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# Bankfull Hydraulic Geometry of Streams Draining the Southwestern Appalachians of Tennessee

Gregory Scott Babbit
*University of Tennessee - Knoxville*

To the Graduate Council:

I am submitting herewith a thesis written by Gregory Scott Babbit entitled "Bankfull Hydraulic Geometry of Streams Draining the Southwestern Appalachians of Tennessee." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

Matthew Gray, Major Professor

We have read this thesis and recommend its acceptance:

Ray Albright, Carol Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Acceptance for the Council:

_Anne Mayhew___________
Vice Chancellor and Dean of
Graduate Studies

(Original signatures are on file with official student records.)

# BANKFULL HYDRAULIC GEOMETRY OF STREAMS DRAINING THE SOUTHWESTERN APPALACHIANS OF TENNESSEE

A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Gregory Scott Babbit
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## ABSTRACT

The purpose of this study was to examine the bankfull recurrence interval for streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee, develop bankfull discharge and hydraulic geometry relationships for streams within the ecoregion and compare those relationships to the Ridge and Valley of Virginia, West Virginia, and Maryland (Keaton *et al.*, 2005) and the Piedmont and Blue Ridge of North Carolina (Harman *et al.*, 1999; Harman *et al.*, 2000). For this investigation, a repeatable, systematic process was developed to locate bankfull stage within the Southwestern Appalachians during the spring and summer of 2005. The intent was to develop regional curves of empirically derived hydraulic relationships for this ecoregion, but first it was necessary to correctly identify bankfull stage in the sample streams. Bankfull discharge was defined as the effective discharge or channel-forming flow. Stream surveys were conducted on 11 study reaches (7 had USGS gages for calibration of bankfull) of various sized drainages across the ecoregion. Recurrence intervals were calculated using log Person Type III flood frequency analysis. Results demonstrated an average bankfull recurrence interval of 1.31 years for the Southwestern Appalachians, which was comparable to other nearby physiographic regions.

Regional curves illustrate hydraulic and geomorphic relationships such as discharge versus watershed area, channel width versus channel cross sectional area and many more such relationships. The principal benefits from regional curves are their assistance in validating channel dimensions, pattern and profile for stream restoration designs. The marked variance in geology, climate, topography, and watershed land-uses across physiographic provinces drives the need for developing regional curves for each specific physiographic province. Stream restoration designs in Tennessee rely on curves from other nearby physiographic regions. A comparison of the Southwestern Appalachians regional curves developed in this study to the Ridge and Valley and the Piedmont and Blue Ridge reveals distinctly different relationships. In the Southwestern Appalachians, bankfull discharge and associated cross sectional area were found to be of much greater magnitude than streams in the other two regions.

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# CHAPTER I
# INTRODUCTION

## Background

Both historical and modern civilizations were constructed in close proximity to streams and rivers for convenient access to stable sources of food and drinking water as well as for transportation and commerce. Consequently, the pragmatic nature of humans to live near flowing water has driven people to search for methods of defining, understanding and predicting relations among hydraulic parameters of the river, such as discharge, width, depth, and velocity (Williams, 1978b).

Streams transport water, sediment and energy while providing habitat for aquatic and terrestrial organisms. Stream channel shape, size, and pattern are a function of many physical processes and to a lesser extent, biological and chemical processes occurring simultaneously within a watershed (Emmett, 1975; FISRWG, 1998). Drainage basin size has been found to be highly correlated with natural channel morphology, specifically cross section area in many physiographic provinces throughout the U.S. (Dunne and Leopold, 1978; Harman, *et al.*, 1999; Smith and Turrini-Smith, 1999; Harman, *et al.*, 2000; Castro and Jackson, 2001; McCandless and Everett, 2002; Sweet and Geratz, 2003; Cinnoto, 2003; McCandless, 2003; Powell, *et al.*, 2004; Emmert, 2004; Keaton *et al.*, 2005). Each river basin has a discharge and sediment load that are products of a number of variables interacting within a watershed, such as local climate (precipitation), geology, soils, vegetation, land use, topography, and valley morphology (Emmett, 1975; Leopold, 1994; Knighton, 1998). Several hydrologic attributes are influenced by these variables, including the quantity, quality, and timing of water and the dispersion of energy throughout a river system (Hewlett, 1982).

Hydrologic, hydraulic and resultant geomorphic processes are the dominant physical processes affecting stream channel morphology. The hydrologic cycle describes the movement of water between the earth and its atmosphere and incorporates the hydrologic processes responsible for helping shape a stream channel (FISRWG, 1998). Schumm (1960) added to the factors controlling channel shape by establishing that stream channel morphology is also a function of the composition of bed and bank materials. In 1977, he established three principal geomorphic processes involving flowing water which include sediment production, sediment transport and sediment deposition. Leopold and Maddock (1953) pioneered hydraulic geometry relationships in the early 1950s, when they examined the width, depth, velocity, discharge and suspended sediment of natural rivers. Their quantitative examination of discharge and sediment load illustrated the dependence of channel shape on the aforementioned physical, chemical and biological characteristics within a watershed.

The magnitude and frequency concept initially set forth by Wolman and Miller (1960) described the dependence of river floodplain and channel shape on flows of moderate magnitude occurring more frequently rather than infrequent, catastrophic storm events of large magnitude (Figure 1-1).

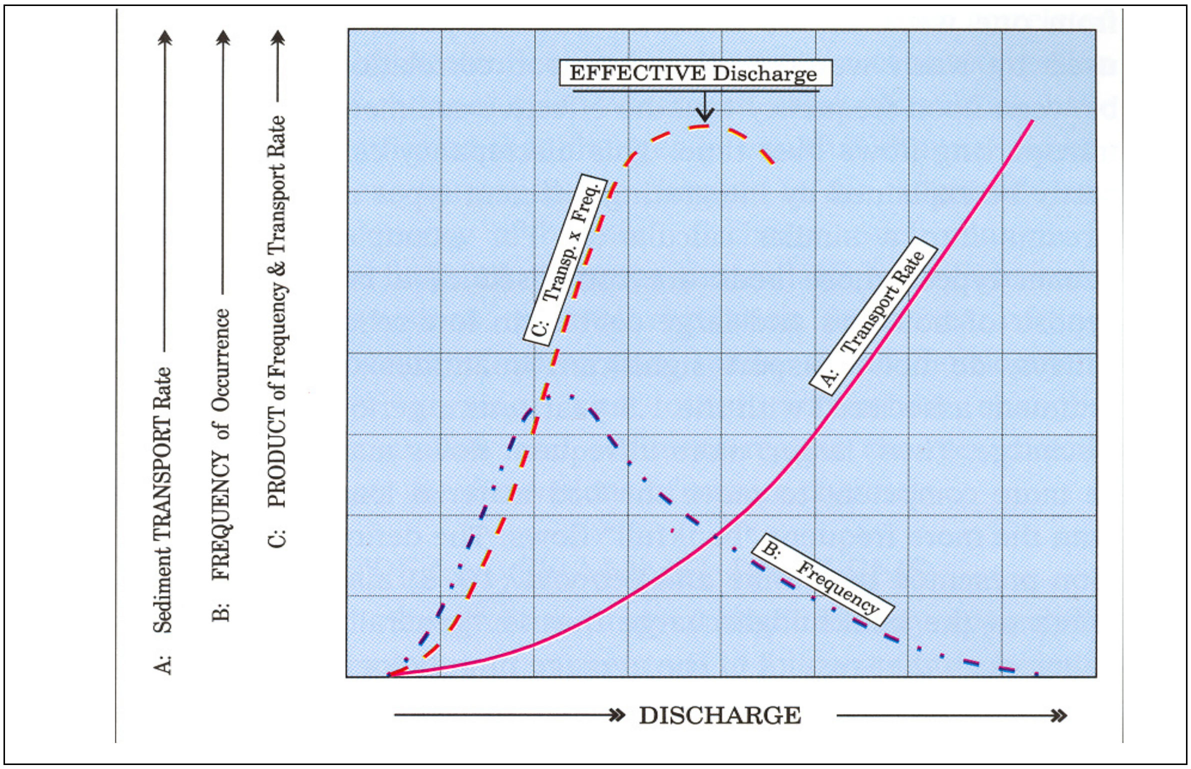


**Figure 1-1. Magnitude and Frequency Concept for Effective Discharge Determination. (After Wolman and Miller, 1960; Rosgen, 1996)**

Leopold, Wolman and Miller (1964) found that stream channel shape is a function of the timing, magnitude, spatial distribution and frequency of stream discharge. Furthermore, they illustrated that the amount, size and shape of sediment transported through a reach and the composition of boundary materials within the channel help dictate channel form. To elaborate on the variables affecting stream channel morphology, Leopold, Wolman and Miller (1964) established eight interrelated hydraulic variables that included width, depth, discharge, velocity, size of sediment, concentration of sediment, water surface slope and boundary roughness. At the decade timescale, Werritty (Thorne *et al*., 1997) summarized the controlling variables affecting river behavior that included sediment supply and flow regime, channel and valley morphology, and the composition and amount of sediment supplied to the river from its watershed. In addition to watershed size, the integration of hydrologic, hydraulic and geomorphic processes affect channel morphology. Understanding these processes is essential to defining and predicting river behavior.

## Bankfull Discharge

Bankfull stage was initially described as the incipient point on the stream bank where water spreads out onto the active floodplain and flooding begins (Wolman and Leopold, 1957; Emmett, 1975; Leopold *et al*., 1964; Rosgen, 1996). However, disagreement over the definition and the subjectivity of identifying bankfull stage in the field has persisted for decades. Williams (1978a) outlined more than 10 possible definitions of bankfull proposed by investigators (Wolman and Leopold, 1957; Nixon, 1959a,b; Woodyer, 1968; Kellerhals *et al*., 1972; Riley, 1972; Dunne and Leopold, 1978; Knighton, 1998) in which there could potentially be eleven different bankfull elevations at a stream channel cross section. Johnson and Heil (1996) examined the disparity between different methods of determining bankfull depth and discharge. Their study concluded a significant uncertainty and variability exists when determining and predicting bankfull depth and discharge. The morphological and hydrological significance of bankfull discharge gives argument to the importance of identifying this flow for rivers in need of improvement (Leopold, 1994). Leopold (1994, pg. 90) states that "it is an empirical fact that, for most streams the bankfull discharge has a recurrence interval of approximately 1.5 years in the annual flood series."

The primary consideration when quantifying stream channel hydraulic geometry is identifying the channel-forming flow because it is the discharge at which channel width, depth, area, and velocity are compared. Bankfull, effective, dominant and channel-forming discharges are terms describing a similar flow and were described by multiple scientists (Leopold and Maddock, 1953; Wolman and Miller, 1960; Kilpatrick and Barnes, 1964; Williams, 1978a; Andrews, 1980; Knighton, 1998). Effective discharge is defined by Andrews (1980) as the increment of flow that transports the largest amount of annual total sediment load over time (Figure 1-1). His work in the Yampa River basin was based on field measurements of 15 USGS gage stations where the frequency of flow that transports the largest quantity of sediment was comparable to the bankfull discharge recurrence interval of 1 to 2 years (Andrews, 1980). Wolman and Miller (1960) established a different definition of effective discharge describing it as a range of flows that transport the largest amount of annual suspended sediment load over the long term. This definition was supported by more recent work to calculate effective discharge using suspended sediment transport rates and the 1.5-year return interval for ecoregions across the country (Simon *et al.*, 2004). Both bankfull and effective discharge were found to be comparable through the comprehensive examination of sediment transport by several studies (Andrews, 1980; Knighton, 1998).

The most widely accepted definition of bankfull stage that most researchers agree upon was proposed by Dunne and Leopold (1978, pgs. 608-609) who stated that the "bankfull stage corresponding to the discharge at which channel maintenance is the most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends or meanders, and generally doing work that results in the average morphologic characteristics of channels." This definition was examined quantitatively from field surveys that confirmed the erosion rate, sediment transport rate and the construction of point bars by deposition are most active during flows at or near bankfull flow (Leopold, 1994). An argument has been made by Knighton (1998, pg. 167) that bankfull discharge is not a product of constant frequency or the most effective flow, but a range of flows, including bankfull, that produce channel morphology. In contrast, he does point out that bankfull discharge is a reference level that can be reasonably defined in natural streams and "it remains intuitively appealing to attach morphological significance to bankfull flow." Typical geomorphic features that are often used as bankfull stage indicators in order of importance are the floodplain break in slope, back of point bars, most prominent bench, top of bank, highest scour line, change in bank materials, and change in vegetation (Leopold, 1994; Harman *et al*., 1999; McCandless and Everett, 2002).

Stream flow regime not only influences channel shape, but also affects channel pattern or meander geometry. Stream pattern or meander geometry can be defined through measuring sinuosity (stream length divided by valley length) (Figure 1-2), meander wavelength, radius of curvature, amplitude and belt width (Figure 1-3, Rosgen, 1996). Meander geometry is a function of bankfull width and has been shown by several scientists to be related to bankfull discharge and channel dimensions (Figure 1-4, Leopold *et al.*, 1964; Langbein and Leopold, 1966; Williams, 1986). It follows, that by identifying bankfull hydraulic geometry, one can also predict stream channel meander geometry.

## Stream Classification

Efforts to classify fluvial systems are abundant (Davis, 1899; Leopold and Wolman, 1957; Schumm, 1963; Galay *et al.*, 1973; Kellerhals *et al.*, 1976; Schumm, 1977; Frissell *et al.*, 1986; Simon and Hupp, 1986; Whiting and Bradley, 1993; Rosgen, 1994; Montgomery and Buffington, 1997; Davenport *et al.*, 2004). Stream classification provides the potential to improve water resource management decisions and enables planners to evaluate stream enhancement or restoration projects (Gordon *et al.*, 1993; Juracek and Fitzpatrick, 2003). However, few natural systems fit perfectly into a logical order or classification and many streams have reaches that are in transition from one type to another. As part of this geomorphic investigation, I chose to use the Rosgen (1994) classification of natural streams because the system:

1) Organizes and stratifies many empirically derived relations (Rosgen, 1996),

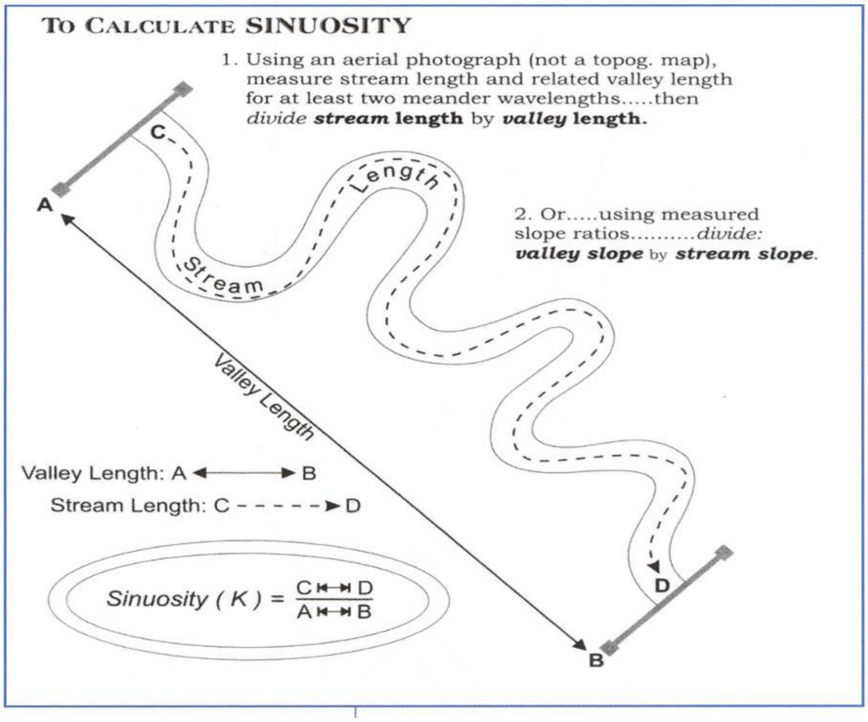


**Figure 1-2. Example of Sinuosity Calculation and Aerial Photo of Stream Channel Pattern. (After Rosgen, 1998; FISRWG, 1998)**

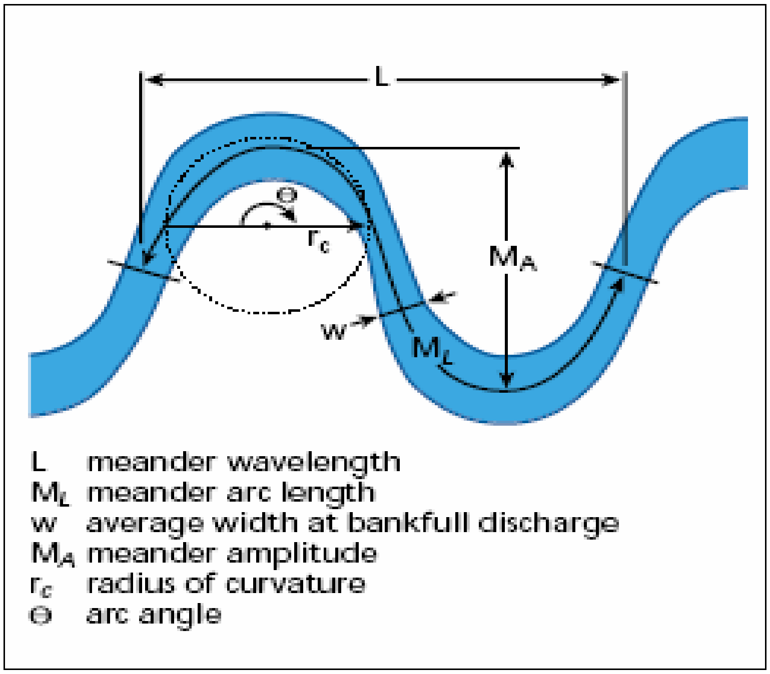


**Figure 1-3. Meander Geometry Variables. (After Williams, 1986; FISRWG, 1998)**

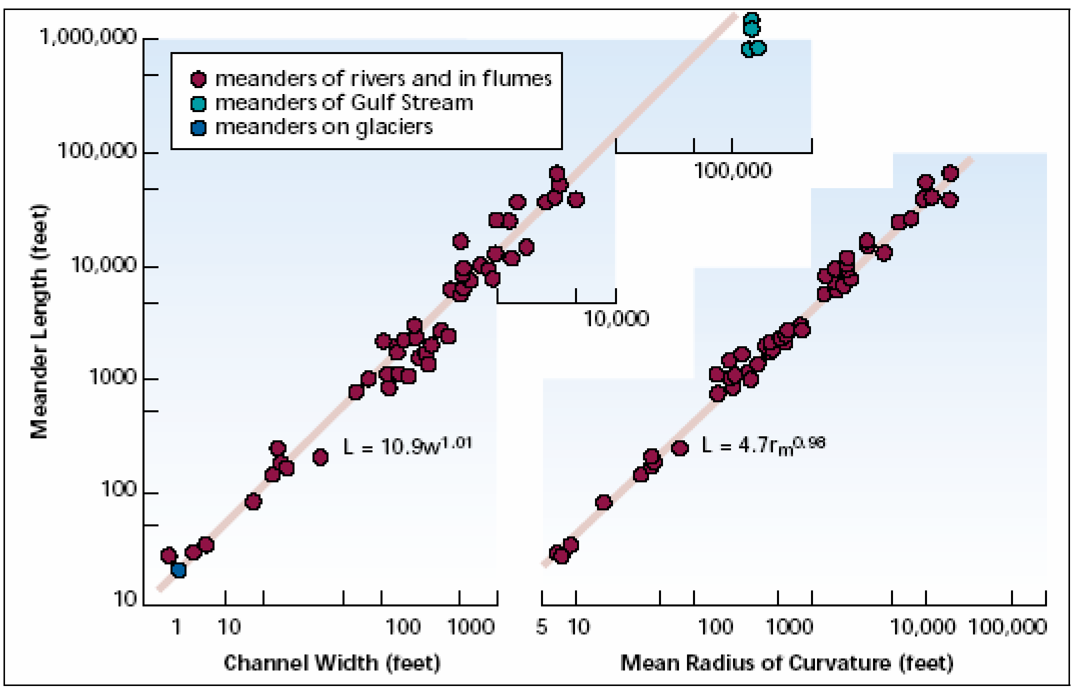


**Figure 1-4. Meander Geometry Relationships. (After Leopold, 1994; FISRWG, 1998)**

2) Categorizes rivers based on channel dimension, pattern, profile and materials (Thorne, 1997),
3) Contains the advantage of implying channel behavior (Leopold, 1994),
4) Provides a morphological stratification for companion inventories (Rosgen, 1994),
5) Is well known and the most widely used stream classification system in the U.S. (Juracek and Fitzpatrick, 2003),
6) Provides a framework for developing specific hydraulic and sediment relations for a given stream state (Rosgen, 1994),
7) Enables extrapolation of site-specific data to other reaches of similar geomorphic attributes (Rosgen, 1994),
8) Most importantly, it provides a consistent, objective, quantitative, and reproducible frame of reference for communication across a wide range of disciplines (Rosgen, 1994; Keane, 2004).

A key to the Rosgen (1996) Classification of Natural Rivers is found in Figure 1-5. For further review of classification systems, please review previous works by Hawkes (1975), Moseley (1987), Downs, (1995) Miller and Ritter, 1996; Thorne *et al.* (1997), Knighton (1998), Naiman *et al*. (1992), Goodwin (1999), Juracek and Fitzpatrick (2003) and Schumm (2005).

**Importance of Regional Curves**

Regional curves are a graphical method of illustrating stream channel bankfull hydraulic geometry as a function of basin drainage area within a specific ecoregion or physiographic province (Harman *et al*., 1999; Sweet and Geratz, 2003). Regional curves are the product of regression analysis performed on the relationships of bankfull discharge, width, mean depth and cross-sectional area to drainage area (Cinotto, 2003). The dependent variables of bankfull discharge, width, mean depth and cross-sectional area can be determined from field geomorphic surveys. The principal reason for developing regional curves is to assist in identifying bankfull stage and channel dimensions in ungaged watersheds and to validate bankfull dimensions and discharge for stream restoration designs (Rosgen, 1994). Bankfull calibration is conducted at a USGS gaging station in which the

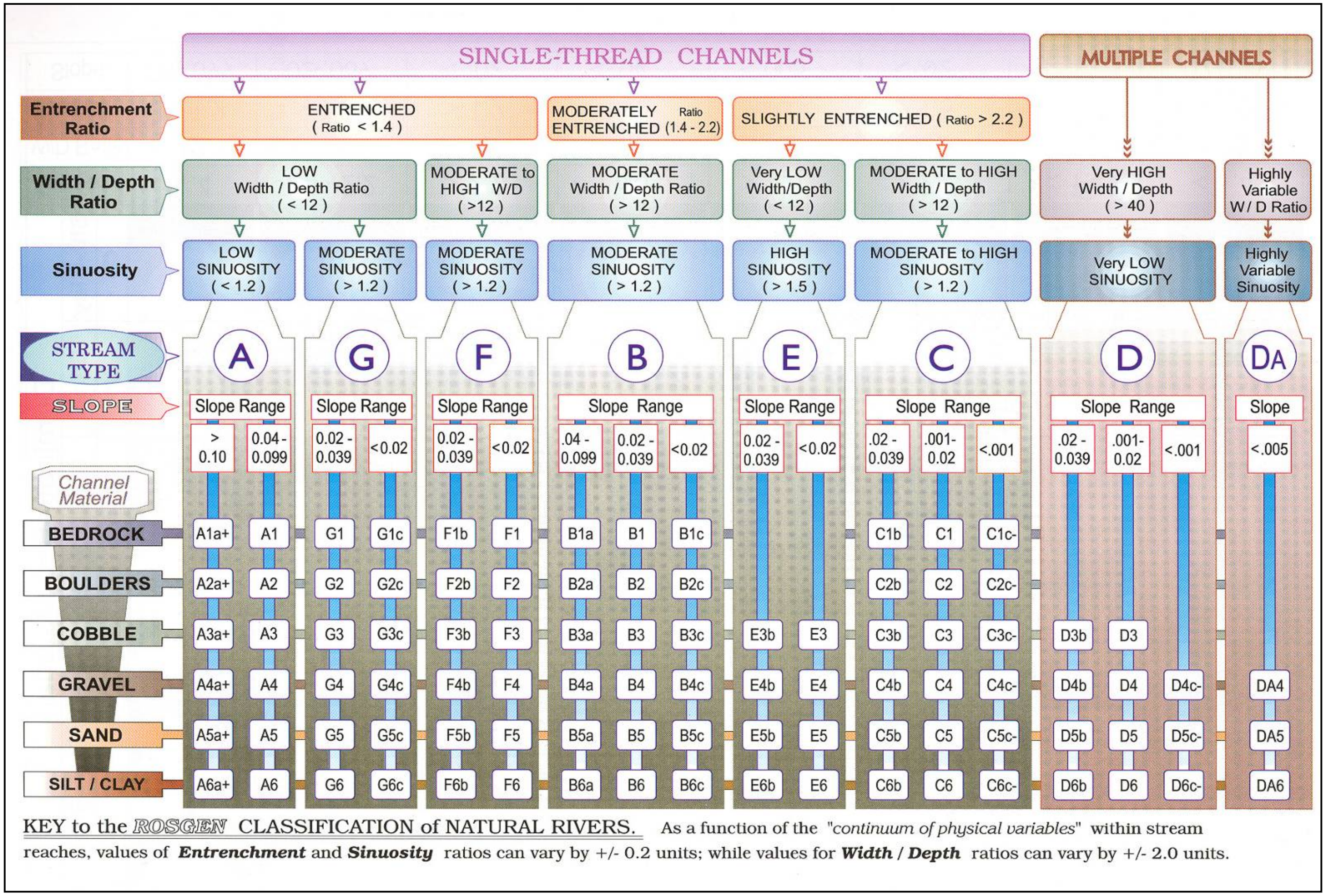


**Figure 1-5. Key to the Rosgen Classification of Natural Rivers. (After Rosgen, 1996)**

field-determined bankfull stage is referenced to the stage-discharge rating table (Rosgen, 1994). The empirical measurement of hydraulic variables from a range of various size streams and rivers across an ecoregion formulate regional hydraulic relationships. The development of bankfull regional hydraulic relationships compares measured *in situ* morphological conditions at-a-gage station with historic flow distributions usually within the 1-2 year recurrence interval, hereafter known as RI (Leopold, 1994).

The development of regional hydraulic geometry relationships was initiated by Dunne and Leopold (1978) in southeastern Pennsylvania and Emmett (1975) in the Upper Salmon River, Idaho. More recently, there has been expanding interest in developing hydraulic geometry relationships for physiographic regions, ecoregions or even at the smaller watershed scale (Harman, *et al*., 1999; Smith and Turrini-Smith, 1999; Harman, *et al*., 2000; White, 2001; Castro and Jackson, 2001; McCandless, 2003; Sweet and Geratz, 2003; Cinnoto, 2003; Powell, *et al.*, 2004; Emmert, 2004; Messinger and Wiley, 2004; Keaton *et al.*, 2005). As recommended in Stream Corridor Restoration: Principles, Processes and Practices (FISRWG, 1998), more regional curves are needed for regions that possess different topographic, geologic, and hydrologic regimes. Additionally, these regional relationships should be developed for specific areas of interest, such as 303(d) listed streams (FISRWG, 1998; USDA Natural Resource Conservation Service (NRCS) website at http://wmc.ar.nrcs.usda.gov/technical/HHSWR/Geomorphic/).

Stream restoration has come to the forefront of environmental actions due, in part, to the mandate by the U.S. Environmental Protection Agency (EPA) to identify the Total Maximum Daily Load (TMDL) for streams and compensatory mitigation promulgated by §404 and §401 of the Clean Water Act. Establishing regional bankfull hydraulic geometry relationships are important for validating and assisting natural stream channel restoration. These regional hydraulic relationships aid in guiding field determination of bankfull stage in highly entrenched, unstable stream channels that are disconnected from their floodplain and display few consistently recognizable bankfull indicators. These relationships provide a means of estimating channel dimensions within a given ecoregion or physiographic area based on drainage area. Recently, efforts have been made to group regions of unique ecosystems with similar geology, hydrology, climate, soils, topography and vegetation into ecoregions (Griffith *et al.*, 1997; Sweet and Geratz, 2003). It is this breakdown of regions by attribute that provides a more accurate depiction of the basin variables affecting stream channel hydraulic geometry. Additionally, more specific catchment attributes such as lithology, land cover, slope and aspect may be examined in small watersheds to more accurately predict the range of channel dimensions for stream restoration design (Lafrenz, 2004). As noted by Montgomery (1999), differences in climate, geology and topography differ from one region to another and impose a significant influence on channel process at the reach or valley segment scale.

Site selection is critical when developing a regional curve. Preferably, "reference reach" quality stream reaches along with a wide range of drainage basin sizes should be selected for inclusion in the regional relationships (Smith and Turrini-Smith, 1999). According to Rosgen (1998), a reference reach is that portion of a river that represents a stable channel within specific valley morphology. A reference reach is a stable portion of a stream that has been documented over time to transport the flows and sediment produced by its watershed in such a manner that the dimension, pattern and profile are maintained without either aggrading or degrading (Rosgen, 1996).

Bankfull regional curves help watershed planners evaluate physical impacts of channel alteration and aid in predicting channel adjustments as a result of those modifications (Smith and Turrini-Smith, 1999). For example, if a stream channel has experienced any dredging or straightening, then a regional curve can help predict the approximate channel dimensions and pattern that would guide the system back towards a state of dynamic equilibrium. The concept of dynamic or quasi-equilibrium suggests that a stream functions as an energy system that possesses a central tendency towards a steady state (Langbein and Leopold, 1964). According to this concept, a stream may experience an increase or decrease in both potential and kinetic energy through changes in land use, climate and vegetation, yet continue to seek a balance to offset the change in the energy system (Marsh, 1998). Bankfull regional curves enable river workers to identify bankfull stage in ungaged watersheds, severely entrenched stream reaches, and channels void of bankfull indicators. It is often difficult to determine bankfull elevation in highly incised channels. Thus, a substantial need exists to develop empirical relationships between bankfull discharge and hydraulic geometry in regions lacking such data.

Bankfull regional curves provide preliminary data on existing stream conditions and can be useful tools in facilitating the decision-making process for both watershed planning and regulatory permitting (Smith and Turrini-Smith, 1999). For example, comparison of a specific stream channel measured dimensions to the regional curve within that region will provide an indication if the stream channel has the appropriate channel dimensions to effectively transport the flows and sediment from its watershed within that specific reach.

Several hindrances to the development of bankfull regional curves exist. Most physiographic regions are restricted by the number and location of USGS gaging stations. For instance, there may be few active gages within an ecoregion, yet most are on large rivers that do not represent an adequate range of drainage basin sizes. Many gages are found on rivers with major impoundments, rendering the gage data useless for regional curve development. Gage data may be of inadequate length (less than 10 years), discontinued, or the gage site may have been moved from its original position. Often, discontinued gaging stations and their associated benchmarks are destroyed when the bridge that they were attached to has been replaced. Most gaging stations are located at or near a road crossing resulting in some direct channel alterations from road construction further impacting bankfull indicators in the reach.

Bankfull regional curves are based only on drainage area within a physiographic region and assume all factors affecting watershed runoff vary consistently. Some variables such as soils, vegetation, and geology can vary within an ecoregion or from one watershed to another. By reducing the scale of physiographic limits, one can produce a more accurate curve, but the cost to produce models at this scale is usually not feasible. The more localized the data collection, the more accurate the model prediction. Bankfull regional curves have no set geographic limits for application (Johnson and Heil, 1996). Unless a bankfull regional curve is developed in an urban setting, the curve does not incorporate urbanized watersheds. Bankfull regional curves are a simplification of many complex physical and biological processes which are difficult to model. It is important to note that regional curves should be used to assist in determining channel dimensions for a natural channel design and should be employed to validate bankfull stage rather than be used to produce deterministic values for channel dimensions (Cinotto, 2003).

## Natural Stream Channel Design

As concerns over water quality and habitat in rivers and streams have grown over the past few decades, so has the applied science behind stream restoration. The term stream restoration in its broadest sense is defined as a measurable improvement to channel stability, water quality, habitat and overall function of a degraded stream (TDEC, 2004). Currently, federal and state regulatory agencies approach stream improvement through methods of natural stream channel design as suggested by websites from the following federal and state agencies: U.S. Army Corps of Engineers Savannah District, Charleston District, Natural Resource Conservation Service (NRCS), U.S. Fish and Wildlife Service (USFWS), Tennessee Department of Environment and Conservation (TDEC) Stream Mitigation Guidelines and the Tennessee Stream Mitigation Program (TSMP). While there are many approaches to stream improvement, natural channel design incorporating the bankfull flow has been the most prevalent method utilized by hydrologists, biologists, engineers, and fluvial geomorphologists on lotic systems throughout the eastern United States in recent years (Doll *et al.*, 2004).

Currently, no useable bankfull discharge regional curve exists for any ecoregion or physiographic province in Tennessee. Regional hydraulic geometry relationships were developed in west Tennessee entitled “Western Tennessee Fluvial Geomorphic Regional Curves” (Smith and Turrini-Smith, 1999), but the bankfull discharge curve lacked sufficient data to represent a range of basin sizes, gages used were on the same river so the data points were interdependent and only three gaging stations met the reach criteria. The development of bankfull regional curves for the Southwestern Appalachians in Tennessee will provide a database of hydraulic geometry to support stream restoration activities within the ecoregion.

The restoration design of natural stream channels follows established relationships between hydraulic and physical parameters such as bankfull discharge and drainage area, stream channel dimensions (width, mean depth, cross-sectional area) and drainage area, bankfull discharge and valley dimensions (belt width, meander width, meander wavelength and valley slope), relative roughness and total channel hydraulic resistance, and flood return intervals (Rosgen, 1996). Bankfull regional curves provide supportive information for the design of natural stream channels in the same physiographic region. By knowing the appropriate bankfull channel dimensions of a stable stream reach, a new channel can be constructed in place of the unstable reach.

## Objectives

My objectives for this investigation were: 1) to test if the bankfull RI for streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee was between 1 and 2 years; 2) develop bankfull discharge and hydraulic geometry relationships for streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee; and 3) compare those relationships to the Ridge and Valley of Virginia, West Virginia, and Maryland (Keaton *et al.*, 2005) and the Piedmont and Blue Ridge of North Carolina (Harman *et al.*, 1999; Harman *et al.*, 2000). My hypotheses were that the bankfull discharge RI of the peak annual series for Southwestern Appalachian streams was within the 1 to 2 years range and that a group of professionals would pick bankfull indicators that fell within the 1 to 2 year range. Furthermore, I hypothesized that the bankfull discharge and hydraulic geometry of streams draining the Southwestern Appalachians was significantly different from that of the Ridge and Valley of Virginia, West Virginia, and Maryland and the Piedmont and Blue Ridge of North Carolina.

## Organization of Thesis

My thesis is organized into five major chapters and an appendix. The thesis consists of an introduction, study area, bankfull determination, bankfull regional curves, and a summary chapter describing conclusions and recommendations. Chapter I (Introduction) provides the reader background information and a literature review of the wealth of information describing bankfull discharge, regional curves and the role these concepts play in stream restoration. Furthermore, there is discussion concerning RIs, bankfull indicators, stream classification, and natural channel design as related to stream restoration. The second chapter (Study Area) describes some of the regional factors affecting stream channel shape and size, which include: climate, physiography and geology, land use and land cover, soils, and vegetation. Additionally, sections within the chapter discuss characteristics of the ecoregion and stream survey selection criteria. Chapter III (Bankfull Determination) discusses the methods and protocol followed in obtaining the bankfull discharge determination and is supplemented by descriptions of bankfull indicators as well as the group tour of streams. Chapter IV (Bankfull Regional Curves) explains the procedure for developing bankfull discharge and hydraulic geometry relationships for the ecoregion. Results of the power regression equations are then statistically analyzed and compared to the recently published regional curves of the Ridge and Valley and the Piedmont and Blue Ridge. The last chapter is a summary of my findings and recommendations for future research. The Appendix contains supplementary information related to the text.

# CHAPTER II
# STUDY AREA

## Ecoregion

Ecoregions of Tennessee group areas of similar climate, geology, physiography, soils, vegetation, hydrology, wildlife and land use (Griffith *et al.*, 1997). I chose to use the Level III ecoregion because it integrates many channel-forming variables such as precipitation, vegetation, geology, physiography and soils into a spatial framework for assessment, research, monitoring and management (Griffith *et al.*, 1997). As reported by Castro and Jackson (2001), ecoregions combine many of the factors that control channel shape. As a result of exhaustive stream surveys at USGS gaging stations in the Pacific Northwest, Castro and Jackson (2001) were able to distinguish ecoregions from climatic patterns and physiography as being the most statistically significant variable affecting the hydraulic geometry of stream channels. In 1992, the National Research Council developed a national aquatic ecosystem restoration strategy that targeted restoration using ecoregions as the geographic unit (Omernik and Bailey, 1997).

The study area for this investigation is defined by the Level III Southwestern Appalachians ecoregion 68 in Tennessee which is composed of Level IV ecoregions Cumberland Plateau 68a, Sequatchie Valley 68b and Plateau Escarpment 68c (Griffith *et al.*, 1997, Figure 2-1). The Southwestern Appalachians cover approximately 11.4% of Tennessee or roughly 5,400 square miles, with the Cumberland Plateau, Sequatchie Valley and Plateau Escarpment comprising 7.6%, 0.6% and 3.3%, respectively (Arnwine *et al.*, 2000). Generally, aquatic habitat among streams draining the Southwestern Appalachians are ranked as follows: the Cumberland Plateau 68a, rated highest in terms of overall quality, followed by the Plateau Escarpment 68c; lowest was the agriculturally dominated Sequatchie Valley 68b (Arnwine *et al.*, 2000). Streams draining the ecoregion ultimately flow into two major river basins: the Cumberland and Tennessee Rivers. The Southwestern Appalachians in Tennessee are drained by the Obed, Sequatchie and Emory Rivers flowing east and to the south before their confluence with the Tennessee River. The Big South Fork, Obey, Wolf, Collins, Calfkiller and Caney Fork Rivers drain the

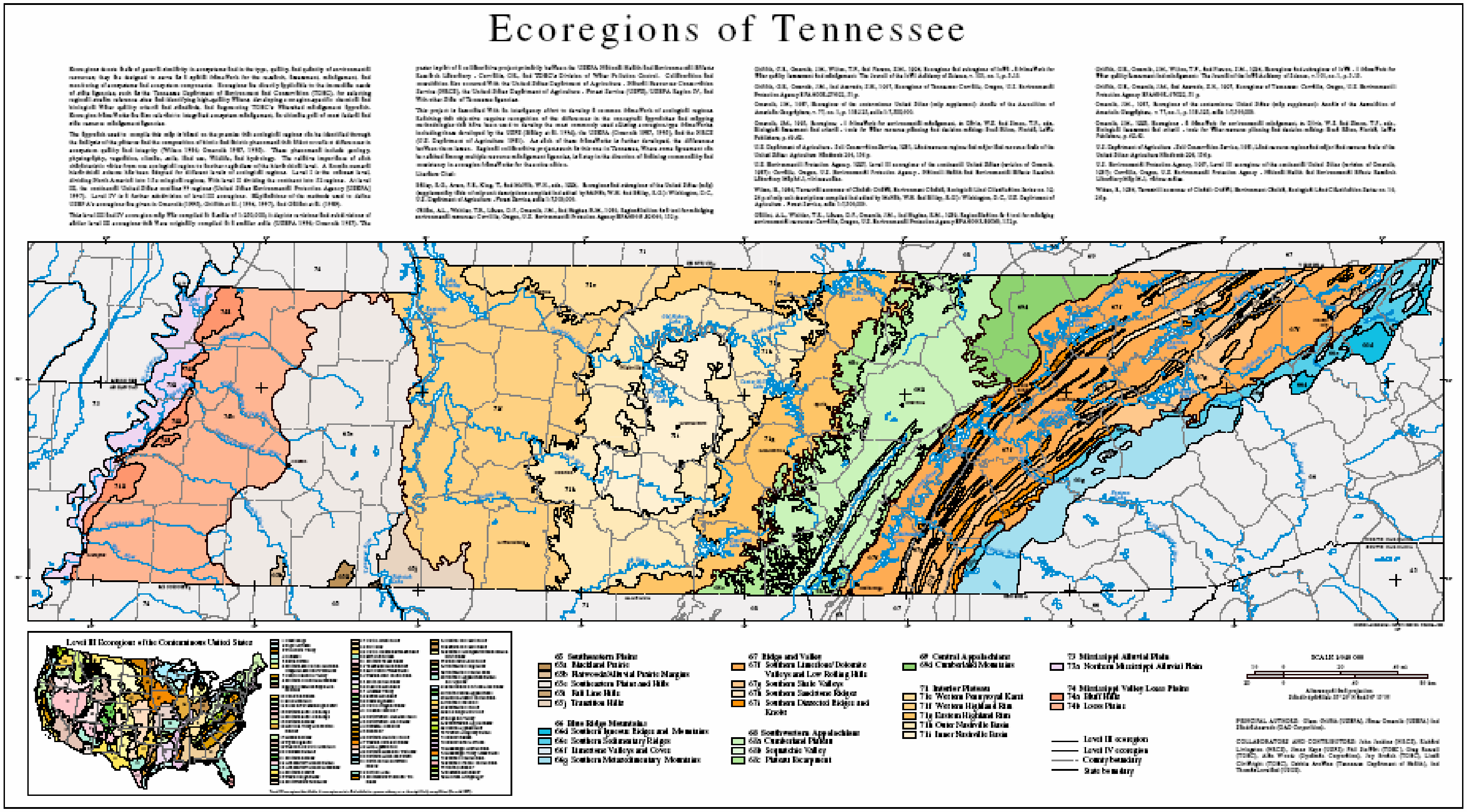


**Figure 2-1. Ecoregions of Tennssee. (Griffith *et al.*, 1997)**
Source: http://www.epa.gov/wed/pages/ecoregions/tn_eco.htm

Southwestern Appalachians by flowing north and west until their confluence with the Cumberland River. The ecoregion is characterized by these rivers and their tributaries carving pathways through the resistant sandstone bedrock and dropping down the steeply graded escarpment to the neighboring Ridge and Valley, Sequatchie Valley and Eastern Highland Rim (Figure 2-2).

The Southwestern Appalachians range from Kentucky to northern Alabama. In Tennessee, the Southwestern Appalachians are bordered by the Eastern Highland Rim 71 to the west, the Central Appalachians 69 to the northeast and the Ridge and Valley 67 to southeast (Griffith *et al.*, 1997). Counties in Tennessee that lie completely or partially within the ecoregion include: Cumberland, Overton, Pickett, Fentress, Morgan, Marion, Sequatchie, Scott, Putnum, Rhea, Bledsoe, Van Buren, Grundy, Hamilton and Franklin. The Cumberland Plateau of the Southwestern Appalachians extends 1200 to 2000 feet above mean sea level (msl) in elevation and possesses a relatively flat to gently rolling landscape commonly referred to as "the tablelands." The eastern boundary of the ecoregion is defined by an abrupt escarpment where the plateau meets the Ridge and Valley. The western ecoregion is bounded by the Interior Plateau Eastern Highland Rim which is characterized by a more crenulated, deeply incised and rougher escarpment (Griffith *et al.*, 1997).

## Climate

The general climate of the Southwestern Appalachians is described as temperate continental, but is variable across the tablelands with regional north-south gradients of precipitation and temperature (Hinkle, 1978). Prevailing storm patterns are a result of the jet stream carrying moisture from the Gulf of Mexico northeast across the ecoregion. General storm patterns and fronts are affected by the abrupt change in topography caused by the Cumberland Plateau escarpment. The orographic effect of the escarpment causes moist air to rise over the abrupt topographic landform significantly increasing the amount of precipitation falling on the Southwestern Appalachians. As a result, mean annual

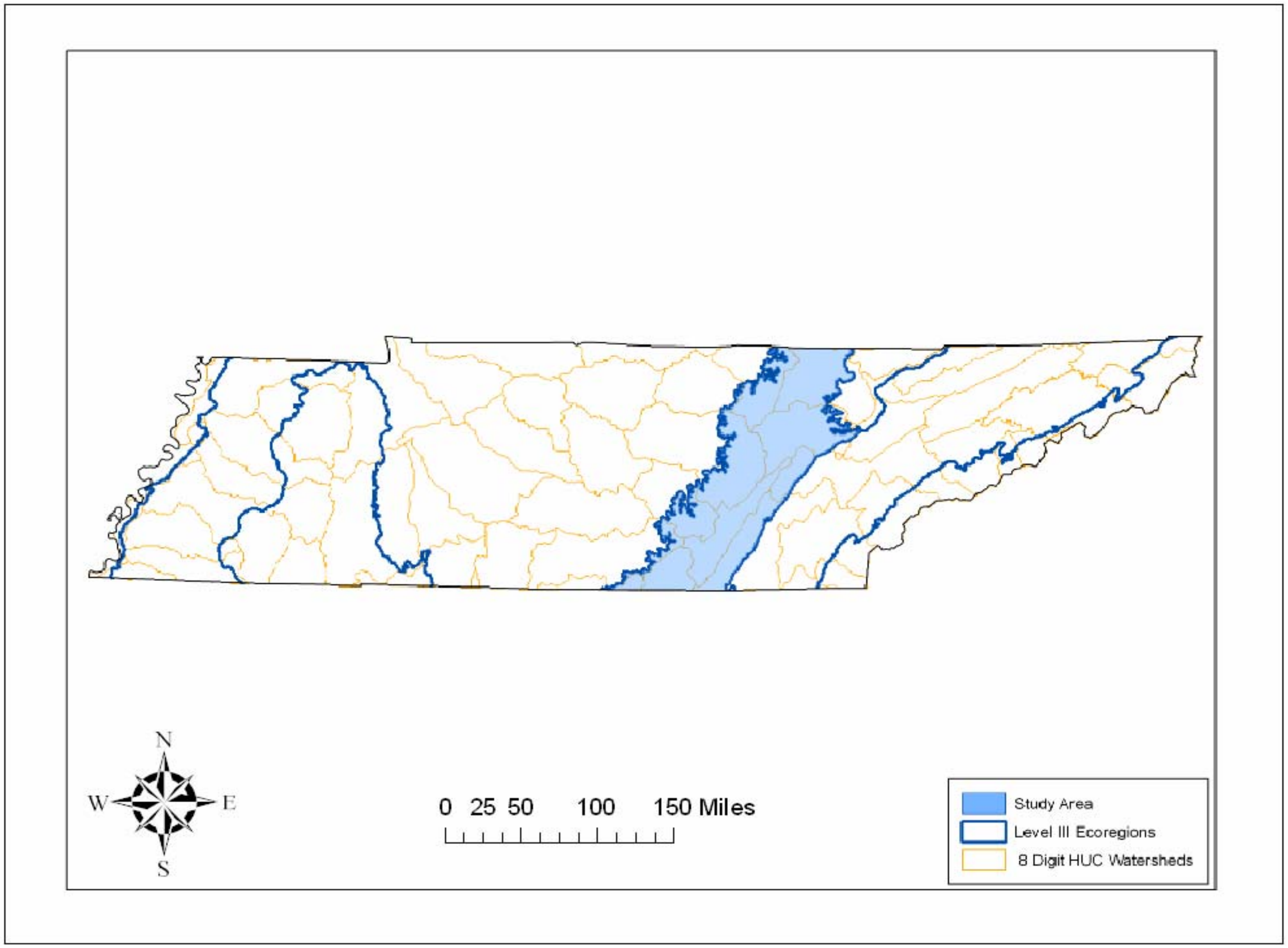


**Figure 2-2. Map of Level III Ecoregion 68 Southwestern Appalachians of Tennessee and River Basins.**

precipitation increases approximately 10 inches per 1,000 feet of elevation change (Hewlett, 1982).

The largest amount of precipitation typically occurs during the winter months and early spring with the exception of infrequent hurricanes and tropical storms originating from the Gulf during late summer and early fall. Predominantly, more frequent large-scale frontal storms move across the region in the winter and early spring (Dickson, 1978). Convective thunderstorms typically occur in July and August bringing frequent torrential rains to the Southwestern Appalachians. Autumn is usually the driest time of year for the ecoregion, due primarily to the higher frequency of slow-moving high pressure areas during this season (Dickson, 1978). Some of the more prominent flood years experienced by streams in the Southwestern Appalachians include 1929, 1937, 1939, 1949, 1963, 1969, 1973, 1977, 1980, 1990, and 1997 (USGS, 2005).

Twelve weather stations were identified and grouped within the Southwestern Appalachians to represent a climatic summary spanning a period between 42 and 92 years of record for the ecoregion (Table 2-1, Southeast Regional Climate Center (SERCC), 2005). Mean annual precipitation varied from 50.63 inches at Fall Creek Falls State Park to 62.29 inches at Monteagle. For the 66 years of record, the highest year of mean precipitation was 82.13 at Monteagle and the lowest was 32.91 in Allardt, Tennessee where the period of record covered 76 years. Mean annual precipitation from the twelve stations illustrated a general trend of decreasing magnitude from south to north, with the station at Fall Creek Falls being the exception. The Southwestern Appalachians receive approximately 10 inches more annual precipitation than the neighboring Ridge and Valley ecoregion to the East. Mean annual temperature across the ecoregion ranges from a maximum of 70.6° F to a minimum of 41.5° F (SERCC, 2005). Mean annual snowfall for the Southwestern Appalachians ranges from 0.3 inches in the lower elevations of Dunlap within the Sequatchie Valley to 19.4 inches in the higher elevations in Jamestown, Tennessee (SERCC, 2005).

**Table 2-1. Mean Monthly and Annual Precipitation (Inches) for Southwestern Appalachians.**
Source: Southeast Regional Climate Center (http://www.dnr.sc.gov/water/climate/sercc/index.html)

| Station | Location | Period | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 402197 | Crossville Airport | 1954-2004 | 4.84 | 4.7 | 5.99 | 4.86 | 5.12 | 4.59 | 5.01 | 3.9 | 3.86 | 3.1 | 4.8 | 5.38 | 56.15 |
| 403044 | Falls Creek Park | 1949-1970 | 5.12 | 4.86 | 5.37 | 4.41 | 3.73 | 3.9 | 5.12 | 3.68 | 3.22 | 2.35 | 3.75 | 5.12 | 50.63 |
| 407184 | Pikeville | 1962-2004 | 4.92 | 4.62 | 5.65 | 4.51 | 4.9 | 4.28 | 4.67 | 3.57 | 4.04 | 3.07 | 4.44 | 4.99 | 53.66 |
| 408184 | Sewanee | 1927-2004 | 5.94 | 5.93 | 6.37 | 5.07 | 4.78 | 4.7 | 5.55 | 4.27 | 4.27 | 3.09 | 4.72 | 5.66 | 60.34 |
| 402360 | Dayton | 1956-2004 | 5.05 | 4.95 | 6.14 | 4.56 | 5.02 | 3.96 | 4.76 | 3.88 | 4.69 | 3.24 | 4.86 | 5.49 | 56.6 |
| 402657 | Dunlap | 1935-1962 | 6.18 | 5.8 | 5.84 | 4.69 | 3.49 | 3.69 | 5.17 | 3.59 | 2.98 | 2.68 | 4.02 | 5.37 | 53.48 |
| 406829 | Oneida 2 W | 1952-2004 | 4.55 | 4.58 | 5.42 | 4.42 | 5.05 | 4.91 | 4.94 | 3.92 | 3.79 | 3.47 | 4.23 | 4.57 | 53.87 |
| 406170 | Monterey 1 E | 1948-2004 | 6.01 | 5.31 | 6.07 | 5.01 | 5.27 | 4.96 | 4.79 | 4.31 | 4.24 | 3.43 | 5.1 | 5.73 | 60.22 |
| 404590 | Jamestown | 1951-2004 | 4.83 | 4.69 | 5.55 | 4.66 | 5.28 | 5.02 | 5.1 | 4.08 | 4.19 | 3.01 | 4.35 | 5.18 | 55.94 |
| 406162 | Monteagle | 1938-2004 | 5.98 | 5.96 | 6.64 | 5.09 | 4.96 | 4.71 | 5.61 | 4.11 | 4.44 | 3.61 | 5.12 | 6.05 | 62.29 |
| 402202 | Crossville Exp Stn | 1912-2004 | 5.48 | 5.1 | 5.87 | 4.76 | 4.82 | 4.57 | 5.16 | 4.34 | 3.73 | 3.21 | 4.41 | 5.54 | 56.99 |
| 400081 | Allardt | 1928-2004 | 4.81 | 4.61 | 5.44 | 4.3 | 4.68 | 5.03 | 5.22 | 4.26 | 3.66 | 2.92 | 4.21 | 4.76 | 53.89 |

## Physiography and Geology

The following descriptions of physiography and geology of the Southwestern Appalachians are summarized from Moore (1994) unless otherwise cited. Tennessee is partitioned into three major physiographic divisions commonly known as the Appalachian Highlands in the east, the Interior Lowlands in the middle, and the Atlantic and Gulf Coastal Plain in the western part of the state. Within these physiographic divisions there are ten physiographic provinces: the Blue Ridge Mountains, Valley and Ridge, Cumberland Plateau, Cumberland Mountains, Eastern Highland Rim, Central Basin, Western Highland Rim, Western Valley of the Tennessee River, Gulf Coastal Plain, and the Mississippi River Alluvial Floodplain (Figure 2-3). The Cumberland Plateau forms the southern portion of the Appalachian Plateau Province bordered to the east by the Cumberland Escarpment, known as Walden's Ridge, which extends from Virginia to Georgia and a rougher, irregularly shaped western escarpment.

The Cumberland Plateau in Tennessee is dissected by two linear valleys referred to as the Sequatchie Valley in the southern portion and the Elk Valley in the northern section. Both valleys are faulted anticlines in which rocks have been folded upward in an arch then broken and moved along the length of the structure (Wilson, 1981). The valleys are a result of head-cutting or stream erosion acting on the fractured Pennsylvanian sandstone of the faulted anticline. Consequently, the underlying soluble calcium carbonate limestone dissolved forming karst topography. Several geologists theorize that the Sequatchie Valley formed from a series of sinkholes that were eroded to develop the current valley (Lane, 1952; Milici, 1968). During the erosion and depositional processes, the Sequatchie River deposited voluminous cobble as terraced alluvium throughout the valley floor (Milici, 1968). The Sequatchie Valley in Tennessee is approximately 60 miles in length and 4-6 miles wide.

### *Pennsylvanian Period in the Paleozoic Era*

During the Pennsylvanian period in Tennessee, a shift in the erosion and depositional rates from previous periods took place, resulting in rocks primarily being

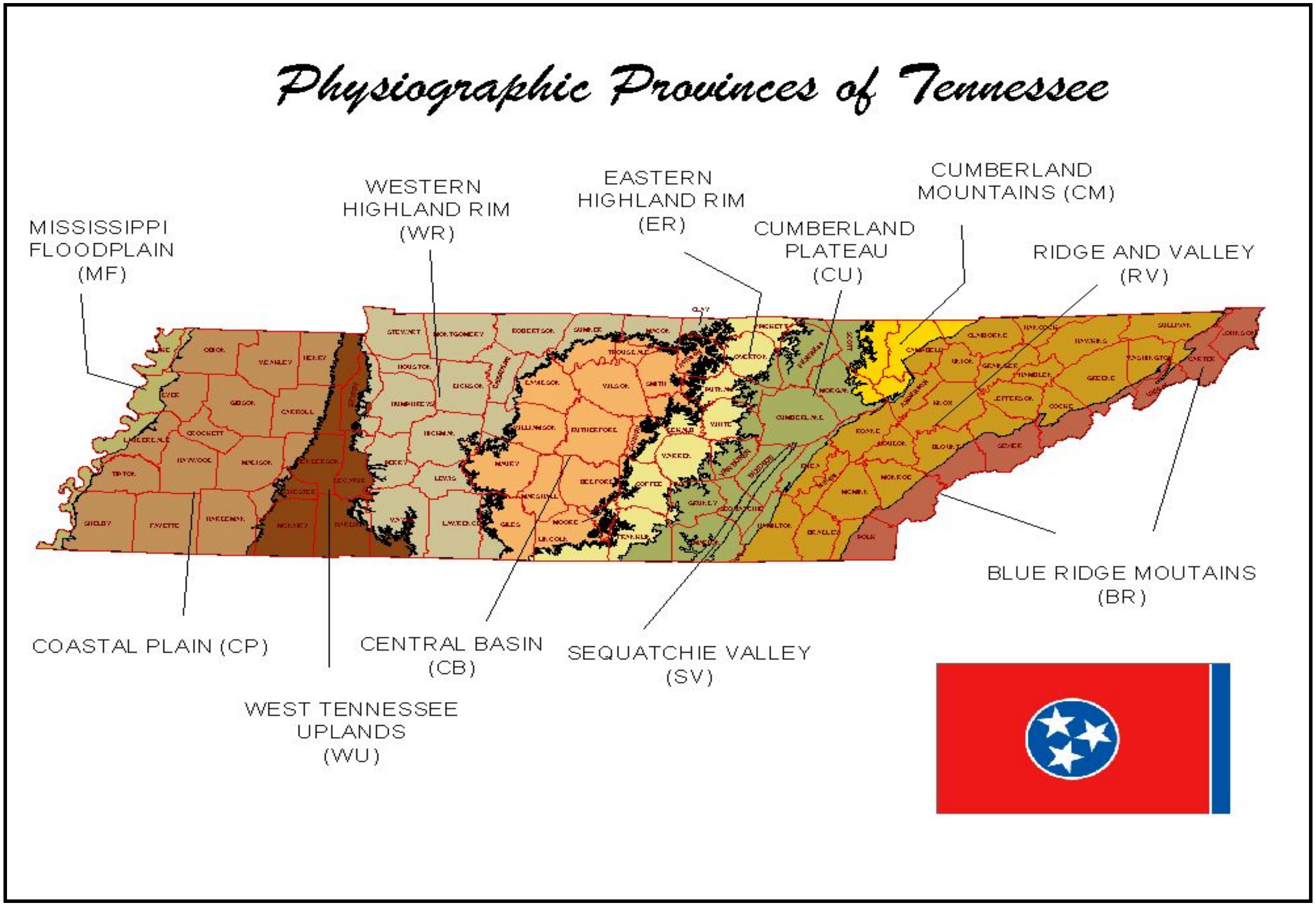


**Figure 2-3. Physiographic Provinces of Tennessee.**
Source: (http://www.tennessee.gov/environment/nh/physprov.jpg

formed in sandstone, siltstone and shale compared to the carbonate rocks of earlier time periods. Pennsylvanian age rocks are primarily found on the Cumberland Plateau where hard, resistant rock has remained through millions of years of erosion and weathering. The Cumberland Plateau was formed from southeast to northwest as uplifting tectonic forces shifted the Pennsylvanian capstone rock folding it over onto the surface of younger rock to the northwest (Manning, 1999). The presence of coal in Pennsylvanian age rock is significant in the geologic history of Tennessee because it signifies the emergence of land plants on the continents (Moore, 1994). The Pennsylvanian age, often referred to as the "Age of Forests," was dominated by forested wetlands and coastal swamps (Moore, 1994). Near the end of the Paleozoic era, sediments were buckled, fractured, folded and faulted as a result of the collision of the continents. This geologic phenomenon, known as the Alleghanian Orogeny, was the last to affect the Southern Appalachians. The end of this episode marked the beginning of millions of years of erosion and deformation of rocks in East Tennessee (Moore, 1994).

## Vegetation and Land Cover/Land Use

Forest composition across the ecoregion varies depending on elevation, slope, aspect and soil conditions. The Southwestern Appalachians are dominated by mixed mesophitic forest communities primarily composed of the oak-hickory association with limited areas of pine species. Most of the mixed deciduous forests in the ecoregion contain a prevalence of broad-leaved deciduous trees and shrubs, whereas pine, hemlock, mountain laurel and magnolias represent the minority in evergreens (Sutton and Sutton, 1993). Typical upland forests are dominated by white oak (*Quercus alba*), chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), southern red oak (*Q. falcata*), northern red oak (*Q. rubra*), post oak (*Q. stellata*), pignut hickory (*Carya glabra*), mockernut hickory (*C. tomentosa*), American beech (*Fagus grandifolia*) red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), sourwood (*Oxydendrum arboreum*), persimmon (*Diospyrus virginiana*), flowering dogwood (*Cornus florida*), sassafras (*Sassafras albidum*), shortleaf pine (*Pinus echinata*) and Virginia pine (*Pinus virginiana*) (Radford *et al.*,1968). In the deeper ravines along valley side slopes, eastern hemlock (*Tsuga* *canadensis*) communities are pervasive. Floodplains are dominated by river birch (*Betula nigra*), sycamore (*Platanus occidentalis*), tulip poplar (*Liriodendron tulipifera*), red maple (*A. rubrum*), and cottonwood (*Populus deltoides*) in the overstory and silky dogwood (*C. amomum*), ironwood (*Carpinus caroliniana*), American hop hornbeam (*Ostrya virginiana*), basswood (*Tilia americana*), pawpaw (*Asimina triloba*), buttonbush (*Cephalanthus occidentalis*), black willow (*Salix nigra*), alder (*Alnus serrulata*), witch-hazel *(Hamamelis virginiana*), spicebush (*Lindera benzoin*), elderberry (*Sambucus canadensis*), and river cane (*Arundinaria gigantea*) in the understory (Radford *et al.*,1968). Approximately 10 to 14 inches of precipitation occurs during the growing season which typically averages 180 and 220 days (Hinkle, 1978).

Current land use across the ecoregion can be categorized into forest, agriculture, mining, and rural residential. According to the Fentress and Pickett county Soil Survey (Campbell and Newton, 1995), approximately 70% of the two counties are currently forested. Deciduous hardwood forests have been converted to pine plantations in many areas across the ecoregion. The timber industry composes a significant portion of industry within the ecoregion. Agriculture is the second largest land use in the ecoregion. Pastures for cattle grazing are the primary form of agriculture with cropland to a lesser extent. Strip mining is prevalent across the Cumberland Plateau and includes primarily coal and stone mining. Public ownership is comprised of three state parks, nine state forests and the Big South Fork National River and Recreation Area.

## Soils

All of the Cumberland Plateau is underlain by sandstone and shale and most of the soils are formed from material weathered from these rocks. Generally, the soils are well drained, pale colored, loamy, and low in natural fertility. The depth to bedrock ranges from approximately 1 foot on short hillsides to 5 feet on broad, smooth interstream divides (Campbell and Newton, 1995). For most of the ecoregion, there is generally a deficiency in soil water storage due to thin soils and the bedrock system (Mayfield, 1984). Soils of the Cumberland Plateau are predominantly classified as Ultisols, mostly Hapludults and Paleudults, and Inceptisols, mostly Dystrochrepts

(Campbell and Newton, 1995). Most soils in the uplands are derived from sandstone and shale bedrock while in the deeper ravines limestone material is found. Generally, soils in the region have been described as acidic, highly leached and lacking nutrients (Hinkle, 1978). Soils in many of the deep, steeply sloped, V-shaped gorges and ravines are generally dominated by colluvial materials composed of sandstone, shale and limestone depending on slope position. For more specific descriptions of soil associations and series throughout the ecoregion, the reader is directed to the Natural Resource Conservation Service Soil Surveys of each county.

## Site Selection Criteria

Within the Southwestern Appalachians of Tennessee, a total of 37 active and discontinued U.S. Geologic Survey (USGS) streamflow gaging stations were considered for inclusion in the study (Law and Tasker, 2003). Selected Hydrologic Unit Codes (HUCs) for the study area included: Big South Fork of the Cumberland River (05130101), Sequatchie River (06020004), the Obey River (05130105), Guntersville Lake (06030001), Upper Elk (06030003) and the Emory River (06010208, Table 2-2**)**. After eliminating unsuitable study sites, 11 USGS streamflow gaging stations and study reaches were used in this investigation (Table 2-2 and Figure 2-4). Site selection criteria for the study area included:

1) At least 10 years of data for annual peak discharges;
2) Recoverable planar survey benchmarks reference to gage or staff plates;
3) Wadeable;
4) Perennial in flow;
5) Sufficient channel length to conduct measurements;
6) Stable gage control where bed is not scouring or incising;
7) Rural watersheds with <10 percent urbanization;
8) Flow regulation <10 percent of drainage area; and the
9) Majority of each catchment must be located within ecoregion boundaries.

**Table 2-2. USGS Hydrologic Unit Codes (HUCs), River Basins, and Counties of Study Streams Draining the Level III Ecoregion 68 Southwestern Appalachians of Tennessee**

| No. | County | HUC | HUC Name | USGS Station No. | Waterway | Drainage Area (mi²) | Period of Record | Active/ Discontinued |
|---|---|---|---|---|---|---|---|---|
| **1** | Fentress | 05130105 | Obey River | N/A* | Trib. #1 Lints Cove Creek | 0.08 | N/A | N/A* |
| **2** | Cumberland | 06010208 | Emory River | N/A* | Pine Creek | 0.60 | N/A | N/A* |
| **3** | Marion | 06020004 | Sequatchie River | 03571600 | Brown Spring Branch | 0.67 | 1955-1978 | Discontinued |
| **4** | Fentress | 05130101 | South Fork Cumberland | 03408600 | Long Branch | 1.11 | 1976-1981 | Discontinued |
| **5** | Pickett | 05130101 | South Fork Cumberland | N/A* | Rock Creek | 5.82 | N/A | N/A* |
| **6** | Marion | 06030001 | Guntersville Lake | 03571800 | Battle Creek | 50.4 | 1955-Present | Active |
| **7** | Overton | 05130105 | Obey River | 03415000 | West Fork Obey River | 81 | 1942-Present | Active |
| **8** | Pickett | 05130105 | Obey River | 03416000 | Wolf River | 106 | 1942-Present | Active |
| **9** | Cumberland | 06010208 | Emory River | 03539600 | Daddy's Creek | 139 | 1957-Present | Active |
| **10** | Fentress | 05130105 | Obey River | 03414500 | East Fork Obey River | 196 | 1942-Present | Active |
| **11** | Scott | 05130101 | South Fork Cumberland | 03409500 | Clear Fork River | 272 | 1930-Present | Active |

*N/A denotes that these study reaches did not have USGS streamflow gaging stations.

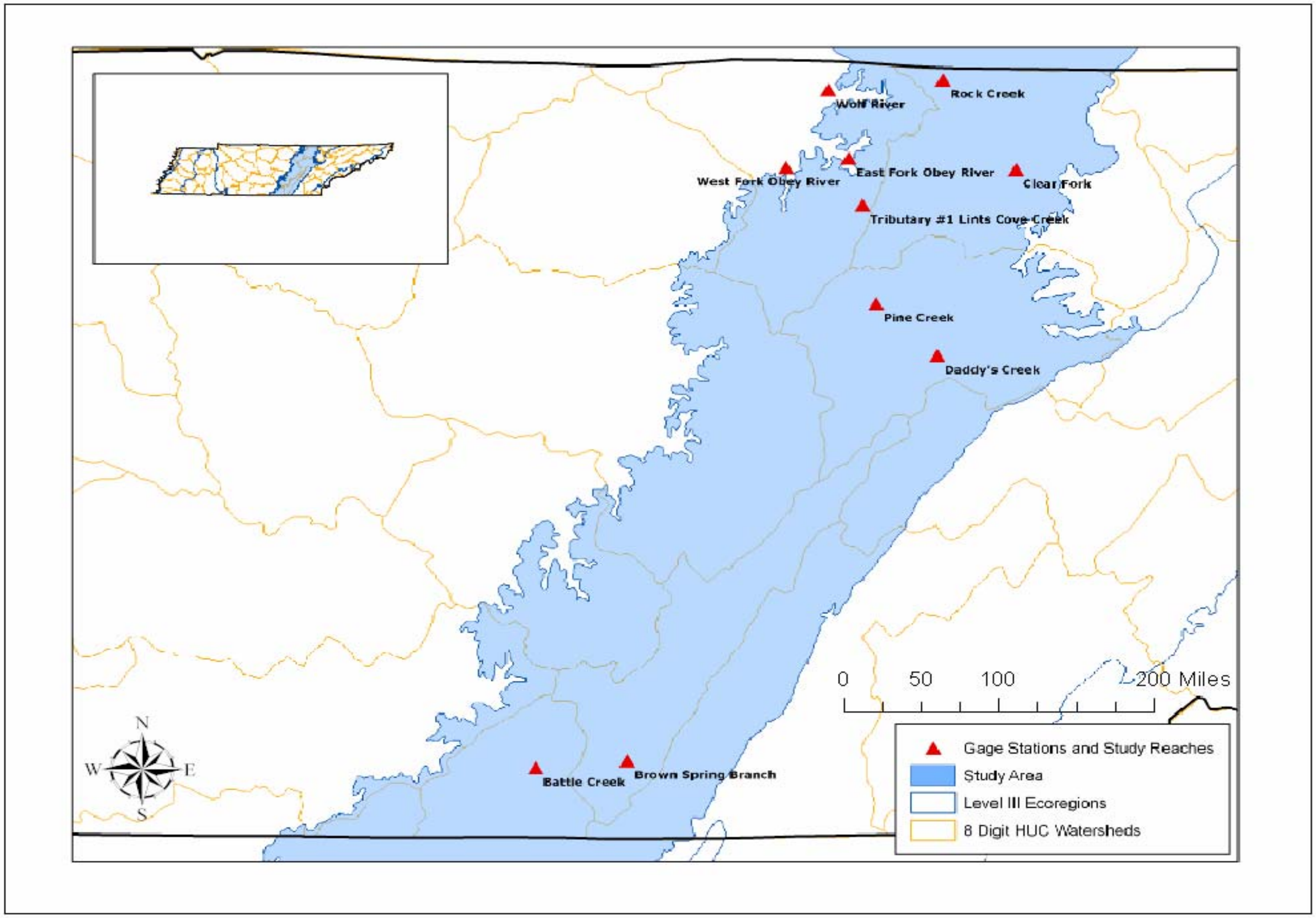


**Figure 2-4. Location of Selected USGS Gaging Stations and Study Reaches in the Southwestern Appalachians 2005.**

For this investigation, every stream with a USGS gaging station within or that drained a significant portion of the Southwestern Appalachians was considered for survey. Both active and discontinued gaging stations were considered for the study because very few gaged streams with <20 square mile drainage areas existed in the ecoregion. Stations <10 years of record were excluded from the RI determination. Prior to field evaluation, remote data such as USGS 7.5-minute topographic quadrangles and digital orthophotos were examined to exclude any sites with major impoundments, significant urbanization in the watershed and direct channel modifications at the gaging station. Upon completion of remote screening, field reconnaissance of each potential site was performed to determine suitability. In some instances, sites were eliminated because benchmarks were destroyed, stream channels were recently dredged and straightened, or an impoundment was recently constructed upstream. After visiting the remaining sites, a list of 8 USGS streamflow gaging stations was compiled for the survey and 29 were eliminated based on the aforementioned criteria (Tables 2-2, 2-3).

One discontinued gaging station with <10 years of data was included in the survey since there was a general lack of streams that met the site selection criteria. Additionally, three small, ungaged streams representative of the ecoregion were included in the survey to strengthen the lower range of drainage area sizes. All of the catchments for the ungaged streams and the majority of the USGS gaging stations were within the Southwestern Appalachian ecoregion boundary. Gaging stations located outside the ecoregion boundary were useful because they provided data on streamflow produced by watersheds with the vast majority of their drainage area within the Southwestern Appalachian ecoregion.

**Table 2-3. USGS Streamflow Gaging Stations Disqualified for Survey in Southwestern Appalachians of Tennessee.**

| USGS Station No. | Waterway | Gage Location | Drainage Area ($mi^2$) | Period of Record | Disqualification |
|---|---|---|---|---|---|
| 3408810 | Trib. of Crooked Creek | Allardt, TN | 0.25 | 1976-1979 | strip mine |
| 3417700 | Matthews Branch Trib. | Livingston, TN | 0.49 | 1955-1985 | channel alteration |
| 3538800 | Trib. of Obed River | Crossville, TN | 0.72 | 1955-1970 | impounded |
| 3539100 | Byrd Creek | Crossville, TN | 1.1 | 1968-1975 | impounded |
| 3418900 | Raccoon Creek | Old Winesap, TN | 1.52 | 1973-1978 | impounded |
| 3408815 | Crooked Creek | Allardt, TN | 3.62 | 1976-1981 | strip mine |
| 3538900 | Self Creek | Big Lick, TN | 3.80 | 1973-1985 | impounded |
| 3579800 | Miller Creek | Cowan, TN | 4.3 | 1955-1978 | urbanized |
| 3538700 | Little Obed | Crossville, TN | 4.71 | 1955-1970 | urbanized |
| 3415700 | Big Eagle Creek | Livingston, TN | 4.77 | 1955-1978 | BM* destroyed |
| 3541100 | Bitter Creek | Camp Austin, TN | 5.53 | 1967-1985 | channel alteration |
| 3538300 | Rock Creek | Sunbright, TN | 5.54 | 1955-1971 | BM* destroyed |
| 3538600 | Obed River | Crossville, TN | 12 | 1955-1995 | urbanized |
| 3409000 | White Oak Creek | Sunbright, TN | 13.5 | 1929-1975 | dredged |
| 3570800 | Little Brush Creek | Dunlap, TN | 15.4 | 1958-1985 | BM* destroyed |
| 3414700 | Puncheon Camp Creek | Allred, TN | 15.5 | 1955-1981 | channel alteration |
| 6030003 | Boiling Fork | Cowan, TN | 17 | 1955-1978 | urbanized |
| 3544500 | Richland Creek | Dayton, TN | 50.2 | 1935-1982 | anastomosed/urban |
| 3578000 | Elk River | Pelham, TN | 65.6 | 1952-1987 | channel alteration |

**Table 2-3 Continued.**

| USGS Station No. | Waterway | Gage Location | Drainage Area ($mi^2$) | Period of Record | Disqualification |
|---|---|---|---|---|---|
| 3538500 | Emory River | Wartburg, TN | 83 | 1934-1968 | channel alteration |
| 3538500 | Daddy's Creek | Crab Orchard, TN | 93 | 1930-1958 | old records |
| 3418500 | Caney Fork River | Clifty, TN | 111 | 1930-1949 | old records |
| 3571500 | Little Sequatchie River | Sequatchie, TN | 116 | 1980-Present | heavily impacted |
| 3539778 | Clear Creek | Lancing, TN | 170 | 1998-2004 | insufficient data |
| 3408500 | New River | New River, TN | 382 | 1934-present | not wadeable |
| 3539800 | Obed River | Lancing, TN | 500 | 1957-present | not wadeable |
| 3421000 | Collins River | McMinnville, TN | 640 | 1924-present | not wadeable |
| 3540500 | Emory River | Oakdale, TN | 741 | 1927-present | not wadeable |
| 3410210 | Big South Fork Cumberland | Leatherwood Ford,TN | 806 | 1983-present | not wadeable |

*BM = Planar Survey Benchmark

# CHAPTER III

# BANKFULL DETERMINATION

## Methodology

Numerous hydraulic studies performed throughout the eastern U.S. and other parts of the world found that on average the bankfull discharge RI is 1.5 years (Wolman and Leopold, 1957; Leopold *et al.*, 1964; Woodyer, 1968; Dury, 1976; Dunne and Leopold, 1978; Leopold, 1994; Harman *et al.*, 1999; Castro and Jackson, 2001; McCandless and Everett, 2002). However, arguments over the significance and value of the bankfull discharge on stream channel morphology have surfaced as stream restoration efforts incorporating bankfull hydraulic geometry are implemented (Kondolf, 1995; Miller and Ritter, 1996; Juracek and Fitzpatrick, 2003; Shields, Jr. *et al.*, 2003; Simon *et al.*, 2004; Simon *et al.*, 2005). It is important to accurately identify bankfull flow because natural stream restoration methods use bankfull discharge and its associated hydraulic geometry as design criteria.

The first objective of my study was to test the assumption that the bankfull discharge recurrence interval (RI) of streams draining the Southwestern Appalachians was between 1 and 2 years. For the purposes of this investigation, bankfull stage was defined in stable streams with floodplain morphology as the incipient point on the stream bank where water spreads out onto the active floodplain and flooding begins. Some streams included in this study lacked well developed floodplains. Under these circumstances, bankfull stage was defined as the point on the stream bank where there was a discrete break from near vertical channel bank to near horizontal slope often in the form of a bench (McCandless and Everett, 2002).

According to Williams (1978a), the four most common ways of determining bankfull discharge include: 1) referencing the stage-discharge rating curve, 2) hydraulic geometry, 3) flood recurrence intervals, and 4) Manning based resistance equations. I chose to use the stage-discharge rating curve for USGS streamflow gaging stations, because bankfull stage could be determined along the longitudinal profile of stream channels and at a representative riffle where bankfull indicators were usually present. It was reasonable to relate the stage-discharge rating curve to the bankfull stage along the study reach and at the riffle floodplain because most riffles were located hundreds of feet from USGS gaging stations. I utilized a number of different techniques to confirm my findings since considerable debate centers around which geomorphic feature represents bankfull stage. The following procedures were used in the bankfull discharge determination:

1. Field assessed bankfull indicators,
2. Examined longitudinal profile,
3. Examined cross section,
4. Field assessed bankfull indicators observed by experts,
5. Graph minimum width/depth ratio, and
6. Compute recurrence interval.

After completing all geomorphic surveys and conducting the group tour, I analyzed the field bankfull stage determination using several methods. First, I considered the longitudinal profile and the average bankfull stage throughout the reach. This method produces a justifiable estimate for the bankfull discharge determination because it takes into account many bankfull indicators along the study reach (Kilpatrick and Barnes, 1964). However, if the observer has identified an erroneous feature that is consistently surveyed throughout the study reach, then the total average bankfull stage would be incorrect resulting in the wrong discharge.

Second, I examined the graph plot of the representative riffle cross section. The y-axis scale (vertical height) was made to reflect the proportional to the x-axis (horizontal distance). Visually, in many cases this improved identifying breaks in slope near the active floodplain. Next, I plotted bankfull hydraulic geometry (mean depth, width, and area) of the cross sections against the stage elevation at 0.10-ft increments to identify any changes in the slope corresponding to bankfull stage. While there were some trends in the graphs, changes in the slope of the curves were not definitive and were deemed inconclusive. Consequently, I further utilized the cross section hydraulic geometry by plotting width/depth ratio against stage elevation in order to identify the minimum width/depth ratio. The width/depth ratios as a function of stage elevation illustrated a definitive change in slope of the curve and either corroborated or did not match my field-determined bankfull stage determination (Figure 3-1).

The next measure of validation was to assess the group bankfull call in the field. This was accomplished by graphing each observer's bankfull elevation on the surveyed cross section. Next, I related their bankfull stage to the USGS stage-discharge tables and identified the associated discharge. After identifying the bankfull discharge associated with each observer selection of bankfull stage, I performed flood frequency analyses using log-Pearson Type III and related the RI to each observer discharge. Observer estimates were compared to my field bankfull elevation. Finally, I considered my field-determined bankfull recurrence interval. By evaluating my field-determined bankfull elevation along the longitudinal profile and riffle cross section, the minimum width/depth ratios, the group bankfull elevations and bankfull RIs, I was confident in my bankfull determination.

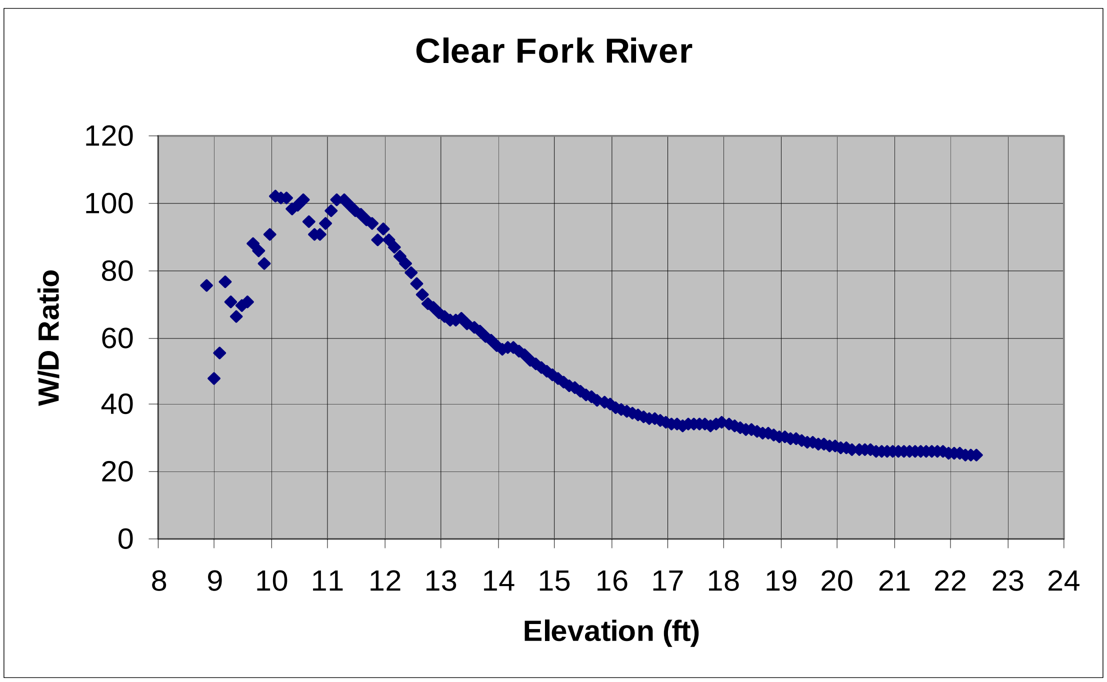


**Figure 3-1. Example Graph of Width/Depth (W/D) Ratio at 0.10-foot Increments of Stage at Riffle Cross Section of Clear Fork River in Southwestern Appalachians.**

## Bankfull Indicators

Identifying bankfull stage in the field is often a formidable challenge and was no different in many of the streams included in my study. Leopold (1994) acknowledged that various points along a channel reach are somewhat different in shape, vegetation, bedrock, location and form of bars and composition of bank materials. He established five principal bankfull indicators in order of utility that included: 1) the top of a point bar, 2) changes in vegetation type and quantity, 3) topographic break in slope or change in bank angle, 4) change in size distribution of channel materials and 5) debris deposits or rack lines. Subsequent investigators have found different bankfull indicators useful, especially in the southeastern U.S.

The geomorphic processes of erosion and deposition are the most formative of channel hydraulic geometry, so the primary bankfull indicators should be related to these processes (McCandless and Everett, 2002). The relatively flat, depositional surface adjacent to stream channels is known as the active floodplain and is thought to be the best indicator of bankfull stage (Harrelson *et al.*, 1994). According to McCandless and Everett (2002), the primary indicator of bankfull stage is the noticeable transition from a vertical stream bank to a relatively flat floodplain known as the floodplain break, followed by the inflection point, scour line, depositional bench and top of point bar (Figure 3-2). One of the requirements in a study on channel geometry in the Piedmont was that the trend line for bankfull elevations should be parallel to the water surface trend line on the longitudinal profile for consistency (Kilpatrick and Barnes, 1964). In New South Wales, Woodyer (1968) examined the bankfull frequency associated with multiple benches and found that the high bench, associated with the present floodplain and the middle bench were both associated with a constant bankfull frequency.

Many of the bankfull indicators that river investigators consistently find throughout the world have been well documented (Woman, 1955; Leopold *et al*., 1964; Barnes and Kilpatrick, 1968; Woodyer, 1968; Pickup and Warner, 1976; Dury, 1976; Williams, 1978a; Stream Systems Technology Center, 1993; Leopold, 1994; Harrelson *et al*., 1994; Harman *et al*., 1999; Castro and Jackson, 2001, McCandless and Everett, 2002; Stream Systems Technology Center, 2003; Sweet and Geratz, 2003; Keaton *et al*., 2005).

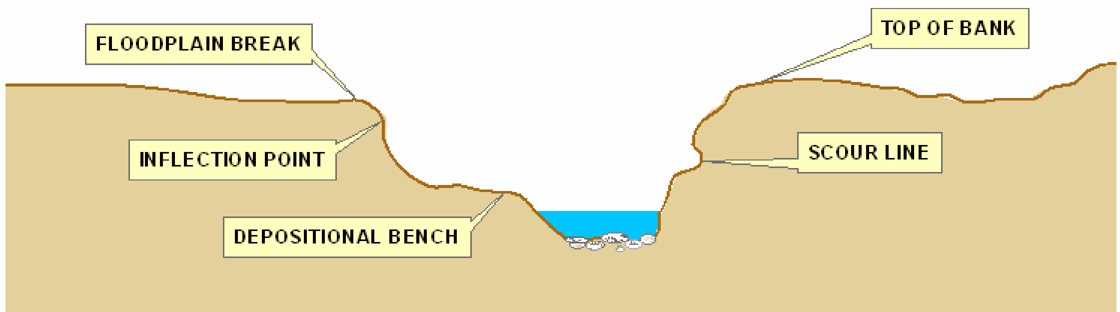


**Figure 3-2. Typical Geomorphic Features Used as Bankfull Indicators on Streams Draining the Southwestern Appalachians of Tennessee. (After McCandless and Everett, 2002)**

In rivers draining the Southwestern Appalachians, I found similar bankfull indicators (Table 3-1). Identifying bankfull stage on rivers in the Southwestern Appalachians was challenging because some of the rivers studied in this research were located in confined alluvial and colluvial valleys (Rosgen Valley Type IV) dominated by bedrock. In some canyon-like valleys, little to no floodplain was present. In these instances, multiple indicators consistently pointing to a common elevation along the study reach were heavily weighted.

**Table 3-1. Primary Bankfull Indicators Associated with Study Reaches on Streams Draining the Southwestern Appalachians of Tennessee.**

| USGS Station No. | Waterway | Gage Location | Drainage Area ($mi^2$) | BKF* Indicators |
|---|---|---|---|---|
| Ungaged | Trib. #1 Lints Cove Creek | East Fork Stables | 0.08 | inflection point |
| Ungaged | Pine Creek | Catoosa WMA | 0.60 | floodplain break |
| 3571600 | Brown Spring Branch | Sequatchie, TN | 0.67 | floodplain break |
| 3408600 | Long Branch | Grimsley, TN | 1.11 | inflection point |
| Ungaged | Rock Creek | Pickett State Park | 5.82 | floodplain break |
| 3571800 | Battle Creek | Monteagle, TN | 50.4 | floodplain break |
| 3415000 | West Fork Obey River | Hwy 52 Alpine, TN | 81 | floodplain break |
| 3416000 | Wolf River | Byrdstown, TN | 106 | floodplain break |
| 3539600 | Daddys Creek | Hebbertsburg | 139 | break in slope |
| 3414500 | East Fork Obey River | Jamestown, TN | 196 | bench/sand deposits |
| 3409500 | Clear Fork | Robbins, TN | 272 | bench |

*BKF = Bankfull

## Field Surveys

Geomorphic surveys were accomplished by investigators during the spring and summer of 2005. At all of the eight USGS gaged stream study reaches, a pedestrian survey was performed along the study reach upstream and downstream of the gage station to assess conditions and potential bankfull indicators. For each of the eight USGS gaging stations, a geomorphic stream survey was achieved following well-established protocol and survey procedures (Harrelson *et al*., 1994; Leopold, 1994; Rosgen, 2004). Discharge rating tables and gage descriptions were obtained from the Nashville and Knoxville USGS offices. Stream surveys were accomplished using a Topcon GTS-226 total station, prism and rod, multiple 300-foot measuring tapes, a 300-foot metal cam-line, rebar, tent stakes, survey arrows, clamps, flagging, pin flags, and a ruler. Precision of surveyed data was recorded at $1/100^{th}$ of a foot. All measurements were recorded in English units with exception to channel substrate materials, which were documented in metric.

### *Longitudinal Profile*

A longitudinal profile of each study reach was conducted for a distance of approximately 20 times the bankfull width of each stream channel (Leopold, 1994). Both vertical and horizontal measurements were taken at each recognizable channel feature or facet such as riffle, run, glide and pool. Measurements taken at the start of each facet included thalweg for bedform, water surface for slope, and bankfull elevation for comparison of consistent morphological indicators along the profile. Because each river was predominantly bedrock controlled, some facets or transitions to other stream features were difficult to discern. All major changes in channel bedform along the profile were surveyed. A series of 300-foot tapes were strung along the river banks following the general stream pattern for measurement of horizontal distances between stream facets. At real-time gaging stations, river stage was recorded on the day and time of survey. Prior to beginning survey measurements, benchmarks tied to the gage datum were located and surveyed for reference to the stage-discharge rating tables. The longitudinal profile extended both upstream and downstream of the gaging station on all rivers except those containing culverts at the gage.

### *Cross Sections*

For the majority of streams, two cross sectional surveys were performed on stable, representative riffles nearest to the gaging station. Detailed cross sections of rivers were surveyed to gather accurate hydraulic geometry. A 300-foot stainless steel cam-line was stretched across each river and associated floodplain perpendicular to the flow of water. On smaller streams, a 100-foot measuring tape was adequate. Cross sectional surveys included floodplain elevations, left and right pins, terraces, significant breaks in slope, bankfull elevation, top of bank, left and right edge of water and thalweg. The width of the flood prone area (twice bankfull elevation at maximum depth) was either surveyed at the cross section or was estimated using a measuring tape (Rosgen, 1996). The distance between each measuring station taken along the channel cross section depended on the size of the river. The interval between measurements on most streams was between one half and two feet with the exception being on large rivers where greater distances such as five to ten feet existed with little change in elevation. From the detailed survey data, bankfull width was measured at the bankfull elevation, bankfull depth was determined from the mean measured depths throughout the channel and cross-sectional area was the product of the two dimensions.

### *Group Field Survey*

I enlisted the opinions from professionals across the southeast for bankfull stage on some of the rivers I had previously surveyed. The intent for having a group tour of streams was to: 1) provide a second opinion or validation of initial bankfull findings, 2) test to see which bankfull indicators were more descriptive or useful and 3) test to see if there was agreement among the group and help confirm the assumption that the bankfull RI ranges between 1 and 2 years in the Southwestern Appalachians. Aside from providing drainage area size onsite, all hydrologic information was purposefully withheld to reduce biased opinions. A group composed of eight persons with various backgrounds in soil science, biology, ecology, fisheries, and engineering toured four rivers with active USGS gaging stations across the northern portion of the Southwestern Appalachians. All individuals participating in the group survey had conducted numerous geomorphic surveys and river assessments and were very experienced in identifying bankfull stage in their respective physiographic regions. Participants represented various physiographic regions from Kentucky, Tennessee, North Carolina and South Carolina.

The East Fork and West Fork of the Obey River, the Wolf River and the Clear Fork of the Big South Fork of the Cumberland River were each investigated during August 27-28, 2005 to identify primary bankfull indicators and establish bankfull stage. The group tour was conducted when most rivers in the Southwestern Appalachian ecoregion were at or near baseflow conditions. During each river visit, each of the eight participants was given a pin flag and allowed to visually survey the study reach for prominent bankfull indicators. Once the group had been given ample time to investigate the river, each person was required to place his pin flag at the location on the stream bank he had judged as the bankfull elevation. The only constraining factor was that each individual had to place his pin flag within or very near to the previously surveyed riffle cross section. The only information given to each participant prior to viewing each river was drainage area. After the tour was finished, I revisited each site and surveyed the elevation of each pin flag, referencing a known elevation on the cross section. The elevation of each pin was related to the discharge rating table for the gage. The RI for the discharge was then calculated.

## Data Analyses

Upon completion of geomorphic surveys, field data were compiled and entered into RIVERMorph Version 3.1 (2005) stream assessment and restoration software. This software application provided an efficient way to organize, analyze and graph many of the hydraulic and geomorphic variables measured in the field. Data from the longitudinal profile for each site were entered and a graph was plotted with best fit lines drawn through the bankfull and water surface points. To ensure consistency of the bankfull profile along the study reach, a comparison of the bankfull best-fit line was made against the water surface best-fit line. If the two lines were parallel, then I was confident that the bankfull profile represented the average bankfull stage along the reach and could be used to indicate the bankfull elevation at the cross sections. Leopold (1994) points out the importance of using all bankfull data along a reach because of inconsistency in using just one point and the possibility of individual error. The average bankfull stage of the longitudinal profile provided the first estimate of the magnitude of bankfull discharge.

Each riffle cross section was plotted separately and shown on the longitudinal profile for reference. Thalweg, left and right edge of water, width of the flood prone area and bankfull elevations were identified on the graphed cross sections. The bankfull hydraulic geometry (cross-sectional area, width and mean depth) were then calculated in RIVERMorph and displayed in each cross section graph. For the bankfull discharge determination, bankfull stage for each stream was surveyed in the field and referenced to the gage datum and stage-discharge rating tables. Bankfull discharge for the active gages was calculated by taking the difference between water surface and the bankfull elevation and adding it to the stage of the river on the day and time of survey. Gaged streams where the river stage was not known required computation of elevations tied to benchmarks or reference points.

***Gage Analysis***

Annual peak streamflow records from the 8 USGS gaging stations were obtained from the Tennessee USGS (2005) website at http://tn.water.usgs.gov. In addition, I contacted both the Nashville and Knoxville USGS offices and requested stage-discharge rating tables or stage-discharge rating curve, gage description notes including benchmarks and reference marks, and available gage summaries (Form 9-207). The RIs of the bankfull elevations picked by each observer were referenced to the gage datum and stage–discharge tables and calculated by fitting the log-Pearson Type III distribution of the annual series as described in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982). Data collected on the four rivers during the group tour were organized into tables for each river (Figure 3-3). A modified (log base 10 transformation of the data) Excel spreadsheet originally produced by NRCS was used to compute the

| WOLF RIVER | | | |
|---|---|---|---|
| ID | STAGE (feet) | Q (cfs) | RI (years) |
| JKW | 6.9 | 4,990 | 1.3 |
| AW | 6.4 | 3,990 | 1.2 |
| MFA | 6.4 | 3,990 | 1.2 |
| RS | 7.18 | 5,490 | 1.4 |
| JGA | 6.61 | 4,410 | 1.2 |
| GF | 4.31 | 1,110 | 1.0 |
| AB | 4.81 | 1,340 | 1.0 |
| LD | 4.54 | 1,310 | 1.0 |
| Mean | | | 1.16 |

| WEST FORK OBEY RIVER | | | |
|---|---|---|---|
| ID | STAGE (feet) | Q (cfs) | RI (years) |
| JKW | 8.96 | 4,210 | 1.2 |
| AW | 6.15 | 1,800 | 1.0 |
| MFA | 6.15 | 1,800 | 1.0 |
| RS | 8.96 | 4,210 | 1.2 |
| JGA | 6.15 | 1,800 | 1.0 |
| GF | 6.15 | 1,800 | 1.0 |
| AB | 8.96 | 4,210 | 1.2 |
| LD | 6.15 | 1,800 | 1.0 |
| Mean | | | 1.08 |

| CLEAR FORK RIVER | | | |
|---|---|---|---|
| ID | STAGE (feet) | Q (cfs) | RI (years) |
| JKW | 8.49 | 5,900 | 1.1 |
| AW | 8.49 | 5,900 | 1.1 |
| MFA | 8.49 | 5,900 | 1.1 |
| RS | 8.49 | 5,900 | 1.1 |
| JGA | 8.49 | 5,900 | 1.1 |
| GF | 8.49 | 5,900 | 1.1 |
| AB | 8.49 | 5,900 | 1.1 |
| LD | 8.49 | 5,900 | 1.1 |
| Mean | | | 1.1 |

| EAST FORK OBEY RIVER | | | |
|---|---|---|---|
| ID | STAGE (feet) | Q (cfs) | RI (years) |
| JKW | 9.34 | 4,480 | 1.0 |
| AW | 9.34 | 4,480 | 1.0 |
| MFA | 9.34 | 4,480 | 1.0 |
| RS | 9.34 | 4,480 | 1.0 |
| JGA | 9.34 | 4,480 | 1.0 |
| GF | 9.34 | 4,480 | 1.0 |
| AB | 9.34 | 4,480 | 1.0 |
| LD | 9.34 | 4,480 | 1.0 |
| Mean | | | 1.0 |

**Figure 3-3. Results of Bankfull Identification from 2005 Group Tour on Sample of Four Rivers in the Southwestern Appalachians of Tennessee.**

discharge of return intervals at 0.1 year increments between 1 and 2 years.The period of record for the four rivers ranged from 33 to 71 years. For each observer, I computed the bankfull discharge and RI (log-Pearson Type III of the annual series) associated with the field-identified bankfull stage.

### *Statistical Analysis*

A sample of four USGS streamflow gaging stations was used to test if the bankfull RI of streams draining the Southwestern Appalachians was between 1 and 2 years. The gaging stations were selected on the basis of proximity to one another and the ability of the group to travel to each within a short time frame. Following the previously mentioned methodology for calculating discharge RIs, I surveyed the stage, identified the corresponding discharge in the rating table and calculated the RI for each observer. All observations were within the 1-2 year bankfull RI range (Figure 3-3).

After confirming my initial hypothesis, I also wanted to test the probability of observing a bankfull RI between 1.1-2.0 years. It is because of the large range in flow between the 1.0 and 1.1 that I chose to use the 1.1 RI as a minimum limit. A binomial distribution was used to examine the hypothesis that each of the experts would select a bankfull indicator that corresponded to a RI between 1.1-2.0 years. The data were analyzed by setting one of two outcomes to either "yes" the observer marked a bankfull indicator within this range or "no" they did not. Due to the nonparametric scope of this experiment, I used a binomial test known as a Bernoulli trial to compare the frequencies of the two categories of a dichotomous variable to the frequencies expected under a binomial distribution with a probability parameter of 0.9 (90%) (SPSS Version 13.0, 2005). Data from the East Fork of the Obey, West Fork of the Obey, Wolf and Clear Fork Rivers were examined to test the probability of selecting a bankfull indicator within 1.1-2.0 year RI.

## Results

### *Bankfull Discharge Recurrence Interval for Selected Streams*

After incorporating the six methods to accurately identify bankfull discharge, I was able to validate my field-determined bankfull stage. The bankfull discharge RI was calculated on seven out of the eleven surveyed streams, because there were only seven USGS gages with sufficient annual peak flow data to properly conduct a flood frequency analysis. I found that the RI ranged from 1.1 to 1.4 years with an average bankfull discharge RI of 1.31 years (standard deviation (sd) = 0.12) This determination was in support of findings by Leopold (1994) who documented bankfull discharge RI to be between 1 and 2 years. The average bankfull RI for the Southwestern Appalachians was also comparable to the Ridge and Valley (1.36 years, sd = 0.28) and the Piedmont and Blue Ridge (1.44 years, sd = 0.22).

### *Group Tour*

Analyses of the stage, discharge and RI of the four sampled rivers were in support of my 1 to 2 year RI hypothesis (Figure 3-3). However, 75% of the 32 observations made on the four rivers were within the 1.0 to 1.1 RI range (Figure 3-4). I did not achieve 90 percent agreement that the probability of the group would identify a bankfull indicator between 1.1-2.0 years. This outcome is of concern because, for example, the range in discharges for the Wolf River between the 1.0 and 1.1 RI is 737 cfs and 3,550 cfs, respectively. The group unanimously chose a RI of 1.0-1.1 for the Clear Fork and East Fork Rivers. The group RI for all four rivers ranged from 1.0 to 1.4, with an average of 1.08 years (sd = 0.11).

## Discussion

I found that the single most prominent indicator of bankfull was the significant break in bank slope at the point of incipient flooding of the active floodplain, also known as the active floodplain break (Table 3-1). This is in agreement with other researchers who conducted similar investigations on streams in the eastern U.S. (Harman *et al.*, 1999; McCandless and Everett, 2002; Keaton *et al.*, 2005). When this primary indicator was

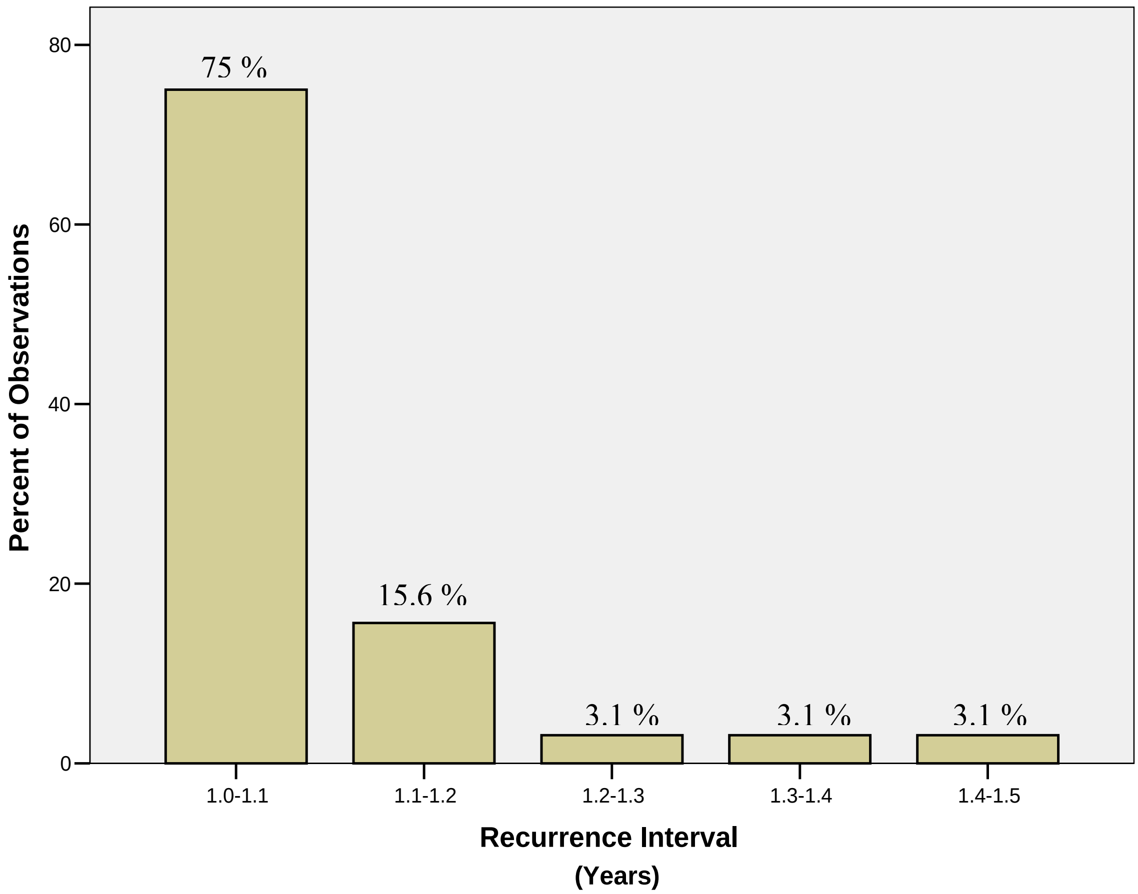


**Figure 3-4. Group Tour Bankfull Discharge RI Frequencies on the East Fork and West Fork of the Obey River, Wolf River and Clear Fork River 2005.**

absent or not pronounced, I used inflection points and prominent benches along the stream bank. Vegetation was also considered, but not used as a primary indicator. The age and size of woody vegetation was examined to rule out relict terraces and to give argument to lower depositional features. In a few instances, the top of point bars were used as bankfull indicators, but this indicator was not prevalent in many streams. For the majority of gaged streams, bedrock was abundant on two out of three sides of each stream channel (left bank, bed, right bank). As a result, great emphasis was placed on identifying the bankfull indicator on the remaining alluvial bank. The highest scour line was considered, but seldom used as a primary bankfull indicator.

Many of the bankfull indicators I used were also similar to those mentioned by participants in the group tour. A summary of bankfull indicators used by the group are as follows: 1) significant break in slope at the point of incipient flooding, 2) highest scour line, 3) alluvial sand deposits and 4) changes in vegetation including moss on boulders. Some participants commented that in the bedrock streams where there was little deposition, the scour line was the better indicator. In other rivers where bedrock control is absent, riffles are built from transported materials rather than scoured bedrock. In these rivers, depositional features were the better indicator.

I documented that a difference in determination of bankfull stage existed among observers. Eight observers were asked to select bankfull stage on four rivers without prior knowledge of flow data. There was close agreement among the group on the primary bankfull indicator for both the East Fork of the Obey and Clear Fork Rivers. However, these were the two rivers for which the group determination of bankfull stage differed most from my own. The difference between my bankfull determination and the group determination could be attributed to my prior knowledge of flow data and opportunity to examine both the longitudinal profile and cross section of each river. A comparison of the 1.5-year discharge of 12,900 cfs to the group selection of 4,480 cfs for the East Fork River was of concern. Identifying bankfull stage on the East Fork River was more complex than most because it lacked a well developed floodplain.

Some subjectivity exists when identifying the bankfull indicator. Significant differences in discharge were experienced between some of the group observers and my findings. The difference in bankfull determinations was likely a consequence of the emphasis placed on the primary bankfull indicator. In my study, the active floodplain was not pronounced in the four sampled rivers of the group tour. Identifying which depositional feature represented the break from channel processes to floodplain processes was the key difference. The debate centered on whether the floodplain was a terrace or still active. This seemed to be a prevailing theme in the literature and certainly gives argument to the subjectivity of the bankfull discharge determination. However, after following the methodology outlined in the above section, my findings for bankfull discharge RI concur with previous studies accomplished in the eastern U.S. (Dunne and Leopold, 1978; Harman *et al.*, 1999; McCandless and Everett, 2002; Keaton *et al*., 2005).

In comparison, my field-determined bankfull stage selection was higher than the overall group consensus on all four rivers. I did agree with the choice of bankfull indicators with some observers on the West Fork and Wolf Rivers. I found the mean RI to be 1.31 years for seven gaging stations compared to 1.08 years found by the group tour on four rivers. There is a possibility that some of the observers might have used the Eastern U.S. regional curve (Dunne and Leopold, 1978) or the Piedmont of North Carolina curve (Harman *et al*., 1999) to estimate bankfull stage. In essence, they were trying to fit their regional curve to the streams we observed in the Southwestern Appalachians. In retrospect, I should not have told them the drainage area onsite.

The first objective of the study was achieved by determining the average bankfull RI. I hypothesized that the bankfull RI in the Southwestern Appalachians was between 1 and 2 years. Results of this investigation are in support of the stated hypothesis. After compiling and analyzing the collected data to determine bankfull stage on the surveyed rivers, I am confident in my bankfull stage determination. The average RI for the Southwestern Appalachians (1.31 years) is very similar to those of the Ridge and Valley of Virginia, W. Virginia and Maryland (1.36 years) and the Piedmont and Blue Ridge of North Carolina (1.44 years). The average RI was slightly less than the 1.5 years and may be attributed to a deficiency in basin storage capacity for surplus water, the nature of groundwater storage systems, significant slope on the escarpment and the abundance of bedrock acting as an impervious surface (Mayfield, 1984). In a recent study on small watersheds at the Coweeta Hydrologic Laboratory in the Southern Appalachians, Henson (1999) found that the bankfull flow RI ranged between 1.0 and 1.3 years for the annual maximum series.

# CHAPTER IV
# BANKFULL REGIONAL CURVES

## Methodology

The second and third objectives of this study were to develop bankfull discharge and hydraulic geometry relationships for streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee (Griffith *et al.*, 1997) and to compare those relationships to the neighboring Valley and Ridge regional curves in Virginia, West Virginia and Maryland (Keaton *et al.*, 2005) and the commonly used regional curves of the Piedmont and Blue Ridge of North Carolina (Harman *et al.*, 1999; Harman *et al.*, 2000). I hypothesized that the bankfull discharge and hydraulic geometry of streams draining the Southwestern Appalachians were significantly different from those streams draining the Valley and Ridge of Virginia and the Piedmont and Blue Ridge of North Carolina. As part of my hypothesis, my intent was to establish a significant correlation between drainage area and bankfull hydraulic geometry of streams in the ecoregion.

The method of data collection followed the Level II protocol outlined by Rosgen (1996), which was built on well established fluvial geomorphic principles by others (Leopold and Maddock, 1953; Wolman, 1954; Wolman 1955; Wolman and Leopold, 1957; Leopold *et al*., 1964; Leopold, 1994). Level II protocol gathers quantitative information regarding stream channel morphological description and enables the investigator to classify a stream based on these measurements. The Level II delineative criteria describe stream channel dimension (width, mean depth, and cross-sectional area), longitudinal profile, pattern, and dominant material as measured in the field. The data collected on these variables are then computed and graphed to illustrate the present form of the stream channel. The methodologies for data collection and analyses are comparable for the three geographic regions. Methods of data collection are organized into the following sections: drainage basin area, channel dimension, channel profile, channel pattern and channel materials.

### *Drainage Basin Area*

The contributing drainage area for each USGS stream gaging station was provided by the USGS web site, http://tn.water.usgs.gov/. Watershed drainage area for each ungaged stream was calculated by delineating watershed boundaries using USGS 7.5-minute topographic quadrangles in digital raster graphic (DRG) format and ArcGIS 9 software (ESRI, 2004). The ArcMap application enabled me to use the polygon tool to delineate and calculate the drainage area within each ungaged stream watershed boundary.

### *Channel Dimension*

For the majority of streams, two channel cross-section surveys were performed on relatively stable, representative riffles closest to the gaging station as possible. According to Leopold (1994), the riffle is the most stable portion of the river. Detailed cross sections of rivers were surveyed to gather accurate hydraulic geometry. A 300-foot stainless steel cam-line was stretched across each river and associated floodplain perpendicular to the flow of water. On smaller streams, a 100-foot measuring tape was adequate. Cross sectional surveys included floodplain elevations, left and right pins, terraces, significant breaks in slope, bankfull elevation, top of bank, left and right edge of water and thalweg. The width of the flood prone area (twice bankfull elevation at maximum depth) was either surveyed at the cross section or was estimated using measuring tape (Rosgen, 1996). The distance between each measuring station taken along the channel cross-section depended on the size of the river. The interval between measurements on most streams was between one half and two feet with the exception being on large rivers where greater distances existed with little change in elevation. Figure 4-1 represents a typical riffle cross-section illustrating each surveyed elevation. From the detailed surveys, bankfull width was measured at the bankfull elevation, bankfull depth was determined from the mean measured depths throughout the channel and cross-sectional area was the product of the two dimensions.

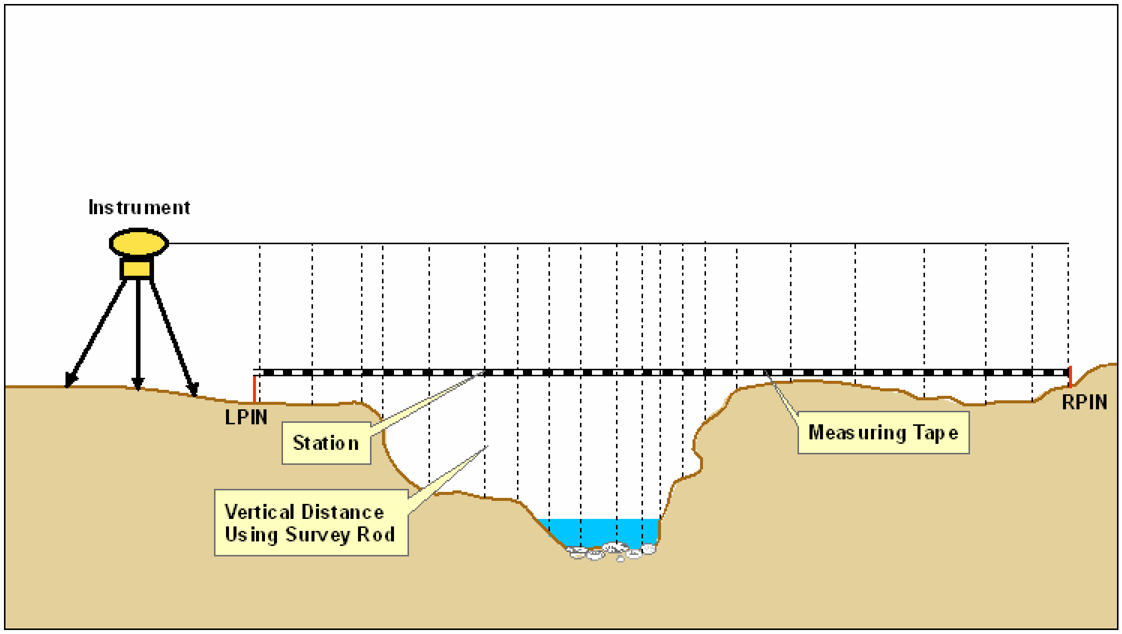


**Figure 4-1. Typical Cross-Sectional Survey. (After Harrelson *et al.*, 1994)**

***Channel Profile***

A longitudinal profile survey of the study reach was conducted for a distance of approximately 20 times the bankfull width of each stream channel (Leopold, 1994). Both vertical and horizontal measurements were taken at each recognizable channel feature or facet such as riffle, run, glide and pool. Elevation measurements taken at each facet included thalweg for bedform, water surface for slope and bankfull elevation for comparison of consistent morphological indicators along the profile. Since each river was predominantly bedrock controlled, some facets or transitions to other stream features were difficult to discern. All major changes in channel bedform along the profile were surveyed. Multiple 300-foot tapes were strung along the river banks following the general stream pattern for measurement of horizontal distances between stream facets. On real-time gaging stations, river stage was recorded on the day and time of survey. Prior to beginning survey measurements, benchmarks tied to the gage datum were located and surveyed for reference to the stage-discharge rating tables. The longitudinal profile extended both upstream and downstream of the gaging station on all rivers except those containing culverts at the gage.

### *Channel Materials*

A modified Wolman (1954) pebble count procedure was followed to document channel materials for the Rosgen (1994) stream classification system. A total of 100 randomly selected particles were sampled at evenly spaced intervals across the bankfull width at ten transects throughout the study reach. To eliminate bias, particles were sampled by reaching down into the channel without looking and randomly selecting the first touched particle. The intermediate axis of each sampled particle was then measured in millimeters with a ruler. A representative reach-wide 100 pebble count was performed on a proportionate number of bed features such as pools, riffles, runs and glides throughout the longitudinal profile. For instance, if 40% of the reach was composed of pools, then four cross sections of ten particles would be sampled in pools and the remaining 60% would be sampled in riffles, runs and glides (Rosgen, 2004).

For ungaged streams, bed material was also sampled in a riffle cross section for an estimate of velocity and discharge. According to Leopold *et al.* (1964), the $D_{84}$ is two standard deviations larger than the median particle size $D_{50}$. The "D" represents the particle size at which the number percent of the particle sample is finer. One hundred particles were sampled within the wetted width of the surveyed riffle cross-section to determine relative roughness. The relative roughness is computed by dividing the $D_{84}$ of the riffle cross-section into the hydraulic radius R ($R/D_{84}$). The hydraulic radius R is calculated by dividing the wetted perimeter into the cross-sectional area of the riffle (Leopold *et al*., 1964).

### *Channel Pattern*

Channel pattern was measured for the purposes of stream classification, but not to produce meander geometry. Sinuosity was calculated by dividing stream length by valley length (Figure 1-3). For most streams, Digital Orthophoto Quarter Quadrangles

(DOQQs) were sufficient to use for measuring stream and valley length. For the smaller channels, stream length and valley length were measured in the field using 300-foot measuring tapes and the horizontal distance component of the total station. Stream channel sinuosity was either determined in the field by measuring stream length and valley length with 300-foot tapes or was calculated using ArcMap and the DOQQs encompassing each study reach. Digital orthophotos were obtained from the Tennessee Spatial Data Server (http://www.tngis.org/).

***Stream Classification***

The Rosgen (1994) stream classification system was used for this study. The delineative criteria set forth in this stream classification system are in the following discussion. The first variable examined in this system is entrenchment ratio, a computed index value that describes the degree of vertical containment of a stream channel, computed by dividing the width of the floodprone area (twice maximum depth at bankfull stage) by the bankfull width. Next, the width/depth ratio is an index value that indicates the channel cross-sectional shape and is computed by dividing bankfull width by mean bankfull depth. Stream channel pattern or plan-form is a measure of sinuosity (K), found by dividing the stream length by the valley length. The slope of the stream channel is taken by averaging the slope of the waters surface for a distance of approximately 20 bankfull channel widths. Last, dominant channel materials are represented by the $D_{50.}$

## Data Analyses

All field data were gathered and recorded in The Reference Reach (Rosgen, 1998) field books and then transposed into the appropriate section in RIVERMorph. RIVERMorph is a software application that allows the user to organize, analyze and graph field collected river data. Data analyses were performed on all measured parameters of the Level II survey methodology. I calculated the bankfull hydraulic geometry (width, mean depth, cross section area) for each surveyed cross-section and classified each reach based on collected data using RIVERMorph (Table 4-1). The following sections describe the manner in which collected data were analyzed.

**Table 4-1. Summary of Bankfull Stream Channel Characteristics in the Southwestern Appalachians of Tennessee 2005.**

| Waterway | Gage Station | Drainage Area (mi²) | Valley Type | Stream Type Rosgen | Bkf[1] Stage (Feet) | Qbkf[2] (cfs) | Velocity (ft/s) | Bkf[3] Area (ft²) | Bkf Width (ft) | Bkf Mean Depth (ft) | RI Years |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trib. #1 Lints Cove Creek | N/A | 0.08 | VIII | E4/1 | N/A | 40 | 6.35 | 6.3 | 7.21 | 0.9 | N/A |
| Pine Creek | N/A | 0.6 | VIII | E5 | N/A | 107 | 4.52 | 23.7 | 16.7 | 1.42 | N/A |
| Brown Spring Branch | 3571600 | 0.67 | VIII | E4 | 4.5 | 65 | 2.5 | 24.4 | 13.1 | 1.9 | 1.2 |
| Long Branch | 3408600 | 1.11 | VIII | E5/1 | N/A | 125 | 4.3 | 29.1 | 16.3 | 1.8 | N/A |
| Rock Creek | N/A | 5.82 | IV | E3/1 | N/A | 482 | 4.82 | 99.7 | 31.42 | 3.2 | N/A |
| Battle Creek | 3571800 | 50.4 | VIII | C4 | 7.64 | 3,210 | 5.11 | 628 | 155.6 | 4.0 | 1.4 |
| West Fork Obey River | 3415000 | 81 | IV | B2/1c | 8.96 | 4,210 | 6.49 | 649.2 | 127.1 | 5.1 | 1.2 |
| Wolf River | 3416000 | 106 | IV | B1/1c | 6.99 | 5,180 | 6.78 | 764.5 | 159.9 | 4.8 | 1.4 |
| Daddys Creek | 3539600 | 139 | IV | F2/1 | 8.87 | 6,690 | 5.74 | 1,166 | 201.3 | 5.8 | 1.4 |
| East Fork Obey River | 3414500 | 196 | IV | B2/1c | 12.51 | 7,620 | 6.74 | 1,130 | 136.3 | 8.3 | 1.1 |
| Clear Fork River | 3409500 | 272 | IV | B2/1c | 11.23 | 10,750 | 5.6 | 1919 | 224 | 8.6 | 1.4 |

Bkf[1] = Bankfull
QBkf[2] = Bankfull discharge in cubic feet per second
Bkf Area[3] = Bankfull cross-sectional area in square feet

### *Geomorphic Setting*

Drainage patterns for study sites within the ecoregion were dendritic. As part of the initial morphological assessment of river systems, Rosgen (1996) characterized different valley formations and typical stream types associated with specific valley types. A summary description of each valley type and associated stream types can be found in Table 4-2.

### *Channel Profile*

Survey data acquired from the longitudinal profile for each stream were entered into the profile data section in RIVERMorph. Once the data were entered, I was able to graph elevations taken at each facet of the river. Both water surface slope and bankfull slope were computed with application tools in the program. Bankfull indicator elevations were surveyed at each recognizable channel feature or facet such as riffle, run, glide and pool and were plotted for average bankfull slope. Additionally, best fit lines were added to represent bedform slope, water surface slope and bankfull slope for comparison of consistent morphological indicators along the profile. The longitudinal profile graph illustrates the variability in bedform, change in water surface and bankfull indicators along the study reach (Figure 4-2). Cross-section locations were also noted on each longitudinal profile.

### *Channel Dimension*

For the representative riffle cross-sections of each river, data were organized, entered and graphed in RIVERMorph. Cross-sections for each stream were plotted, and the bankfull hydraulic geometry of the ecoregion was computed and compared to the other two regions. The y-axis scale of the graphed cross-section was adjusted to reflect the proportional vertical height in comparison to the horizontal distance. The graph of each surveyed cross-section was edited to eliminate vertical exaggeration and allow examination of breaks in bank slope at the proper scale. Stream channel cross-section stations were also noted on the longitudinal profile. On rivers where two riffle cross-section surveys were performed, channel dimensions were compared for consistency.

**Table 4-2. Description of Valley Types. (Adapted from Rosgen, 1996)**

| Valley Type | Associated Stream Types | Description |
|---|---|---|
| I | A and G | "V" shaped, confined and often structurally controlled |
| II | B | Moderately steep, gentle sloping side slopes, colluvial valleys |
| III | A, G, D, B | Depositional in nature, alluvial fans and debris cones |
| IV* | F and C | Gentle gradient canyons, gorges and confined alluvial valleys |
| V | D, C, G | "U" shaped glacial troughs, moderatly steep side slopes |
| VI | B, C, F | Moderately steep, fault controlled valleys |
| VII | A and G | Steep, highly dissected fluvial slopes |
| VIII* | C, E, F, G, D | Wide, gentle slopes with well developed floodplain adjacent to river terraces |
| IX | C and D | Broad, moderate to gentle slopes from glacial outwash and/or eolian sand dunes |
| X | C, E, DA | Very broad, gentle slopes with extensive floodplains |
| XI | DA | Deltas |

*Valley types found in this study for streams in the Southwestern Appalachians

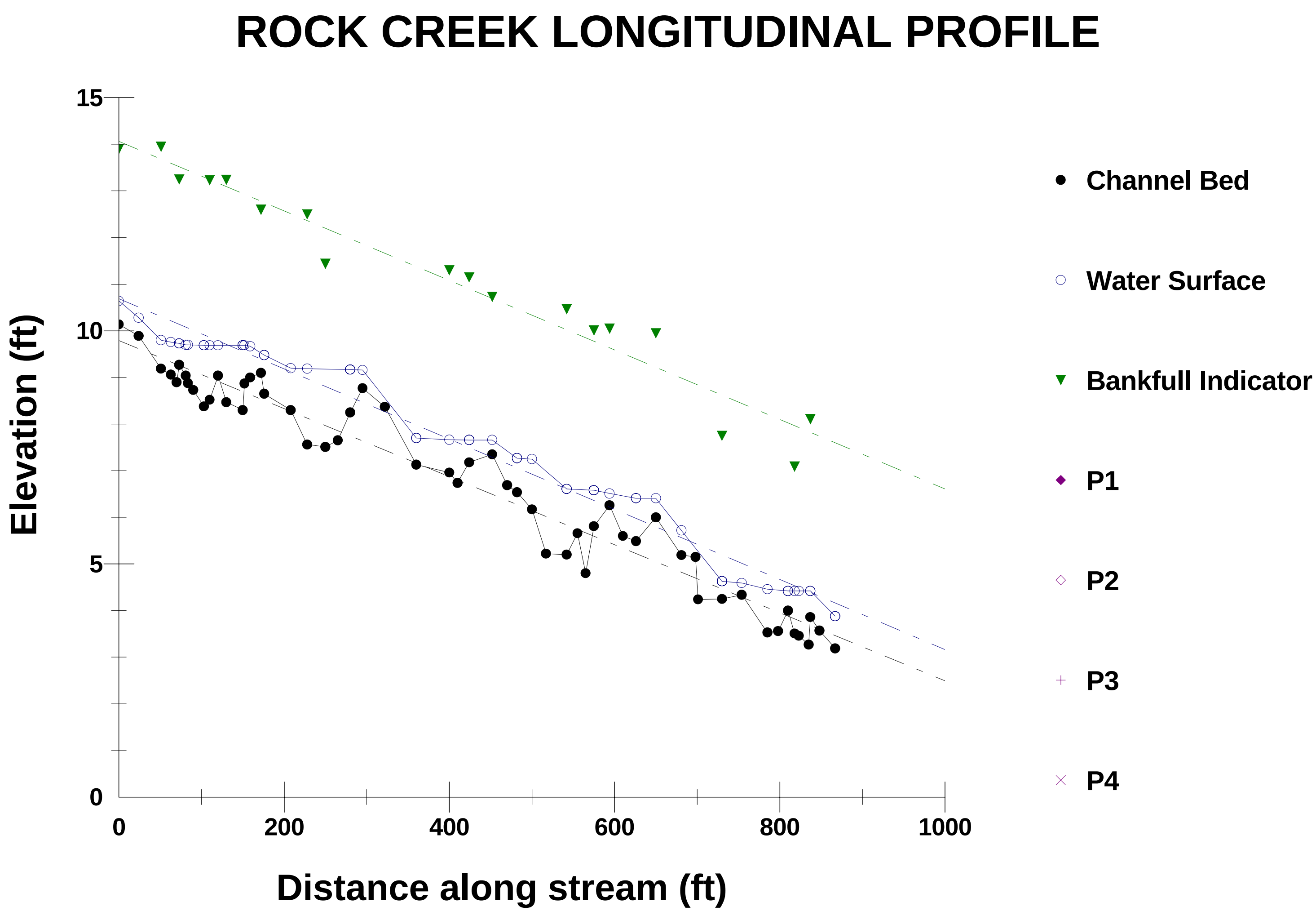


**Figure 4-2. Example of a Longitudinal Profile Survey Depicting Channel Bed Elevation (solid dot), Water Surface Elevation (empty dot), and Bankfull Elevation (solid triangle). Trend Lines are Best-Fit Applied in RIVERMorph.**

Graphs of cross sectional surveys included notes on floodplain elevations, left and right pins, bankfull elevation, floodprone elevation, top of bank, left and right edge of water and thalweg (Figure 4-3). Using the hydraulics by stages output in RIVERMorph, I computed the width of the channel at each 0.10 foot increment in elevation and divided by the associated mean depth. The minimum width/depth ratio was determined by graphing the increments of the width/depth ratio against elevation using Excel software.

### *Channel Materials*

All pebble count data from both the representative reach-wide count and the riffle pebble count were transferred from field books to the particles section in RIVERMorph. The program computes the total particle count, the item percentage and the cumulative percentage of samples grouped into size categories (silt/clay, sand, gravel, cobble, boulder, and bedrock) recommended by the American Geophysical Union Subcommittee on Sediment Terminology (Emmert, 2004). Particle sizes representing the percentage ≤ $D_{16}$, $D_{35}$, $D_{50}$, $D_{84}$ and $D_{95}$ were computed and graphed (Figure 4-4). The percentage class is the total percentage of the sample in a given size class, such as sand. Figure 4-5 is a typical example of a summary particle size analysis from Rock Creek.

### *Bankfull Discharge Calculations*

For ungaged streams included in the survey, bankfull discharge had to be estimated through the use of resistance equations. As described by Emmert (2004), bankfull discharge on those streams lacking USGS gaging stations was determined by estimating water velocity using a variation of the Darcy-Weisbach resistance coefficient (f). It is represented by the ratio of mean velocity to mean shear velocity (u/u*). The measured hydraulic geometry and channel roughness *in situ* reduced the margin of error in estimating velocity, resulting in more accurate discharge computations. The following equation (4-1) is a transformed version of the Darcy-Weisbach resistance coefficient:

$$u = (8gRS/f)^{1/2} \qquad \textbf{(4-1)}$$

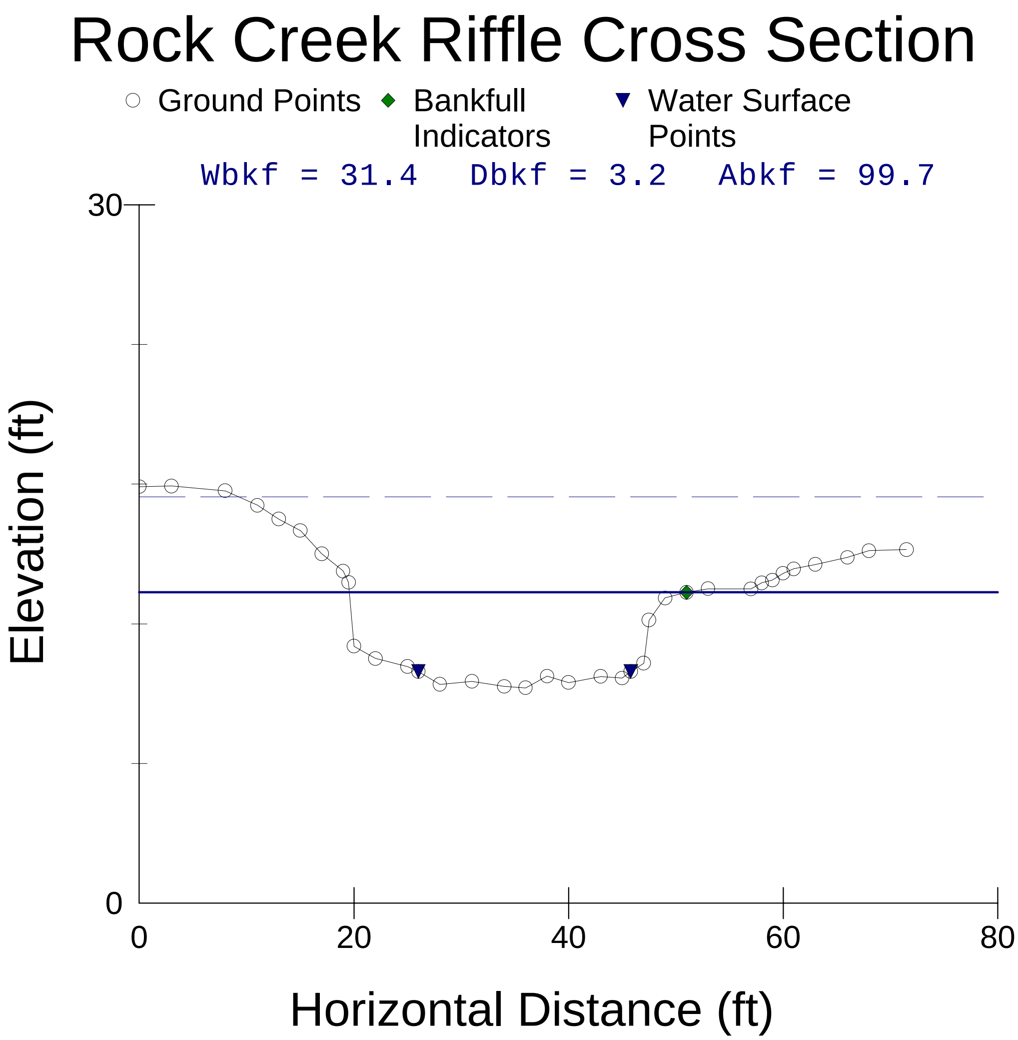


**Figure 4-3. Example of a Typical Cross Section Survey. Solid Triangles Depict Water Surface, Solid Line Depicts Bankfull Elevation, and Dashed Line Depicts Flood-Prone Elevation.**

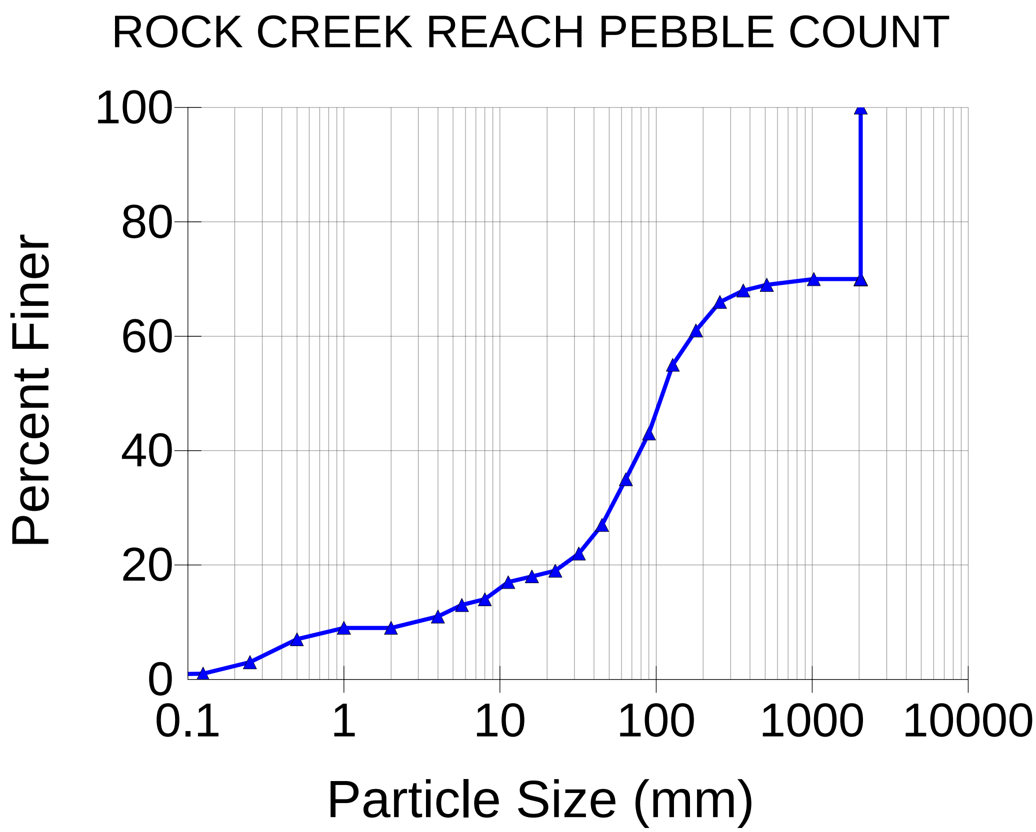


**Figure 4-4**. **Typical Example of a Particle Size Analysis for Rock Creek in Southwestern Appalachians of Tennessee 2005.**

PARTICLE SIZE SUMMARY

------------------------------------------------------------------

Reach Name: Rock Creek

Sample Name: Riffle

------------------------------------------------------------------

| Size (mm) | TOT # | ITEM % | CUM % |
|---|---|---|---|
| 0 - 0.062 | 0 | 0.00 | 0.00 |
| 0.062 - 0.125 | 0 | 0.00 | 0.00 |
| 0.125 - 0.25 | 0 | 0.00 | 0.00 |
| 0.25 - 0.50 | 1 | 1.00 | 1.00 |
| 0.50 - 1.0 | 0 | 0.00 | 1.00 |
| 1.0 - 2.0 | 2 | 2.00 | 3.00 |
| 2.0 - 4.0 | 11 | 11.00 | 14.00 |
| 4.0 - 5.7 | 4 | 4.00 | 18.00 |
| 5.7 - 8.0 | 3 | 3.00 | 21.00 |
| 8.0 - 11.3 | 9 | 9.00 | 30.00 |
| 11.3 - 16.0 | 1 | 1.00 | 31.00 |
| 16.0 - 22.6 | 1 | 1.00 | 32.00 |
| 22.6 - 32.0 | 3 | 3.00 | 35.00 |
| 32 - 45 | 1 | 1.00 | 36.00 |
| 45 - 64 | 5 | 5.00 | 41.00 |
| 64 - 90 | 12 | 12.00 | 53.00 |
| 90 - 128 | 14 | 14.00 | 67.00 |
| 128 - 180 | 11 | 11.00 | 78.00 |
| 180 - 256 | 9 | 9.00 | 87.00 |
| 256 - 362 | 8 | 8.00 | 95.00 |
| 362 - 512 | 3 | 3.00 | 98.00 |
| 512 - 1024 | 1 | 1.00 | 99.00 |
| 1024 - 2048 | 1 | 1.00 | 100.00 |
| 2048 - | 0 | 0.00 | 100.00 |

| | |
|---|---|
| D16 (mm) | 4.85 |
| D35 (mm) | 32 |
| D50 (mm) | 83.5 |
| D84 (mm) | 230.67 |
| D95 (mm) | 362 |
| D100 (mm) | 2047.9 |
| Silt/Clay (%) | 0 |
| Sand (%) | 3 |
| Gravel (%) | 38 |
| Cobble (%) | 46 |
| Boulder (%) | 13 |
| Bedrock (%) | 0 |

**Figure 4-5. Example of a Particle Summary Report for Rock Creek in Southwestern Appalachians of Tennessee 2005.**

where

$u$ = Mean velocity (ft/s)

$g$ = Gravitational acceleration (ft/s²)

$R$ = Hydraulic radius (ft)

$S$ = Bankfull average water surface slope (ft/ft)

$f$ = Darcy-Weisbach coefficient

The Darcy-Weisbach coefficient is related to the ratio of mean velocity to mean shear velocity by the following equation (**4-2**) (Bathurst, 1997):

$u/u^* = (8/f)^{1/2}$

where

$u^* = (gRS)^{1/2}$ = mean shear velocity (ft/s) (**4-2**)

The mean velocity is computed by the friction factor/channel roughness relationship (Rosgen, 1998) in the following equation (**4-3**):

$u = u^*(2.83+5.7\log R/D_{84})$ (**4-3**)

where

$R$ = Bankfull hydraulic radius (ft)

$D_{84}$ = $D_{84}$ from pebble count conducted at riffle cross section (ft)

By using the previously calculated parameters of wetted perimeter, hydraulic radius, hydraulic slope and cross sectional area at a riffle, I was able to estimate velocity and compute bankfull discharge.

***Statistical Analysis***

Simple linear regression was used to develop power function equations for bankfull hydraulic geometry of streams draining the Southwestern Appalachian ecoregion in Tennessee using SPSS version 13.0 software. The bankfull hydraulic geometry data and estimated bankfull discharge data for all 11 sites were regressed on drainage area at a log-log scale. For each bankfull regional curve, the dependent variable (bankfull discharge, width, mean depth and cross sectional area) was regressed on the independent variable of basin drainage area (DA). A least-squares power function equation was determined by fitting a best-fit line through each bankfull channel geometry relationship. This method was accomplished using the curve estimation tool in the regression menu of SPSS version 13.0. Goodness-of-fit statistics for each regional curve included the regression coefficient ($R^2$), standard error of the estimate, the $F$-statistic, and the $P$-value. A significance level of $\alpha = 0.05$ was used for all statistical analyses.

A comparison of the slopes of the regional curves from my data for the Southwestern Appalachians of Tennessee, against the North Carolina Piedmont and Blue Ridge and the Ridge and Valley of Virginia, West Virginia and Maryland was accomplished using analysis of covariance in SPSS. This statistical analysis was recently performed by others who compared several regional curves developed in the same physiographic province (Keaton *et al*., 2005). The covariate was drainage area (DA), the independent variable was region and the dependent variables were bankfull discharge, cross-sectional area, width, and mean depth. For this analysis, the major interest was in the differences in group means, after adjusting for the effects of the covariate (drainage area) which is known to affect each hydraulic parameter. I tested for equality of slopes among curves by including an interaction term in the model. Consequently, I conducted a test on between-subject effects and calculated parameter estimates to allow for different slopes.

## Results

### *Regional Curves for the Southwestern Appalachians in Tennessee*

The second objective of this investigation was to develop bankfull discharge and hydraulic geometry relationships for streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee. Power function regression equations and the respective coefficients of determination, standard error of the estimate and the *F*-statistic are shown in Table 4-3. The bankfull discharge ranged from 40 cubic feet per second (cfs) to 10,750 cfs. Bankfull velocities ranged from 2.5 to 6.78 feet per second (f/s) and averaged 5.36 f/s (sd = 1.29). Bankfull discharge for streams draining the Southwestern Appalachians was significantly related to drainage area with a coefficient of determination $R^2 = 0.985$. Basin drainage area for the surveyed streams ranged from 0.08 to 272 square miles. Drainage area explained 98% of the variability in bankfull discharge. Of the four dependent variables (discharge, cross-sectional area, width and mean depth), bankfull cross section area had the highest $R^2 = 0.996$. Each bankfull regional curve (discharge, area, width and mean depth) had a $R^2 > 0.95$, which signified that each dependent variable was highly related to drainage area.

**Table 4-3. Power Function Equations and Statistics for the Southwestern Appalachian Regional Curves.**

| Equation | *P*-value | $R^2$ | Standard Beta Coeff. | Standard Error | *F*-statistic[1] |
|---|---|---|---|---|---|
| Bankfull Discharge (cfs) $Q = 150.06(DA)^{.75}$ | 0.001 | 0.985 | 0.992 | 0.285 | 573 |
| Bankfull Cross-sectional Area ($ft^2$) $Area = 32.48(DA)^{.701}$ | 0.001 | 0.995 | 0.998 | 0.144 | 1970 |
| Bankfull Width (ft) $Width = 18.51(DA)^{.444}$ | 0.001 | 0.971 | 0.985 | 0.233 | 301 |
| Bankfull Mean Depth (ft) $Depth = 1.76(DA)^{.256}$ | 0.001 | 0.966 | 0.983 | 0.147 | 253 |

[1]For all models (n = 11), degrees of freedom $(df)_{numerator} = 1$ and $df_{denominator} = 9$
DA = Drainage Area

***Curve Comparison***

Bankfull discharge and hydraulic geometry relationships as a function of drainage area for stream channels draining the Southwestern Appalachians were compared to those determined by Harman *et al*. (1999 and 2000) and Keaton *et al*. (2005) (Figures 4-6, 4-7, 4-8, 4-9). Through analysis of covariance (ANCOVA), a statistically significant difference was found between the slopes of the regional curves for the Southwestern Appalachians and the other two regions except for curves of bankfull mean depth (Table 4-4). The Southwestern Appalachians had consistently higher values of bankfull discharge, cross-sectional area and width than the other two regions.

The mean difference between bankfull mean depth for the Southwestern Appalachians and the North Carolina Piedmont and Blue Ridge was 0.02 feet, which was not significant ($P = 0.96$). However, both the bankfull mean depth for the Southwestern Appalachians and the North Carolina Piedmont and Blue Ridge were significantly greater than the bankfull mean depth of the Ridge and Valley with a mean difference of 1 foot ($P = 0.014$) and 0.962 feet ($P = 0.005$), respectively. As a result of my study, conclusive evidence exists in support of different bankfull discharge, bankfull cross-sectional area, and bankfull width for streams draining the Southwestern Appalachians of Tennessee.

**Table 4-4. Comparison of Mean Differences between the Three Regions.**

| Variable | Southwestern Appalachians | | Ridge and Valley | | Piedmont and Blue Ridge | |
|---|---|---|---|---|---|---|
| | Mean | SE | Mean | SE | Mean | SE |
| Bankfull Area ($ft^2$) | 575 [a] | 44 | 250 [b] | 23 | 349 [c] | 32 |
| Bankfull Width (ft) | 97.3 [a] | 7.2 | 70.6 [b] | 3.8 | 75.2 [b] | 5.2 |
| Bankfull Mean Depth (ft) | 4.1 [a] | 0.33 | 3.0 [b] | 0.17 | 4.0 [a] | 0.24 |
| Bankfull Discharge (cfs) | 3441 [a] | 274 | 1221 [b] | 144 | 1924 [c] | 198 |

[1]Means within rows followed by unlike letters are significantly different at $P < 0.05$
[2]Covariates appearing in the model are evaluated at Drainage Area = 74.7484 $mi^2$

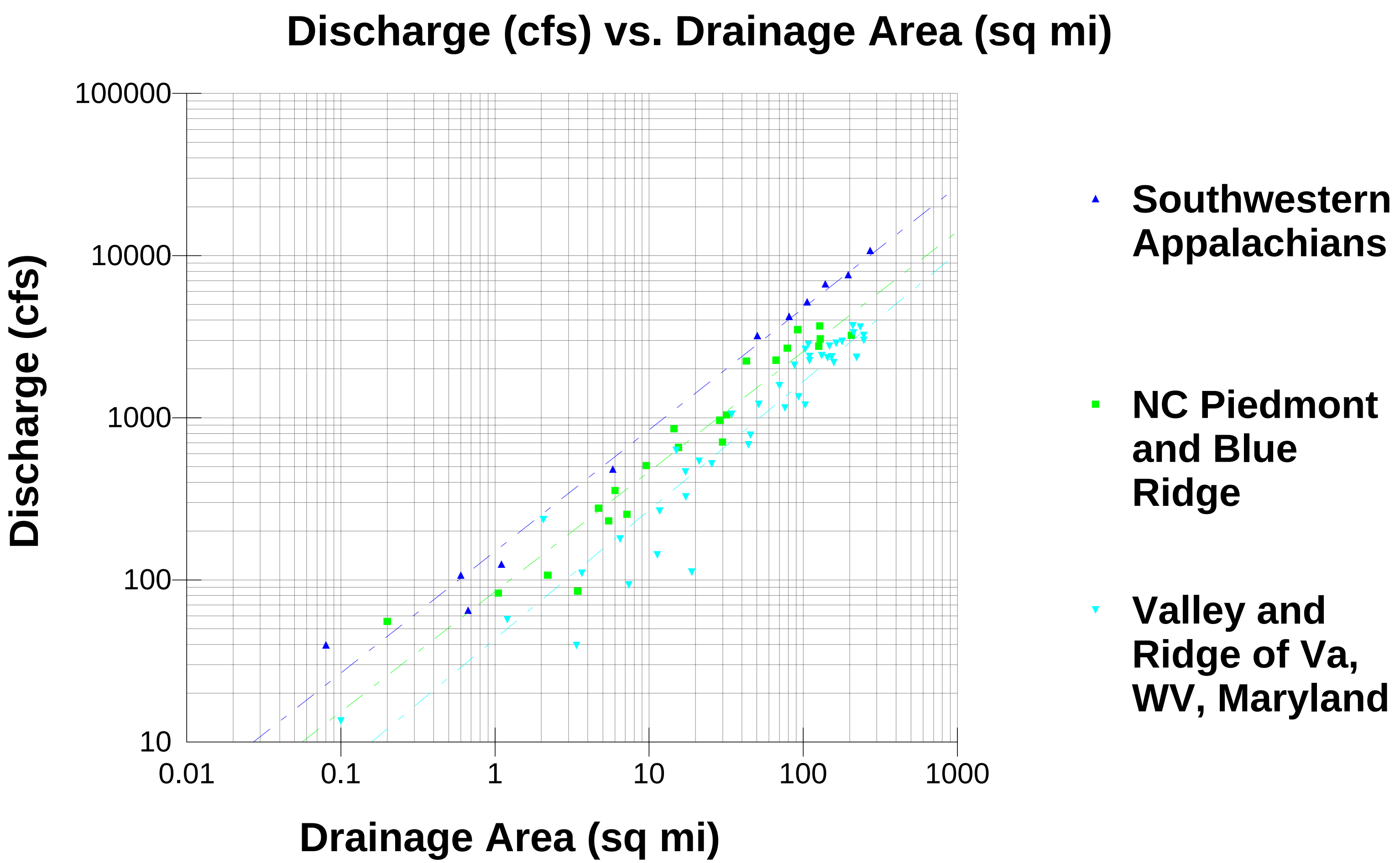


**Figure 4-6. Bankfull Discharge to Drainage Area for Study Sites in Southwestern Appalachians of Tennessee Compared to the Valley and Ridge, and Piedmont and Blue Ridge.**

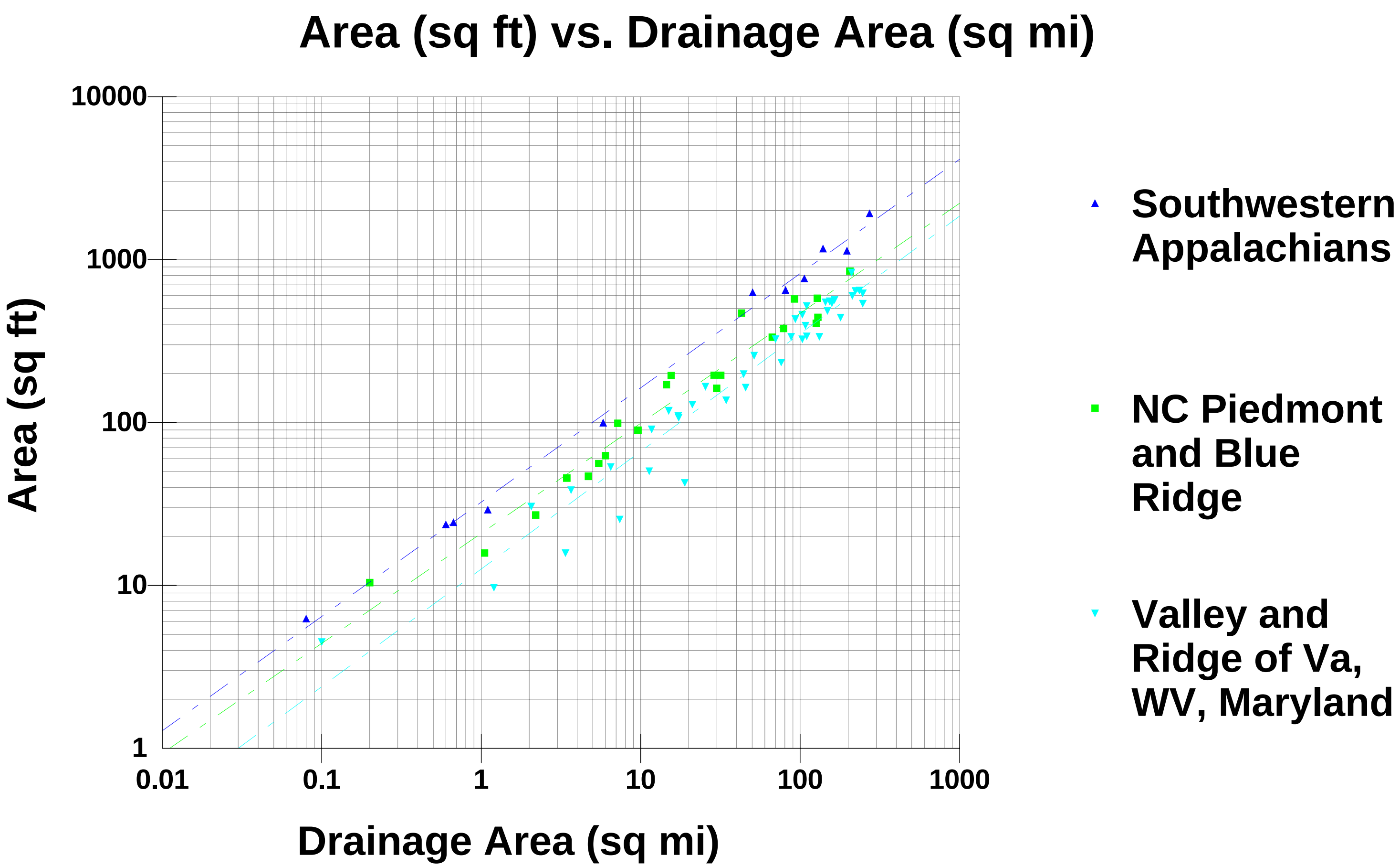


**Figure 4-7. Bankfull Cross-Sectional Area to Drainage Area for Study Sites in Southwestern Appalachians of Tennessee Compared to the Valley and Ridge, and Piedmont and Blue Ridge.**

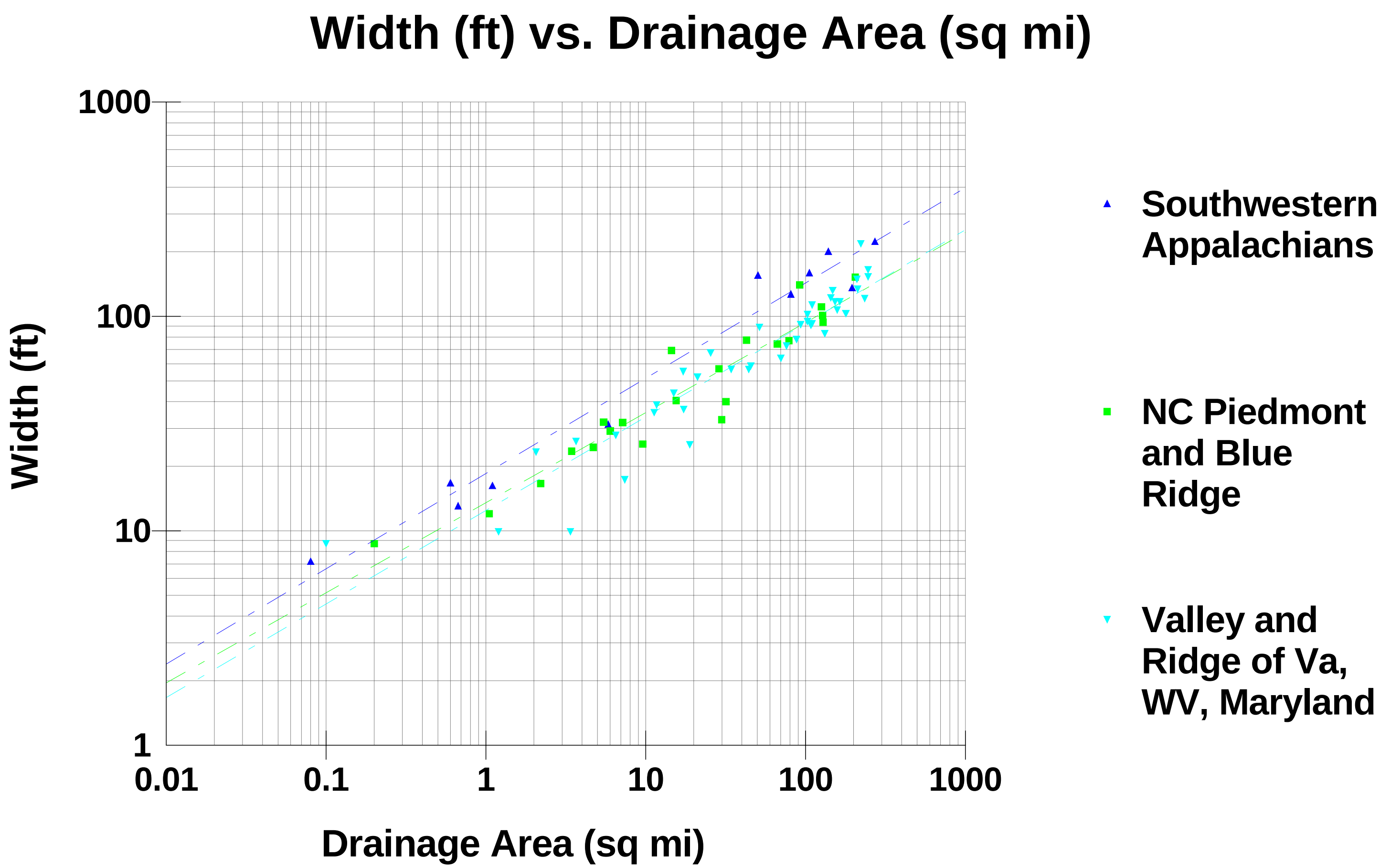


**Figure 4-8. Bankfull Width to Drainage Area for Study Sites in Southwestern Appalachians of Tennessee Compared to the Valley and Ridge, and Piedmont and Blue Ridge.**

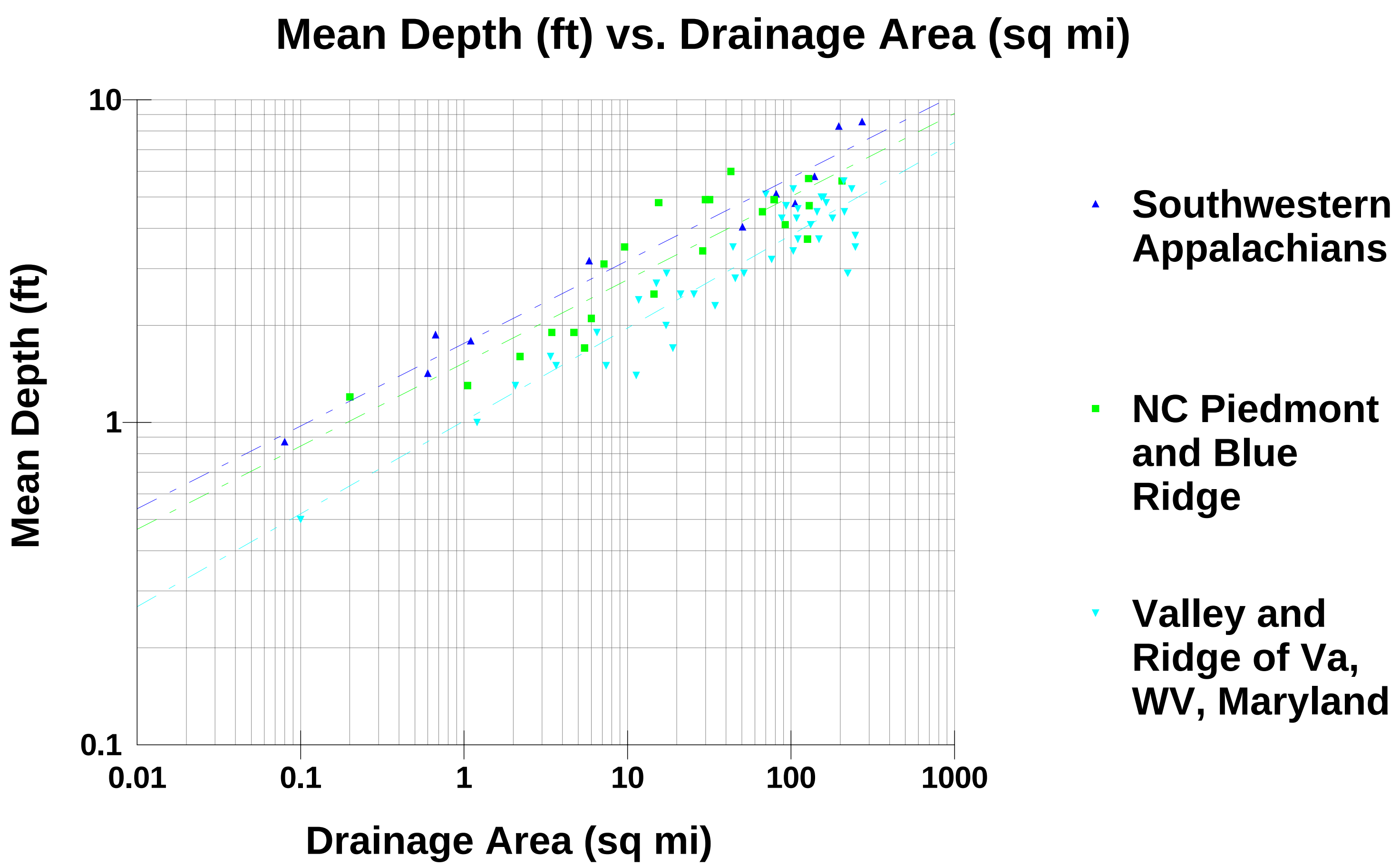


**Figure 4-9. Bankfull Mean Depth to Drainage Area for Study Sites in Southwestern Appalachians of Tennessee Compared to the Valley and Ridge, and Piedmont and Blue Ridge.**

## Discussion

The development of bankfull discharge and hydraulic geometry regional curves for the Southwestern Appalachians in Tennessee was challenging because of the lack of usable USGS gaging stations in the ecoregion. Out of 37 possible sites, nearly every gaged stream had experienced some form of human manipulation or modification. Many gaging stations were discontinued or their benchmarks were obliterated primarily because of bridge or road construction. Six out of the eight USGS gaging stations surveyed for this investigation had drainage areas greater than 50 square miles. It was imperative to find smaller streams representative of the region with drainage areas less than 20 square miles since the majority of stream restoration projects are conducted on first and second order streams. The three ungaged streams included in this study have not been monitored long enough to determine if they are reference reach quality streams. However, these streams are representative of watersheds possessing historical and current land use, vegetation, geology, topography, soils and climate typical of the ecoregion.

The gaged bankfull velocity associated with Brown Spring Branch does not appear to be reasonable. The USGS streamflow gaging station was a discontinued crest gage located on a box culvert. The shape of the culvert is an inaccurate representation of the natural channel shape, thus explaining the lower velocity and associated discharge. The stage-discharge rating table does not appear to be a correct representation of the flows experienced by the Brown Spring Branch stream channel.

Since the regional curves for the Southwestern Appalachians dramatically differ from those of the adjacent Ridge and Valley, it becomes apparent that it is vital for those practicing stream restoration based on natural channel design to have accurate regional curves at their disposal. Several explanations for the significant difference in regional curves were proposed by investigators during the course of my study.

First, the Southwestern Appalachians are extremely different from the other physiographic regions used in this comparison. The unique geology, such as the sandstone cap covering the ecoregion may play a tremendous role in the timing, magnitude and rate of surface runoff. The thin layer of sandy loam soils underlain by an abundance of bedrock may initially have high infiltration rates. Once water percolates through the thin layer of soil and reaches the bedrock or impervious layer, then runoff rates may significantly increase because of the lack of storage capacity, resulting in higher frequency and higher magnitude flows. Second, mean annual precipitation is approximately 10 inches more than the Ridge and Valley. Third, the significant slopes of streams flowing down the escarpment may explain increased velocities and flashiness during storm events. A comparison between the 1.5-year RI of the Southwestern Appalachians and the Ridge and Valley illustrate a much greater discharge for the Southwestern Appalachians for the same recurrence time of flow (Figure 4-10). This attribute suggests that there are larger magnitude bankfull flows for the Southwestern Appalachians. As identified in this study, bankfull discharge is significantly correlated to bankfull cross-sectional area with a coefficient of determination of $R^2 = 0.9924$ (Figure 4-11). It follows, that bankfull cross-sectional area is much greater because of the larger magnitude of bankfull discharge. Further examination of discharge and cross-sectional area demonstrate similar relationships for the three regions (Figure 4-12). This graph shows that the calculated discharges for the smaller streams are consistent with all three regional relationships.

Seven of the rivers surveyed in the Southwestern Appalachians were dominated by bedrock. Stream channels predominantly composed of bedrock substrates have natural grade control, which substantially affects bankfull width because the channel is forced to make lateral adjustments over the decadal timescale. I found that this channel characteristic created a condition in which discharge is highly sensitive to stage. Each slight increase in stage dramatically increased width and cross section area, thereby significantly increasing discharge. The higher width/depth ratio streams typically associated with Rosgen B stream types were indicative of this channel characteristic. Stream channels controlled by bedrock on both the bed and one bank were usually found in valley type IV. Another aspect of bedrock-dominated streams is the fact that velocity and shear stress are typically much greater than in alluvial systems (Tinkler and Wohl, 1998.

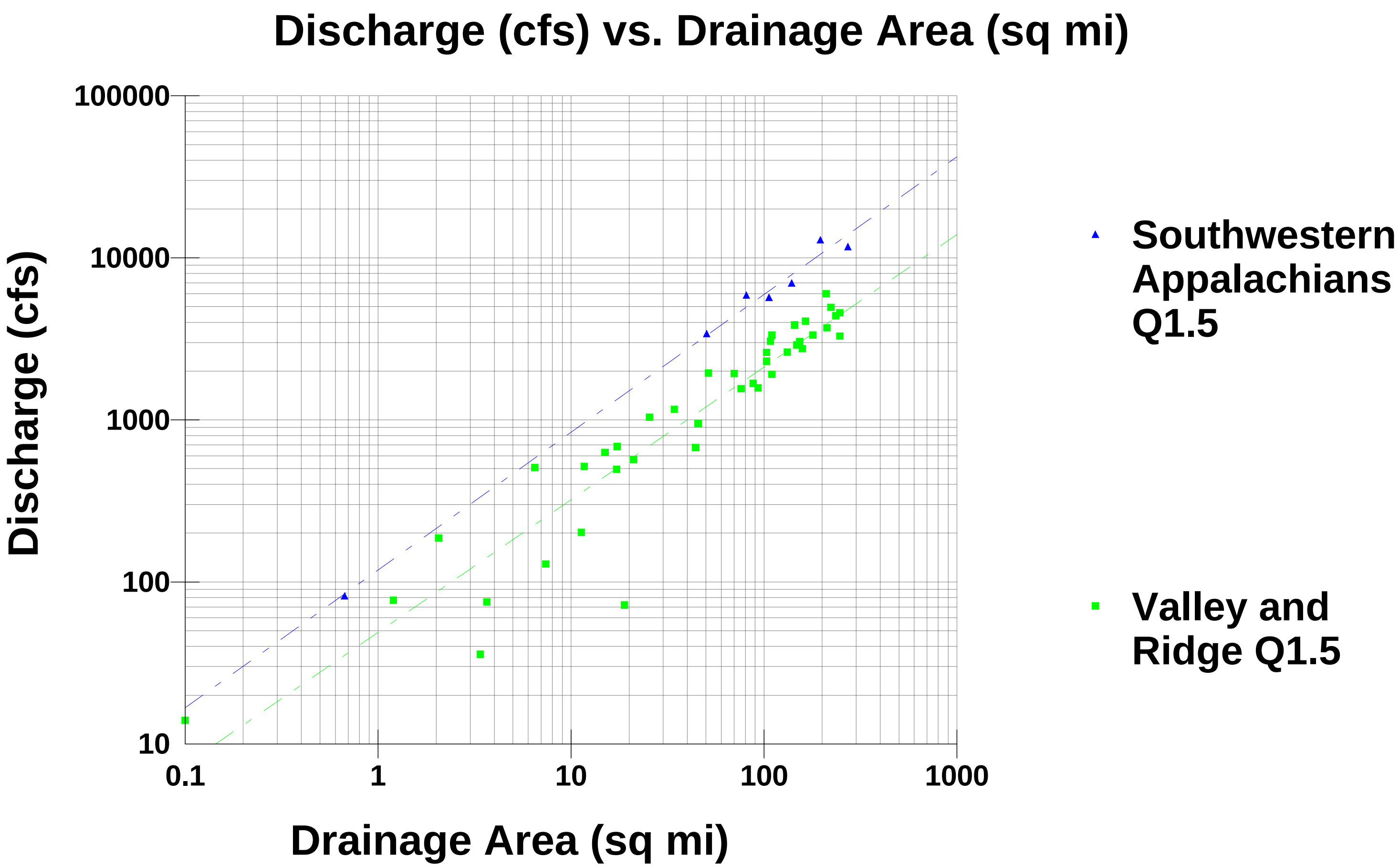


**Figure 4-10. 1.5-Year Flows of Southwestern Appalachian Gaging Stations Compared to the Valley and Ridge.**

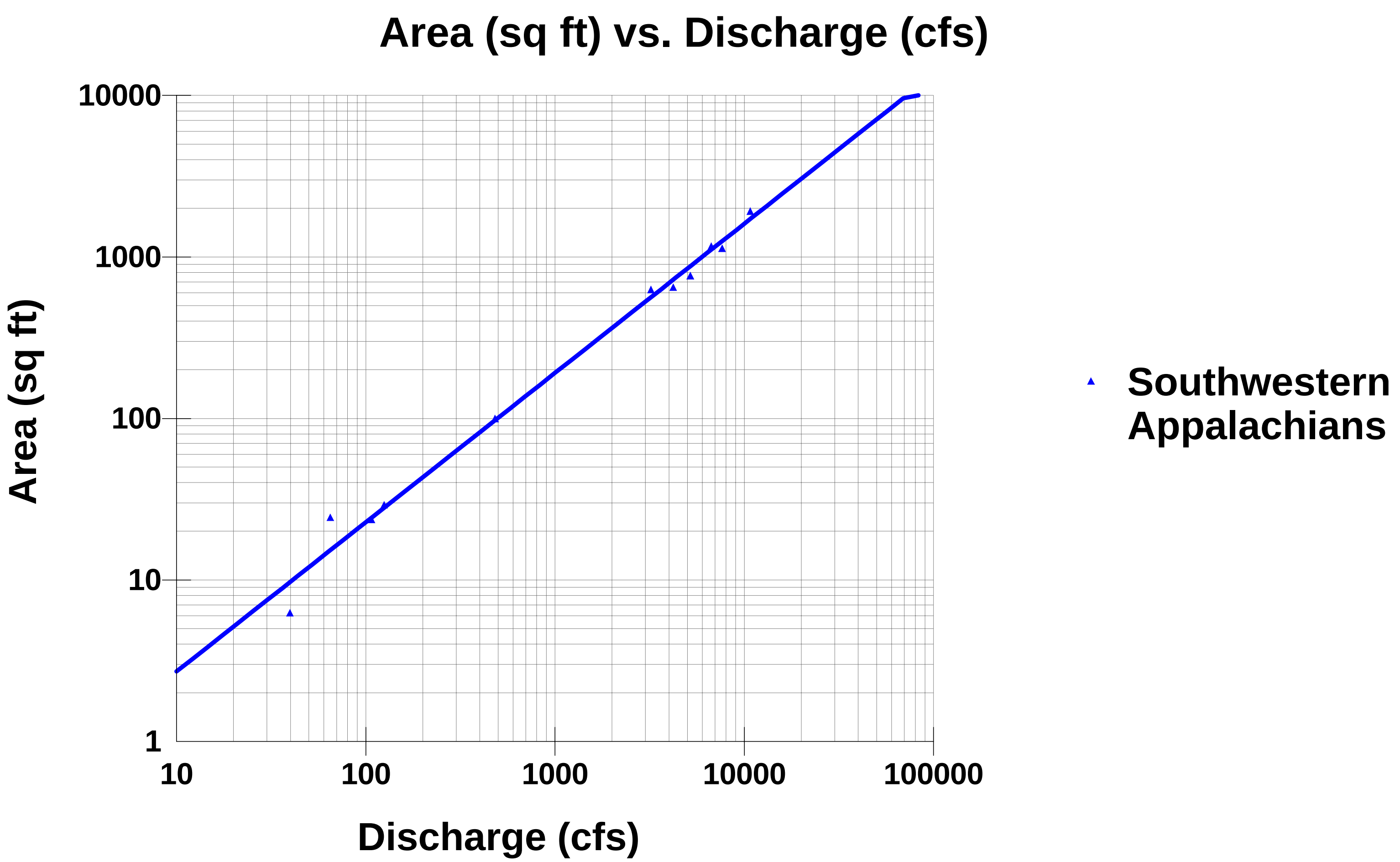


**Figure 4-11. Bankfull Discharge versus Cross-Sectional Area for Study Sites in Southwestern Appalachians of Tennessee 2005.**

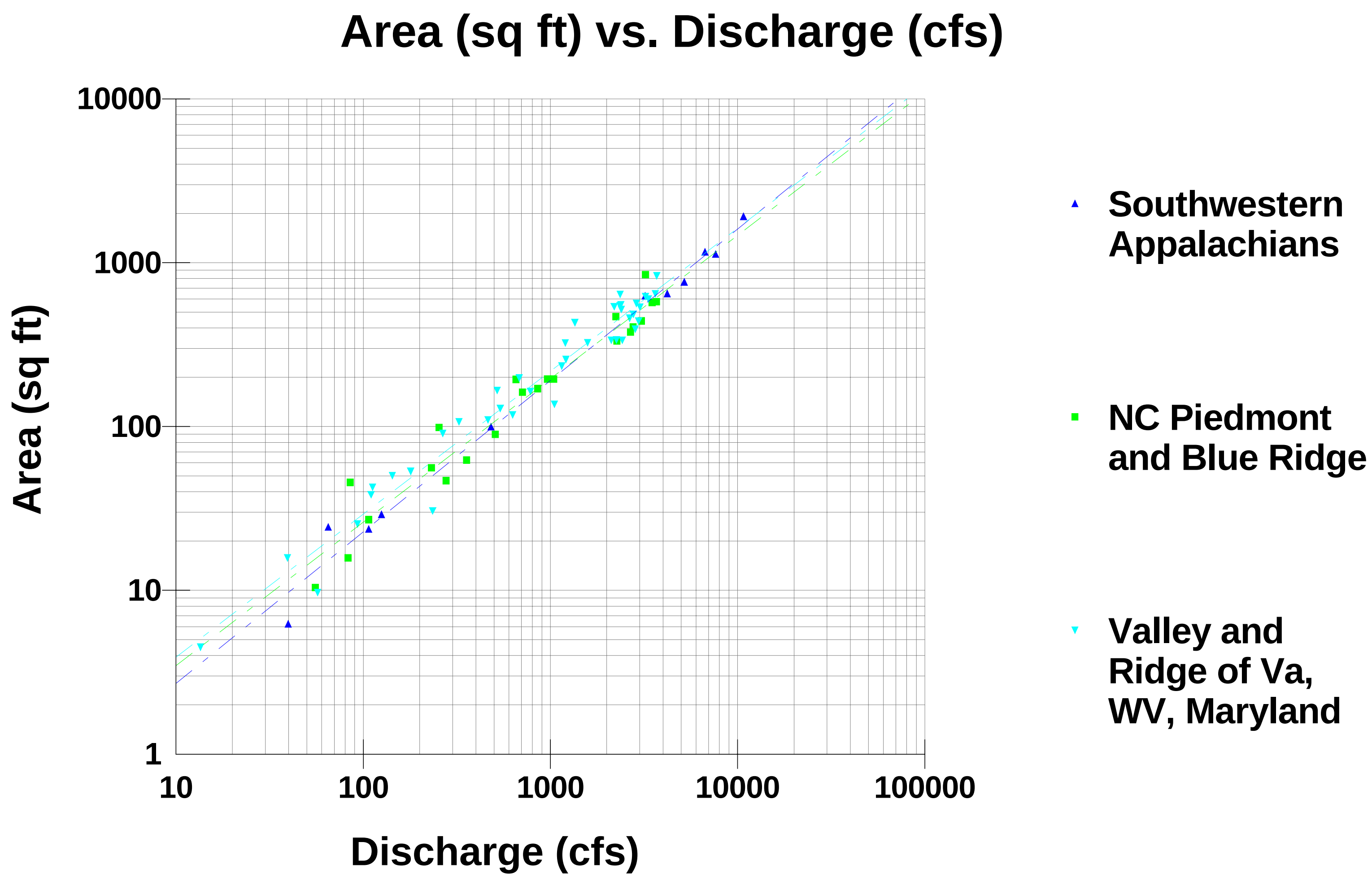


**Figure 4-12. Bankfull Discharge versus Cross-Sectional Area for the Southwestern Appalachians, Valley and Ridge, Piedmont and Blue Ridge.**

# CHAPTER V
# CONCLUSIONS AND RECOMMENDATIONS

My investigation was accomplished during the spring and summer of 2005 and included a geomorphic assessment of 11 stream reaches. At each study reach, the longitudinal profile, channel cross-sections and channel materials were surveyed. The first objective of this study was to test if the bankfull RI of streams draining the Southwestern Appalachians Level III Ecoregion 68 of Tennessee was within the widely published bankfull RI of 1 to 2 years. I hypothesized that the bankfull RI for the Southwestern Appalachians was between 1 and 2 years. This hypothesis was supported by the concurrence of a group of professionals who surveyed bankfull indicators along a sample of rivers and by my examination of field-identified bankfull indicators, longitudinal profiles, cross-sections, minimum width/depth ratio and log-Pearson Type III flood frequency analysis of records from seven USGS gaging stations.

For the East Fork and West Fork of the Obey River, the Wolf River and the Clear Fork of Big South Fork of the Cumberland River, 75 % of the group of professionals observed bankfull indicators within a range that calculated to have a RI of 1.0 -1.1. I found that the bankfull RI ranged from 1.1-1.4 years and averaged 1.31 years for the Southwestern Appalachians in Tennessee. The average RI was slightly less than the commonly accepted 1.5 years, but was similar to the RIs found in the Valley and Ridge of Virginia, West Virginia, Maryland and the Piedmont and Blue Ridge of North Carolina.

The lower RI may be attributed to a lack of soil water storage capacity and the influence of the sandstone bedrock cap found throughout the ecoregion. Also, the high gradient streams cascading down the escarpment may explain the flashiness of many of the rivers. Comparing the 1.5-year flows for the Southwestern Appalachians to the Valley and Ridge demonstrated a much greater magnitude of stream flows for the Southwestern Appalachians. Increased runoff rates may be explained by an investigation into infiltration and soil moisture storage. Calculations of runoff rates using the NRCS TR 55 model may give insight to stream flows produced by a specific size storm event.

Further rainfall/runoff studies are needed to expand on stream flows of larger magnitude and greater frequency in this ecoregion. Additional surveys of streams with USGS gaging stations would increase sample power.

My second objective was to develop bankfull discharge and hydraulic geometry relationships as a function of watershed area for streams draining the Southwestern Appalachians and compare those relationships to the neighboring Valley and Ridge regional curves in Virginia, West Virginia, Maryland (Keaton *et al.*, 2005) and the commonly used regional curves of the Piedmont and Blue Ridge of North Carolina (Harman *et al.*, 1999; Harman *et al*. 2000). I hypothesized that the bankfull discharge and hydraulic geometry of streams draining the Southwestern Appalachians are significantly different from those streams draining the Valley and Ridge of Virginia, West Virginia, Maryland and the Piedmont and Blue Ridge of North Carolina. Power function regression equations and the respective coefficients of determination were computed for bankfull discharge, cross sectional area, width and mean depth as a function of drainage area. These regional relationships demonstrated that drainage area explained from 96.6 to 99.5 percent of the variability in bankfull hydraulic geometry. This study confirmed a significant difference in the magnitude of channel forming flows as well as stream channel geometry between the Southwestern Appalachians in Tennessee, Ridge and Valley in Virginia, West Virginia, Maryland and the Piedmont and Blue Ridge of North Carolina.

Comparisons of the four bankfull regional curves (discharge, cross-sectional area, width and mean depth) associated with each region reveal a statistically significant difference between the Southwestern Appalachian curves and the Valley and Ridge and Piedmont and Blue Ridge with exception to bankfull mean depth. Bankfull mean depth did not differ significantly between the Southwestern Appalachians and the Piedmont and Blue Ridge. However, average bankfull mean depths for the Southwestern Appalachians and the North Carolina Piedmont and Blue Ridge were approximately 25 percent greater than those determined for the Valley and Ridge. Bankfull discharge in the Southwestern Appalachians was approximately 180 percent greater than that of the Piedmont and Blue Ridge of North Carolina and approximately 282 percent greater than the Ridge and

Valley of Virginia, West Virginia and Maryland when the curves are evaluated using a drainage area of 75 square miles. Comparisons of bankfull cross sectional area show a difference of 165 percent and 230 percent, respectively. A comparison of bankfull width of the three regions illustrates that Southwestern Appalachian streams are approximately 130 percent wider than streams in the Piedmont and Blue Ridge of North Carolina and 138 percent wider than the Valley and Ridge.

Due to the natural variability among processes acting on river basins, the reader should be advised that the regional curves developed in this study are preliminary and intended to be used as a tool for stream assessment and bankfull validation, and should not be relied on for precise bankfull calculations. The regional curves for the Southwestern Appalachians may be used to augment detailed fluvial geomorphic studies conducted on a particular stream reach within the ecoregion. Future investigations of streams in the Southwestern Appalachian ecoregion may be used to supplement the preliminary regional curves developed for this study.

As stream restoration efforts involving natural channel design increase in the state of Tennessee, development of bankfull regional relationships for unique ecoregions across the state is critical. Those who design natural stream channel restoration projects without valid bankfull regional relationships run the risk of misidentifying bankfull stage. Without accurate regional curves, there is a lack of supportive data to validate a bankfull determination. Furthermore, by using bankfull regional curves developed for a different ecoregion or physiographic province, risks determining bankfull stage incorrectly. Designing a stream channel with inaccurate channel dimensions could exacerbate bed and bank erosion, create lateral and vertical instability and result in increased sediment input to the fluvial system.

Results of this study have shown a need to develop regional bankfull discharge and hydraulic geometry relationships for Tennessee. Fluvial geomorphic investigations of streams throughout Tennessee will improve our understanding of regional morphological characteristics and aid in stream assessment. Future studies are needed to more accurately predict bankfull discharge and hydraulic geometry for other regions in Tennessee.

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**APPENDIX**

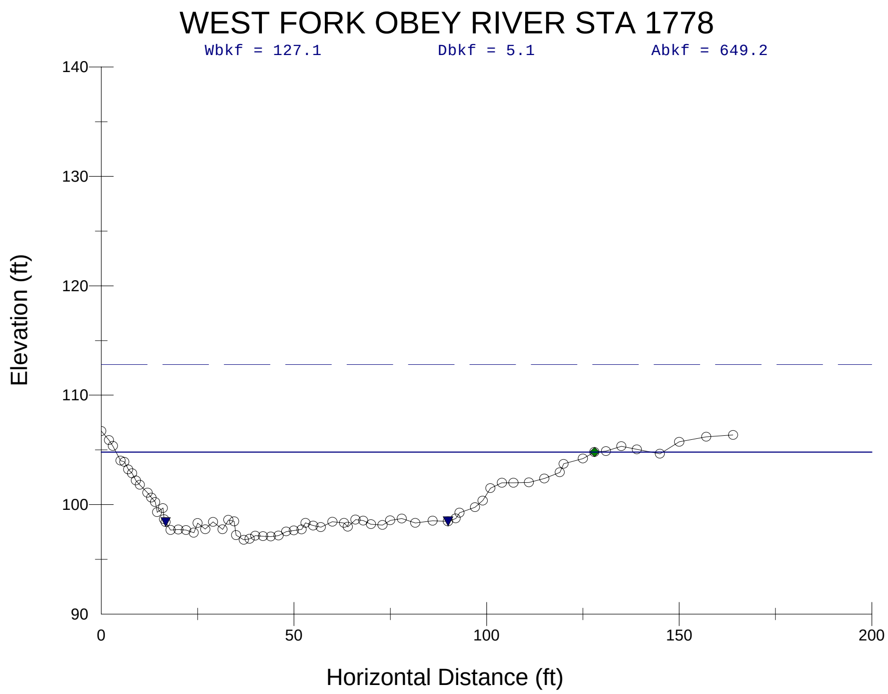
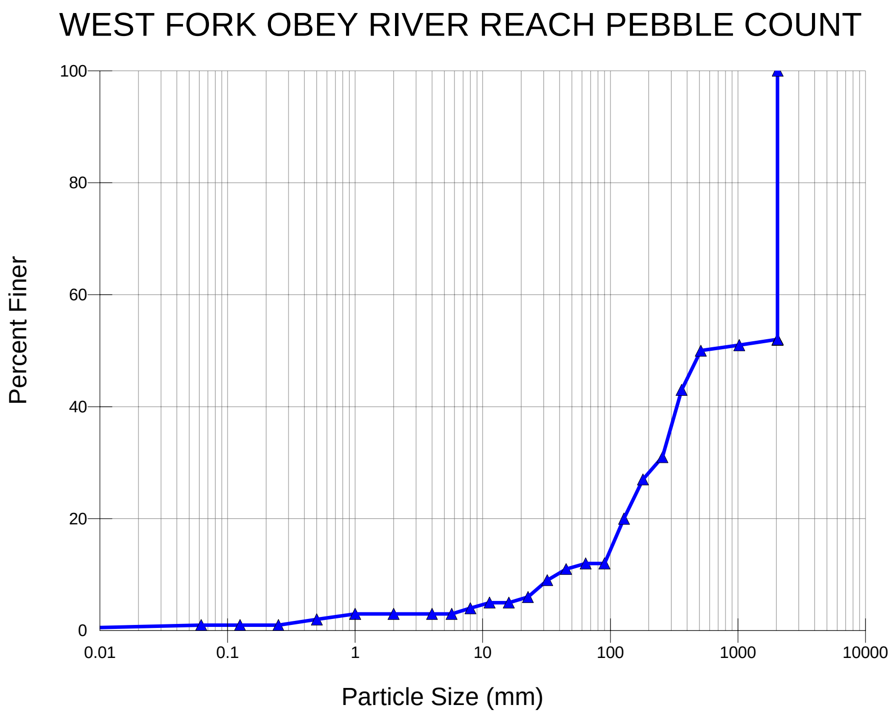



**Figure A-1. West Fork Obey River.**



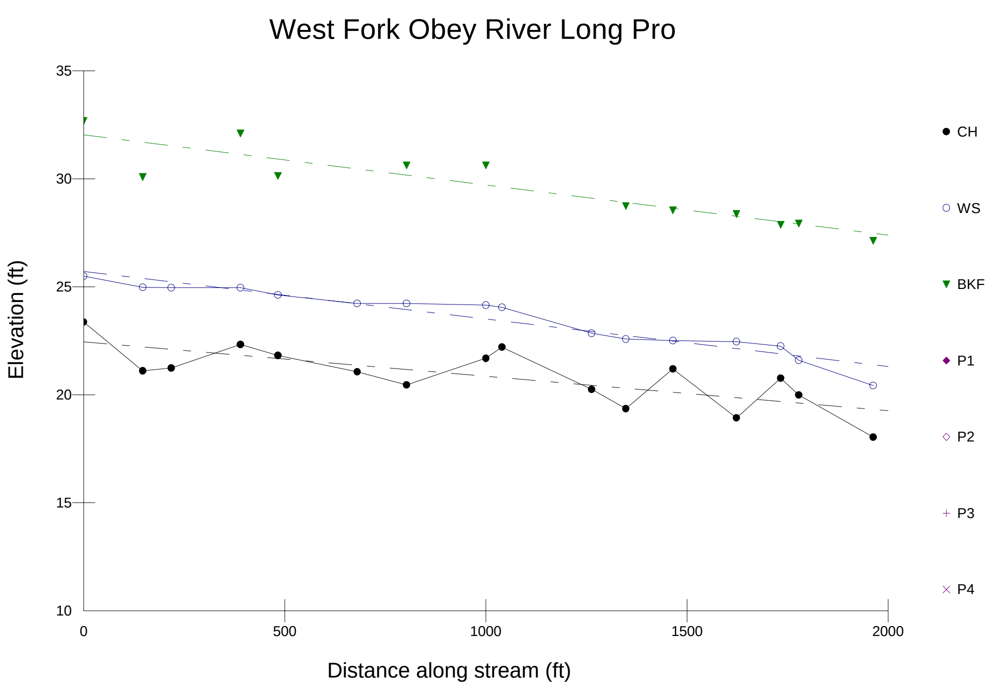




**Figure A-1. Continued.**

STREAM CHANNEL CLASSIFICATION

-----------------------------------------------------------------------

River Name: Big South Fork Cumberland River
Reach Name: West Fork Obey River
Drainage Area: 81 sq mi
State: Tennessee
County: Overton
Latitude: 36 23 50
Longitude: 85 10 28
Survey Date: 04/16/05

-----------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type IV |
| Valley Slope: | 0.0025 ft/ft |
| Number of Channels: | Single |
| Width: | 127.11 ft |
| Mean Depth: | 5.11 ft |
| Flood-Prone Width: | 250 ft |
| Channel Materials D50: | 512 mm |
| Water Surface Slope: | 0.00258 ft/ft |
| Sinuosity: | 1.14 |
| Discharge: | 4210 cfs |
| Velocity: | 6.49 fps |
| Cross Sectional Area: | 649.19 sq ft |
| Entrenchment Ratio: | 1.97 |
| Width to Depth Ratio: | 24.87 |
| Rosgen Stream Classification: | B 2/1c |

**Figure A-1. Continued.**

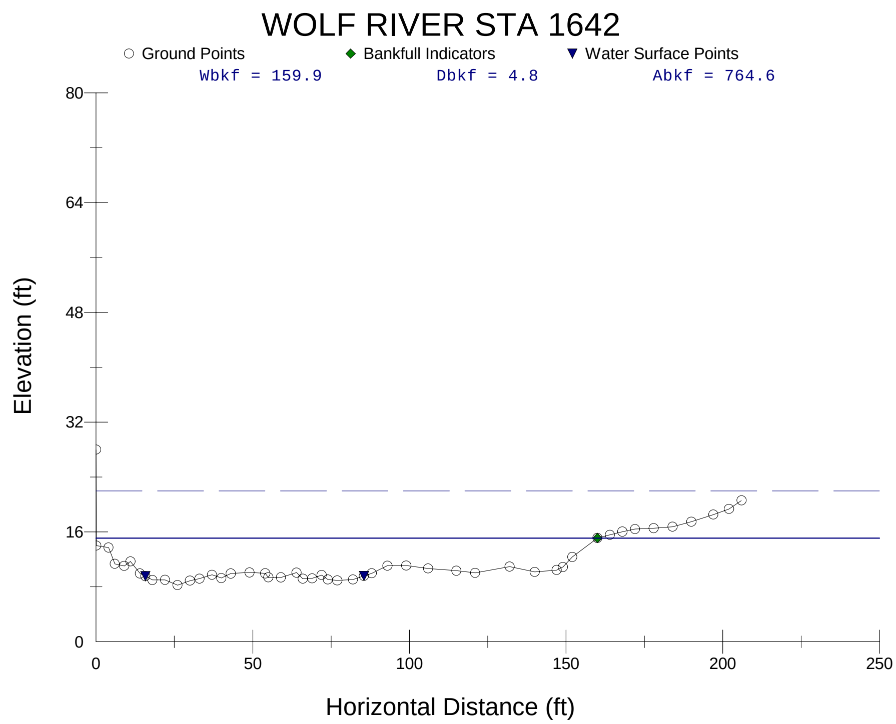
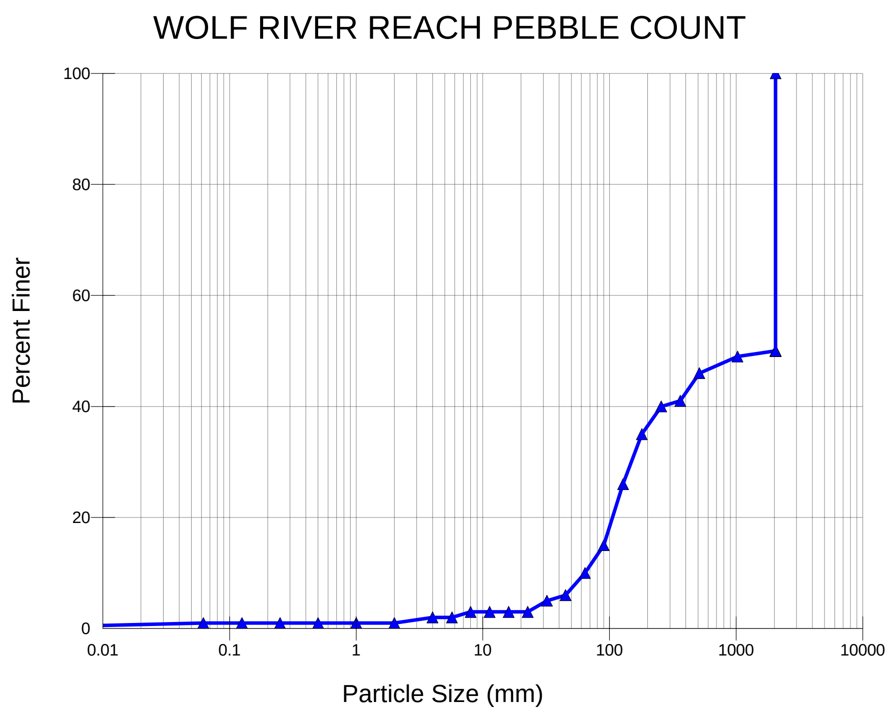



**Figure A-2. Wolf River.**



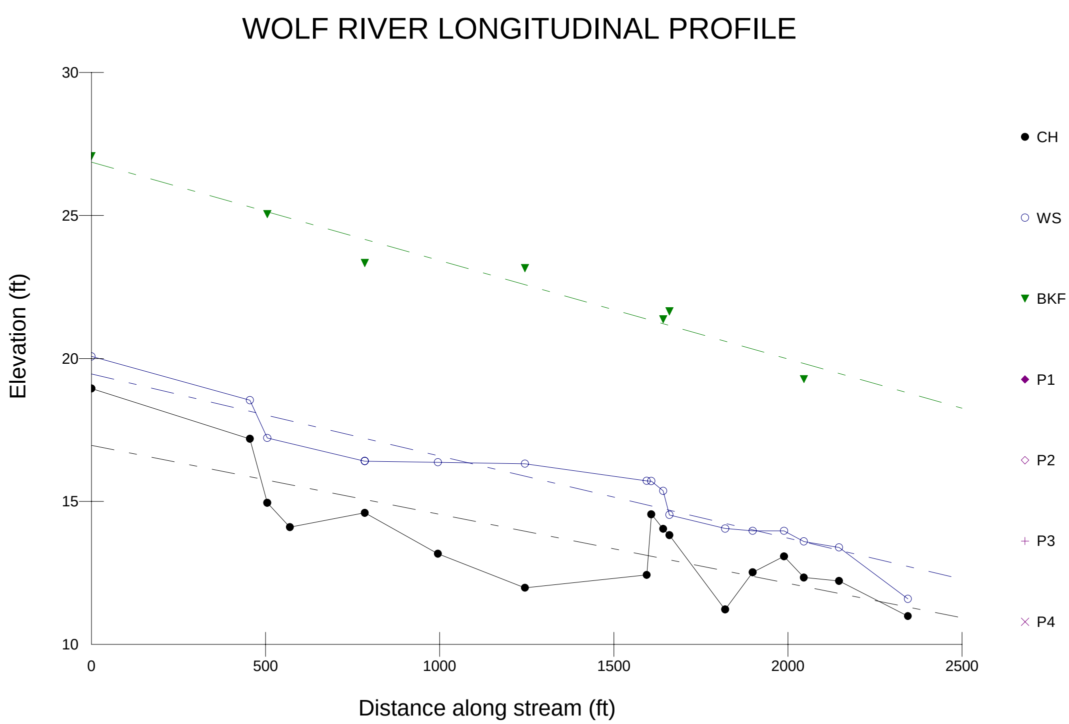




**Figure A-2. Continued.**

STREAM CHANNEL CLASSIFICATION

--------------------------------------------------------------------

River Name: Big South Fork Cumberland River
Reach Name: Wolf River
Drainage Area: 106 sq mi
State: Tennessee
County: Pickett
Latitude: 36 33 37
Longitude: 85 01 35
Survey Date: 05/18/05

--------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type IV |
| Valley Slope: | 0.0043 ft/ft |
| Number of Channels: | Single |
| Width: | 159.91 ft |
| Mean Depth: | 4.78 ft |
| Flood-Prone Width: | 253 ft |
| Channel Materials D50: | 2048 mm |
| Water Surface Slope: | 0.0036 ft/ft |
| Sinuosity: | 1.2 |
| Discharge: | 5180 cfs |
| Velocity: | 6.78 fps |
| Cross Sectional Area: | 764.55 sq ft |
| Entrenchment Ratio: | 1.58 |
| Width to Depth Ratio: | 33.45 |
| Rosgen Stream Classification: | B 1/1c |

**Figure A-2. Continued.**

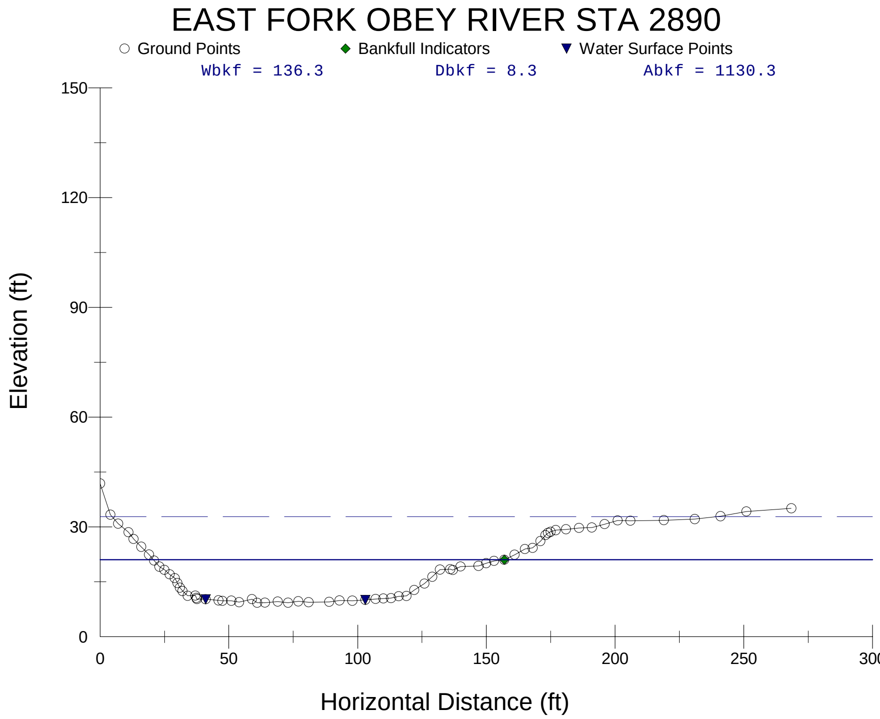
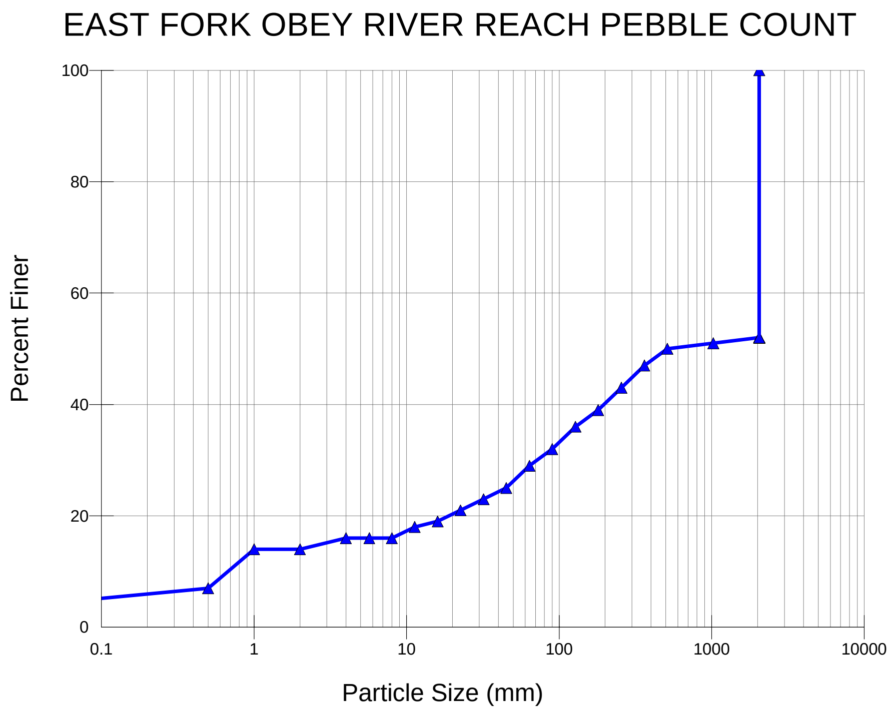



**Figure A-3. East Fork Obey River.**



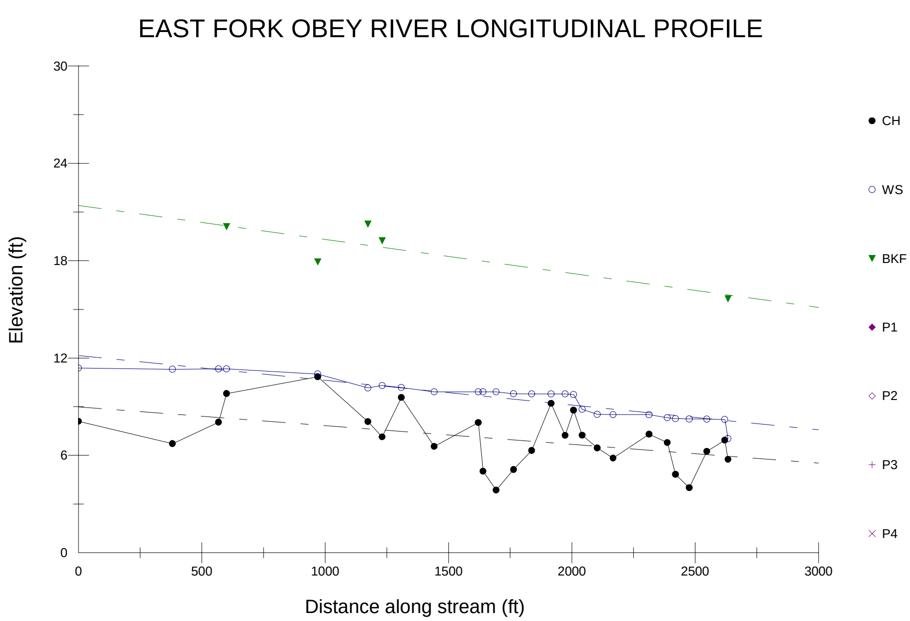




**Figure A-3. Continued.**

STREAM CHANNEL CLASSIFICATION

--------------------------------------------------------------------

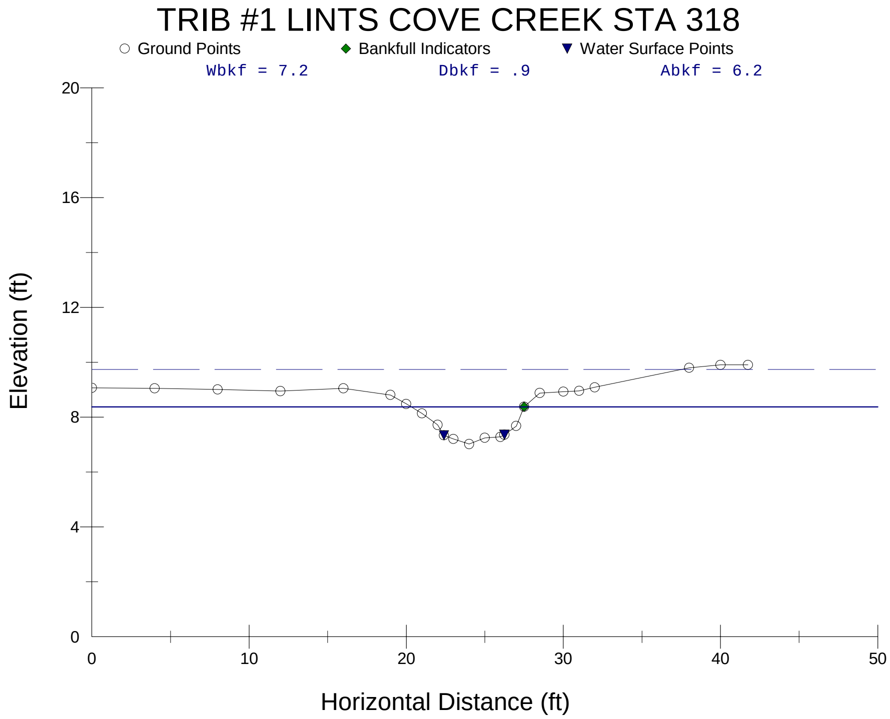
River Name: Big South Fork Cumberland River
Reach Name: East Fork Obey River
Drainage Area: 196 sq mi
State: Tennessee
County: Fentress
Latitude: 36 24 58
Longitude: 85 01 35
Survey Date: 06/17/05

--------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type II |
| Valley Slope: | 0.0011 ft/ft |
| Number of Channels: | Single |
| Width: | 136.28 ft |
| Mean Depth: | 8.29 ft |
| Flood-Prone Width: | 240 ft |
| Channel Materials D50: | 512 mm |
| Water Surface Slope: | 0.0009 ft/ft |
| Sinuosity: | 1.1 |
| Discharge: | 7620 cfs |
| Velocity: | 6.74 fps |
| Cross Sectional Area: | 1130.27 sq ft |
| Entrenchment Ratio: | 1.76 |
| Width to Depth Ratio: | 16.44 |
| Rosgen Stream Classification: | B 2/1c |

**Figure A-3. Continued.**



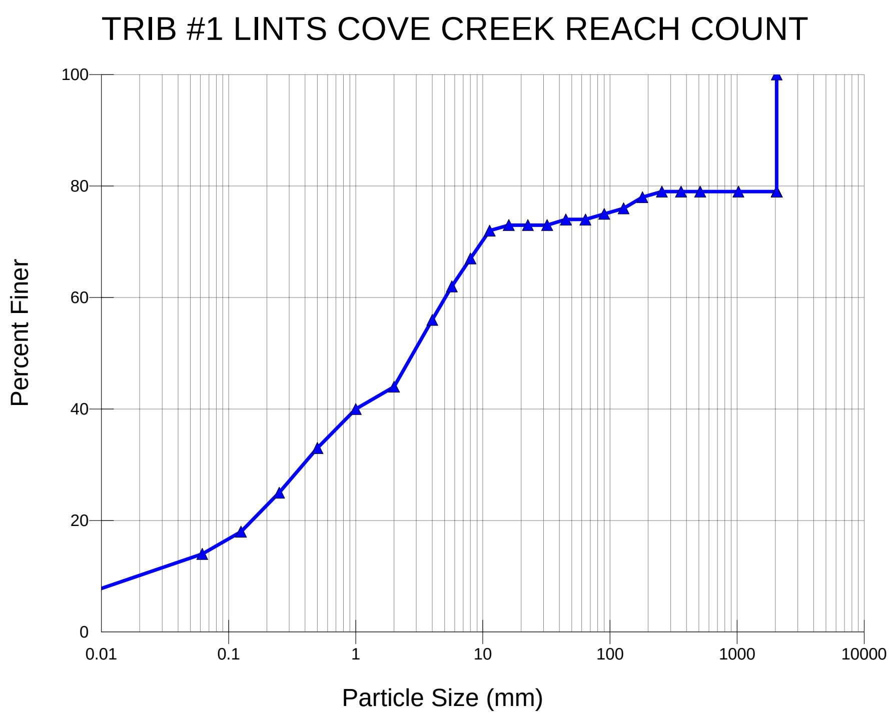
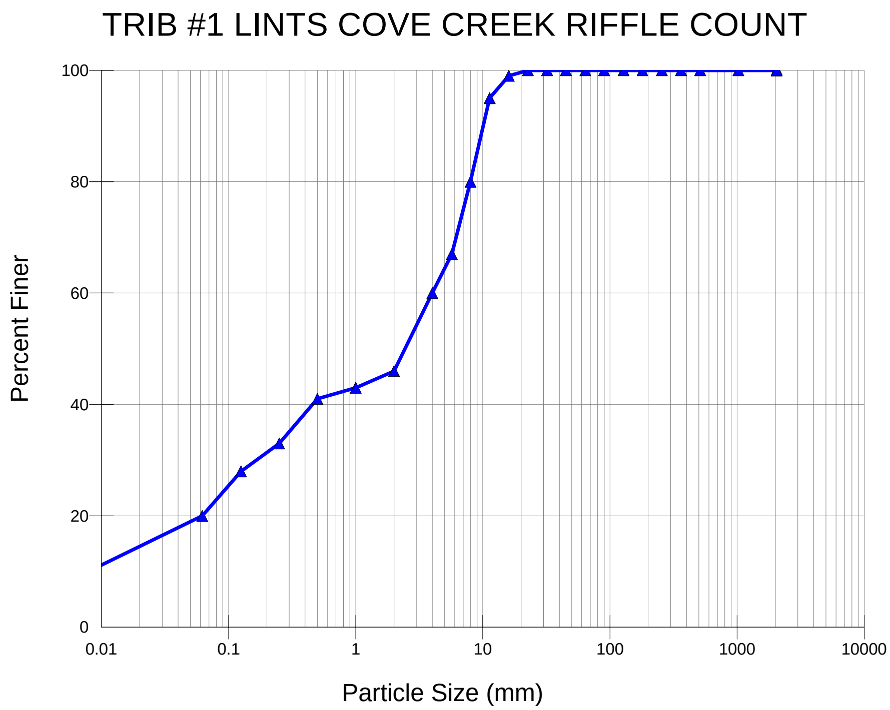




**Figure A-4. Tributary #1 Lints Cove Creek.**



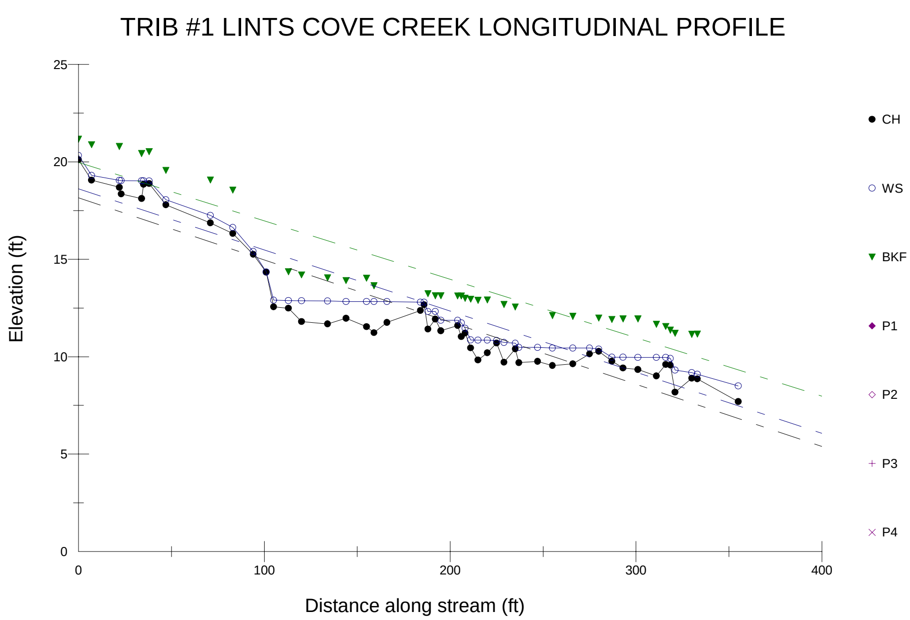




**Figure A-4. Continued.**

STREAM CHANNEL CLASSIFICATION

-----------------------------------------------------------------------

River Name: Big South Fork Cumberland River
Reach Name: Tributary #1 Lints Cove Creek
Drainage Area: 0.08 sq mi
State: Tennessee
County: Fentress
Latitude: 36 19 00
Longitude: 84 59 40
Survey Date: 08/19/05

-----------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type VIII |
| Valley Slope: | 0.0401 ft/ft |
| Number of Channels: | Single |
| Width: | 7.21 ft |
| Mean Depth: | 0.87 ft |
| Flood-Prone Width: | 80 ft |
| Channel Materials D50: | 3 mm |
| Water Surface Slope: | 0.016 ft/ft |
| Sinuosity: | 1.2 |
| Discharge: | 39.7 cfs |
| Velocity: | 6.35 fps |
| Cross Sectional Area: | 6.25 sq ft |
| Entrenchment Ratio: | 11.1 |
| Width to Depth Ratio: | 8.29 |
| Rosgen Stream Classification: | E 4/1 |

**Figure A-4. Continued.**

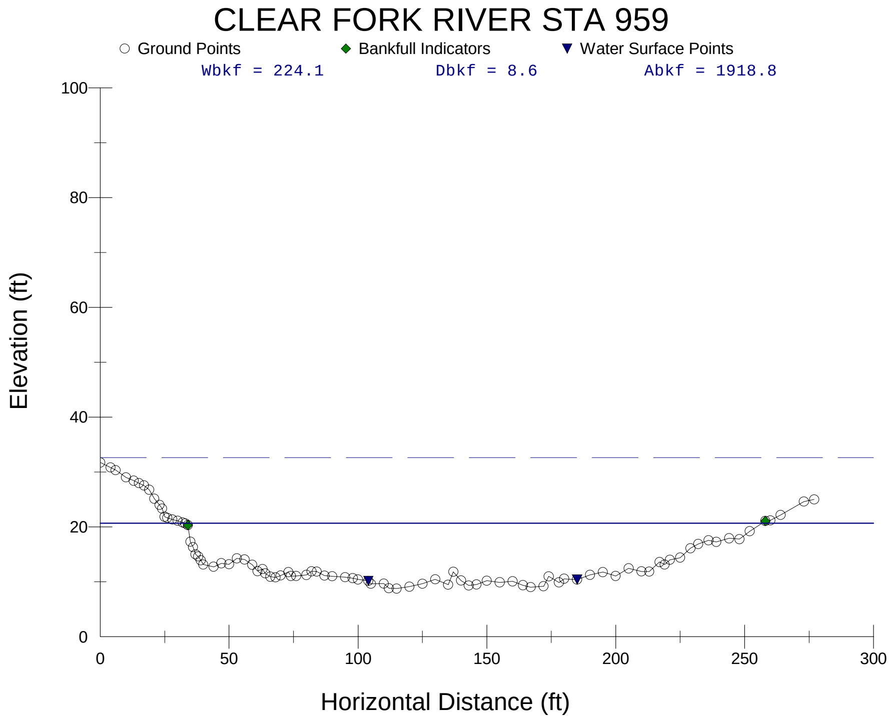
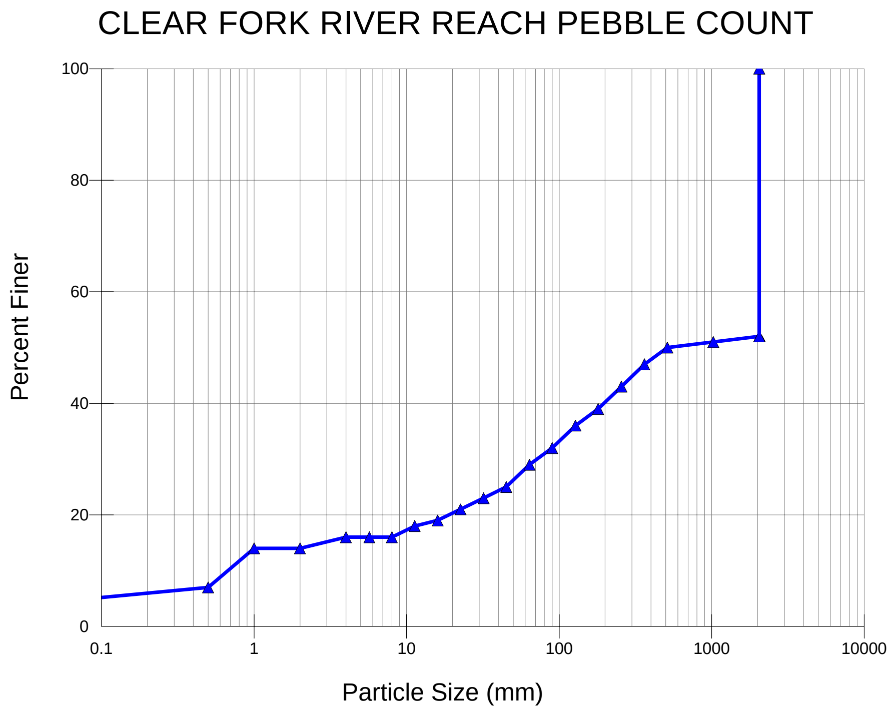



**Figure A-5. Clear Fork River.**



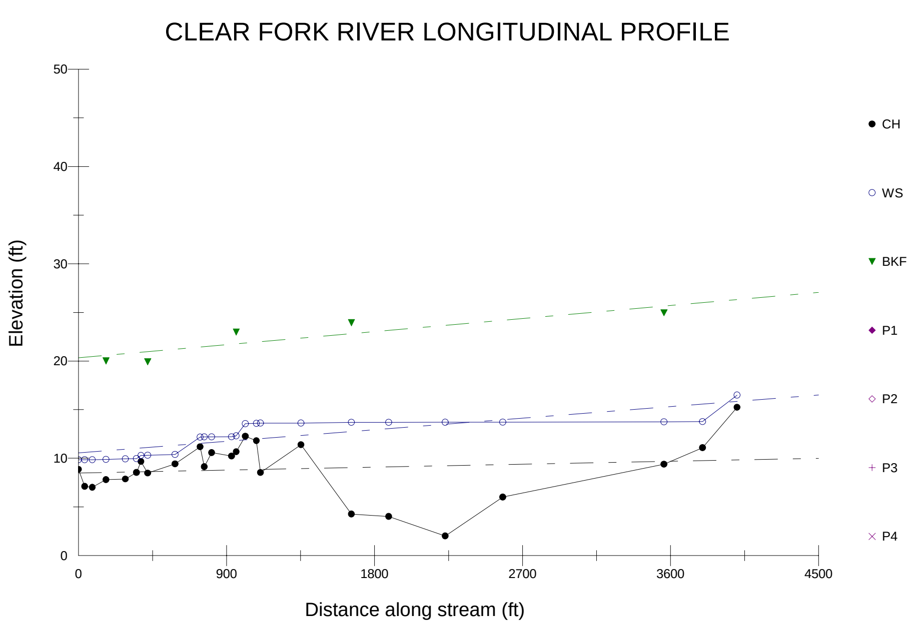




**Figure A-5. Continued.**

STREAM CHANNEL CLASSIFICATION

--------------------------------------------------------------------

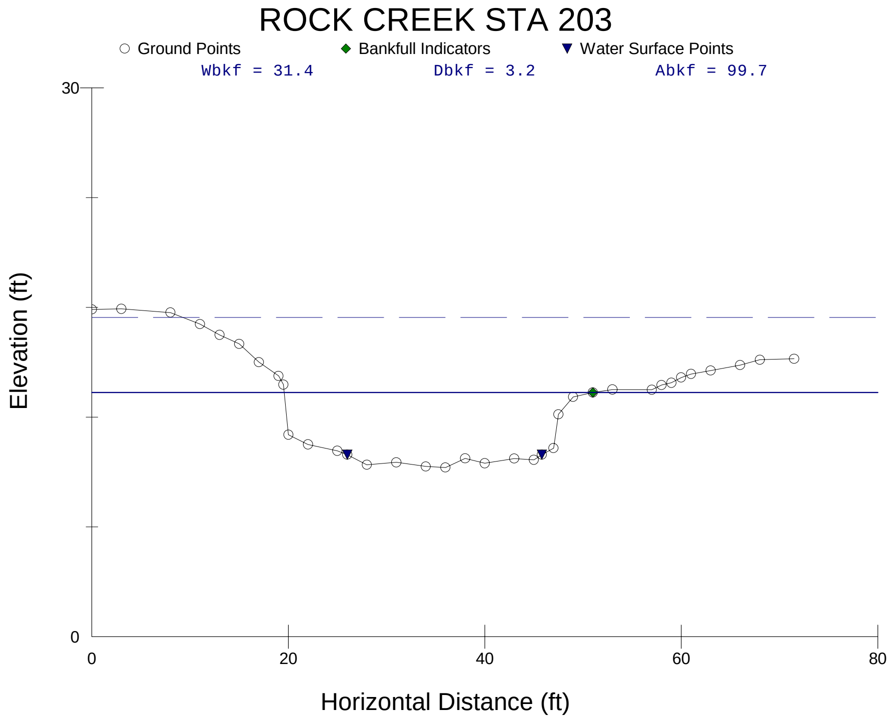
River Name: Big South Fork Cumberland River
Reach Name: Clear Fork River
Drainage Area: 272 sq mi
State: Tennessee
County: Scott
Latitude: 36 23 18
Longitude: 84 37 49
Survey Date: 08/02/05

--------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type IV |
| Valley Slope: | 0.0018 ft/ft |
| Number of Channels: | Single |
| Width: | 224.14 ft |
| Mean Depth: | 8.56 ft |
| Flood-Prone Width: | 325 ft |
| Channel Materials D50: | 512 mm |
| Water Surface Slope: | 0.00167 ft/ft |
| Sinuosity: | 1.1 |
| Discharge: | 10750 cfs |
| Velocity: | 5.6 fps |
| Cross Sectional Area: | 1918.84 sq ft |
| Entrenchment Ratio: | 1.45 |
| Width to Depth Ratio: | 26.18 |
| Rosgen Stream Classification: | B 2/1c |

**Figure A-5. Continued.**



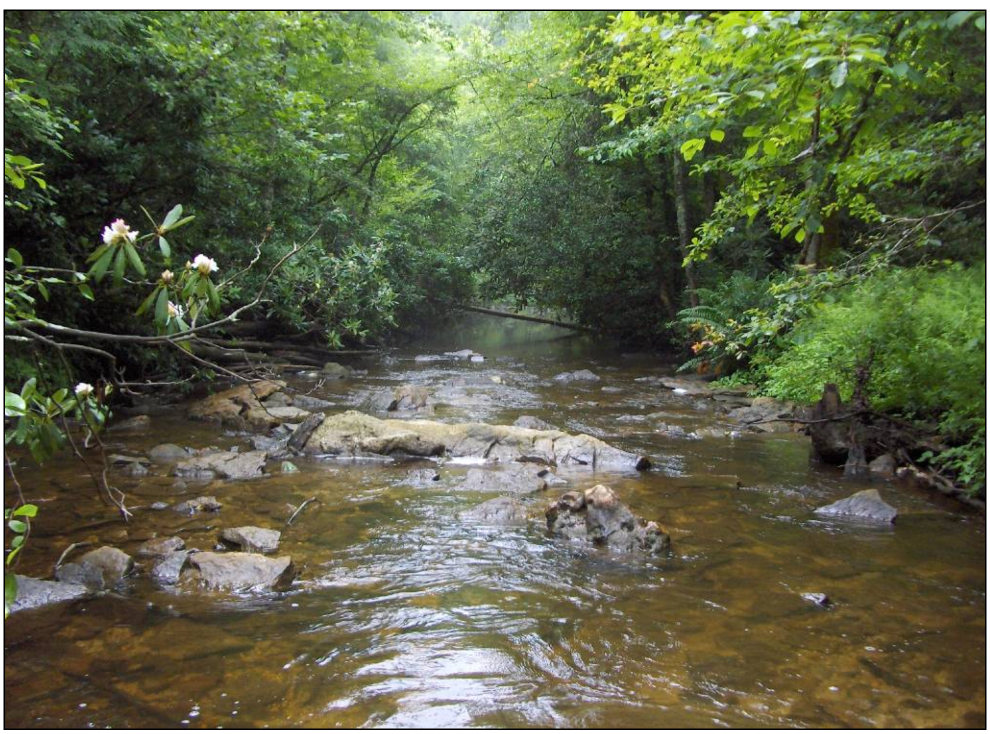
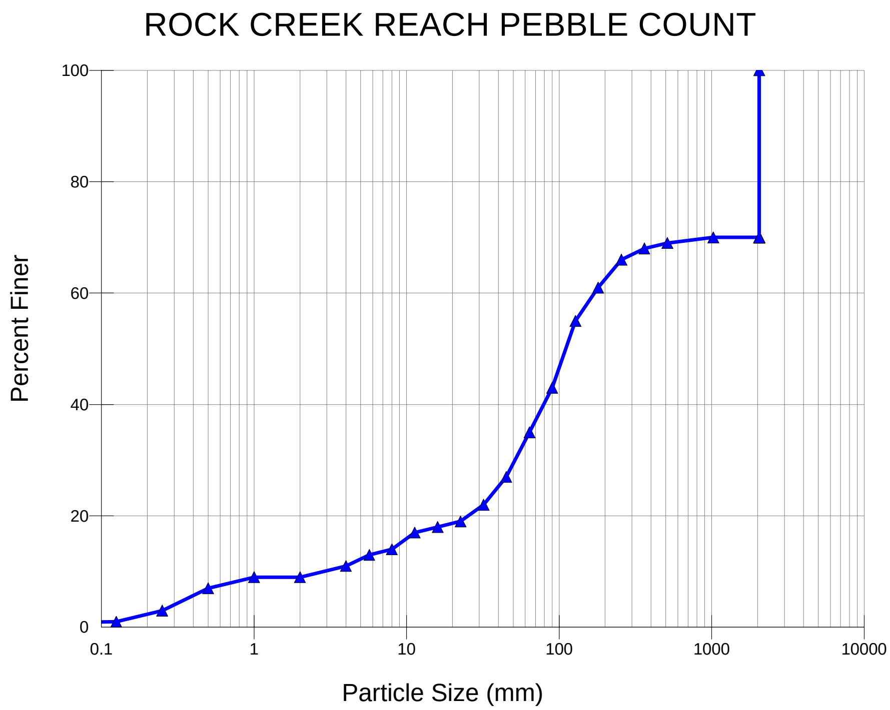



**Figure A-6. Rock Creek in Pickett State Park.**



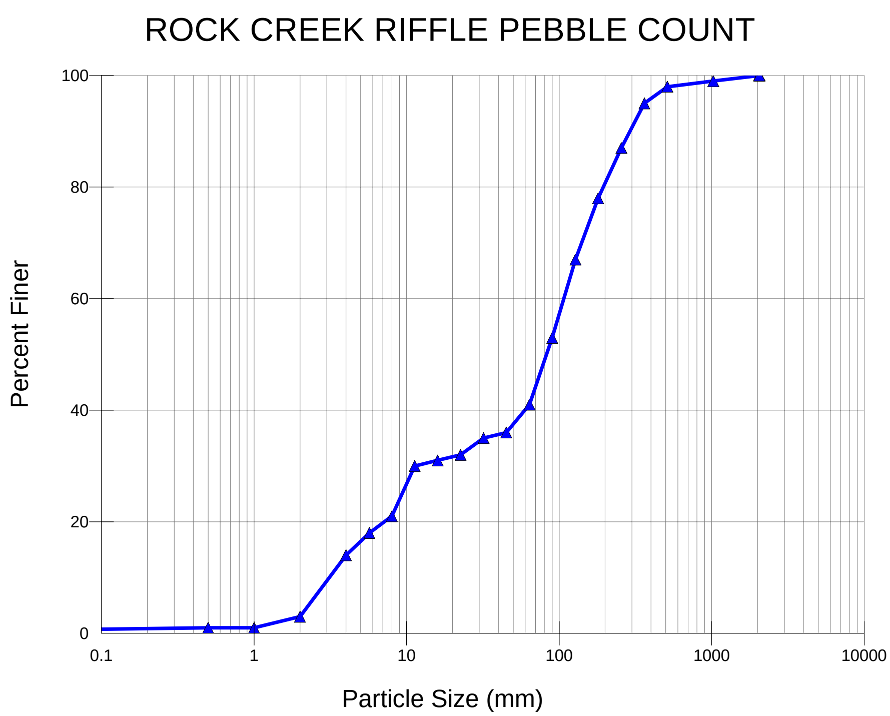




**Figure A-6. Continued.**

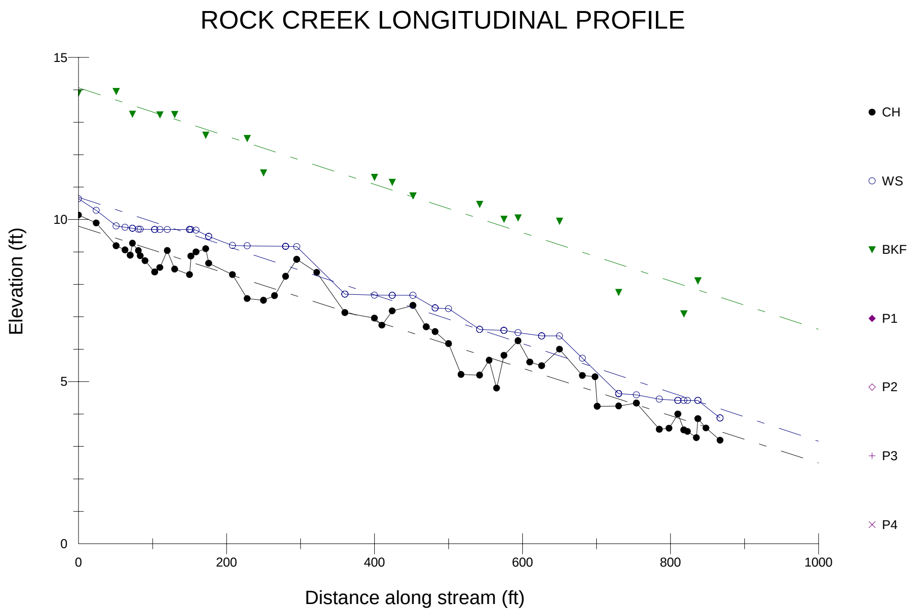



**Figure A-6. Continued.**

STREAM CHANNEL CLASSIFICATION

-------------------------------------------------------------------

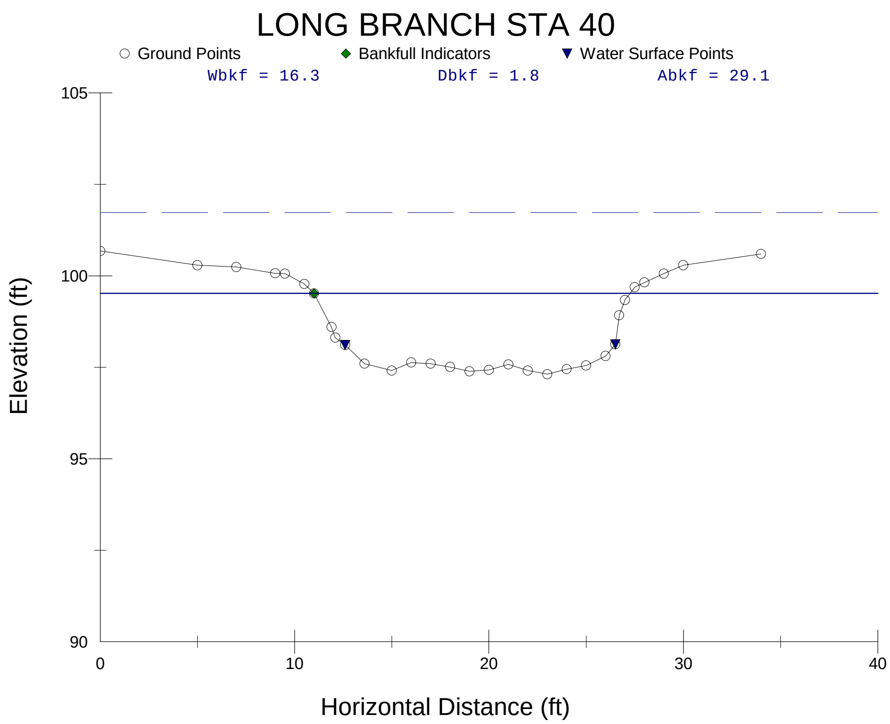
River Name: Big South Fork Cumberland River
Reach Name: Rock Creek
Drainage Area: 5.82 sq mi
State: Tennessee
County: Pickett
Latitude: 36 34 45
Longitude: 84 48 00
Survey Date: 07/17/05

-------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type II |
| Valley Slope: | 0.005 ft/ft |
| Number of Channels: | Single |
| Width: | 31.42 ft |
| Mean Depth: | 3.17 ft |
| Flood-Prone Width: | 140 ft |
| Channel Materials D50: | 112.17 mm |
| Water Surface Slope: | 0.0078 ft/ft |
| Sinuosity: | 1.2 |
| Discharge: | 482 cfs |
| Velocity: | 4.84 fps |
| Cross Sectional Area: | 99.66 sq ft |
| Entrenchment Ratio: | 4.46 |
| Width to Depth Ratio: | 9.91 |
| Rosgen Stream Classification: | E 3/1 |

**Figure A-6. Continued.**



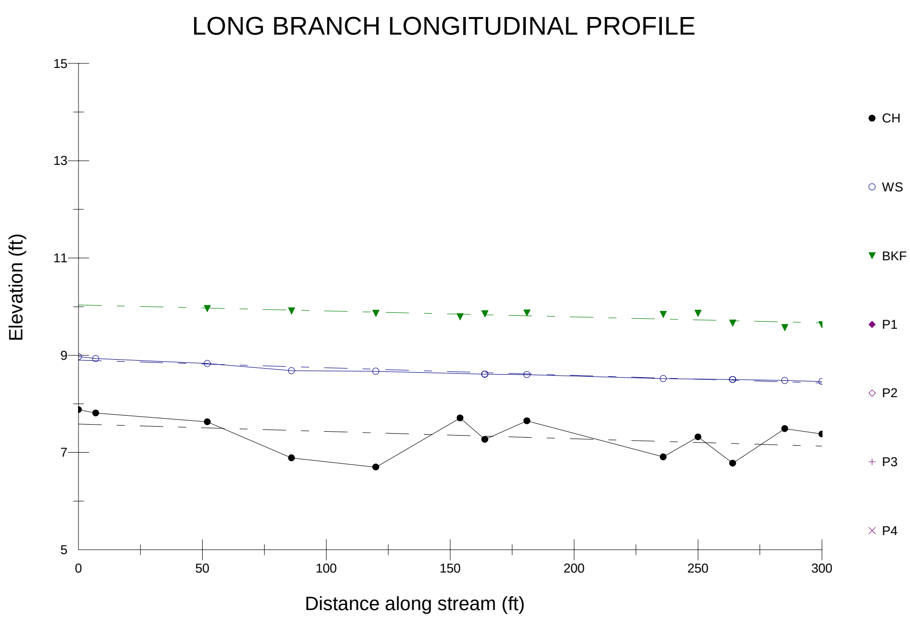
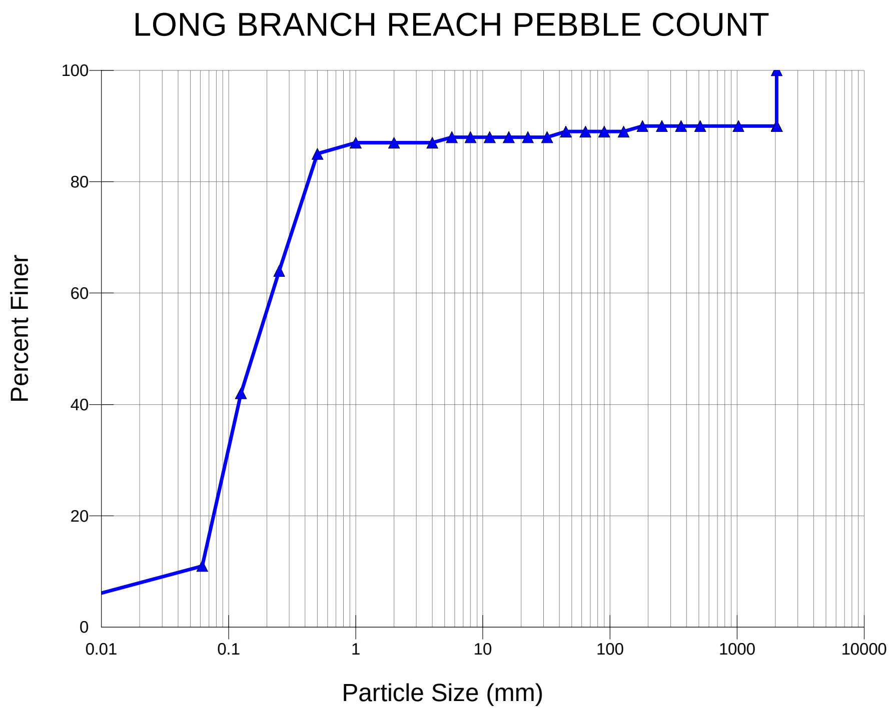




**Figure A-7. Long Branch.**



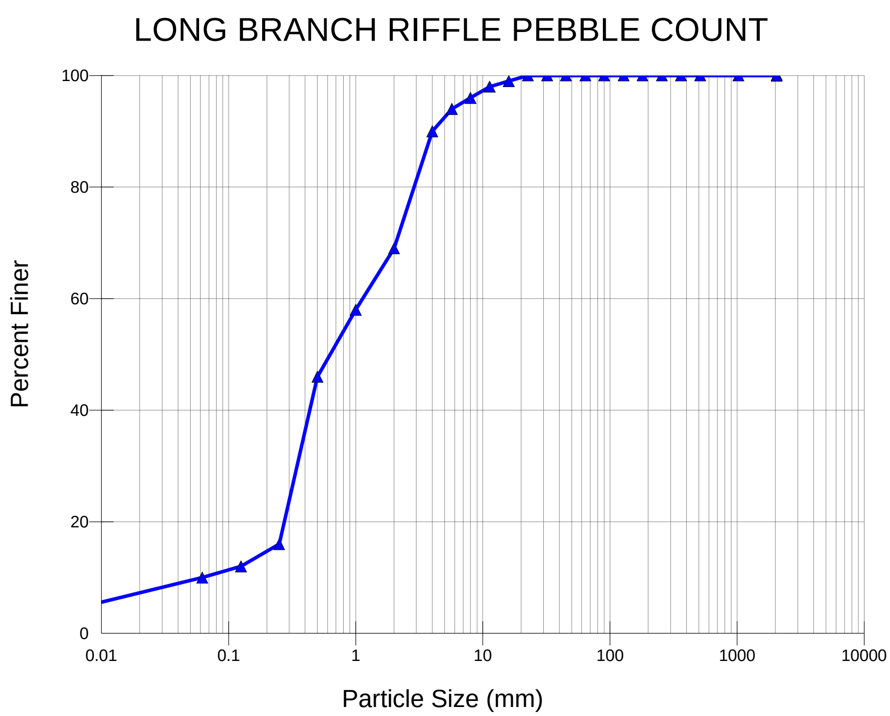




**Figure A-7. Continued.**

STREAM CHANNEL CLASSIFICATION

-------------------------------------------------------------------

River Name: Big South Fork Cumberland River
Reach Name: Long Branch
Drainage Area: 1.1 sq mi
State: Tennessee
County: Fentress
Latitude: 36 15 32
Longitude: 84 57 40
Survey Date: 05/24/05

-------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type VIII |
| Valley Slope: | 0.0016 ft/ft |
| Number of Channels: | Single |
| Width: | 16.26 ft |
| Mean Depth: | 1.79 ft |
| Flood-Prone Width: | 140 ft |
| Channel Materials D50: | 0.17 mm |
| Water Surface Slope: | 0.0018 ft/ft |
| Sinuosity: | 1.1 |
| Discharge: | 125 cfs |
| Velocity: | 4.29 fps |
| Cross Sectional Area: | 29.13 sq ft |
| Entrenchment Ratio: | 8.61 |
| Width to Depth Ratio: | 9.08 |
| Rosgen Stream Classification: | E 5/1 |

**Figure A-7. Continued.**

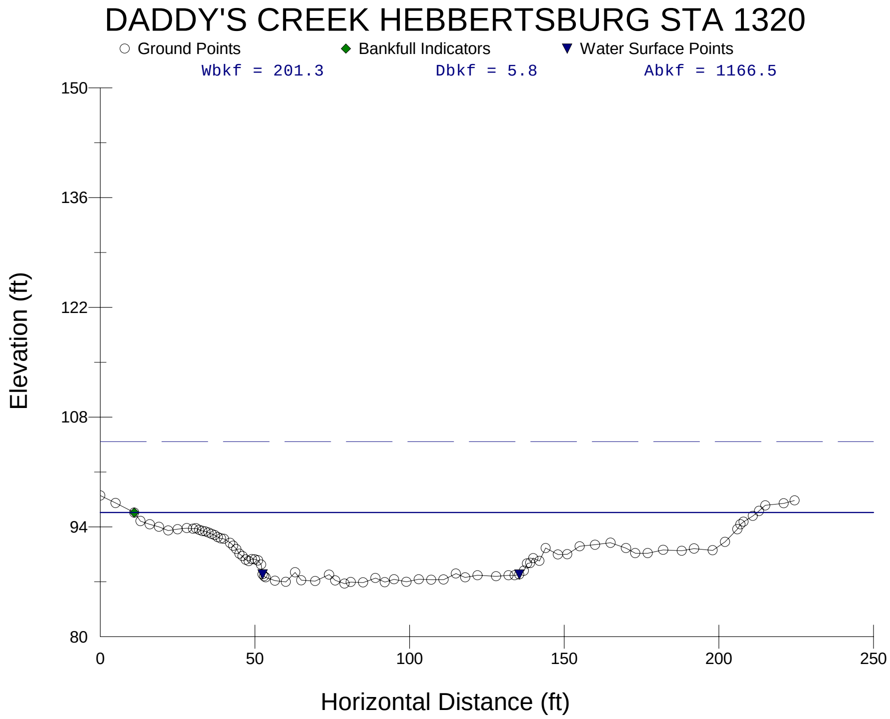
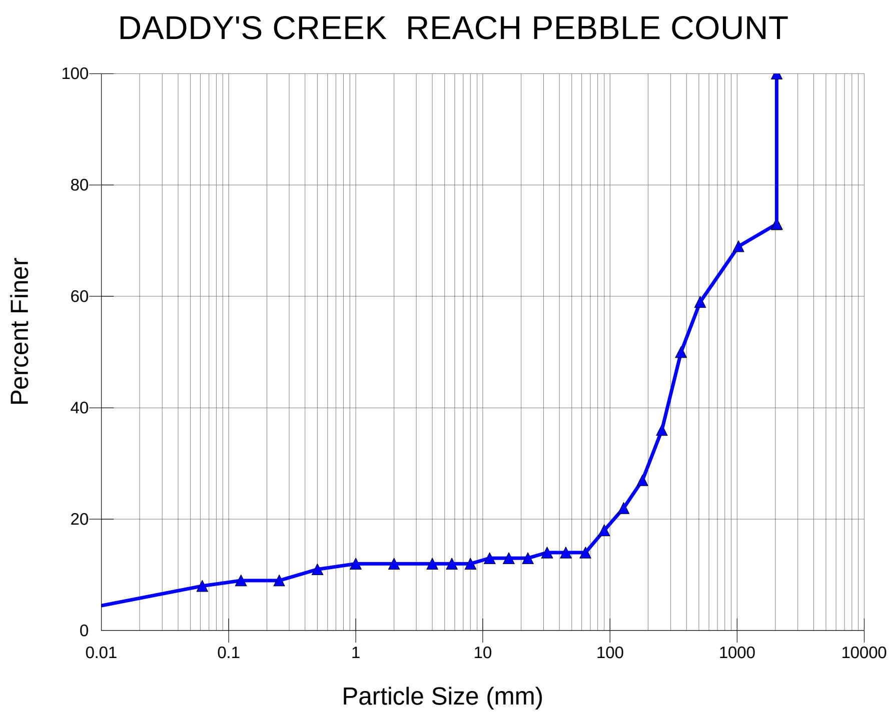



**Figure A-8. Daddy's Creek Hebbertsburg.**



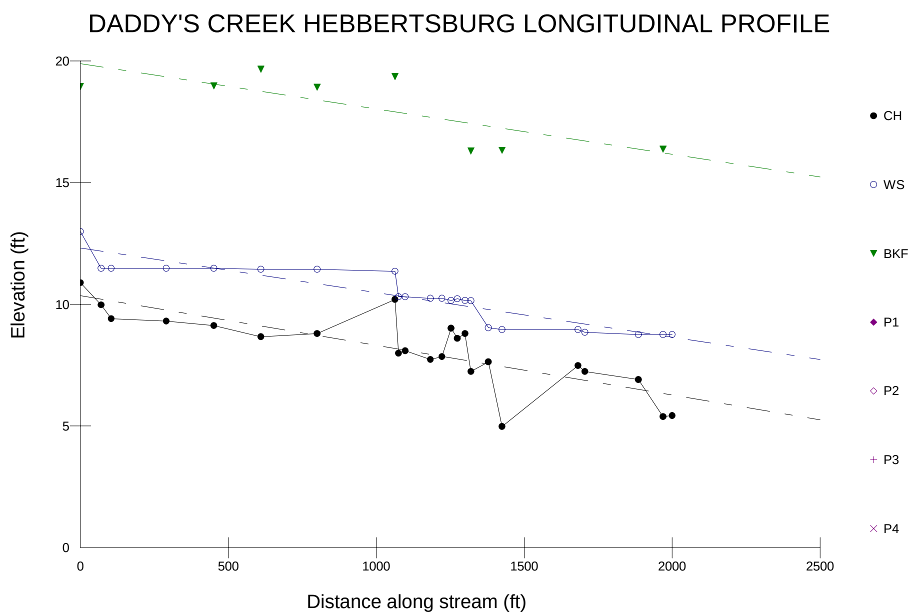




**Figure A-8. Continued.**

STREAM CHANNEL CLASSIFICATION

-------------------------------------------------------------------

River Name: Emory River
Reach Name: Daddy's Creek Hebbertsburg
Drainage Area: 139 sq mi
State: Tennessee
County: Cumberland
Latitude: 35 59 51
Longitude: 84 49 21
Survey Date: 06/20/05

-------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type IV |
| Valley Slope: | 0.0025 ft/ft |
| Number of Channels: | Single |
| Width: | 201.34 ft |
| Mean Depth: | 5.79 ft |
| Flood-Prone Width: | 250 ft |
| Channel Materials D50: | 362 mm |
| Water Surface Slope: | 0.0021 ft/ft |
| Sinuosity: | 1.2 |
| Discharge: | 6690 cfs |
| Velocity: | 5.74 fps |
| Cross Sectional Area: | 1166.46 sq ft |
| Entrenchment Ratio: | 1.24 |
| Width to Depth Ratio: | 34.77 |
| Rosgen Stream Classification: | F 2/1 |

**Figure A-8. Continued.**

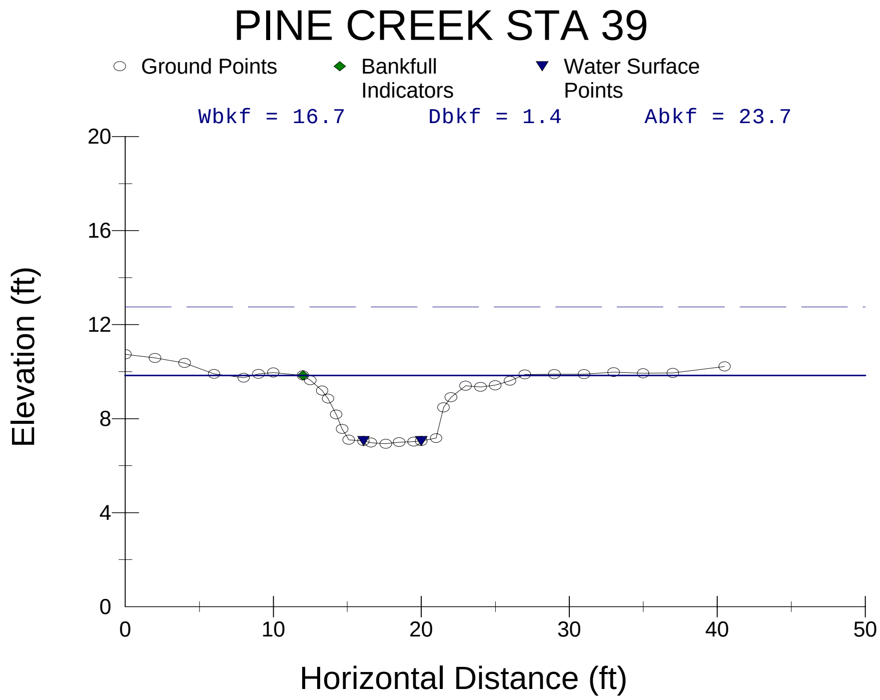
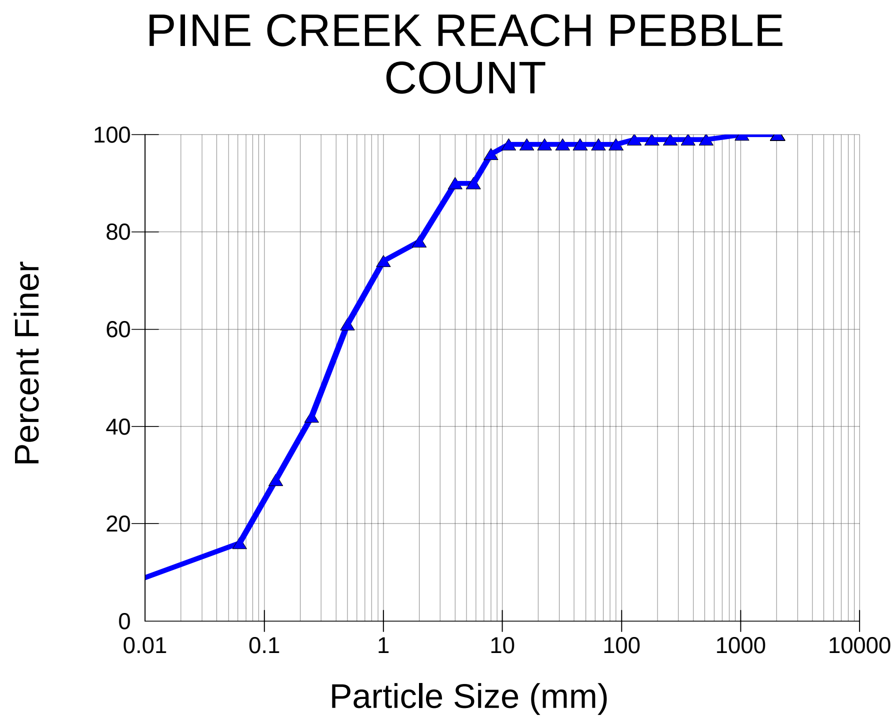



**Figure A-9. Pine Creek in Catoosa WMA.**



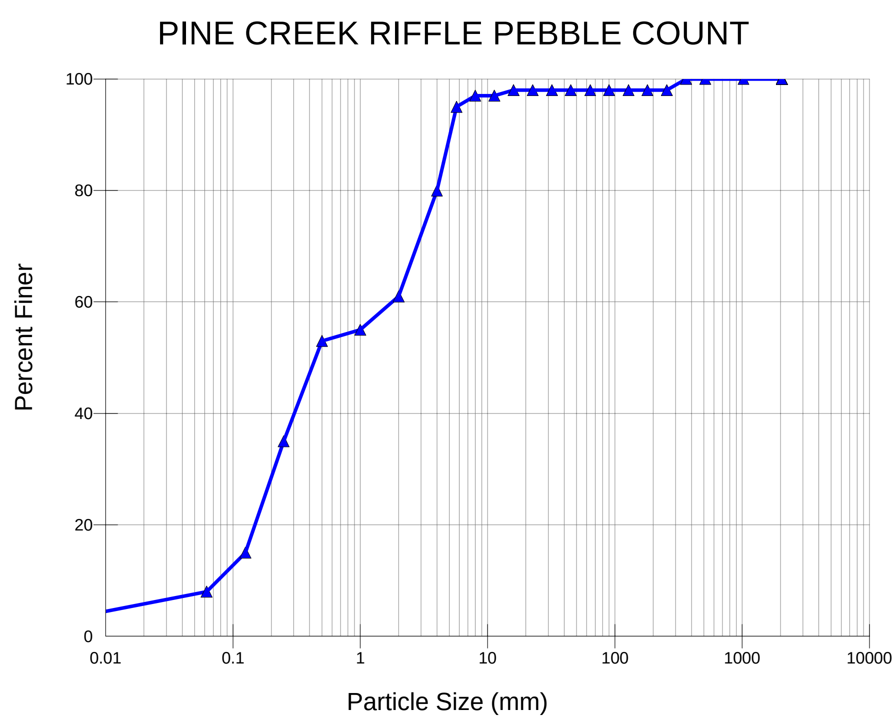




**Figure A-9. Continued.**

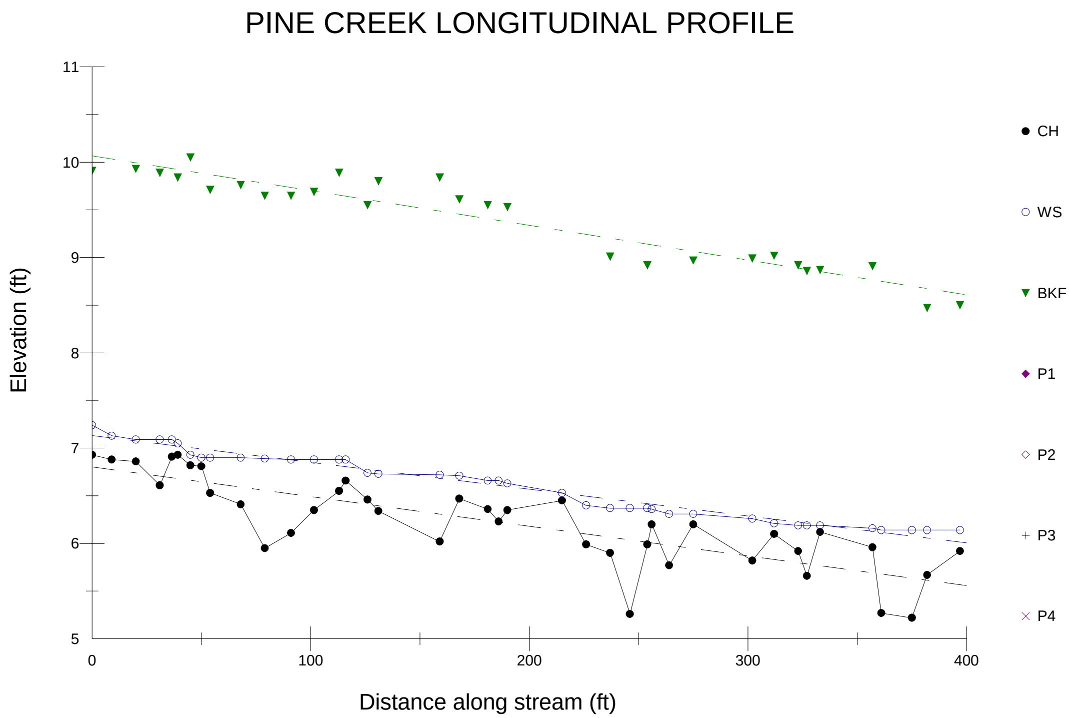



**Figure A-9. Continued.**

STREAM CHANNEL CLASSIFICATION

---------------------------------------------------------------------

River Name: Emory River
Reach Name: Pine Creek
Drainage Area: 0.6 sq mi
State: Tennessee
County: Cumberland
Latitude: 36 06 30
Longitude: 84 57 55
Survey Date: 08/17/05

---------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type VIII |
| Valley Slope: | 0.0035 ft/ft |
| Number of Channels: | Single |
| Width: | 16.73 ft |
| Mean Depth: | 1.42 ft |
| Flood-Prone Width: | 200 ft |
| Channel Materials D50: | 0.36 mm |
| Water Surface Slope: | 0.0028 ft/ft |
| Sinuosity: | 1.25 |
| Discharge: | 107 cfs |
| Velocity: | 4.52 fps |
| Cross Sectional Area: | 23.68 sq ft |
| Entrenchment Ratio: | 11.95 |
| Width to Depth Ratio: | 11.78 |
| Rosgen Stream Classification: | E 5 |

**Figure A-9. Continued.**

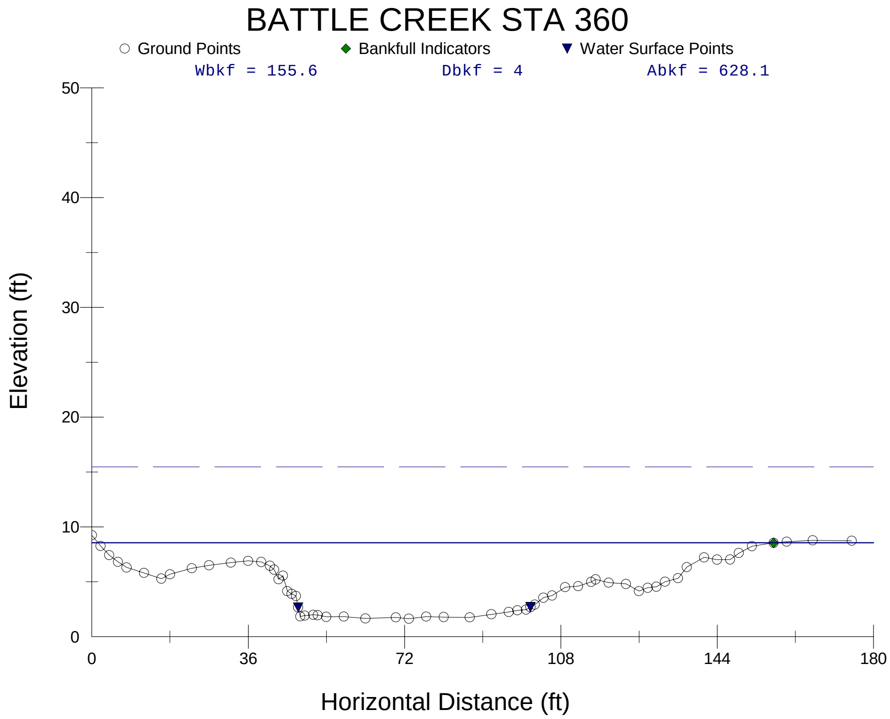
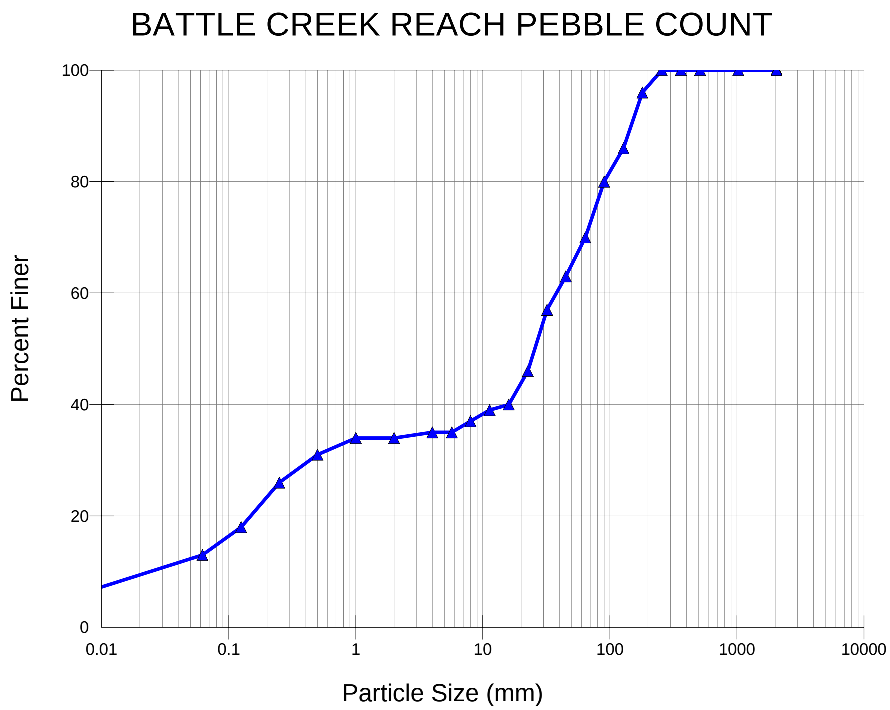



**Figure A-10. Battle Creek.**



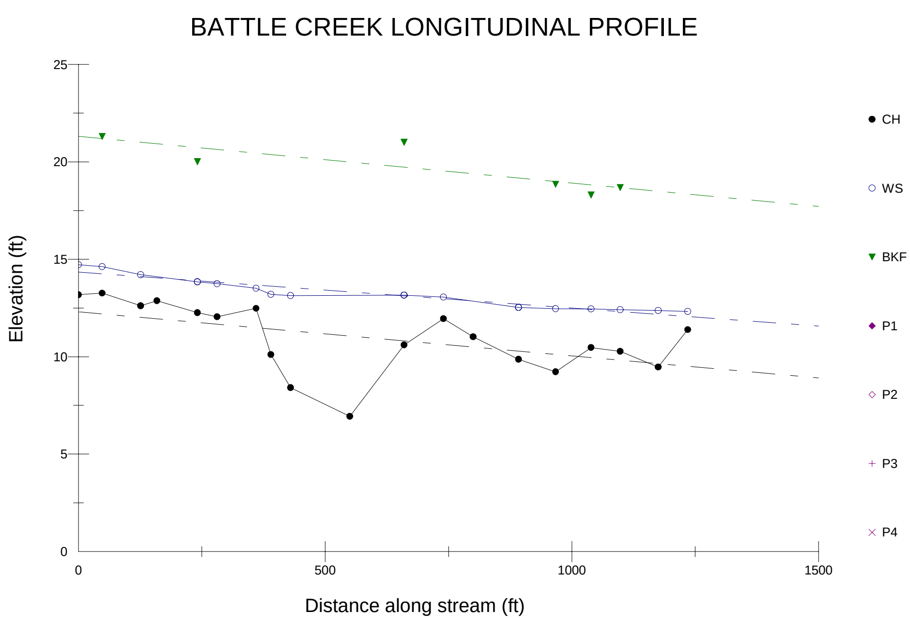




**Figure A-10. Continued.**

STREAM CHANNEL CLASSIFICATION

--------------------------------------------------------------------

River Name: Nickajack Lake Tennessee River
Reach Name: Battle Creek
Drainage Area: 50.4 sq mi
State: Tennessee
County: Marion
Latitude: 35 08 03
Longitude: 85 46 15
Survey Date: 07/22/05

--------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type VIII |
| Valley Slope: | 0.0024 ft/ft |
| Number of Channels: | Single |
| Width: | 155.57 ft |
| Mean Depth: | 4.04 ft |
| Flood-Prone Width: | 400 ft |
| Channel Materials D50: | 26.02 mm |
| Water Surface Slope: | 0.002 ft/ft |
| Sinuosity: | 1.2 |
| Discharge: | 3210 cfs |
| Velocity: | 5.11 fps |
| Cross Sectional Area: | 628.13 sq ft |
| Entrenchment Ratio: | 2.57 |
| Width to Depth Ratio: | 38.51 |
| Rosgen Stream Classification: | C 4 |

**Figure A-10. Continued.**

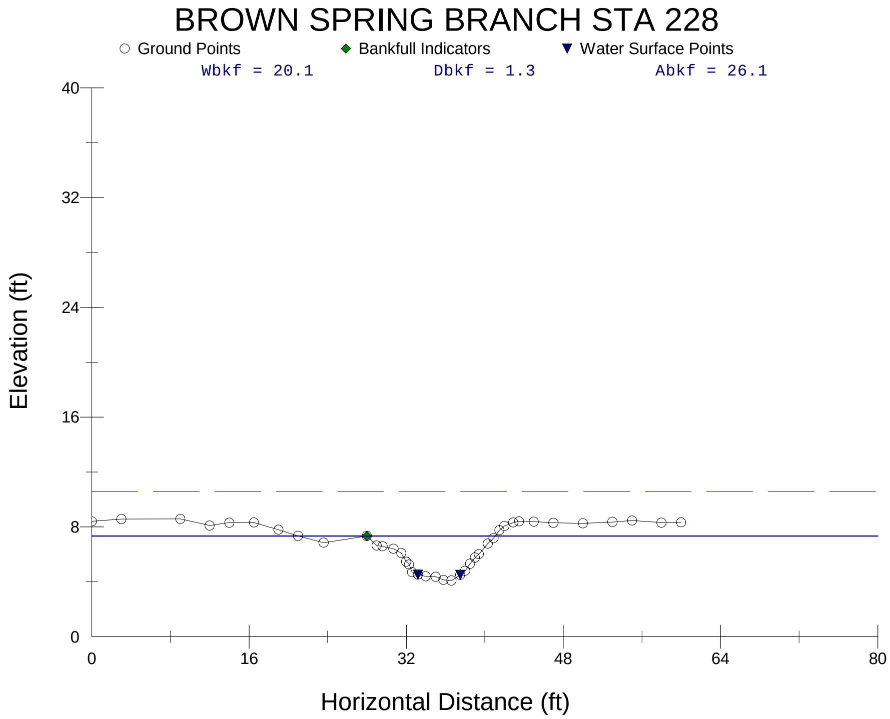
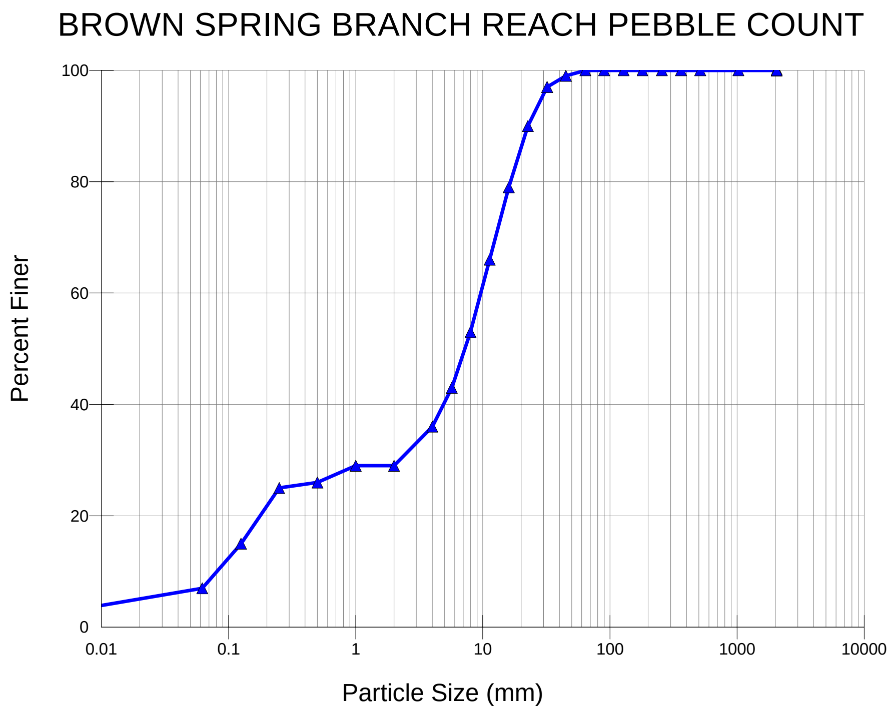



**Figure A-11. Brown Spring Branch.**



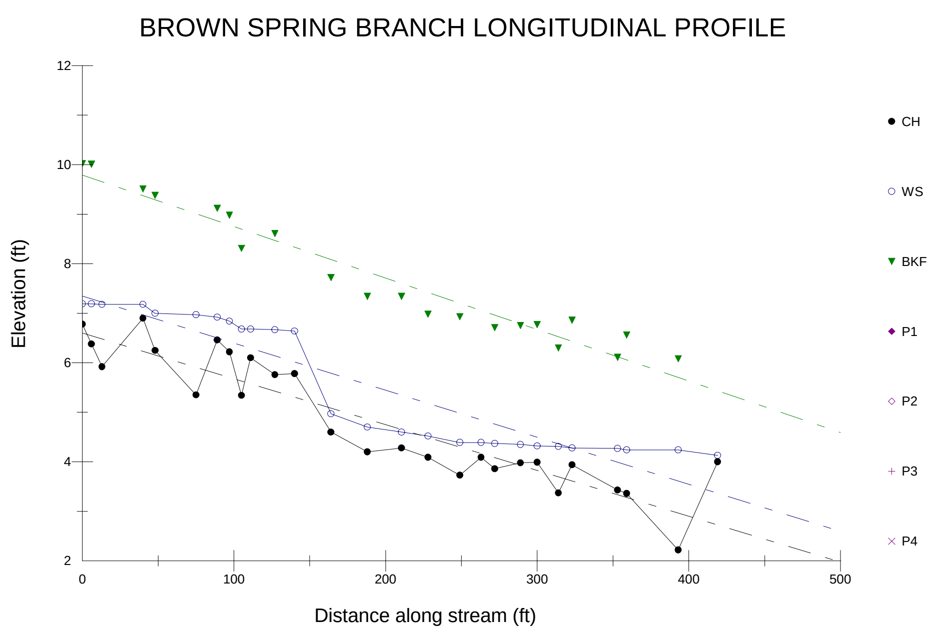




**Figure A-11. Continued.**

STREAM CHANNEL CLASSIFICATION

--------------------------------------------------------------------

River Name: Sequatchie River
Reach Name: Brown Spring Branch
Drainage Area: 0.67 sq mi
State: Tennessee
County: Marion
Latitude: 35 08 55
Longitude: 85 33 28
Survey Date: 07/21/05

--------------------------------------------------------------------

Classification Data

| | |
|---|---|
| Valley Type: | Type VIII |
| Valley Slope: | 0.008 ft/ft |
| Number of Channels: | Single |
| Width: | 13.07 ft |
| Mean Depth: | 1.87 ft |
| Flood-Prone Width: | 300 ft |
| Channel Materials D50: | 7.31 mm |
| Water Surface Slope: | 0.0073 ft/ft |
| Sinuosity: | 1.1 |
| Discharge: | 65 cfs |
| Velocity: | 2.67 fps |
| Cross Sectional Area: | 24.38 sq ft |
| Entrenchment Ratio: | 22.95 |
| Width to Depth Ratio: | 6.99 |
| Rosgen Stream Classification: | E 4 |

**Figure A-11. Continued.**


**Figure A-12. Group Photos from Tour of Streams 2005.**

**Figure A-12. Continued.**

**Figure A-12.  Continued.**

## VITA

Gregory Scott Babbit was born in Atlanta, Georgia on April 28, 1973. He received his early education at Kincaid Elementary and McCleskey Middle Schools within the Cobb County, Georgia public school system. Greg graduated from Sprayberry High School in Marietta, Georgia in the spring of 1991. He began pursuing a career in aviation in the fall of 1991 at Auburn University where he received a private pilot's license in addition to instrument and commercial flight training. In 1993, Greg began studying forestry and completed an internship with the Alabama Forestry Commission where he participated in the National Forest Health Monitoring Program administered by the U.S. Forest Service and EPA. He eventually received a Bachelor of Science degree in Forest Resources from Auburn University in the spring of 1996.

Following graduation, he obtained a position as a consulting forester with Canal Forest Resources where he conducted forest inventories across the southeast and managed timberland in north Florida for two years. In 1998, Greg began working for Eco-South, Inc., an environmental consulting firm based in Covington, Georgia. For the next six years, he performed wetland delineations, ecological surveys, §404/401 of the Clean Water Act permitting and managed stream and wetland restoration projects. He entered The University of Tennessee Graduate Program in the Department of Forestry, Wildlife and Fisheries Knoxville, Tennessee in January of 2004 and held a Graduate Research Assistantship for the duration of his studies. In December of 2004, Greg began working for the Tennessee Stream Mitigation Program and served as the East Tennessee Project Manager where he was responsible for identifying, managing and supervising stream restoration projects throughout east Tennessee.

Greg received his Master of Science degree in Forestry in December of 2005. He is a member of the Society of Wetland Scientists, American Water Resources Association and the Xi Sigma Pi Forestry Honor Society. He was married to Elizabeth McCord Wallace in the spring of 2001 and expects his son Gabriel Scott Babbit to be born in February of 2006.