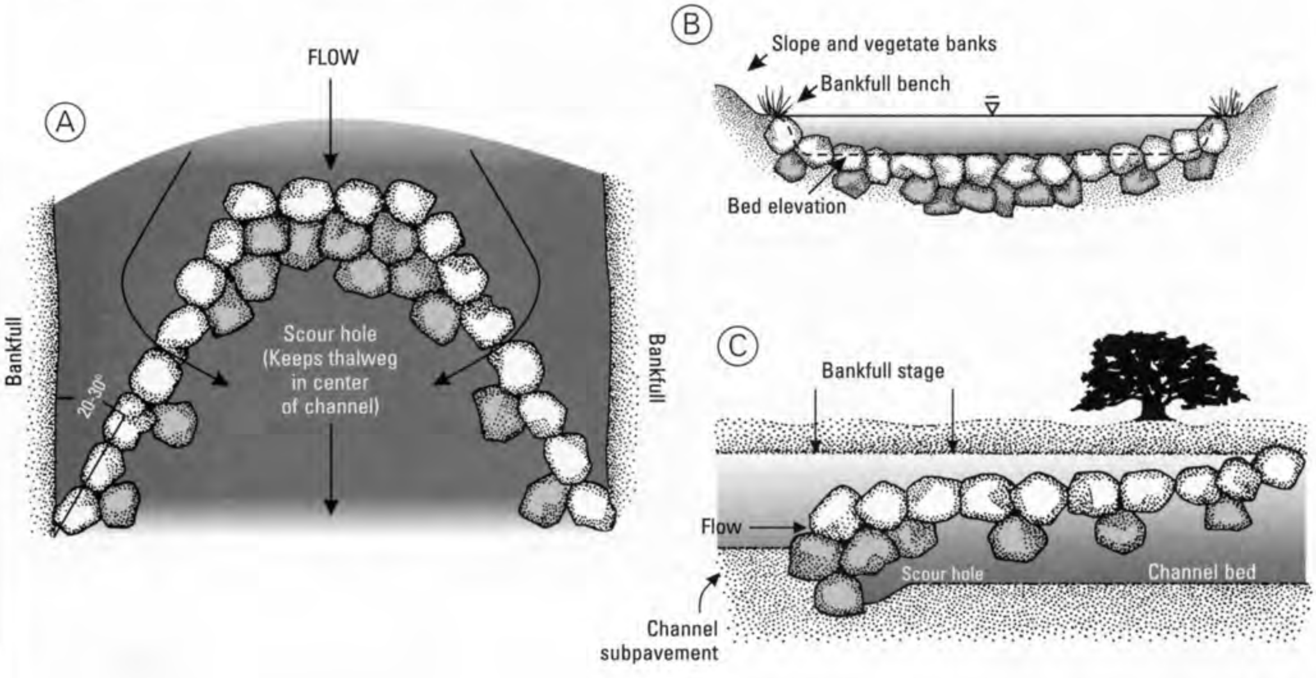
Before using the design specifications and suggestions in this fact sheet to install root wads and rock vanes, the designer must first complete a thorough morphological assessment of the stream reach and watershed. Selecting methods for stabilizing a streambank is one of the last steps in a natural channel 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.



Notes:
Rocks in vane are not spaced.
Rocks in "J" section are spaced 1/2 rock width.

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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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) _______

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

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

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

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

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

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

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

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

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

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

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

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

Pool Width Ratio = W_{pool} / W_{bkf} (ft/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 Belt Width, W_{blt} (ft) ____________

Radius of Curvature, R_c (ft) ____________

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

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

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

Pebble Count Results (reachwide):

Median Particle Size, d50 (mm) ____________

Pebble Count

Site ____ Date ____________

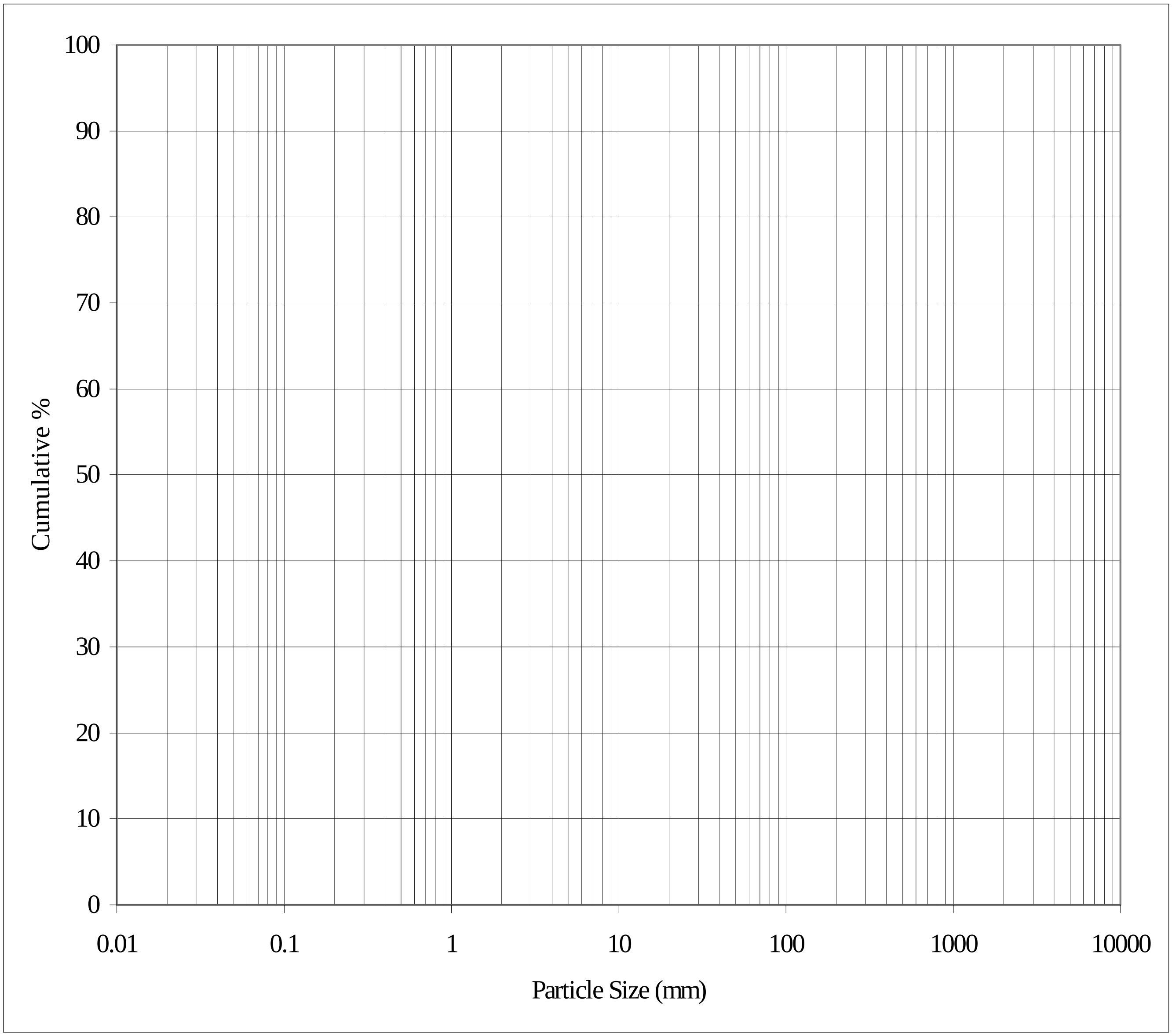
Survey Crew ____

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 ____

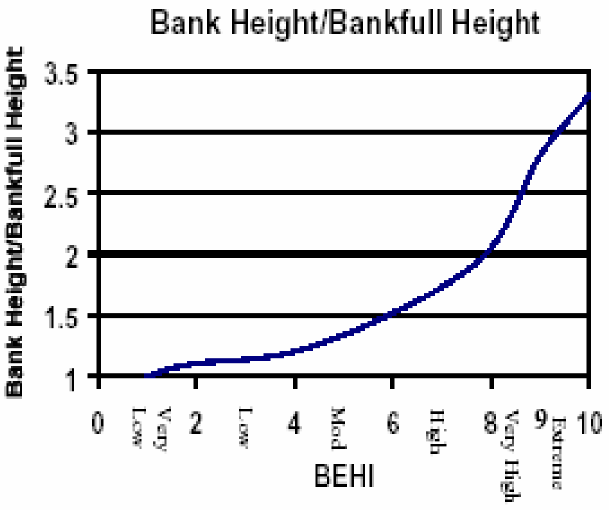
Category		Bank Ht Ratio (ft/ft)	Root Depth Ratio (%)	Root Density (%)	Bank Angle (degrees)	Surface Protection (%)	Total Index
Very Low	**Value**	1.0 – 1.1	100 – 80	100 – 80	0 – 20	100 – 90	
	Index	1 – 2	1 – 2	1 – 2	1 – 2	1 – 2	< 10
Low	**Value**	1.1 – 1.2	80 – 55	80 – 55	20 – 60	90 – 50	
	Index	2 – 4	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 _______

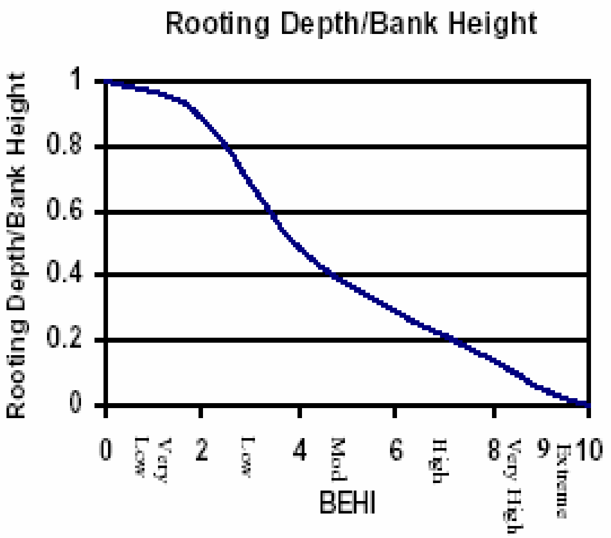
Numerical Adjustments _______

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

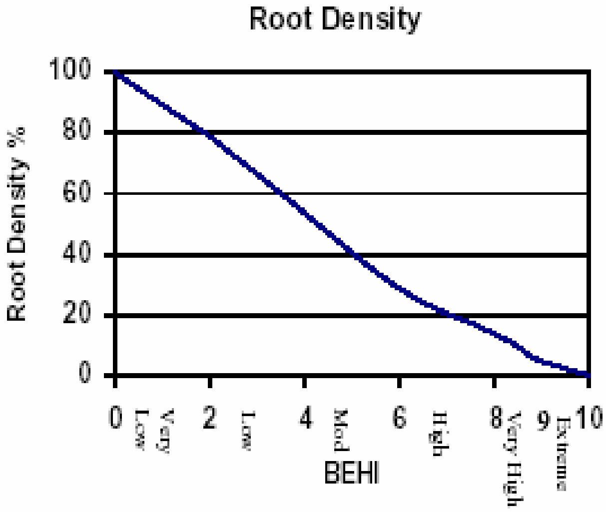
Adjusted BEHI ________



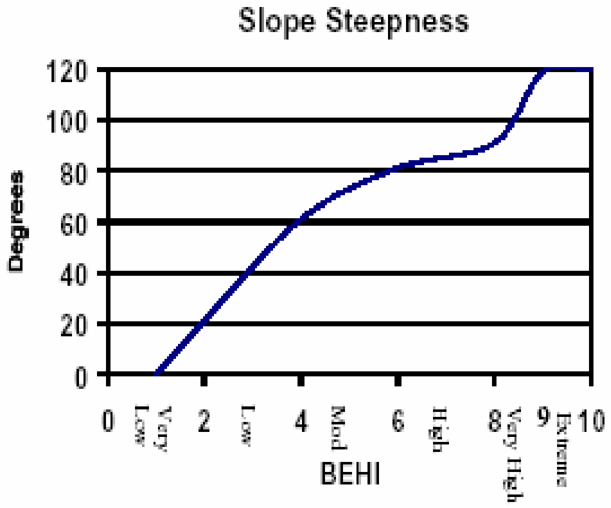
Bank Height/Bankfull Height



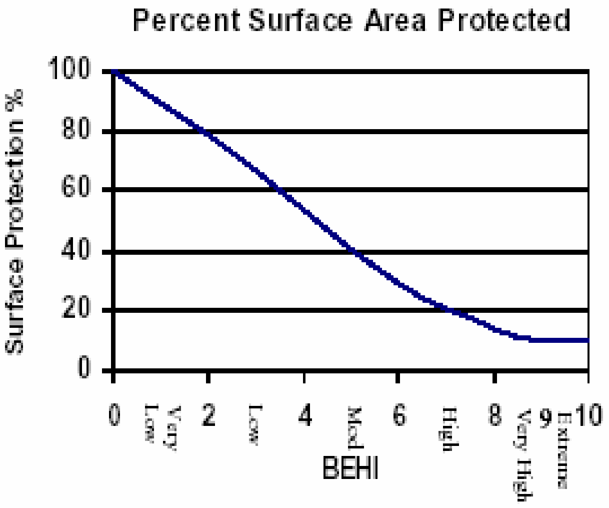
Rooting Depth/Bank Height



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

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)

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

UNITED STATES DEPARTMENT OF INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION
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 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	
.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

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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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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.

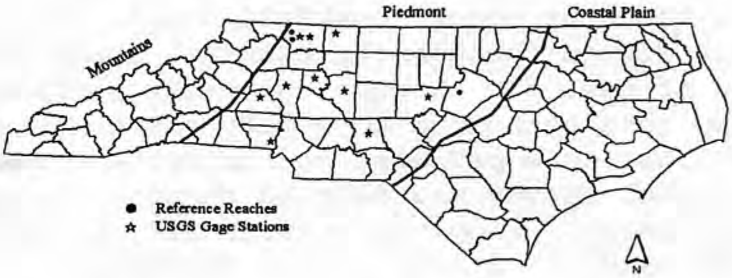

Figure 1: North Carolina map showing physiographic provinces with gaged and un-gaged study reaches.

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:

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

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

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

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

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.

LITERATURE CITED

Dunne, T., and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman Co. San Francisco, CA.
Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices.
Harrelson, C.C., J.P. Potyondy, C.L. Rawlins. 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. U.S. Department of Agriculture, forest Service, Fort Collins, Colorado.
Johnson, P.A., and T.M. Heil. 1996. Uncertainty in Estimating Bankfull Conditions. Water Resources Bulletin. Journal of the American Water Resources Association 32(6):1283-1292.
Kilpatrick, F.A., and H.H. Barnes Jr. 1964. Channel Geometry of Piedmont Streams as Related to Frequency of Floods. Professional Paper 422-E. US Geological Survey, Washington, DC.
Knighton, D. 1984. Fluvial Forms and Process. Edward Arnold, London.
Leopold, L.B., 1994. A view of the River. Harvard University Press, Cambridge, Massachusetts.
Leopold, L.B., and T. Maddock Jr., 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252, 57 pp.

Merigliano, M.F. 1997. Hydraulic Geometry and Stream Channel Behavior: An Uncertain Link. Journal of the American Water Resources Association 33(6):1327-1336.

Nixon, M. 1959. A Study of Bankfull Discharges of Rivers in England and Wales. In Proceedings of the Institution of Civil Engineers, vol. 12, pp. 157-175.

Pope, Benjamin F. 1999. Estimating Magnitude and Frequency of Floods in Rural North Carolina Basins. US Geological Survey, Water Resources Investigations Report, 99-XXXX (In Press). Raleigh, NC.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22(1994):169-199.

Schumm, S.A. 1960. The Shape of Alluvial Channels in Relation to Sediment Type. U.S. Geological Survey Professional Paper 352-B. U.S. Geological Survey, Washington, DC.

U. S. Geological Survey. 1969. Techniques of Water-Resources Investigations of the United States Geological Survey: Discharge Measurements at Gaging Stations. Book 3, Chapter A8. U.S. Geological Survey, Washington, DC.

U. S. Geological Survey. 1982. Guidelines for Determining Flood Flow Frequency. Bulletin # 17B of the Hydrology Subcommittee. Reston, Virginia.

Williams, G.P., 1978. Bankfull Discharge of Rivers. Water Resources Research 14(6):1141-1154.

Wolman, M.G. and L.B. Leopold. 1957. River Floodplains: Some Observations on their Formation. USGS Professional Paper 282-C. U.S. Geological Survey, Washington, DC.

This paper should be cited as follows: Harman, W.H. et al. 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. AWRA Wildland Hydrology Symposium Proceedings. Edited By: D.S. Olsen and J.P. Potyondy. AWRA Summer Symposium. Bozeman, MT.

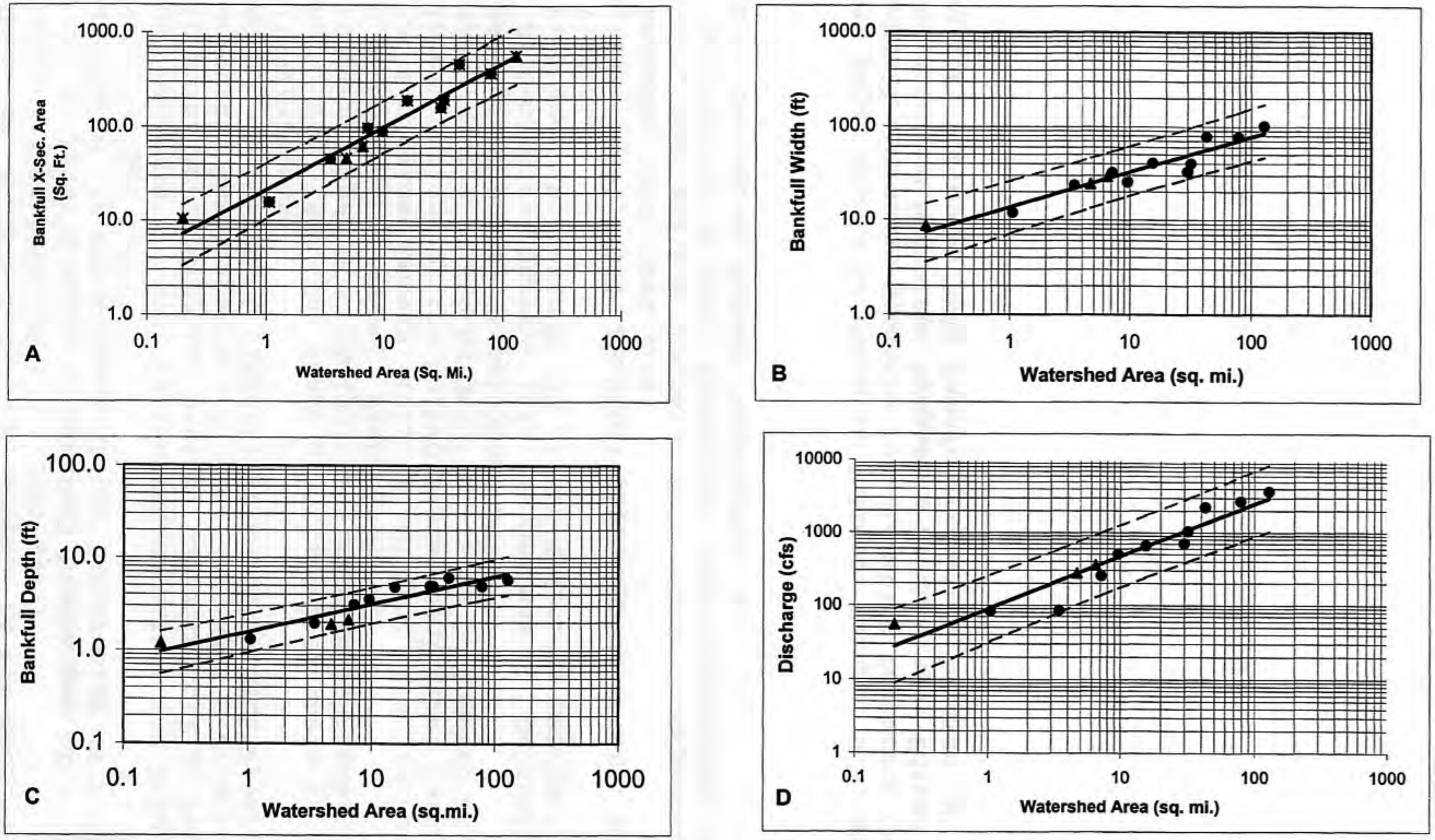

Figure 3: Bankfull hydraulic geometry relationships for rural Piedmont North Carolina Streams. The four graphs represent: a) cross sectional area, b) width, c) depth, and d) discharge. The circles represent gage stations and the triangles represent ungaged streams.

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-

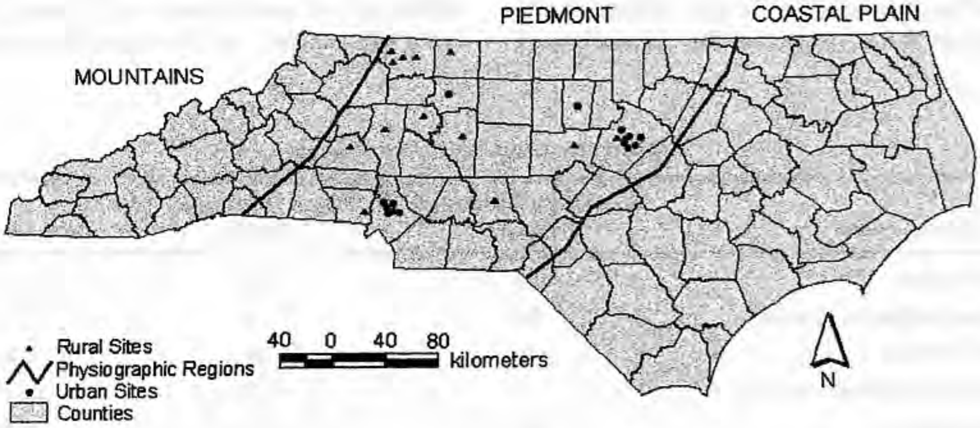


Figure 1. Survey Sites in North Carolina.

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.

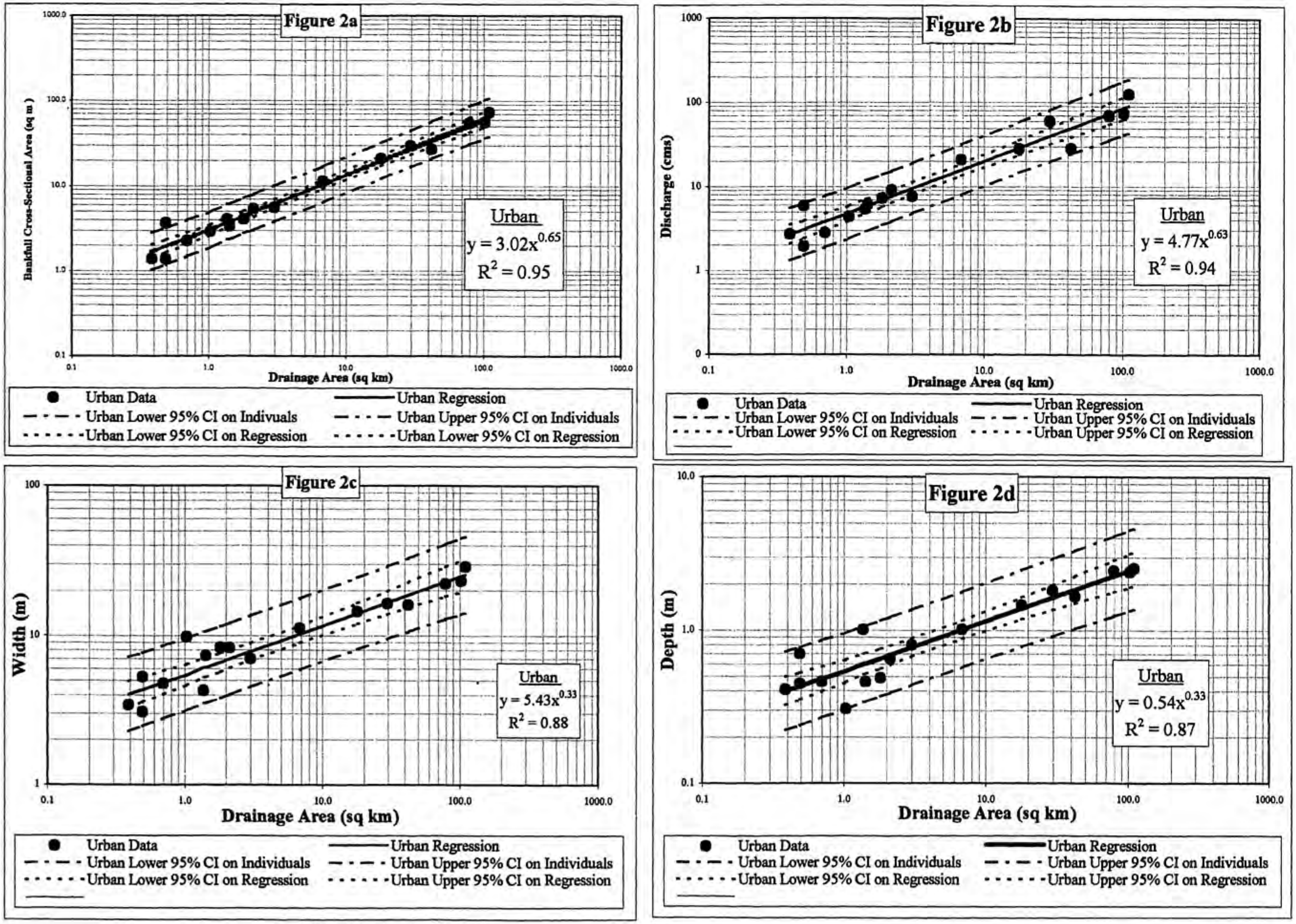


Figure 2. Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Urban Streams in the North Carolina Piedmont.

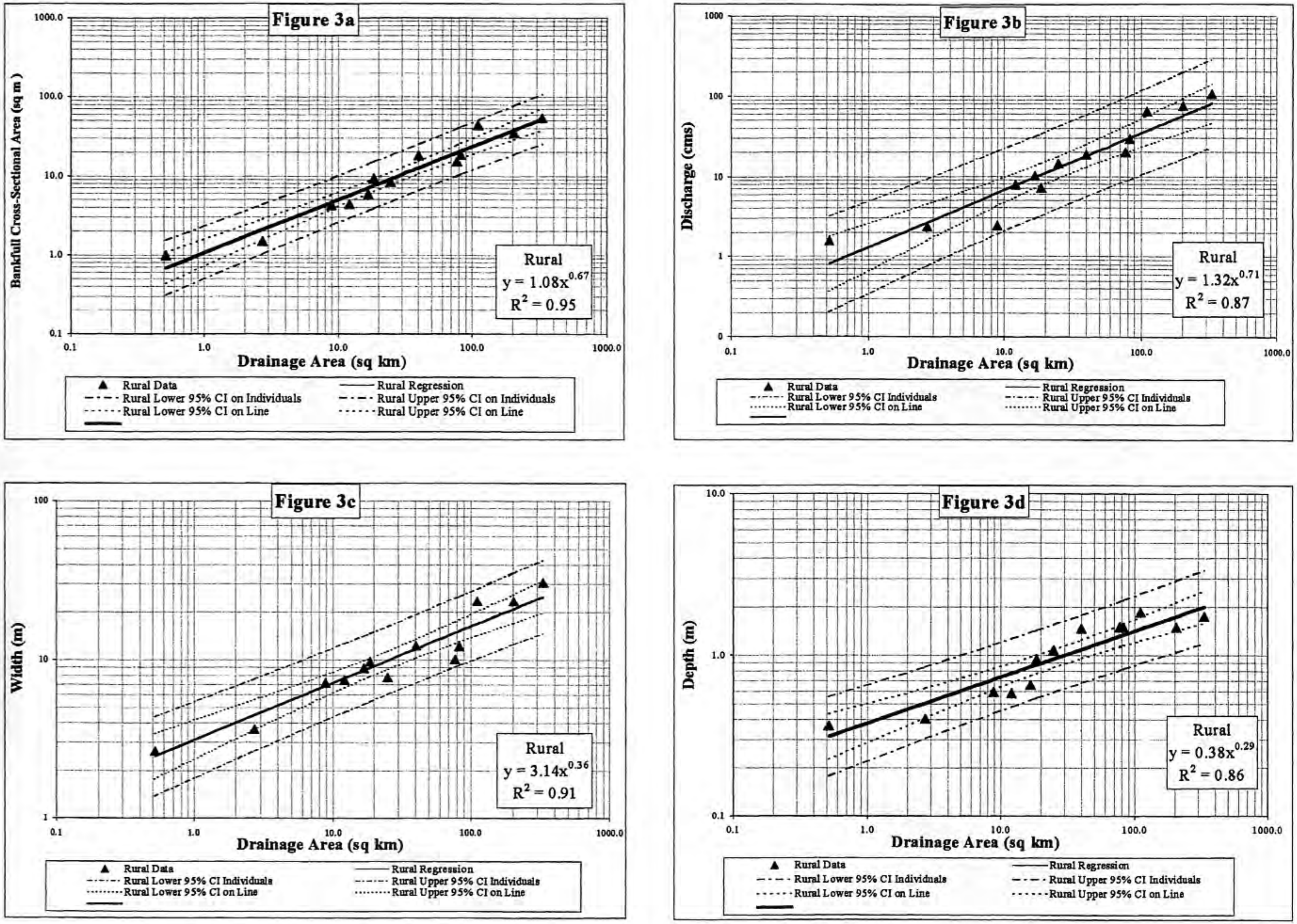


Figure 3. Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Rural Streams in the North Carolina Piedmont from Harman *et al.* (1999).

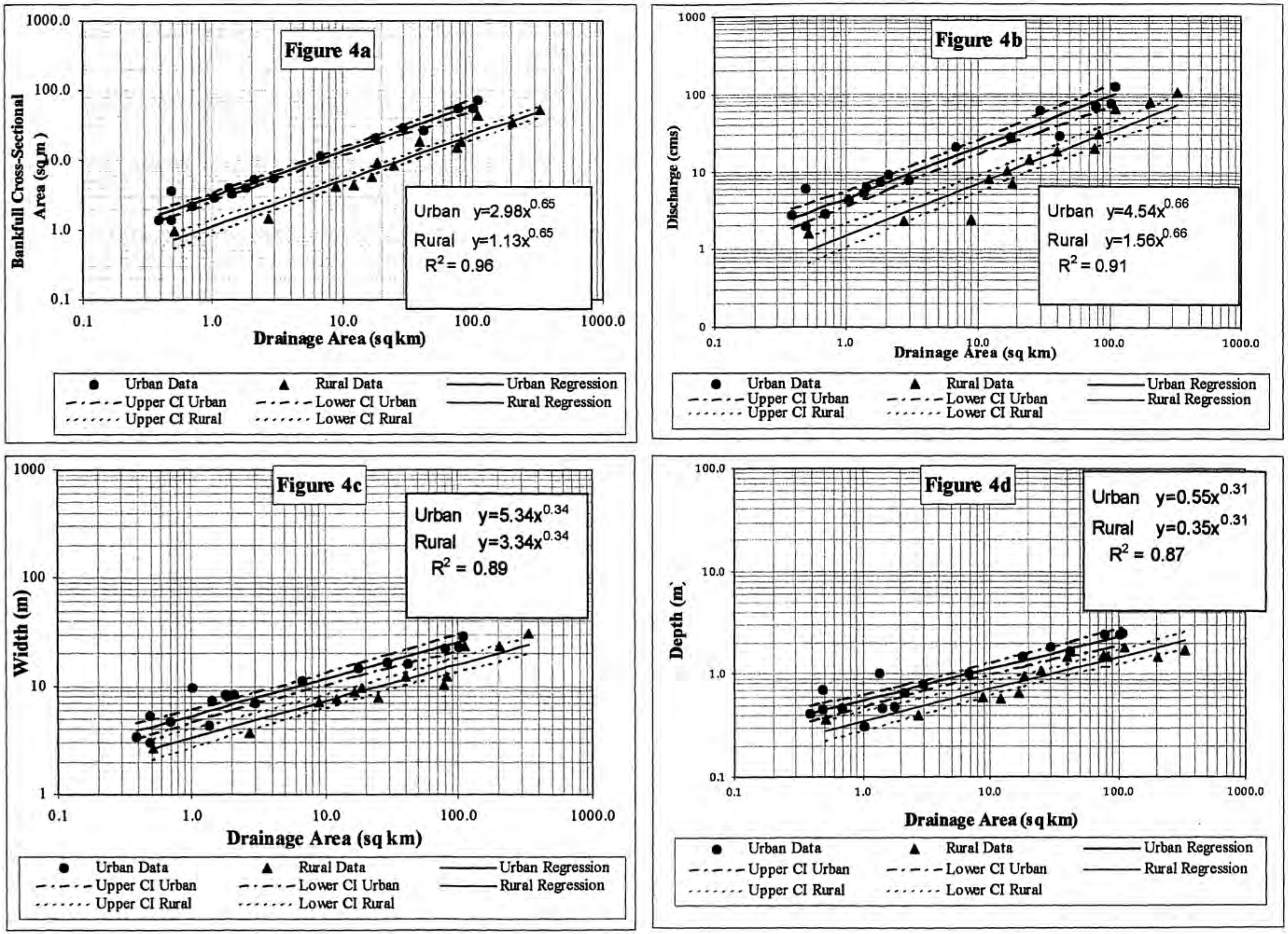


Figure 4. Comparison of Urban Versus Rural Regional Hydraulic Geometry Relationships of: (a) Bankfull Cross-Sectional Area, (b) Discharge, (c) Width, and (d) Depth Compared to Watershed Area for Streams in the North Carolina Piedmont.

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.

LITERATURE CITED

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer, 1976. A Land Use and Land Cover Classification System for Use With Remote Sensor Data. U.S. Geological Survey Professional Paper 964, Reston, Virginia, 33 pp.

Chow, V. T., 1959. Open Channel Hydraulics. McGraw-Hill, Inc., New York, New York, 680 pp.

Dunne, T. and L. B. Leopold, 1978. Water in Environmental Planning. W.H. Freeman Co., San Francisco, California, 818 pp.

EPA (Environmental Protection Agency), Office of Water, 1998. 1:250,000 Scale Quadrangles of Landuse/Landcover GIRAS Spatial Data of CONUS in BASINS. *Available at* www.epa.gov/OST/BASINS.

FISRWG (Federal Interagency Stream Restoration Working Group), 1998. Stream Corridor Restoration: Principles, Processes and Practices. National Technical Information Service, Springfield, Virginia.

Hammer, T. R., 1972. Stream Channel Enlargement Due to Urbanization. Regional Science Research Institute Discussion Paper Series, No.55. Philadelphia, Pennsylvania, 41 pp.

Hammer, T. R., 1973. Impact of Urbanization on Peak Streamflow. Regional Science Research Institute Discussion Paper Series, No. 63, Philadelphia, Pennsylvania, 76 pp.

Harman, W. A., G. D. Jennings, J. M. Patterson, D. R. Clinton, L. O. Slate, A. G. Jessup, J. R. Everhart, and R. E. Smith, 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. *In:* AWRA Wildland Hydrology Proceedings, D. S. Olsen and J. P. Potyondy (Editors). AWRA Summer Symposium, Bozeman, Montana, pp. 401-408.

Harrelson, C. C., J. P. Potyondy, and C. L. Rawlins, 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245, U.S. Department of Agriculture, Forest Service, Fort Collins, Colorado, 66 pp.

Horton, Wright and Victor Zullo (Editors), 1991. The Geology of the Carolinas, Carolina Geological Society Fiftieth Anniversary Volume. The University of Tennessee Press, Knoxville, Tennessee.

Kunickis, S. H., 2000. The Effects of Riparian Buffers With Controlled Drainage on Soil Redox Potential. Ph.D. Dissertation, North Carolina State University, Raleigh, North Carolina, 209 pp.

Leopold, L. B. and T. Maddock, Jr., 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252.

Leopold, L. B., 1994. A View of the River. Harvard University Press, Cambridge, Massachusetts, 298 pp.

NRCS (Natural Resource Conservation Service), 1986. Urban Hydrology for Small Watersheds. Technical Release 55, Second Edition, U.S. Department of Agriculture, Washington, D.C., pp. 2.1–2.16.

Rosgen, D. L., 1994. A Classification of Natural Rivers. Catena 22(1994):169-199.

Rosgen, D. L., 1996. Applied River Morphology. Printed Media Companies, Minneapolis, Minnesota, 350 pp.

Schueler, T., 1995. The Importance of Imperviousness. Watershed Protection Techniques 1(3):100-111.

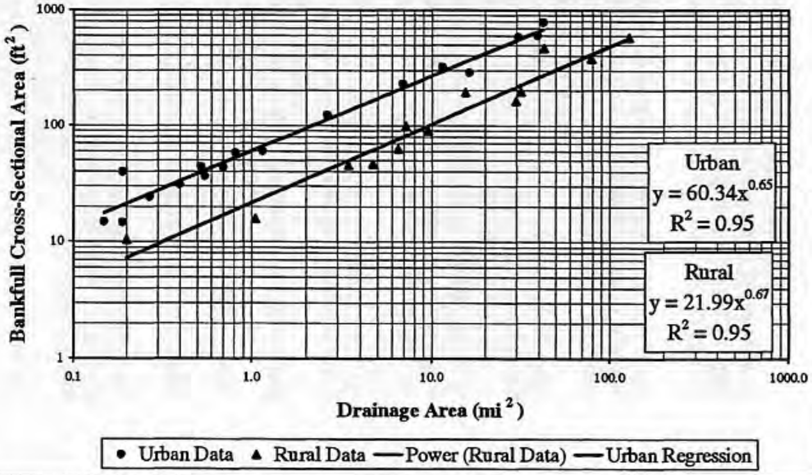
Simon, A., 1989. A Model of Channel Response in Disturbed Alluvial Channels. Earth Surface Processes and Landforms 14(1):11-26.

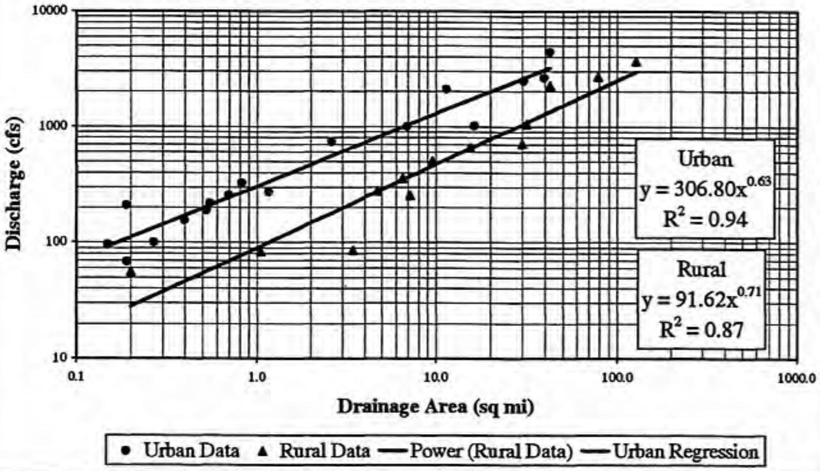
USGS (U.S. Geological Survey), 1969. Techniques of Water-Resources Investigations of the United States Geological Survey: Discharge Measurements at Gaging Stations. Book 3, Chapter A8, U.S. Geological Survey, Washington, D.C., 13 pp.

USGS (U.S. Geological Survey), 1982. Guidelines for Determining Flood Flow Frequency. Bulletin No. 17B of the Hydrology Subcommittee, Reston, Virginia, pp. 14-20.

USGS (U.S. Geological Survey), 1996. Estimation of Flood-Frequency Characteristics of Small Urban Streams in North Carolina. Water-Resources Investigations Report 96-4084, Denver, Colorado, 21 pp.

Wilkerson, S. D., 1998. Development and Analysis of Hydraulic Geometry Relationships for the Urban Piedmont of North Carolina. M.S. Thesis, Civil Engineering Department, University of North Carolina-Charlotte, Charlotte, North Carolina.


North Carolina Piedmont Regional Curve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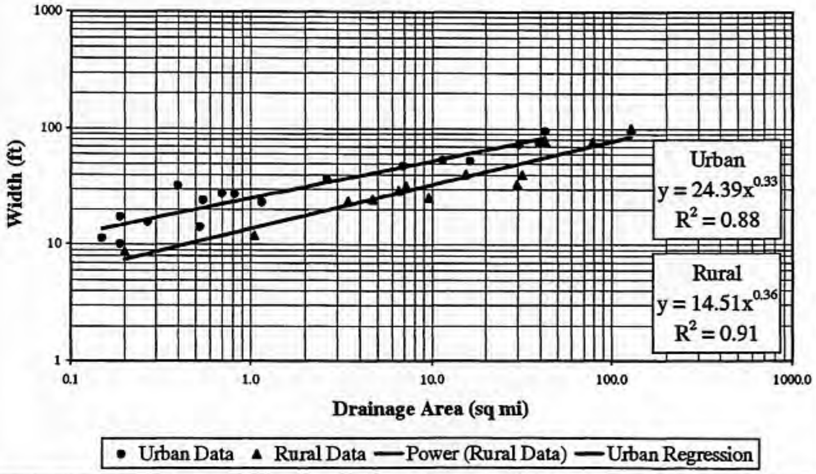
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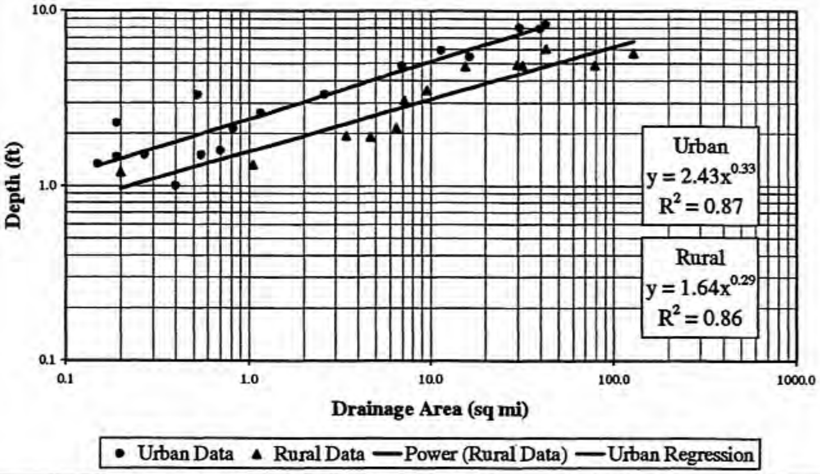
North Carolina Piedmont Regional Curve

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.

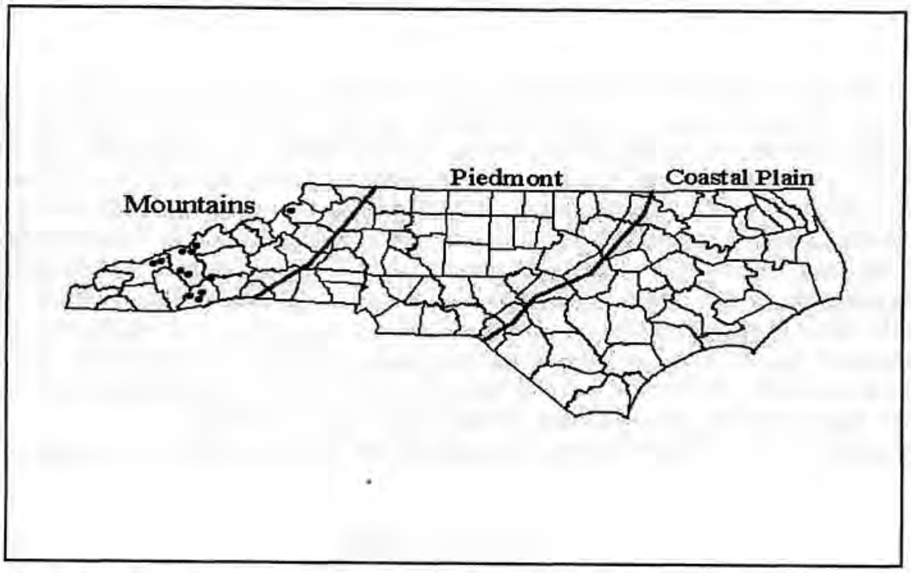

Figure 1: North Carolina map showing physiographic provinces with Mountain study sites shown has dots.

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.

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LITERATURE CITED

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

Federal Interagency Stream Restoration Working Group (FISRWG), 1998. Stream Corridor Restoration: Principles, Processes, and Practices.

Harman, W.A., G.D. Jennings, J.M. Patterson, D.R. Clinton, L.O. Slate, A.G. Jessup, J.R. Everhart, and R.E. Smith, 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. Wildland Hydrology. AWRA Symposium Proceedings. Edited by: D.S. Olsen and J.P. Potyondy. American Water Resources Association. June 30-July 2, 1999. Bozeman, MT

Harrelson, C.C., J.P. Potyondy, C.L. Rawlins, 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. U.S. Department of Agriculture, forest Service, Fort collins, Colorado.

Johnson, P.A., and T.M. Heil, 1996. Uncertainty in Estimating Bankfull Conditions. Water Resources Bulletin. Journal of the American Water Resources Association 32(6):1283-1292.

Kilpatrick, F.A., and H.H. Barnes Jr. 1964, Channel Geometry of Piedmont Streams as Related to Frequency of Floods. Professional Paper 422-E. US Geological Survey, Washington, DC.

Knighton, D, 1984. Fluvial Forms and Process. Edward Arnold, London.

Leopold, L.B., 1994. A view of the River. Harvard University Press, Cambridge, Massachusetts.

Leopold, L.B., and T. Maddock Jr., 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252, 57 pp.

Nixon, M., 1959. A Study of Bankfull Discharges of Rivers in England and Wales. In Proceedings of the Institution of Civil Engineers, vol. 12, pp. 157-175.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22(1994):169-199.

Schumm, S.A., 1960. The Shape of Alluvial Channels in Relation to Sediment Type. U.S. Geological Survey Professional Paper 352-B. U.S. Geological Survey, Washigton, DC.

U. S. Geological Survey, 1982. Guidelines for Determining Flood Flow Frequency. Bulletin # 17B of the Hydrology Subcommittee. Reston, Virginia.

Williams, G.P., 1978. Bankfull Discharge of Rivers. Water Resources Research 14(6):1141-1154.

Wolman, M.G. and L.B. Leopold., 1957. River Floodplains: Some Observations on their Formation. USGS Professional Paper 282-C. U.S. Geological Survey, Washigton, DC.

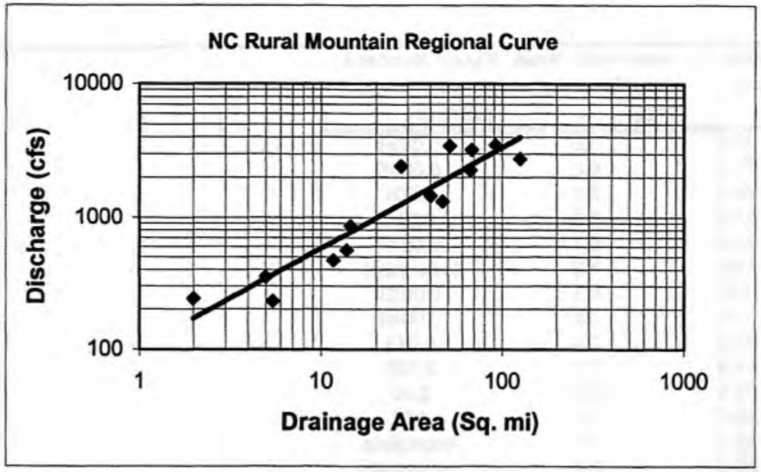

Figure 2a - Bankfull Discharge vs Drainage Area

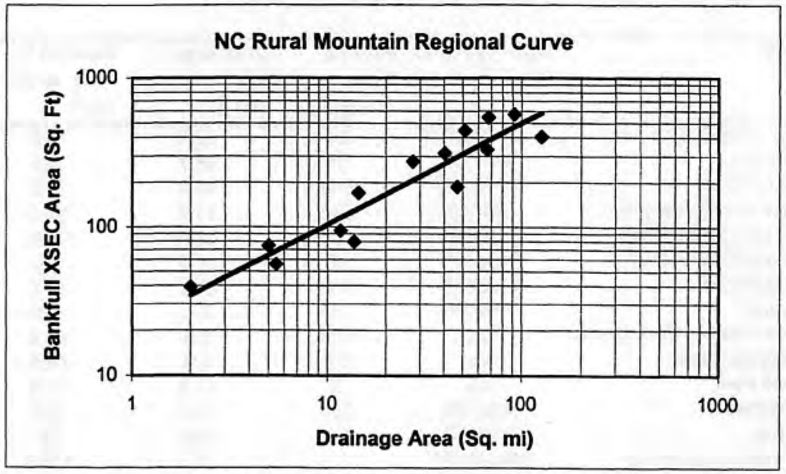

Figure 2b - Bankfull Cross Sectional Area vs Drainage Area

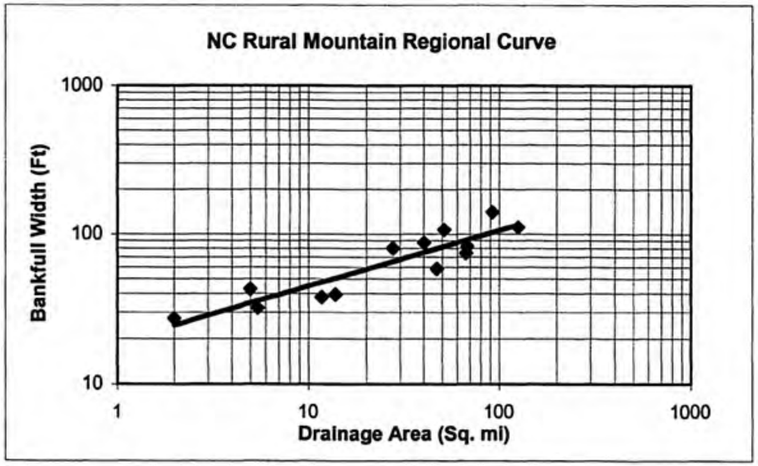

Figure 2c - Bankfull Width vs Drainage Area

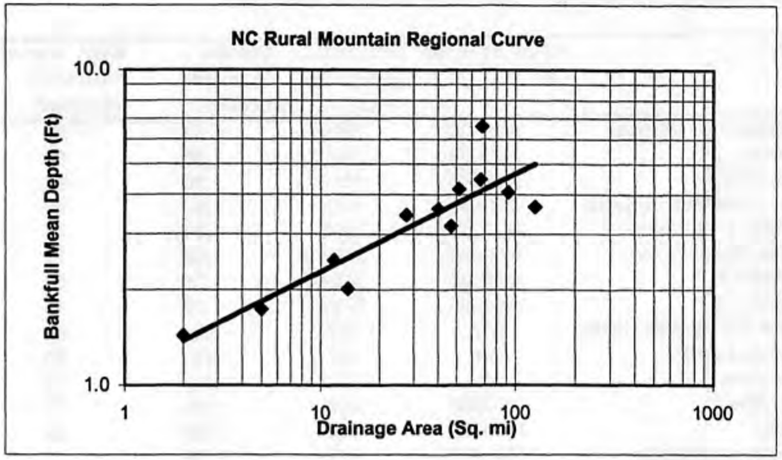

Figure 2d - Bankfull Depth vs Drainage Area

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	