

**Bankfull Geomorphic Relationships and Reference Reach Assessment of the Ridge and Valley
Physiographic Province of East Tennessee**

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Degree

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Abstract

Many waterways have been geomorphically altered or disturbed by development, mining, agriculture, and other human activities. Section 404 of the Clean Water Act determined that these impacts to our waterways must be mitigated for channel alterations. Stream restoration has been one method to mitigate for these impacts to our water resources. Stream restoration is defined as providing a measurable improvement to the channel stability, water quality, habitat or overall function of a degraded stream system. Practices of stream restoration have changed in the last 10 to 20 years with the introduction of natural channel design methods. Natural channel design involves rebuilding a stream channel with the appropriate channel dimensions, slope, and planform to accommodate water and sediment inputs from its drainage basin without excessively aggrading or degrading. Dimensions of restored stream channels are based on a stage that is termed bankfull. The bankfull discharge is the flow that fills the channel just to the tops of its banks, reaching the incipient point of flooding. Design dimensions used in natural channel design are based on bankfull stage and discharge because practitioners believe it is responsible for the average morphology of a stream channel. Practitioners of stream restoration use two primary tools to aid in the determination of these stable channel conditions which are 1) regional relationships between drainage area and either channel geometry or discharge (regional curves), and 2) dimensionless bankfull channel geometry ratios derived from stable reference reaches. These tools are both developed for ecoregions that have similar climates, topography, geology, soils, hydrology and vegetation because these are also the features that dictate stream channel form. Regional curves and reference reach dimensionless ratios were developed for the Level III Ecoregion 67 Ridge and Valley, Tennessee. The regional power function equations of bankfull cross sectional area, width, mean depth, and discharge to drainage, and the dimensionless bankfull channel geometry ratios of reference reaches will help determine the bankfull channel dimensions to use in natural channel design.

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Chapter I

Introduction

Water engineering is one of man's most ancient activities. Throughout history civilizations have settled near water sources. Growing populations and a rise in demand for water placed new importance on this resource. Development has placed restrictions on how efficiently stream systems can transport water, sediment, and nutrients. Often, the results are loss of physical and biological habitat and unstable channel morphologies. The southern section of the Level III Ecoregion 67 Ridge and Valley that traverses northeast to southwest through East Tennessee has for many years been modified through urbanization, mining, and agriculture. Due to this many of the waterways that drain this region have been geomorphically altered in some way. Section 404 of the Clean Water Act determined that these disturbances to our nation's water resources could not persist, and that reparation needed to be implemented to offset the impacts. Stable stream channels are necessary to ensure water quality standards and ecosystem diversity. Stream restoration, using natural channel design, has led the way in recent years to ameliorate geomorphic impacts and ecosystem deterioration.

Natural channel design for stream restoration is based on stream classifications and channel geometry relationships at bankfull stage. Hydraulic geometry relationships represent predictive models for channel cross sectional area, width, and mean depth as dependent variables as a function of the independent variable drainage area (Knighton, 1998). Bankfull discharge is believed to be the discharge where channels are stable and transporting sediment and water inputs. When drainage area is used as a predictive variable for bankfull discharge and the associated hydraulic geometry, these relationships are known as regional curves. Chapter 2 provides the background information for bankfull discharge and regional curves.

Stream restoration practitioners utilize regional curves to guide their designs to carry the water and sediment at the equilibrium condition. The equilibrium condition is the presumed morphologically stable form of stream channels. A stream restoration designer must select a design discharge relative to the drainage area to accomplish the engineered design. It is rational to use bankfull discharge because the current literature defines it as the discharge that controls channel cross-sectional area. Therefore regional curves based on a bankfull stage are essential to the natural channel design methodology. The natural channel design approach to stream restoration is described in detail in Chapter 2.

Once stream restoration practitioners have estimated the width and depth for a given design reach, other morphological details are needed for design. For example, morphological details include pool-riffle spacing, depths, and bed slopes, as well as other natural habitat features. Many of the other natural morphological variables used in design are expressed as dimensionless ratios such as width/depth ratio or max riffle depth/mean depth ratio. This information is developed by morphological surveys of reference stream channels. Reference streams are basically streams in currently undisturbed watersheds, which generally include forested watersheds with little to no drainage modifications. It is impossible to know the true disturbance history of a watershed, so reference reaches are subjective in their designation. However, because they are being used for design, one could simply state that they are streams with desirable geomorphological features for a natural channel design project. Additional information regarding reference reaches is provided in Chapter 2.

This study was funded by the Tennessee Stream Mitigation Program (TSMP). The TSMP administers much of the mitigated restoration in the state of Tennessee. The purpose of this study was to provide practitioners of natural channel design that are employed by the TSMP with tools to aid in the design of stream restoration projects in east Tennessee. To implement stream restoration effectively, the regional relations of drainage area to bankfull discharge and its associated hydraulic

geometry of cross section area, width, and mean depth, and the detailed morphological conditions of reference reaches have been used as tools to validate and support stream restoration designs. By utilizing geomorphic relationships and desirable morphological conditions the designer is able to better estimate what channel geometry conditions may represent equilibrium in a degraded system.

The objectives of the study were to do the following: 1) determine if the bankfull recurrence interval for streams draining the southern Ridge and Valley Level III Ecoregion 67 of Tennessee was between 1 and 2 years, as was found in earlier studies; 2) develop relationships (regional curves) for bankfull discharge, cross sectional area, width, and mean depth hydraulic geometry to drainage area for streams draining the Southern Ridge and Valley Level III Ecoregion 67 of Tennessee; 3) compare those relationships to those found for the Ridge and Valley of Virginia, West Virginia and Maryland (by Keaton *et al.* (2005); 4) develop a reference reach database for the Southern Ridge and Valley Level III Ecoregion 67 of Tennessee; and 5) compare the reference reach bankfull discharges and hydraulic geometry to those proposed by the resulting Level III Ecoregion 67 Ridge and Valley of Tennessee regional power function equations to validate the reference reach bankfull levels.

Chapter II

Background

Stream Restoration

Natural Channel Design

Throughout the nation the reconstruction of degraded or altered stream channels is becoming an important part of ensuring that water quality needs are met. Many states now require that impacts to streams from development, mining and other activities be mitigated based on the implementation of section 404 of the Federal Clean Water Act. Restoration can be termed as a measureable improvement to channel stability, water quality, habitat, and overall function of a degraded stream (TDEC, 2004; Babbitt, 2005). Currently, a popular method of stream restoration is practiced by following natural channel design protocols. This practice is suggested by the U.S Army Corps of Engineers, the United States Department of Agriculture, the Natural Resource Conservation Service, the U.S. Fish and Wildlife Service, and the Tennessee Department of Environment and Conservation. Natural channel design involves rebuilding a channel with the dimensions, slope, and plan-view pattern that will convey the water and sediment loads from the drainage basin without aggrading or degrading (Keaton *et al.*, 2005; Hey, 2006). Natural channel design has been the most prevalent method for stream restoration used by biologists, fluvial geomorphologists, and engineers throughout the Eastern United States in recent years (Doll *et al.*, 2004; Babbitt, 2005). Natural channel design incorporates the bankfull discharge and uses it as a base for channel dimension measurements (Rosgen, 1996). The bankfull discharge has been related to a peak flow return frequency of approximately 1 to 2 years (Knighton, 1998). The bankfull discharge and associated channel geometry characteristics of cross section area, width, and mean depth have been shown to be highly correlated with drainage area (Dunne and Leopold, 1978; Keaton *et al.*, 2005).

The regression relations of drainage area and these characteristics are therefore helpful in identifying bankfull levels and channel dimensions in disturbed watersheds.

Another component of natural channel design is the utilization of a reference reach. According to Chow (1959), many historical methods of river engineering rely on clear water discharge, rigid boundaries, uniform flow and channel materials. These methods are often not observed in nature and can lead to poor channel design. Rosgen (1998) states that empirically derived regime equations, often used to establish channel dimensions and slope, can be very appropriate if the stream being restored is similar to the stream from which the relationships have been developed. It can be difficult to determine the origin of the relation and stream types that a model truly represents, so it is suggested that regime equations be stratified by the stream types from which they were derived. However, the relations do not necessarily represent a stable form of the channel, nor do they describe the potential of the stream to adjust its geometry and planform based on its current drainage basin conditions or sediment inputs.

Stream Classification

The desire to classify river channels can be explained as a means of reducing an extremely complex environmental feature into a series of discrete units which facilitate further study or help organize management operations (Downs, 1995). Numerous classification systems have been implemented (Leopold and Wolman, 1957; Kellerhalls *et al.*, 1976; Nanson and Croke, 1992; Whiting and Bradley, 1993; Rosgen, 1994; Montgomery and Buffington, 1997). For engineering and management purposes it is often useful to classify channels using a range of geomorphological channel types that minimize the variability within type and maximize differences between types (Thorne *et al.*, 1997). Typically, any classification scheme is unlikely to be generally applicable for all uses, but applied geomorphological classifications have tended to adopt a reach level spatial scale and prolonged temporal scale ($10^0 - 10^2$ years) with watershed management and infrastructure protection in mind

(Downs, 1995). The Rosgen (1994) stream classification system was used for this study. This system delineates streams into 7 types that differ in entrenchment ratio, width/depth ratio, sinuosity, slope, and dominant channel materials. Entrenchment ratio represents the vertical containment of the stream channel and is computed by dividing the flood prone width by the bankfull width. Width/depth ratio is a metric representing the channel cross section shape and is computed by dividing bankfull width by mean bankfull depth. Stream channel pattern is a measure of sinuosity, found by dividing the stream length by the valley length or by dividing the stream water surface slope by its valley slope. The slope of the channel is measured by averaging the slope of the water surface for a distance of approximately 20 bankfull widths. The dominant channel materials are represented by the D_{50} , calculated from the riffle pebble count and representing the intermediate axis of the sample larger than 50 percent of the samples taken.

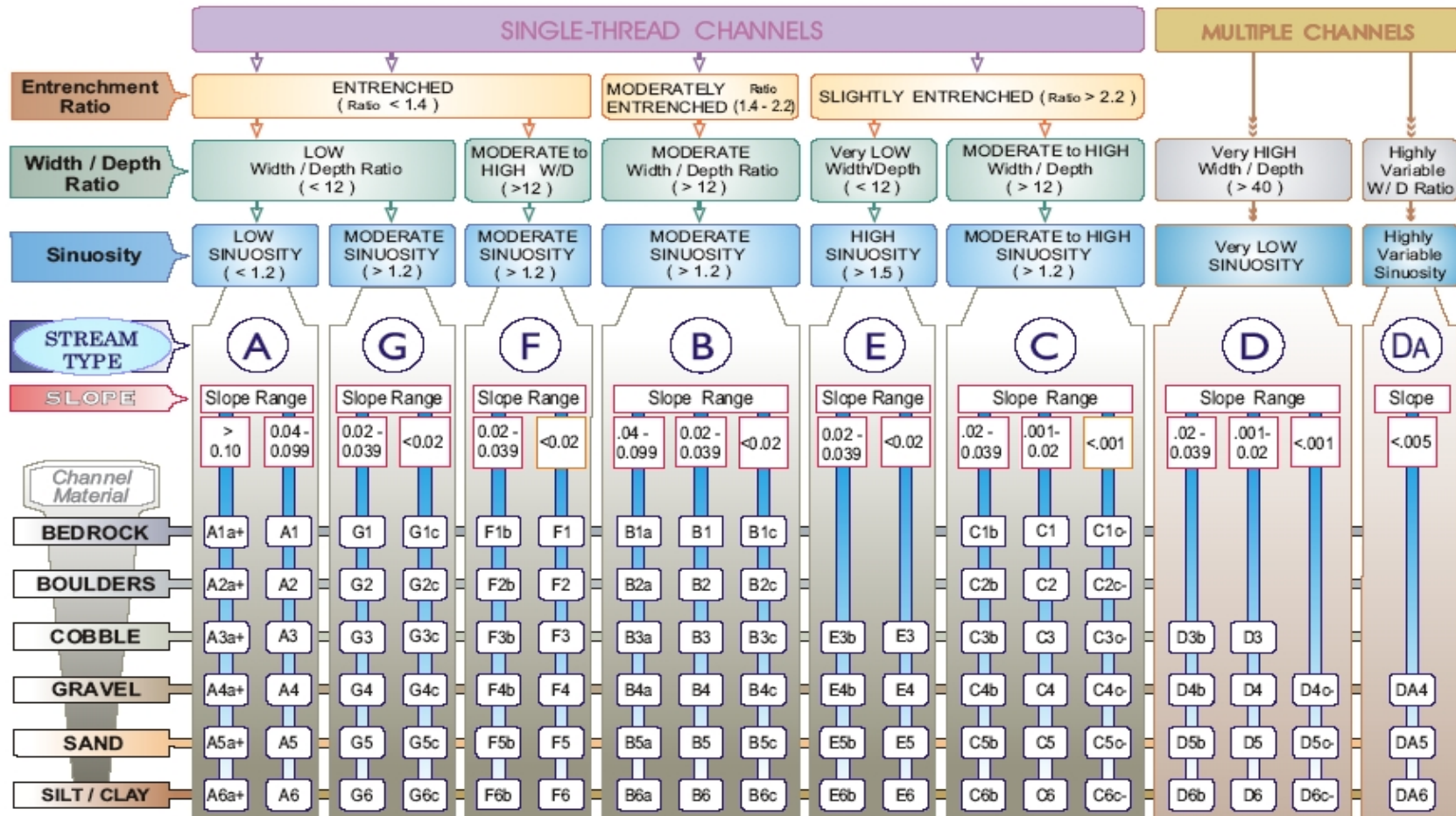
I decided to use the Rosgen (1994) geomorphic classification of natural streams because the system:

- 1) Is based on extensive field observations and quantitative investigations of basin characteristics, valley types and landforms (Rosgen, 1996).
- 2) Provides a mechanism to integrate companion inventories (Rosgen, 1996).
- 3) Provides a method to utilize sediment data, bank erosion and stability procedures (Rosgen, 1996).
- 4) Contains the advantage of specifying channel evolution sequences in response to changes in their controlling variables (Leopold, 1994; Downs, 1995).
- 5) Is the most widely accepted manner of classifying a channel (Leopold, 1994).

6) Enables extrapolation of site specific data to other reaches of similar geomorphic character (Rosgen, 1994).

7) Provides a consistent framework for organizing river information that can be understood across a wide range of disciplines (Rosgen, 1994). A key to the Rosgen (1994) classification system can be found in Figure 2-1.

The Key to the Rosgen Classification of Natural Rivers



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS.

As a function of the "continuum of physical variables" within stream reaches, values of **Entrenchment** and **Sinuosity** ratios can vary by +/- 0.2 units; while values for **Width / Depth** ratios can vary by +/- 2.0 units.

Figure 2-1. Key to Rosgen (1994) Classification of Natural Rivers.

Valley Type

The drainage basin is considered the fundamental unit of the fluvial landscape (Ritter *et al.*, 2002). Streams draining the Ridge and Valley physiographic province typically have a trellis drainage pattern. As part of the initial assessment of the study reaches chosen, basins were classified by Rosgen (1996) valley type to characterize the different valley formations and basin attributes. A summary of Rosgen valley types and associated stream types is shown in Table 2-1.

Table 2-1. Valley Type Descriptions and Associated Stream Types of Streams Draining the Ridge and Valley (Rosgen, 1996)

Valley Type	Stream Type	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, moderately 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 floodplains adjacent to river terraces
IX	C and D	Broad, moderate to gentle slopes from glacial outwash and or eolian deposits
X	C, E, DA	Very broad, gentle slopes with extensive floodplains
XI	DA	Deltas

* Denotes valley types observed for streams in the Southern Ridge and Valley

Regional Curves

In the 1950s Leopold and Maddock (1953) pioneered the determination of hydraulic geometry relationships in the U.S. Geological Survey Professional Paper 252. They examined characteristics of channel shape, such as width, depth, sediment, and velocity in response to changes in discharge (Leopold and Maddock, 1953). Regional curves are graphical representations of bankfull hydraulic geometry as a function of drainage area (Harman *et al.*, 1999; Babbitt, 2005). These are produced by regressing the relationships of bankfull discharge, width, mean depth and cross sectional area on their respective drainage basin area. Hydraulic geometry relationships have proved very useful when determining width, depth, cross sectional area and velocity as functions of drainage area. Where the stream types associated with a bankfull width/ depth ratio, slope, and channel materials are similar to the streams from which the hydraulic geometry have been derived, extrapolation of these relations can be appropriate for design purposes (Rosgen, 1998). Regional curves provide tools that aid the engineer in determining bankfull stage and the associated channel geometry while providing a means to validate stream restoration designs (Babbitt, 2005; Rosgen, 1994). Regional curves also aid in watershed decision making by documenting existing stream conditions, establishing baseline data on specific reaches, and by providing a means to predict what channel conditions approximate a natural equilibrium in disturbed or previously altered systems. The development of regional hydraulic geometry relations was initiated by Dunne and Leopold (1978) and Emmet (1975). In recent years, the development of hydraulic geometry relationships has expanded and many exist for the Eastern United States (Harman *et al.*, 1999; Cinotto, 2003; McCandless, 2003; Chaplin, 2005; Keaton *et al.*, 2005; Parola *et al.*, 2007). There is still a need for regional curves to be developed in areas that have degraded stream systems and unique physiographic features.

The drainage basin is the fundamental component of the fluvial channel. Stream channel size, shape and pattern are a function of many physical and to a lesser extent biological and chemical weathering processes that occur simultaneously. Each basin has a unique discharge and sediment load that are products of all the variables interacting within a watershed, such as climate, geology, soils, vegetation, land use, topography and basin morphology (Leopold, 1994; Knighton, 1998; FISRWG, 1998). Channel dimensions can vary through time in response to changes in the supply of water and sediment, especially those induced by man (Hewlett, 1982; Knox, 1972). Efforts have been made to group areas with similar geologic, hydrologic, climatic, topographic and vegetative features into Ecoregions because these features are the key drivers of geomorphic form and process (Babbitt, 2005; Griffith *et al.*, 1997; Sweet and Geratz, 2003). The delineation of geographic regions by similar features that dictate geomorphic processes has allowed a more accurate representation of the basin features that affect stream channel form. Regional curves can provide much insight to equilibrium approximations in regions where bankfull discharge and hydraulic geometry relations do not currently exist and are essential to successful stream restoration projects (Babbitt, 2005).

Bankfull Discharge

The bankfull discharge at a river cross section is the flow which just fills the channel to the tops of the banks (Leopold *et al.*, 1964; Rosgen, 1996; Williams, 1978). It is above this point that flooding is initiated and floodplain interaction occurs. Debate has centered on the true definition of bankfull stage for many years. Williams (1978) outlined more than 10 definitions of bankfull in which there could be 10 different bankfull elevations in the same stream or river cross section. Johnson and Heil (1996) determined that significant uncertainty existed in the determination of bankfull depth and discharge utilizing methods outlined by Williams (1978). Williams showed that the bankfull discharge return periods varied from 1 to 25 years, but he studied various landscapes and climates and he was not clear

in his distinction between the elevations of low terrace and the active floodplain, the low terrace being an abandoned floodplain (Chang, 1988). Leopold (1964) studied 13 gaging stations in the Eastern U.S. and found that the bankfull discharge occurred with a frequency of approximately 1.5 years based on flood frequency analyses and using the active floodplain connection as the bankfull indicator.

In 1960, Wolman and Miller proposed the magnitude and frequency concept that described the importance to geomorphic processes of extreme flow events and the more frequent flow events of smaller magnitude in terms of “work done”. Their study indicated that most of the work of moving sediment within or from the drainage basin was done by frequent flows of moderate size, specifically the bankfull discharge (Wolman and Miller, 1960). Bankfull has been correlated with other channel forming discharges such as the effective or dominant discharge. Andrews compared the effective and bankfull discharge average annual total sediment load at 15 USGS gaging stations in the Yampa River Basin that had self-forming channels. Andrews (1980) defined the effective discharge as that which transports the largest fraction of the annual sediment load over a period of time. He used the bankfull discharge definition as that which filled the channel to the level of the floodplain. At all gaging stations he determined that the effective discharge and bankfull discharge were nearly equal. Simon *et al.*, (2004) and Wolman and Miller (1960) defined the effective discharge as the discharge or range of discharges that transports the largest proportion of the annual suspended-sediment load over the long term. In years past, the definition has been modified to include bed load (Simon *et al.*, 2004), and is based on the standpoint of channel form adjustment proposed by Knighton (1998). Knighton (1998) also proposed that channel form is the product of a range of discharges, and that fluvial systems have a memory for past events, which, to an extent, influence the current channel form and subsequent discharges.

The most widely accepted definition of the bankfull discharge in channel form is that of Dunne and Leopold (1978). They stated that the bankfull stage corresponded to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, bar formation and deformation, and meander bend migration are generally doing the work that results in the average morphological characteristics of channels. Geomorphic features that correspond to this definition are often used as the bankfull indicators. Indicators consist of active floodplain connection, tops of point bars, most prominent bench, top of bank, scour line, change in bank material size, and vegetation change (Babbitt, 2005; Leopold, 1994).

Determining the bankfull stage from visual inspection alone can be a difficult task. Bankfull determination can be complicated when the valley type does not allow for a natural floodplain or where abandoned floodplain terraces exist. A change in any one of these variables sets up a series of channel adjustments which lead to a change in channel form. Leopold (1994) identified five principal bankfull indicators in an order of utility: 1) top of point bar, 2) changes in vegetation type and amount, 3) topographic breaks in slope or change in bank angle, 4) change in size distribution of channel materials and 5) debris deposits or wrack lines. Subsequent investigators in the southeastern U.S. have found different bankfull indicators useful (Babbitt, 2005).

The processes of erosion and deposition are the fundamental elements of channel form and geometry, and bankfull indicators should relate to these processes (Knighton, 1998; McCandless and Everett, 2002). It is thought that the most reliable estimator of the bankfull stage is the relatively flat depositional surface adjacent to stream channels, known as the active floodplain (Harrelson et al., 1994; Babbitt, 2005). Leopold (1994) did acknowledge that various points along a channel reach are somewhat different and this is partly due to the characteristics of these features depending on local channel

morphology (Parola, 2007). This study chose to use the active floodplain connection to represent the primary bankfull discharge at sites chosen for survey.

It was important that the selection of a bankfull discharge be consistent among sites chosen for survey. This was in order to:

- 1) classify streams using Rosgen (1994, 1996) stream and valley types;
- 2) extrapolate morphological data from similar stream types of differing size;
- 3) develop dimensionless ratios from the channel geometry relations.

A design that emulates a stable natural channel that has been self formed and maintained allows a determination of dimension, pattern and profile using the dimensionless ratios (Rosgen, 1998). Also, without consistency of a bankfull discharge, confusion could develop among engineers utilizing dimensionless ratios or regional curves. The bankfull discharge and associated channel geometry characteristics of cross sectional area, width and mean depth have been shown to be highly correlated with drainage area (Dunne and Leopold, 1978). Regression relationships between drainage area and the bankfull channel characteristics and dimensionless ratios are used to determine bankfull dimensions in unstable watersheds with no gage data, experienced field technicians, or visible bankfull indicators.

Streamflow Gaging Stations

The United States Geological Survey stream flow gaging stations record stream discharge at a specific location in the drainage basin. The discharge is related to the stage of water elevation in the channel. The results are stage-discharge relationships relative to the stage control in the river cross section. When determining bankfull discharge for regional curves a field determined bankfull water surface elevation representative of the reach is referenced to the stage-discharge rating tables of the stream gage (Rosgen, 1994; Babbitt, 2005). Although this is a necessary part of the development of

regional curves, it can also limit their development because most physiographic provinces have a limited number of available USGS gaging stations. Many gaging stations are inactive and no longer have the necessary benchmarks and reference points that define the stage-discharge rating table's reference. Other gaging stations could be located on waterways that are too large for inclusion, have regulated flows, or have been impacted in some other way. Also, gage data may be of inadequate length to perform flood frequency analyses, less than ten years (Babbitt, 2005; Keaton *et al.*, 2005).

Reference Reaches

The utilization of a reference reach in natural channel design aids in the determination of channel conditions that approximate natural equilibrium by making a series of measurements at streams of similar type that effectively accommodate discharge and sediment without excessive channel erosion or deposition. The use of a reference reach provides the designer with bankfull channel geometry measurements that characterize a stable form of the physical and hydraulic environment. Measured channel characteristics are presented as dimensionless ratios, such as width/depth ratio, and are extrapolated to the project site for incorporation into the restoration design (White, 2001). It provides these bankfull geometry measurements specifically for riffle, run, pool and glide meso-habitat units and other measurements (Table 2-2). If the stream being restored differs significantly from the streams used to create the regional hydraulic geometry relations available, the channel geometry measurements from the reference reach assessment can help reduce error in design. The selection of the reference reach must be of similar stream and valley type to the disturbed reach because these classifications provide a baseline delineation that can characterize the depositional materials, relief, pattern and channel geometry features of the stream in question.

Table 2-2. Bankfull Morphological Variables and Dimensionless Ratios Rosgen (1996)

Variables/Ratios	Variables/Ratios	Variables/Ratios	Variables/Ratios	Variables/Ratios
1. Bankfull Width	10. Channel Materials: D15, D35,	19. Riffle Slope	28. Glide Slope	37. Ratio of run depth/mean depth
2. Bankfull mean depth	11. Bar material: D15, D35, D50, D84, D95,	20. Ratio of riffle slope/average slope	29. Ratio of glide slope/average slope	38. Run width/depth
3. Width/depth ratio (1)/(2)	12. Stream Type	21. Riffle max depth ratio (4)/(2)	30. Glide depth	39. Ratio of run w/d average to w/d
4. Bankfull max depth	13. Bankfull cross sectional area (1)x(2)	22. Pool slope	31. Ratio glide depth/mean depth	40. Meander length (Lm)
5. Width of floodprone area	14. Drainage area	23. Ratio of pool slope/average slope	32. Glide w/d ratio	41. Ratio of Lm/bankfull width
6. Entrenchment ratio (5)/(1)	15. Wetted perimeter (P)	24. Max pool depth	33. Run slope	42. Radius of curvature (Rc)
7. Valley slope	16. Hydraulic radius (13)/(15)	25. Ratio of max depth/mean depth	34. Run slope	43. Ratio of Rc/bankfull width
8. Average water surface slope	17. Bankfull velocity	26. W/D ratio of pool	35. Ratio of run slope/average slope	44. Belt width
9. Sinuosity (7)/(8)	18. Bankfull discharge	27. Ratio of pool w/d to riffle w/d	36. Run depth	45. Meander width ratio (Wblt/Wbkf)

By incorporating dimensionless ratios that characterize an apparently stable stream reach into the restoration design, practitioners assume the newly designed reach will function as effectively as the reference reach at transporting discharge and sediment (White, 2001). A description and example of the Rosgen (1994, 1996) stream and valley type classification schemes used for stratifying reference reaches can be found in the following chapter. Reference reaches selected for use in natural channel design are intended to be stable or in a state of equilibrium with the sediment and water inputs from their drainage basin. There is no universally accepted set of criteria for determining whether all or part of a system is in equilibrium (Knighton, 1998), but systems can become relatively stable in the sense that, if disturbed, they will tend to return approximately to their previous state when the perturbation is decreased. Mackin (1948) described equilibrium as a state of grade, in which, over a period of years, slope is delicately adjusted to provide just the velocity required with available discharge and prevailing channel characteristics, to transport the load supplied from the drainage basin. There may not be

numerous streams available that are considered reference quality by this definition. In areas where agriculture and urban development have been dominant in the last century the conditions that represented equilibrium may now be permanently adjusted to the current conditions of the drainage basin. In these areas, care must be taken to avoid extrapolating channel geometry conditions from a reference reach that are not representative of the stream being restored and its drainage basin. To effectively execute natural channel design it will be necessary to compile a group of reference reaches by region to aid in determination of a stable and natural channel form for that region.

Chapter III

Study Area

Ecoregion

Level I Ecoregion delineations divide the continent into broad ecological areas. Level II Ecoregion delineations provide a more detailed description of the areas nested within Level I. Level I and II Ecoregions encompass much larger areas that can have dramatic changes in physiography and climate within the delineations. The delineation of Level III Ecoregions groups landforms with similar climate, geology, physiography, soils, vegetation, hydrology, wildlife and land use (Griffith *et al*, 1997). Some of these same main features control channel form in the drainage basin. This is the reason regional curves are typically completed specifically for Level III Ecoregions. Castro and Jackson (2001) reported that they were able to distinguish ecoregions from climatic patterns and physiography as being the most statistically significant variable affecting the hydraulic geometry of stream channels, and 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). Tennessee contains 8 separate Level III Ecoregions as delineated by Omernik and Bailey (1997).

The study area for this research is the Level III Ridge and Valley Ecoregion 67 of Tennessee (Figure 3-1). The province is drained in the northeast by the Holston and French Broad Rivers, which converge 4 miles northeast of Knoxville. The northwest portion is drained by the Clinch River until it joins the Tennessee River in Roane County (Martin, 1971). The southeast portion is drained by the Little Tennessee River which flows into the Tennessee River in Loudon County. The Level III Ecoregion of the Ridge and Valley in Tennessee consists of four smaller Level IV Ecoregions (Figure 3-2) which include 67f Southern limestone/ Dolomite Valley and Rolling Hills, 67g Southern Shale Valleys, 67h Southern Sandstone Ridges, and 67i Southern Dissected Ridges and Knobs. The morphological quality of streams

in the province varies somewhat, but generally decreases heading southwest where agriculture has dominated the landscape. The Level III Ecoregion of the Ridge and Valley in Tennessee accounts for 7,703 acres or 18.2 % of the total land area in the state. The southern portion of the Level III Ecoregion of the Ridge and Valley in Tennessee houses the valley of East Tennessee and is the focus of this study. The Southern section of the province begins at the New River and Tennessee River Basin divide, just west of Wytheville, Virginia, and continues through eastern Tennessee and into northern Alabama. High ridges are often capped with hard resistant sandstone and valley bottoms are commonly underlain with limestone, founding the base for karst features. The lower ridges and valleys in the Southwestern part of the province are usually formed of shale and dolomite (Bingham, 1991; Keaton *et al.*, 2003).

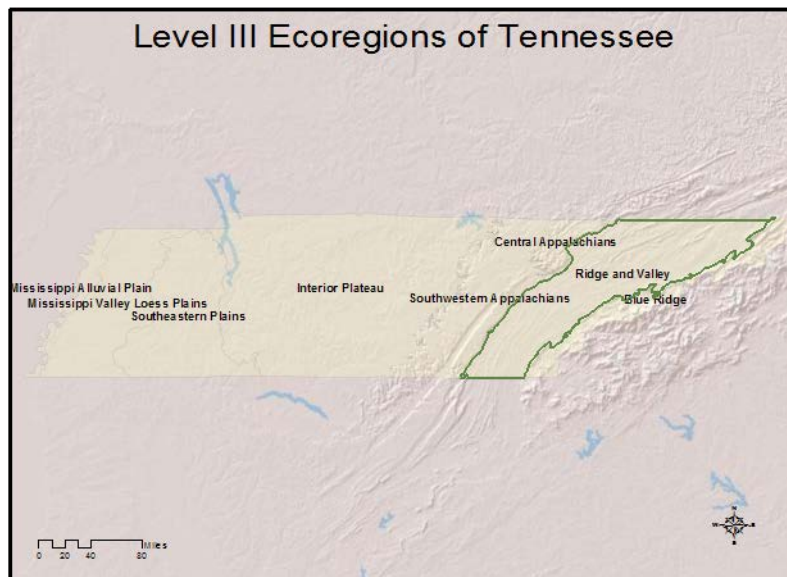


Figure 3-1. Omernik and Bailey (1997) Level III Ecoregions of Tennessee.

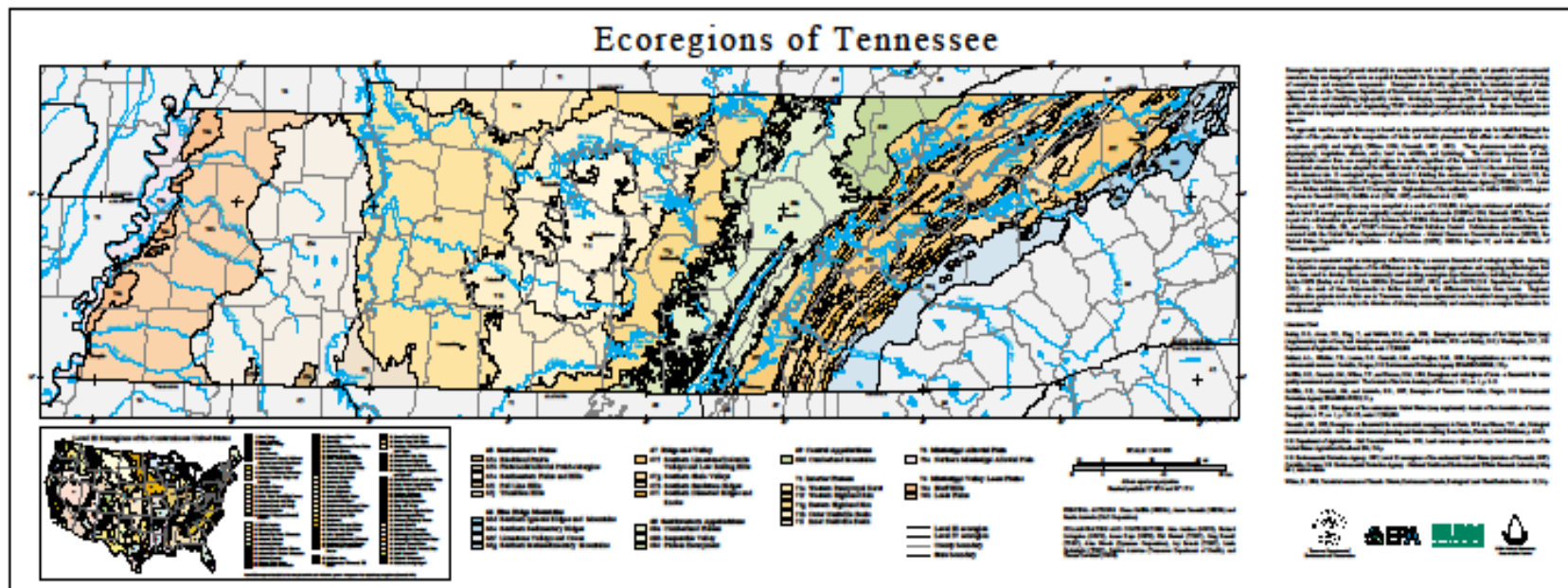


Figure 3-2. Level IV Ecoregions of Tennessee. http://ftp.epa.gov/wed/ecoregions/tn/tn_front.pdf

Physiography

The Level III Ecoregion 67 Ridge and Valley in Tennessee is underlain by a complex system of parallel valleys and ridges trending northeast to southwest and extending from New York to Alabama. Fenneman (1938) proposed that the development of the Level III Ecoregion of the Ridge and Valley resulted from the deposition of Paleozoic sediments in a geosyncline followed by folding, faulting and subsequent erosion of the strata; the latter geologic events probably occurred during the Appalachian Revolution at the close of the Paleozoic era with erosion continuing to the present. Interpreting the development of this vast landscape is difficult to due to complex structure and lithology. According to Fenneman (1938) there were two to three peneplain surfaces developed during the tertiary period resulting in the topography seen today. In the northern parts of the province prominent ridges called mountains extend approximately 3000 feet in elevation and many miles horizontally, and consist of resistant Ordovician and Silurian sandstone. The crests of these mountains are the upper levels of the Schooley peneplain, which is the oldest of the eroded surfaces (Martin, 1971).

Sandstone ridges and knobs are present in the southeastern portion of the province. They usually have much less relief with elevations of 300 to 400 feet. Even further East, dissected shale knobs can be seen with elevations around 220 feet and extend for several miles in a northeast direction. Between these high ridges and knobs the valley relief depends upon the underlying bedrock. Flattened valleys indicate less resistant shales and rolling topography indicates the presence of limestone or dolomite bedrock that is less resistant. These landforms were termed, the Coosa, and are more prominent south of the Tennessee River drainage. Hack (1960) proposed that the Ridge and Valley was formed through processes other than peneplanation. The process is now termed dynamic equilibrium where chemical and physical weathering erodes bedrock with differential rates due to different bedrock

characteristics. Milici (1967) presented evidence of this physiographic development while working on the Appalachian Plateau and in the Sequatchie Valley.

Lithology

Folding, thrust faulting and subsequent erosion of Paleozoic rocks has resulted in the exposure of rocks of different geologic age and type in the Ridge and Valley as well as the trellis drainage pattern observed today (Martin, 1971). The dominant strata are Cambrian and Ordovician (Rogers, 1953). The Lower or Early Cambrian consists of the Rome formation and is the oldest formation exposed widely across the valley (Martin, 1971). It is also the formation with the highest elevation and greatest local relief because resistant sandstone beds dominate the strata. The weathering of the less characteristic layers in the strata of limestone, shale, dolomite and siltstone has led to the comby or knobby ridge forms (Rodger, 1953). The Middle Cambrian rocks are limestone and shales. Collectively they are known as the Conasauga group. Lithologic variation in this group across the valley floor has resulted in alternating beds of limestone and shale. Areas such as Rutledge, Maryville and Maynardville contain little to no chert. The shale units consist of Conasauga, Pumpkin Valley, Rogersville and Nolichucky and weather into valleys (Martin, 1971). Upper Cambrian and Lower Ordovician rocks are members of the Knox dolomite or Knox group. The Knox group occupies 33 to 40 percent of the Ridge and Valley (Case, 1925). The Upper Cambrian member of the Knox group is the Copper Ridge dolomite and the members of the Ordovician age are Chapultepec, Longview, Kingsport and Mascot dolomites (Martin, 1971). Middle Ordovician strata consist of shales, limestone and sandstone complexes. These shales are associated with intricately dissected topography known locally as the slate or shale knobs (Martin, 1971).

Soils

Most of the soils of the Ridge and Valley have formed from erosion of Paleozoic strata or from colluvium or alluvium derived from the strata deposited later in geologic time (Martin, 1971). Until settlement by man the soils were developed under forests and vegetation has had a major influence on soil development in the region. Most soils that were developed from colluvium and alluvium are now under cultivation and occupy the lower slopes and floodplains. Soils of the Ridge and Valley are dominantly Ultisols, of the suborder Udults, Alfisols, Inceptisols and Entisols.

The Ultisols, mostly Paleudults from cherty dolomitic limestone and dolomitic limestone, persist on deep, well drained soils developing on broad, rounded hills and ridges with local relief ranging from 100 to 280 feet and slopes ranging from 5 to 25 percent (Martin, 1971). In this Fullerton series there is generally an inverse relationship with the amount of chert and water holding capacity. These soils are also strongly leached, acidic and low in natural fertility. Higher percentages of clay in the B horizons usually indicate more water holding capacity. The Paleudults created from the dolomitic limestone or limestone are generally less cherty and are found on lower hills and slopes. Depths usually range from 7 to 30 feet; they are well drained and moderately acidic (Martin, 1971). Paleudults created from alluvium are associated with gentle rolling relief and gradual slopes. These soils have moderate natural fertility and are strongly acidic. Other alluvial soils are associated with terraces 50 to 200 feet above the floodplain and are mostly under cultivation because they are deep, well drained and are strongly acid in reaction. The Hapludults that were developed from the non calcareous shale are less deep being 4 feet or less to bedrock. These soils have formed by weathering of shale and are thus associated with low relief valleys. Other soils developed from non calcareous shale have less depth to bedrock and textured with silty clay, reducing their water holding capacity.

The Alfisols, suborder Hapludults, formed from limestone generally have shallow depth relative to the limestone bedrock and are relatively higher in base saturation (Martin, 1971). The clayey subsoil and shallow nature of the soils indicate a low water holding capacity.

The Inceptisols, suborder Dystrochrepts, formed from sandstone and shale are generally shallow to bedrock. They occur mostly on narrow continuing ridges with steep slopes. They are generally low in fertility and are extremely acidic. The Eutrochrepts developed from calcareous shale are known as the slate or shale knobs and occupy the Eastern portion of the Ridge and Valley. These soils are shallow to bedrock and have a low water holding capacity because of this. Water holding capacity is also reduced by shale fragments throughout the soil column and fine textured subsurface horizons (Martin, 1971). Haplaquepts formed from alluvium have developed from recent stream deposits and colluvial deposits from upslope. These soils are located along stream banks and the floodplains. These soils have poor drainage and are subject to frequent flooding due to their high affinity for holding water and location near the water table. Most of the production of this soil type has been ceased as the major drainage ways have been impounded (Martin, 1971).

The Entisols, suborder Haplaquents, formed from alluvium are the most recent and are without horizon differentiation. The soils are poorly drained and exist adjacent to small creeks and tributaries.

Climate

The climate of the Ridge and Valley is temperate continental (Martin, 1971) with cool winters and warm summers. The growing season typically lasts about 205 days throughout the province (Bingham, 1991). The principal source of precipitation is the Gulf of Mexico and a trend of decreasing rainfall is seen from south to north in the Ridge and Valley. Annual amounts of precipitation range from 52.91 inches per year in Chattanooga to 43.57 inches per year in Kingsport with an annual amount of precipitation in Knoxville of 47.33 inches (SERCC, 2011). The majority of precipitation is received during

the winter and spring months, but a secondary maximum can be seen in mid-summer months. The climate is often modified in the Ridge and Valley by the Cumberland Plateau to the west and Great Smoky Mountains to the east. These two physiographic conditions act as incline planes that lift warm moist air. When this air cools and condenses it is released in the form of afternoon thunderstorms that are observed so often in the area.

Vegetation

The Ridge and Valley was once covered with hardwood forests throughout, with pines and oaks covering the sloped ridges (Amick, 1934). Exploitation of the resource permanently changed the nature of those forests. Today, much of those deciduous hardwood forests have been cut multiple times and the forested areas that remain are declining in quality and diversity. Segregation of plant communities using topographic characteristics realized that Oak-Hickory populations occupied slopes with stands of *Pinus echinata* (shortleaf pine) and *Pinus virginiana* (Virginia Pine), and were mixed with hardwoods on drier uplands and ridges; a mixture of mesophytic woody taxa occupied the wetter coves. In the Great Valley of Tennessee four major vegetation complexes have been determined by Martin (1971). The White Oak Complex is the most widespread and consisted of nine vegetation types. The Chestnut Oak Complex is second in importance and consists of four vegetation types. The Tulip Poplar and Mixed Mesophytic Complexes also represent portions of the forests in the Ridge and Valley. Pine vegetation is characterized by communities dominated by *Pinus echinata* (shortleaf pine), *Pinus strobus* (Eastern White Pine) and *Pinus virginiana* (Virginia Pine). Restricted upland vegetation consists of communities dominated by *Quercus falcata* (southern red oak) *Quercus muhlenbergii* (chinkapin oak), *Q. shumardii* (shumard oak), *Q. rubra* (red oak), *Q. stellata* (post oak) and *Q. velutina* (black oak). Bottomland communities were dominated by *Fraxinus pennsylvanica* (green ash), *Platanus occidentalis* (sycamore), *Acer saccharum* (sugar maple), *Aesculus octandra* (yellow buckeye) *Fagus grandifolia* (beech), *Tilia*

heterophylla (basswood) and *Q. phellos* (willow oak) (Martin, 1971). Agriculture constitutes the main land use in the region and has been supported by the fertile soils derived from limestone in the valley bottoms for many years. In the last century the population of the Southern Ridge and Valley in East Tennessee has grown considerably when compared to other areas of the province (Keaton *et al.*, 2003).

Chapter IV

Methods

The methods of data collection in this study followed well known and repeated protocols for completing regional curve and reference reach studies (Rosgen, 1996; Harrelson *et al.*, 1999). These methods were originally based on morphological data collection by Leopold and Wolman (1964). Since, these practices have been improved upon by Dave Rosgen (1996) following his level II survey methodology that morphologically describes a stream, and by the U.S Forest Service's *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson *et al.*, 2002). Rosgen's (1996) level II protocol characterizes the stream channel morphology and enables the investigator to classify a stream based on measurements. To classify each reach the stream channel dimension (width, mean depth, cross section area), longitudinal profile, pattern, and dominant channel materials are measured. The U.S. Forest Service's *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson *et al.*, 2002) is a protocol for gathering data about the physical characteristics of a reference reach and provides guidelines for surveying, bankfull identification, and other data collection techniques, and was implemented in the reference reach assessments. Protocols for regional curve reach site selection were brought together from previous studies in the eastern United States, such as Babbitt, (2005); Keaton *et al.*, (2005); and Parola, (2007). Protocols for reference reach site selection were modeled after Rosgen's (1998) filtering criteria. The bankfull discharge determinations were completed using Leopold's and Wolman's (1964) methods of referencing a bankfull stage to the existing stage-discharge relationship for the regional curve reaches. For the reference reaches, Manning's equation was used to estimate mean riffle velocity. Surveyed riffle cross section area and the calculated velocity were used to estimate reference reach bankfull discharge for comparison and bankfull stage validation. The methods used in

this study were tested for similarity to those from Keaton *et al.* (2005) by repeating a site from their previous study and comparing a set of predetermined measurements to our own.

Regional Curve Site Selection

Site selection is important to regional curve development because the relationships will only represent the stream types and morphological conditions of streams included in the studies. Site selection for the regional curve study differed from that of the reference reach study. Ideally, for a regional curve study, reference quality streams across a broad range of drainage basin sizes should be included in the relationships. It is unusual for streams in the study area that are monitored for flow to be of reference quality or in completely forested watersheds with no drainage modifications, therefore a list of criteria determined from previously completed studies was used to screen a preliminary list of sites. All USGS streamflow gaging stations draining the Level III Ecoregion 67 Ridge and Valley of East Tennessee were considered potential sites for survey. A list of filtering criteria was used to obtain the most stable and representative regional curve reaches. The site reach selection criteria (Babbitt 2005; Chaplin, 2005; Parola, 2007) for this study included:

- 1) At least 10 years of streamflow data for peak annual discharges;
- 2) Recoverable survey benchmarks or reference points to USGS gage or staff plates
- 3) Wadeable;
- 4) Perennial flow;
- 5) Sufficient channel length of 10 – 20 bankfull widths;
- 6) Stable gage control;
- 7) < 20 percent urbanization of drainage basin;

- 8) < 10 percent of drainage area flow regulated;
- 9) Majority of catchment located within Ridge and Valley Level III Ecoregion;
- 10) Drainage area within the range of 0.1 to 250 square miles.

Reference Reach Site Selection

Stream reaches to be surveyed for reference geomorphological information are preferred to be in a state of quasi equilibrium with the sediment and water inputs from their drainage basin. These reaches are usually found in forested watersheds with little to no drainage modifications. A list of filtering criteria determined from Rosgen (1994) was utilized to screen potential reference reaches. Selection of the reference reaches to be included in the study began by referring to the Tennessee Ecoregion Project for potential sites (Arnwine *et al.*, 1999). The Tennessee Ecoregion Project was implemented to determine biological reference quality streams for the Level IV Ecoregions of Tennessee. In the appendix of the report, the streams were listed according to the Ecoregion they occupied with physical site descriptions and habitat assessment scores. The scores and descriptions were reviewed and the most likely geomorphically stable candidates were investigated on foot. Criteria for inclusion to the reference reach database were:

- 1) The reference reach had to be free to adjust channel boundaries;
- 2) Be stable or in equilibrium but did not have to be pristine;
- 3) Had to extend at least two full meander wavelengths or approximately 20 bankfull widths;
- 4) Have consistent bankfull indicators (Rosgen, 1994).

Regional Curve and Reference Reach Remote Sensing

After all initial regional curve and reference reaches had been determined GIS information was used to investigate for potential disturbances to the reaches and to assess the drainage basin

characteristics. Channelization, instability and impoundments were assessed by viewing topographic, aerial, and historical images in ArcGIS. After removing sites with obvious impacts, the remaining sites were visited and assessed for local impacts and consistency of bankfull indicators.

Regional Curve and Reference Reach Geomorphic Data Measurements

Field Surveys

A pedestrian survey of 20 bankfull widths upstream and downstream of each USGS gage station was completed to assess bankfull indicator consistency and overall reach conditions. Geomorphic surveys for this study were completed by researchers between March and October of 2010. All geomorphic surveys measurements were completed following protocol and procedure as outlined in the literature (Harrelson *et al.*, 1994; Leopold, 1994; Rosgen, 1996; Rosgen, 2004). Stream surveys for channel dimensions were completed with a Trimble 3600-Geodimeter total station, prism and rod, 300 foot fiberglass tapes, stakes, rebar, clamps, flags and caps. Survey measurements were allowed to have no more than 2% total horizontal or vertical error by closing the surveys on the beginning benchmark then calculating the percent deviation.

Basin Drainage Area

Basin drainage area was provided for each streamflow gaging station by the USGS website, <http://tn.water.usgs.gov/>.

For the seven selected reference reaches the drainage basin area was calculated by displaying digital topographic models from the Geospatial Gateway in ArcGIS and delineating the watershed using the polygon tool, then calculating the drainage area using the calculate geometry command in the attribute table (ESRI, 2010). Watershed drainage area for the Walker Branch Experimental Watershed was provided by the Oak Ridge National Laboratory Environmental Sciences Division (Mulholland, 2010).

Channel Dimension

For all streams included in the study, two stable riffle cross sections in close proximity to the gage site were chosen and surveyed. Detailed cross sections were surveyed to capture the hydraulic geometry data. Fiberglass tapes were positioned perpendicularly to the stream flow and extended across the floodplain to a height of at least twice the maximum bankfull depth to capture the flood prone width (Rosgen, 1996). Intervals between cross section measurements depended on consistency of the bed and bank elevations. Points included in the cross sections included but were not limited to bankfull indicators, slope breaks, edge of water, thalweg, point bars, tops of bank, inner berms and terraces. Bankfull width was measured in the cross section at the bankfull elevation, bankfull depth was measured as the mean depth through the cross section, and cross section area was the product of these two dimensions.

Reference reaches were surveyed in the same manner as listed above with the addition of one pool cross section per reach. The additional pool cross section was selected to be representative of the reach and was necessary for hydraulic modeling and dimensionless ratio determination.

Channel Profile

A longitudinal profile of each reach was surveyed for a distance approximately 10 to 20 times the bankfull width of each channel (Leopold, 1994). Due to the limited number of sites that met the initial site selection criteria, a distance less than 20 bankfull widths was considered acceptable if the reach had consistent morphology. Regional curve site surveys were continued through the gage unless large pools, weirs, or box culverts affected the area near the gage (Babbitt, 2005; Keaton *et al.*, 2005). Measurements were taken at the start of each facet for thalweg, bankfull features, and water surface, and at each successive habitat facet. In some streams, bedrock made the delineation of riffle, run, glide and pool habitat facets more difficult to discern, so all major bed elevation changes were surveyed. All

regional curve site surveys were tied into the gage datum by surveying reference points and benchmarks for reference to the stage-discharge rating tables. All reference reach surveys were initiated and closed on a local survey datum that was installed at the time of the survey.

Channel Pattern

In this study, channel pattern was measured in order to classify the streams using the Rosgen classification system and to produce meander geometry for reference reaches (Figure 3-1). Meander geometry is a function of the bankfull width and has been shown to be related to the bankfull discharge and channel dimensions (Leopold *et al.*, 1964; Babbitt, 2005). Sinuosity is the ratio of stream length to valley length (Rosgen, 2008). Belt width is the lateral distance between the outside edges of two meanders that occupy opposite sides of the valley (Rosgen, 2004), and is used as an index of lateral containment of a stream when compared to the width. Meander wavelength is the longitudinal distance between the apexes of two sequential meanders (Rosgen, 2004). Meander wavelength ratio is the ratio of meander wavelength to bankfull width. Radius of curvature is a measure of the tightness of an individual meander bend, and is negatively correlated with stream sinuosity (Rosgen, 2004). Radius of curvature is measured from the far bank of the bankfull channel to the intersection point of the two lines that perpendicularly bisect the tangent lines of each curve departure point on the outside bank (Rosgen, 2004). Values for all these characteristics for larger streams were measured by using Digital Orthophoto Quarter Quadrangles (DOQQ) and for smaller streams were measured in the field using multiple 300 foot tapes.

Geometry of Meanders

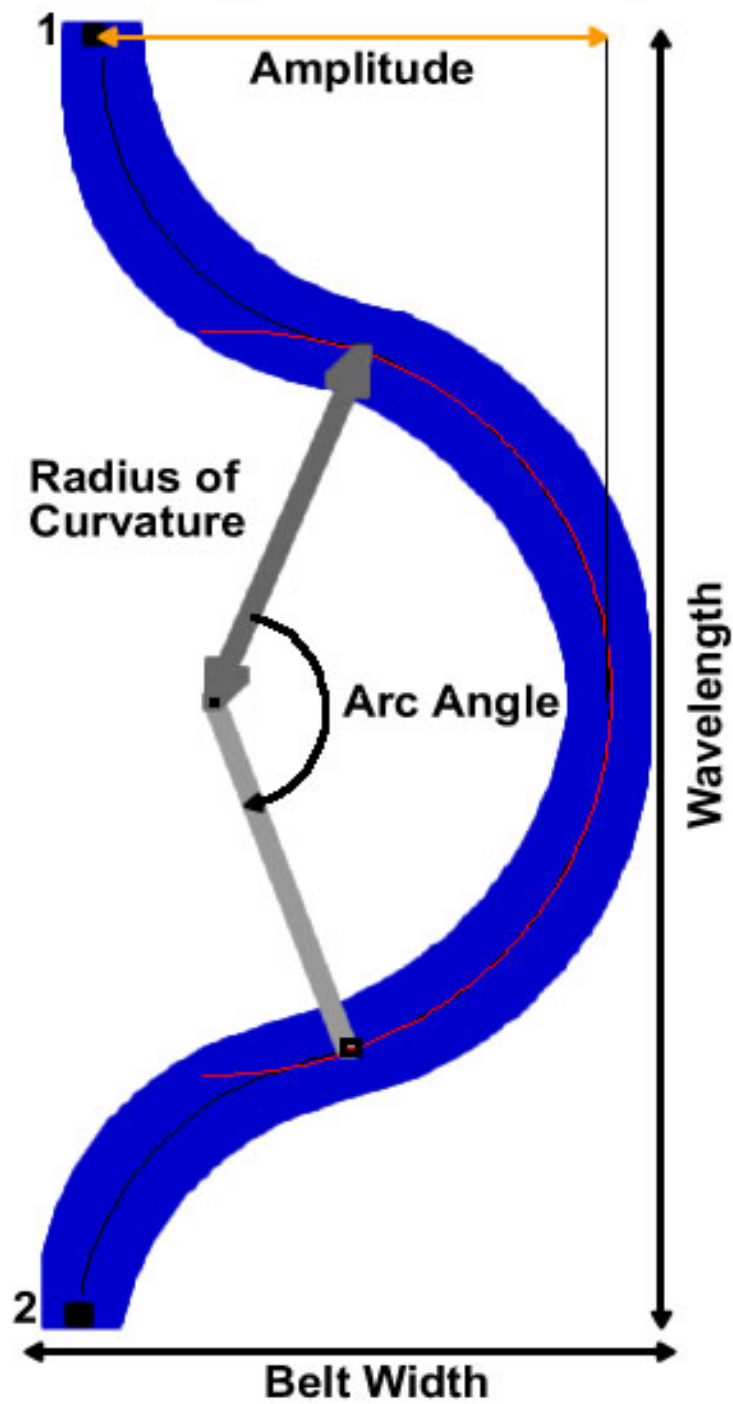


Figure 4-1. Meander Geometry Measurements. Endreny (2003). <http://www.fgmorph.com>

Channel Bed Material

In this study, a modified Wolman (1954) pebble count procedure was implemented to characterize the channel materials for sizing of the D_{50} . The D_{50} is the particle sample that is larger than 50 percent of the 100 samples taken in the riffle. A reach wide pebble count was conducted in the proportionate number of bed features, such as riffle, run, pools and glides throughout the longitudinal profile for the Rosgen (1994) stream classification. For example, if 50 percent of the reach was composed of pools, then five transects of ten particles would be taken in the pools and the remaining 50 samples would be taken from riffles, runs and glides (Rosgen, 1994). The modified Wolman (1954) riffle pebble count was conducted at all sites for estimating relative roughness. A total of 100 samples were randomly selected by dividing the riffle into ten even transects and taking ten evenly spaced samples along each transect within the riffle. To eliminate bias in sampling, samples were taken by no look, first feel at each interval. The intermediate or B axis (Figure 4-2) was then measured in millimeters with a ruler and removed from the stream bed to avoid double sampling. The b axis is measured by quantifying the size of the particle not along its longest plane nor along its shortest plane, but along its intermediate or middle length plane.



Figure 4-2. Example of Intermediate B Axis of Particle Sample. (<http://pubs.usgs.gov/sir/2004/5156/>)

For reference reaches, bed load was sampled at the downstream 1/3 of the lateral point bar area and approximately ½ the distance between the thalweg and the bankfull stage (Rosgen, 1996). The core sample was obtained from an open bottom bucket not to exceed a depth of twice the maximum particle diameter. Where point bars were absent from the system a pavement/sub pavement sample was taken in the riffle where the pebble count was conducted. Rosgen Level II protocol was followed while implementing these procedures (Rosgen, 1996). Materials were sieved and weighed in situ using the sieve dimensions: 2 (mm), 4 (mm), 12.5 (mm), 25 (mm), 63 (mm), and 100 (mm).

Data Analyses

Annual peak streamflow records for the 8 USGS gaging stations were obtained from the Tennessee USGS (2010) website at <http://tn.water.usgs.gov>. Also, stage discharge rating tables or curves, full gage descriptions, and gage summaries when available were collected. The bankfull stage elevations were referenced to the gage datum and stage-discharge tables. Streamflow records for the East Fork of Walker Branch were obtained from the Oak Ridge National Laboratory Environmental Sciences Division (Mulholland, 2010).

The collected field data were used to compute bankfull channel hydraulic characteristics and to graphically represent the survey data using the Reference Reach Spreadsheet, provided by the Ohio Division of Wildlife and Natural Resources & Ohio State University (1998). This graphical representation of channel form is often the most revealing step in understanding a fluvial system. The main purpose of the Reference Reach Spreadsheet is to aid in the analysis of geomorphological and hydrologic data, and provides a means to effectively and efficiently reduce the measured field data (Mecklenburg and Ward, 2004).

Longitudinal profile, channel bed material, channel pattern and channel dimension information can be reduced and analyzed using the spreadsheet. The longitudinal profile parameters of bed surface, bankfull, and water surface are represented graphically using different colored lines. Points included in the survey are displayed on the graph as different shapes as well. A trend line was plotted through the bankfull indicator and water surface measurements separately for comparison of slopes. Habitat unit spacing and slope were calculated by the spreadsheet after the units were delineated at their start on the longitudinal profile. Channel bed material data from pebble counts and bar samples are able to be transposed to the spreadsheet in the standard millimeter size delineations. Percent cumulative distribution and percent finer are also calculated and displayed graphically once data are input. Channel pattern can be represented graphically if each station in the longitudinal profile is entered with an azimuth or bearing. If the longitudinal profile survey does not contain this information it can be measured and entered in appropriate cells on the pattern profile sheet and will be displayed in the summary tables of the spreadsheet. The bankfull channel dimensions are calculated from the cross sectional data entered in the dimension section. In this study, where cross sections were found to be similar, hydraulic geometry and other related geometric variables were averaged. Channel cross sections were represented graphically; bankfull and flood prone levels were shown as horizontal lines on the graph. Bankfull hydraulic characteristics and associated hydraulic geometry were calculated using the bankfull levels and displayed graphically. Each reach was classified into Rosgen (1994) stream types through the aid of the spreadsheet. Using the spreadsheet, data analyses were performed on all levels of the Rosgen (1996) level II survey methodology for streams included in the regional equations.

Bankfull Discharge Regional Curve Determination

Bankfull discharge can be estimated and validated in multiple ways. The four most common methods include: 1) referencing the existing stage-discharge rating curve, 2) hydraulic geometry, 3)

flood recurrence intervals, and 4) Manning based resistance equations (Williams, 1978a). In this study, referencing the bankfull stage to the existing stage-discharge relationship was used to estimate bankfull discharge for the reaches in the regional relations of drainage area to cross sectional area, width, mean depth, and discharge. Where accurate relationships still existed, it was practical to relate the stage-discharge rating curve to the average bankfull stage along the study reach because this method averages multiple field calls and can be tested by examining the bankfull and water surface trendlines. If the bankfull and water surface trendlines are roughly parallel then confidence can be gained in the bankfull stage estimation (Kilpatrick and Barnes, 1964; Leopold, 1994). Bankfull stage for regional curve reaches was calculated by taking the difference between bankfull elevation and water surface elevation at the same station and adding that difference to the stage of the river on the day of the survey. The bankfull stage measurements from the whole reach were averaged and the mean stage was then referenced on the stage discharge tables. Where stage was not known, computations of elevations tied to benchmarks and reference points were required. The first method used to validate bankfull discharge was graphically examining the riffle cross section data for morphological indicators relative to the bankfull indicator trendline produced from the survey points in the Reference Reach Spreadsheet. By examining the morphologic characteristics of the channel graphically it is easier to verify breaks in slope that correspond to the active floodplain connections and bankfull stage. If the bankfull trend lines corresponded to the bankfull level indicated by the morphology in the cross sections, then it was determined to be a good estimate of bankfull stage.

Flood Frequency Analyses

Flood frequency analyses are based on recorded past streamflow events. They are used to supply predictions of future flows and their probability of occurrence. The technique involves using peak flow discharge data to compute statistical information such as mean values, standard deviations,

skewness, and recurrence intervals. Flood frequency analyses were performed for each streamflow gaging station by fitting a Pearson Type III frequency distribution to the logarithms of the annual peak discharge as described in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982). The bankfull gage height that was referenced to the stage-discharge tables was referenced to the flood frequency analyses. The results of the discharge analyses were used to verify that the field determined bankfull features corresponded to a discharge within the 1 to 2 year recurrence interval. If the discharge recurrence interval was between 1 and 2 years I was confident this was a good estimate of bankfull stage.

USGS Site Comparison

The study considered streams draining the southern portion of the Level III Ecoregion 67 Ridge and Valley in Virginia acceptable for inclusion to the study because most Tennessee streams or rivers with large drainage areas (50 to 250 square miles) have regulated flows and could not be included. This created an opportunity to test the data collection methods for similarity to those of Keaton *et al.*, (2005). In the Maryland, Virginia, and West Virginia Ridge and Valley regional curves three reaches were chosen to be resurveyed by separate USGS offices to test for repeatability and similarity of data collection methods. The comparative measurements chosen were bankfull discharge, the channel bed material D_{50} particle, and the hydraulic geometry variables of bankfull cross sectional area, width, and mean depth. The data from the Keaton *et al.*, (2005) regional curves were not reviewed prior to the surveys in order to maintain an objective comparison. Measurements varying from those of the original study by less than 25% were considered acceptable.

Bankfull Discharge Reference Reach Determination

For the ungaged reference reaches, bankfull discharge was estimated through the use of channel flow equations. The bankfull stage was to be validated by comparing the bankfull geometry and

estimated discharge to those proposed by the Level III Ecoregion 67 of Tennessee regional relations following work that had been done by White (2001) in the study of the Lowland Sections of the Piedmont Physiographic Province, Pennsylvania and Maryland. White (2001) compared reference reach bankfull channel geometry measurement and discharge calculations to those of the Lowland regional curves to validate his field determined bankfull stage, which would be used to calculate dimensionless ratios in a stream restoration design.

Bankfull discharge was estimated using Manning's Equation:

$$V = (1.49/n) * R^{2/3} * S^{1/2} \quad (4-1)$$

where

V = mean velocity (ft/sec)

R = hydraulic radius (ft)

S = slope (ft/ft)

n = Manning's roughness coefficient

Manning's n was computed by the Reference Reach Spreadsheet (Mecklenburg and Ward, 2004) as a function of the D_{84} , hydraulic radius, and max depth using equations developed by Hey (1979):

$$n = \frac{R^{1/6} u^*}{\sqrt{g} u} \quad (4-2)$$

and

$$\frac{u}{u^*} = 5.75 \log \left(\frac{aR}{3.5D_{84}} \right) \quad (4-3)$$

$$\text{and } a = \frac{11.1}{\left(\frac{R}{d_{max}} \right)^{3.14}} \quad (4-4)$$

where

g = gravitational constant, 32.2 (ft/sec²)

u* = shear velocity (ft/sec)

u = mean cross section velocity (ft/sec).

Bankfull discharge could then be estimated by using the reference reach measured parameters of wetted perimeter, hydraulic radius, energy gradient, and cross sectional area at the downstream.

Bankfull discharge was then also modeled for all seven reference reaches using the one-dimensional program HEC RAS 4.1 (Brunner, 2001). The inputs required to define the channel shape are a minimum of 2 cross sections and an estimate of the channel roughness using the Manning n coefficient. Two riffle cross sections and one pool cross section were surveyed at each site for modeling purposes. Cross section data were taken directly from the reference reach spreadsheets used to calculate the bankfull dimensions. Roughness values were estimated using the Limerinos (1970) relation and Chow's (1959) tables of roughness coefficients for floodplain areas. The Limerinos relation was applied where roughness could be attributed mostly to the channel bed using the D_{84} particle size from the pebble count and the mean bankfull depth from the surveyed cross section geometry. Adjustments were made for reach sinuosity according to (USGS, 1984). Floodplain roughness coefficients were applied according to Chow's (1959) tables.

For the HEC RAS modeling, the bankfull discharge was varied until the modeled flow elevations most closely matched the best fit line of the bankfull indicators. The downstream boundary condition was adjusted to obtain the best fit with the cross section data, with the initial downstream boundary conditions based on surveyed elevations. Riffle crest-to-crest slopes were calculated and used as a boundary condition (Table 4-1). The use of the downstream bankfull indicator was suggested by Parola (2007) and is considered to be more useful where obvious bankfull indicators exist. The consistent and clear bankfull indicators observed at the reference sites allowed for this boundary condition to be used and compared to the riffle crest-to-crest-slopes. It was found that the riffle crest-to-crest slopes produced more robust models.

The East Fork of Walker Branch was the only reference site with measured stage-discharge data. Bankfull stage for the East Fork of Walker Branch was referenced to the stage-discharge relationship of the 120 degree V- notch weir used to monitor discharge. Enough data existed to perform a flood frequency analysis on the peak annual discharges and gave insight to the estimation of bankfull discharge during the iterative process of modeling bankfull flow using either Manning's equation or HEC RAS.

Table 4-1. HEC RAS Modeling Summary Table

Stream Name	Drainage Area (mi²)	¹ Slope (ft/ft)	³ Discharge Validated in HEC RAS	² Cross Section Number	Cross Sections Interpolated in Model	Downstream Boundary Condition
UT to Mill Branch	0.2	0.009	Yes	3	Yes	Normal Depth
East Fork Walker Branch	0.2	0.039	Yes	3	Yes	Normal Depth
Walker Branch	0.4	0.019	Yes	3	Yes	Normal Depth
Mill Branch	0.4	0.012	Yes	3	Yes	Normal Depth
Shanty Branch	1.0	0.006	Yes	3	Yes	Normal Depth
White Creek	1.3	0.011	No	3	Yes	Normal Depth
UT to Big Creek	2.0	0.010	Yes	3	Yes	Normal Depth

1 = Riffle Crest-to-Crest Slope Used for Normal Depth

2 = Two Riffle Cross Sections & One Pool Cross Section Surveyed

Chapter V

Results

Regional Curve Study Results

Site Selection

A total of eight USGS gaging stations were determined to be suitable for geomorphic survey and flood frequency analysis. One stream (East Fork of Walker Branch) was located within the Department of Energy's ORNL Walker Branch Experimental Watershed and also had sufficient stage discharge data to perform a flood frequency analysis. For this study, it was determined from Parola (2007) that the geographic distribution of the sites throughout the study area would not be a determining factor in site selection because there were a limited number of streamflow gages that met the selection criteria (Figure 5-1). Many of the other gages initially considered for survey had experienced channel instability, flow modification, or destruction of reference points and benchmarks.

Regional Curve Reach Locations

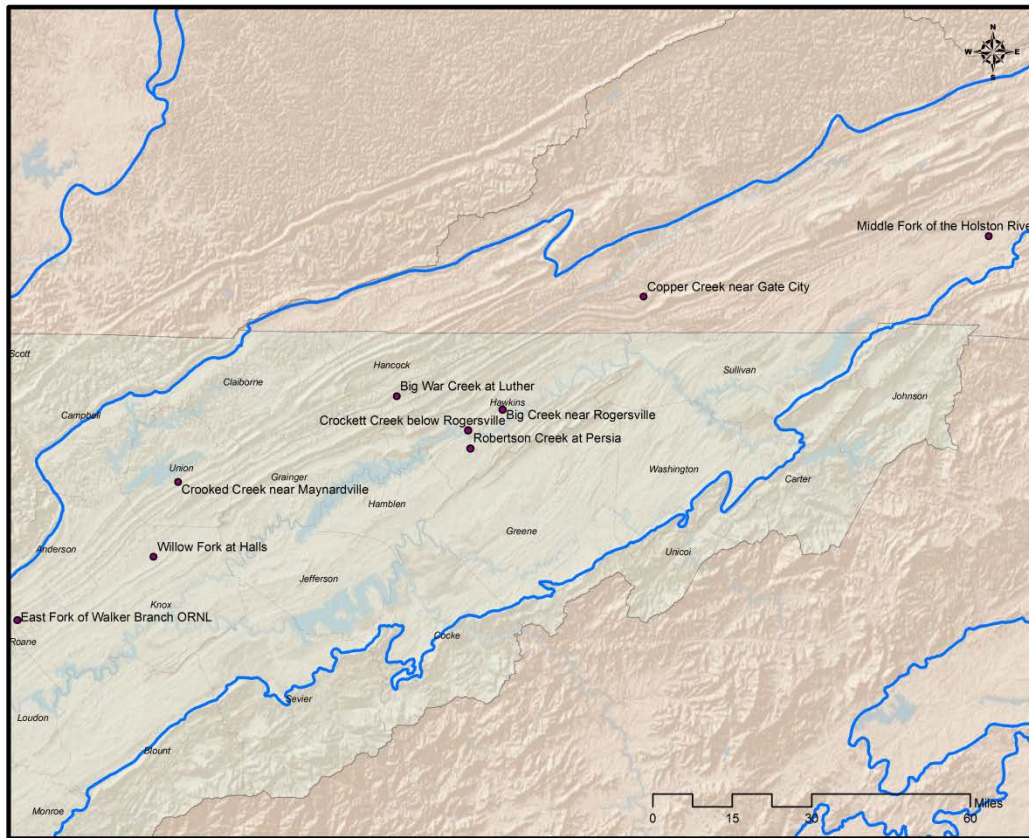


Figure 5-1. Geographic distribution of regional curve reaches in Level III Ecoregion 67.

Bankfull Indicators

The primary bankfull indicators determined by Leopold (1994) were not observed at every site in this study, partly due to the characteristics of these features depending on local channel morphology (Parola, 2007). The bankfull features observed during these pedestrian surveys included one or more of the following indicators (Table 5-1): 1) top of bank or active flood plain connection, 2) point of inflection or prominent break in slope, or 3) a bench feature on the bank. These indicators coincided with those found by McCandless and Everett (2002) in other areas of the Level III Ecoregion 67 Ridge and Valley Physiographic Province. Vegetation types and debris deposits or wrack lines were not found to be useful as primary indicators but were used as secondary indicators to confirm bankfull levels. One reach (Middle Fork of the Holston) had a consistent bankfull level represented by a depositional lateral bench that persisted throughout the entire reach. The reach of Big Creek included in the study was located in a confined valley type and the bankfull level was indicated by a prominent break in slope.

Table 5-1. Primary Bankfull Indicators Regional Curve Reaches Draining the Southern Ridge and Valley

USGS Station No.	Waterway	Gage Location	Drainage Area (mi ²)	Bankfull Indicator
ORNL*	East Fork Walker Branch	ORNL*	0.228	Floodplain Connection
3528390	Crooked Creek	Maynardville, TN	2.23	Floodplain Connection
3535180	Willow Fork	Halls, TN	3.23	Floodplain Connection
3491544	Crockett Creek	Rogersville, TN	4.67	Floodplain Connection
3491540	Robertson Creek	Persia, TN	14.3	Floodplain Connection
3527800	Big War Creek	Luther, TN	22.3	Break in Slope
3491000	Big Creek	Rogersville, TN	47	Break in Slope
3526000	Copper Creek	Gate City, VA	106	Floodplain Connection
3474000	Middle Fork Holston River	Seven Mile Ford, VA	132	Depositional Bench

*ORNL = Department of Energy Oak Ridge National Laboratory Experimental Watershed

Regional Curve Bankfull Return Intervals

The first objective of this study was achieved by determining the average bankfull return interval of streams draining the Southern Ridge and Valley. The recurrence intervals for streams draining the southern Ridge and Valley region in East Tennessee were found to range between 1.1 to 1.7 years (Table 5-2). The mean bankfull return interval for the Southern Ridge and Valley was 1.4 years, which is very similar to the 1.36 years for the Ridge and Valley of Virginia, W. Virginia, and Maryland of 1.36 years found by Keaton *et al.*, (2005). This determination supported findings by Leopold (1994) and others who documented bankfull discharge recurrence intervals to be between 1 and 2 years on average.

Bankfull Stream Channel Characteristics of Streams Draining the Southern Ridge and Valley

Waterway	USGS Gage Station	Drainage Area (mi²)	Valley Type (Rosgen)	Stream Type (Rosgen)	Period of Record (years)	Bankfull Stage (ft)	Bankfull Discharge (cfs)	Velocity (ft/sec)	Bankfull Area (ft²)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Return Period (years)	Slope (ft/ft)
East Fork Walker Branch	N/A	0.23	II	B4	39	1.65	15.1	4.3	6.2	10.4	0.6	1.6	0.039
Crooked Creek	3528390	2.23	VIII	C4	21	2.61	161.0	6.3	49.1	29.9	1.6	1.4	0.009
Willow Fork	3535180	3.23	VIII	C4	40	5.97	170.0	4.4	30.5	20.1	1.5	1.8	0.003
Crockett Creek	3491544	4.67	VIII	E4	18	3.14	269.5	5.8	59.7	24.8	2.4	1.3	0.010
Robertson Creek	3491540	14.30	VIII	C4/1	21	10.02	518.8	4.4	150.1	47.9	3.1	1.1	0.003
Big War Creek	3527800	22.30	VI	B4c	21	6.76	1018.8	3.2	79.2	38.4	2.1	1.3	0.003
Big Creek	3491000	47.00	II	B1c	66	5.76	2144.0	5.6	354.0	94.9	3.7	1.5	0.004
Copper Creek	3526000	106.00	VI	C4	62	8.11	1820.0	4.2	411.2	86.6	4.8	1.3	0.001
Middle Fork Holston River	3474000	132.00	VIII	C4	67	3.45	1930.0	4.2	276.5	88.2	3.1	1.5	0.002

N/A = Oak Ridge National Laboratory Experimental Watershed

cfs = cubic feet per second

Bankfull Area = average of 2 riffle cross sectional area's in square feet

Bankfull Regional Curves

The second objective of this study was achieved by developing bankfull discharge and hydraulic geometry relationships for streams draining the Level III Ecoregion 67 Ridge and Valley of Tennessee. The resulting power function equations and diagnostic statistics can be found in Table 5-3. The bankfull discharge ranged from 15 cubic feet per second (cfs) to 2144 cfs. Drainage area explained 96 % of the variation observed in the regression relations of drainage area with bankfull discharge, with an R^2 of 0.960. The scope of the project placed emphasis on selecting reaches that had drainage areas between 0.1 and 50 square miles because restoration is most often implemented on streams of this size. Reach basin drainage area ranged from 0.2 to 132 square miles, and seven out of the nine streams selected in the survey had less than 50 square miles of drainage area. Bankfull cross sectional area and width both had 91 % of the variation explained by drainage area, with R^2 values of 0.918 and 0.914, respectively. Bankfull mean depth had the least amount of variation explained by drainage area, with an R^2 of 0.843. Each relationship was strong and indicated the efficacy of using drainage area as a predictor of bankfull discharge and the associated hydraulic geometry (Figures 5-2 to 5-9). All standard errors were large due to small sample size, but the distribution of the residuals was random in all cases, satisfying the assumption of independent error in linear regression.

Table 5-3. Power Function Equations and Statistics for the southern Ridge and Valley Regional Curves

Equation	P - value	R^2	Standard Error	F Statistic
Bankfull Discharge (cfs) $Q = 68.82 (DA)^{.77}$	0.0001	0.96	0.343	171
Bankfull Cross Sectional Area (ft²) $Area = 19.59 (DA)^{.63}$	0.0001	0.918	0.411	79
Bankfull Width (ft) $Width = 16.97 (DA)^{.35}$	0.0001	0.914	0.237	75
Bankfull Mean Depth (ft) $Depth = 1.15 (DA)^{0.28}$	0.0005	0.843	0.263	38

All models n = 9

DA = Drainage Area (mi²)

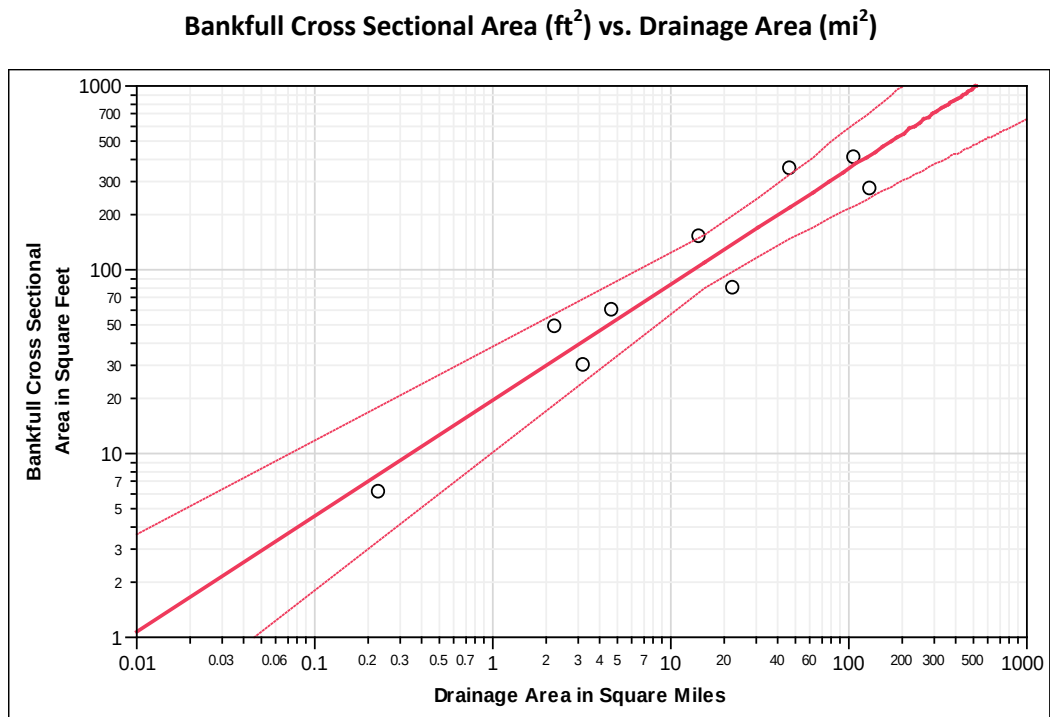


Figure 5-2. Regional curve relating cross sectional area to drainage area in the southern Ridge and Valley Physiographic Province. Red dashed line represents 95 percent confidence interval.

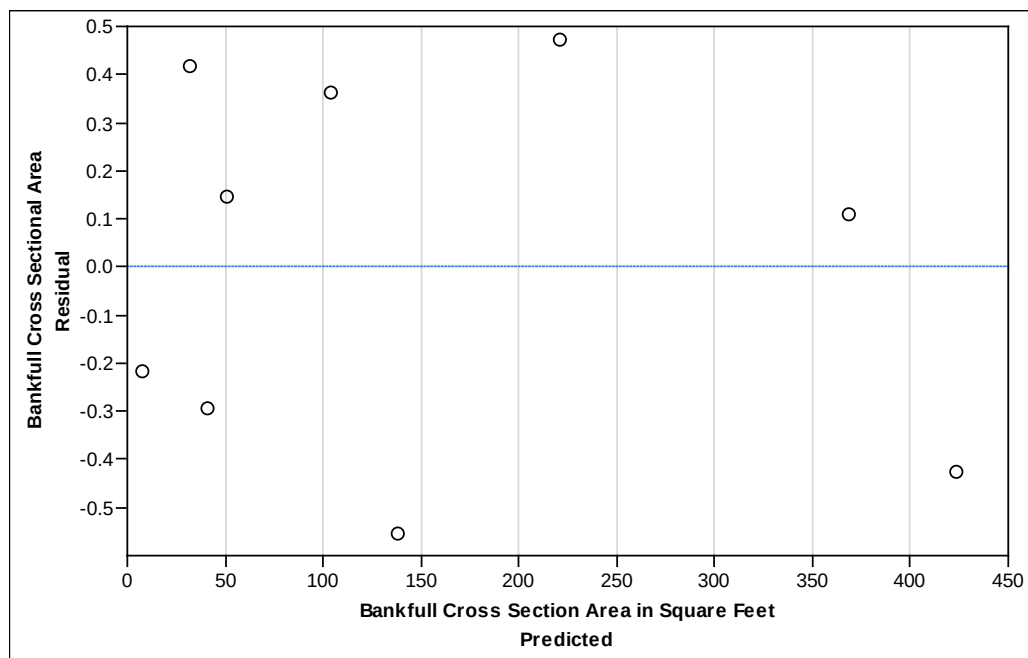


Figure 5-3. Bankfull cross sectional area residual by predicted plot.

Bankfull Width (ft) vs. Drainage Area (mi²)

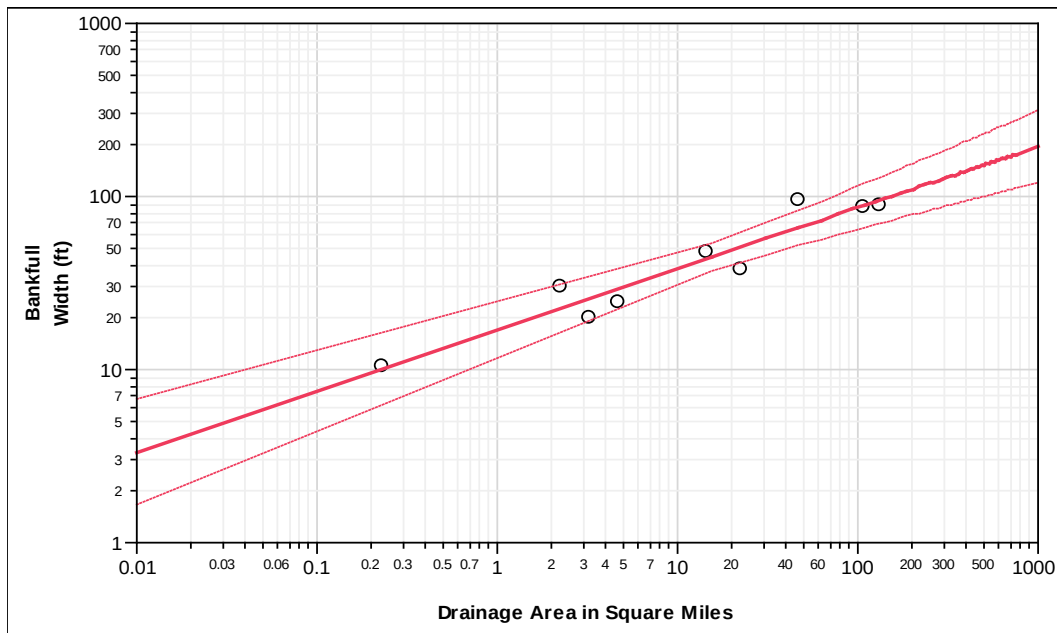


Figure 5-4. Regional curve relating bankfull width to drainage area in the southern Ridge and Valley Physiographic Province. Red dashed Line represents 95 percent confidence interval.

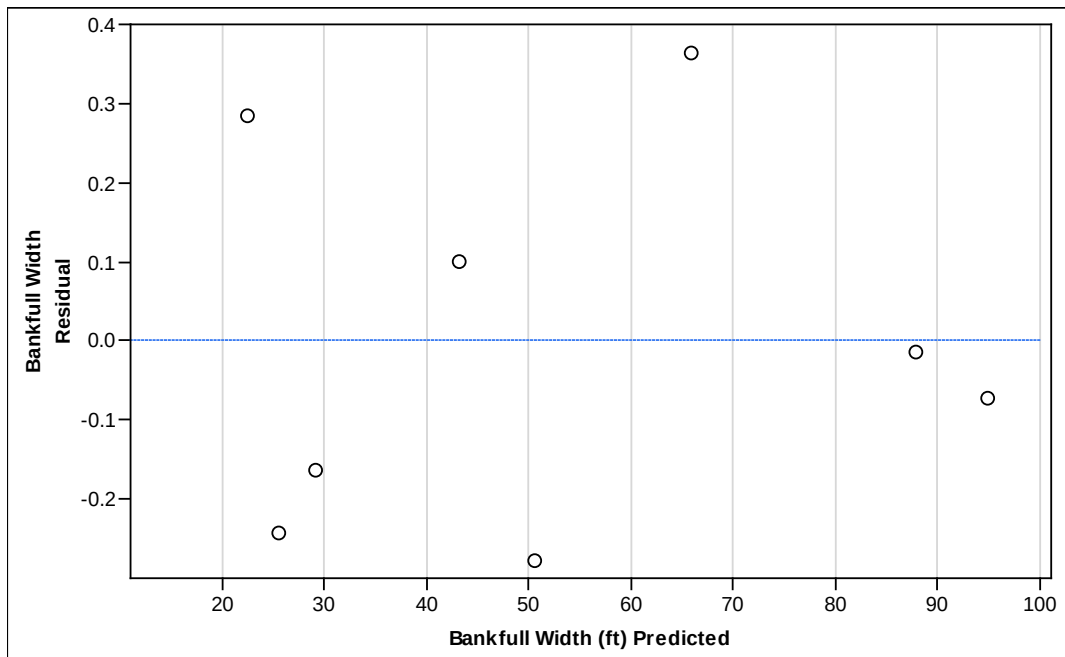


Figure 5-5. Bankfull width residual by predicted plot.

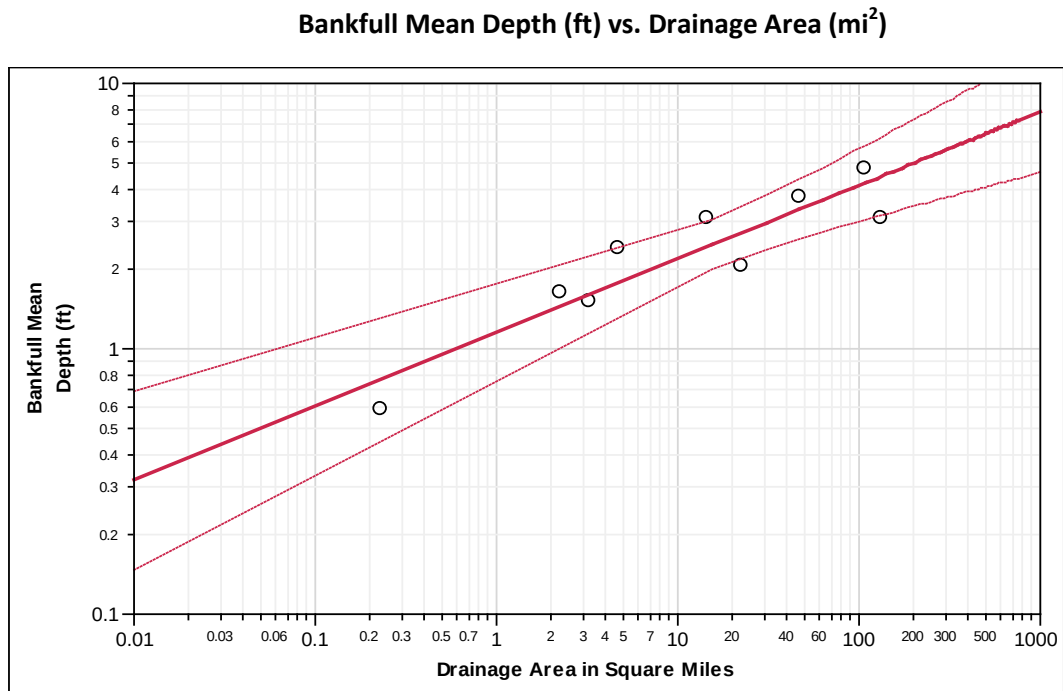


Figure 5-6. Regional curve relating bankfull mean depth to drainage area in the southern Ridge and Valley Physiographic Province. Red dashed line represents 95 percent confidence interval.

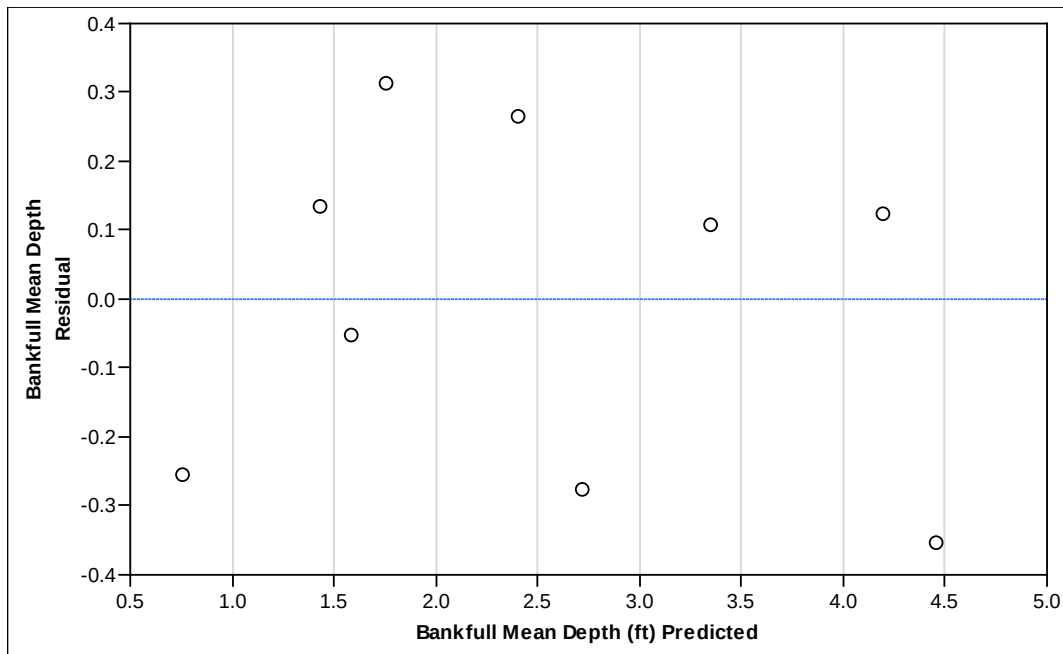


Figure 5-7. Bankfull mean depth residual by predicted plot.

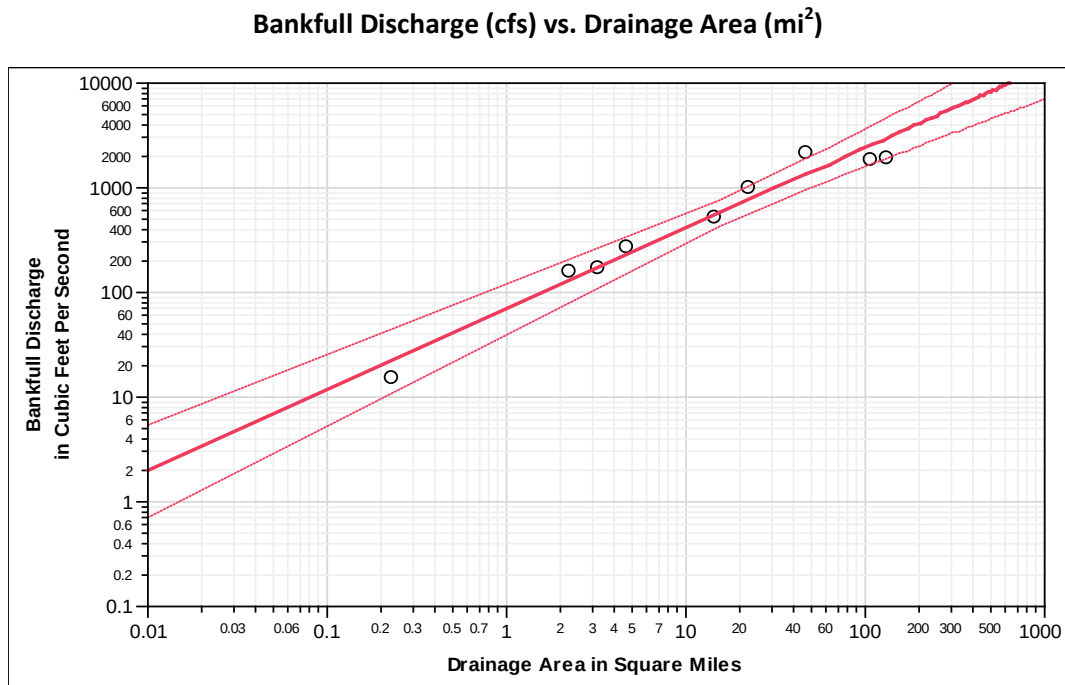


Figure 5-8. Regional curve relating bankfull discharge to drainage area in the southern Ridge and Valley Physiographic Province. Red dashed line represents 95 percent confidence interval.

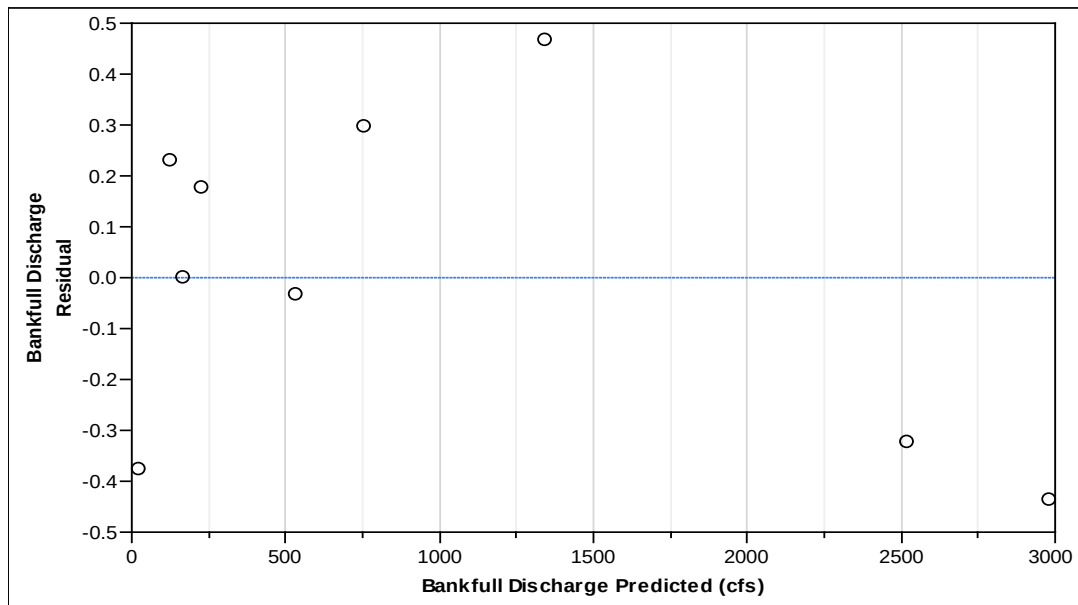


Figure 5-9. Bankfull discharge residual by predicted plot.

USGS Site Comparison

All measurements for comparison to the earlier study of Keaton *et al.*, (2005) were within 25% of the original measurements made for the Middle Fork of the Holston River (Table 5-7), providing some confidence that the methods used in each study were similar and repeatable and could be further analyzed for similarity. During the calculation of the flood frequency analysis it was observed that the peak flows recorded followed a bi-modal distribution after 1977. This was due to either the low flow diurnal fluctuations caused by a mill upstream of the gage, or the construction of Interstate Route 81 and its effects on the stage discharge relationship, so all flows prior to 1977 were removed from the analysis. It was not stated in Keaton *et al.*, (2005) whether or not these adjustments were made and could account for some of the difference in the estimated bankfull discharge because annual peak flows with varying discharges were removed from the analysis.

Regional Curve Comparison

The third objective of this study was to test the discharge and hydraulic geometry relationships developed with those completed in the Ridge and Valley by Keaton *et al.*, (1999) in Maryland, Virginia and West Virginia (Figures 5-6 through 5-9). Using the analysis of covariance, no statistically significant differences at the 0.05 significance level were found between the slopes or intercepts for the southern Ridge and Valley and the works completed by Keaton *et al.*, (1999). The residuals were evaluated to test the fit of the models. Some of the models showed evidence of unequal variances, or heteroscedasticity. The relationships of bankfull cross sectional area and bankfull discharge to drainage area showed a small amount of lack of fit when estimating area and discharge below 100 square feet and 450 cubic feet per second, respectively (Figures 5-11 & 5-17). The bankfull mean depth relations to drainage area are the most critically heteroscedastic, as indicated by the pattern of rise and fall of the residuals as mean depth increases (Figure 5-15). The bankfull width relations had a random distribution of residuals (Figure 5-

13). Least square means and standard errors are reported for comparison in Table 5-4. There was no evidence supporting separating the regional equations completed for the Ridge and Valley Province in the states of Pennsylvania, Maryland, Virginia, West Virginia, and Tennessee. All p values reported were greater than 0.05, failing to reject the null hypotheses of equal slopes and intercepts in all cases compared at the 0.05 significance level (Table 5-5).

Table 5-4. Channel Geometry and Discharge Comparisons for Middle Fork of Holston River

Measurement Designation	Cross Sectional Area (ft ²)	Width (ft)	Mean Depth (ft)	Estimated Discharge (cfs)	Recurrence Interval (years)	1.5-year Discharge	D ₅₀ (mm)
McPherson (2011)	276.5	88.2	3.1	1930.0	1.45	1980.0	57.0
Keaton (2005)	336.0	83.0	4.1	2420.0	1.40	2620.0	46.1
% Difference	17.7	6.3	24.4	20.2	3.6	24.4	23.6

Table 5-5. Least Square Means & Standard Error Comparison of Ridge and Valley Regional Curves

Dependent Variables	McPherson, 2011		Keaton <i>et al.</i> , 2005	
	Mean	SE	Mean	SE
Bankfull Area (ft ²)	265.3	51.5	267.4	17.8
Bankfull Width (ft)	72.8	8.2	74.2	2.8
Bankfull Mean Depth (ft)	3.3	0.4	3.1	0.2
Bankfull Discharge (cfs)	1521.0	195.0	1383.0	67.7

Region Main Effect Differences Evaluated at Drainage Area = 79.6388 mi²

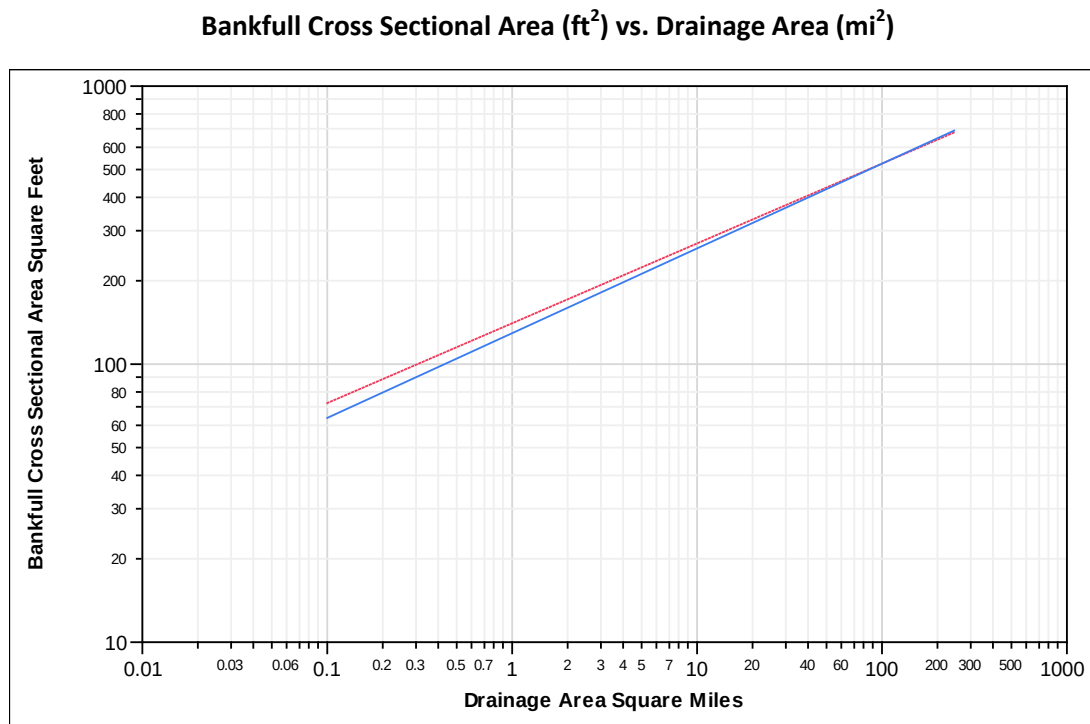


Figure 5-10. Bankfull cross sectional area for study sites in the southern Ridge and Valley compared to the Ridge and Valley of Virginia, West Virginia and Maryland. Dashed line = Keaton *et al.*, 2005. Solid line = McPherson, 2011.

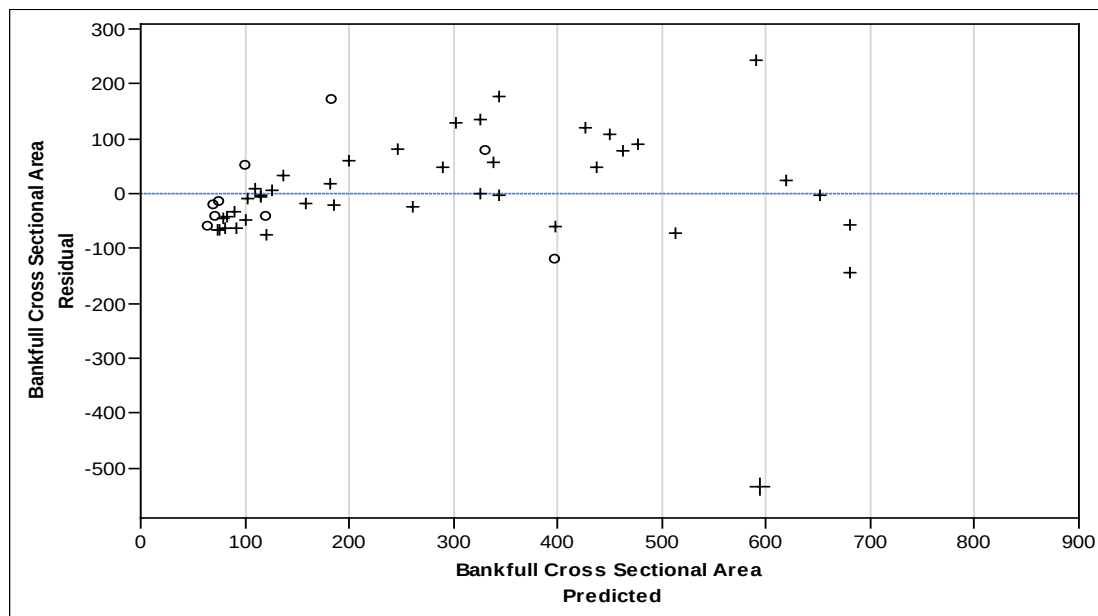


Figure 5-11. Analysis of Covariance residual plot for bankfull cross sectional area. O = McPherson, (2011) + = Keaton *et al.*, (2005).

Width (ft) vs. Drainage Area (mi²)

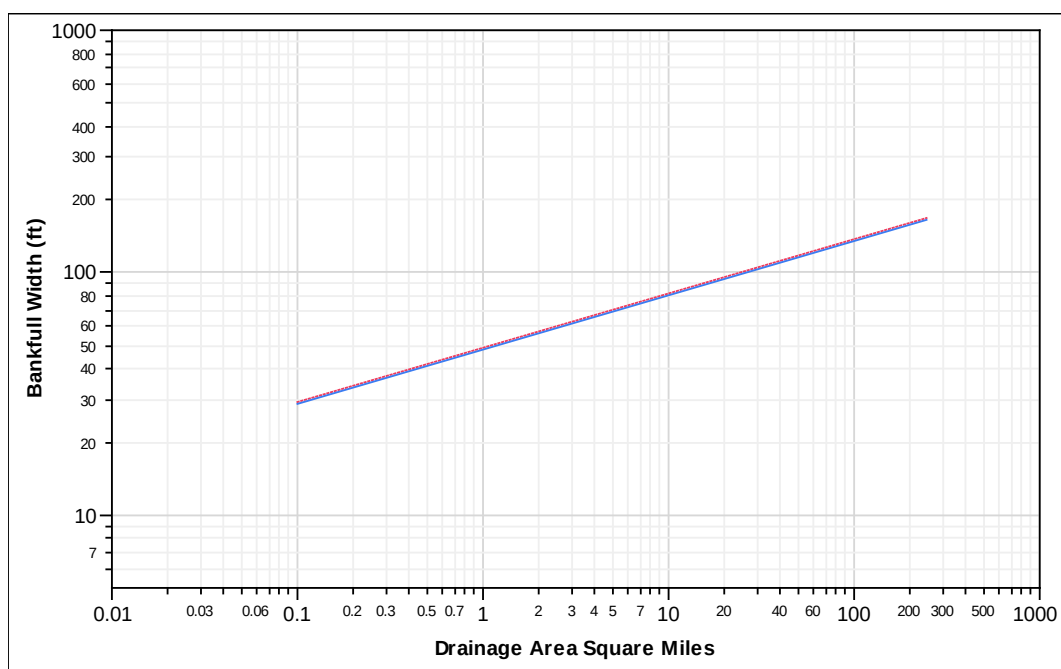


Figure 5-12. Bankfull width for study sites in the southern Ridge and Valley compared to the Ridge and Valley of Virginia, West Virginia and Maryland. Dashed line = Keaton *et al.*, 2005. Solid line = McPherson, 2011.

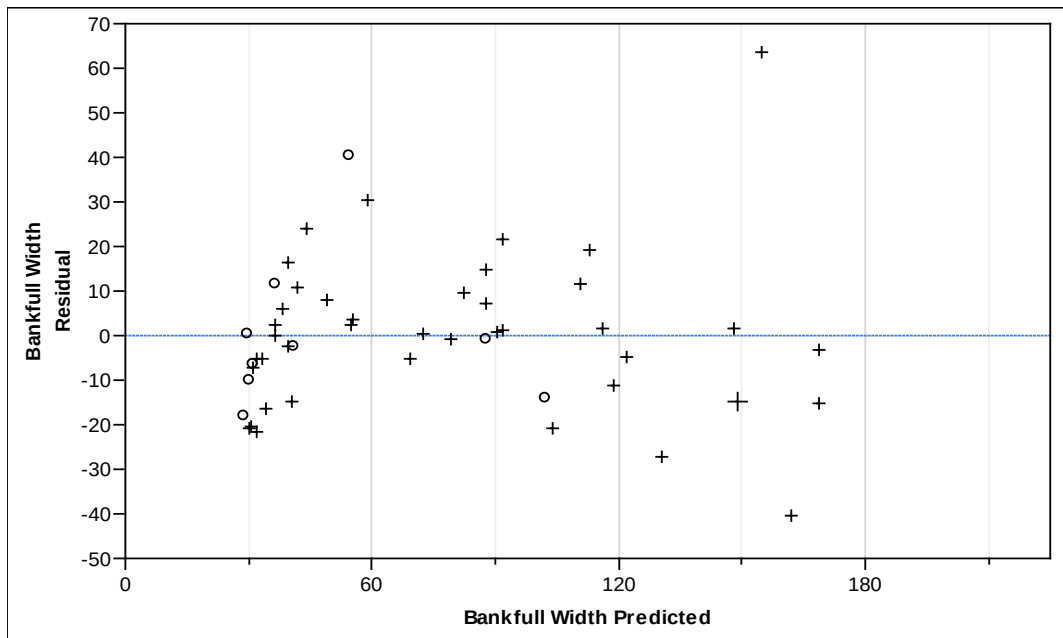


Figure 5-13. Analysis of Covariance residual plot for bankfull width. O = McPherson, (2011)
+ = Keaton *et al.*, (2005).

Mean Depth (ft) vs. Drainage Area (mi²)

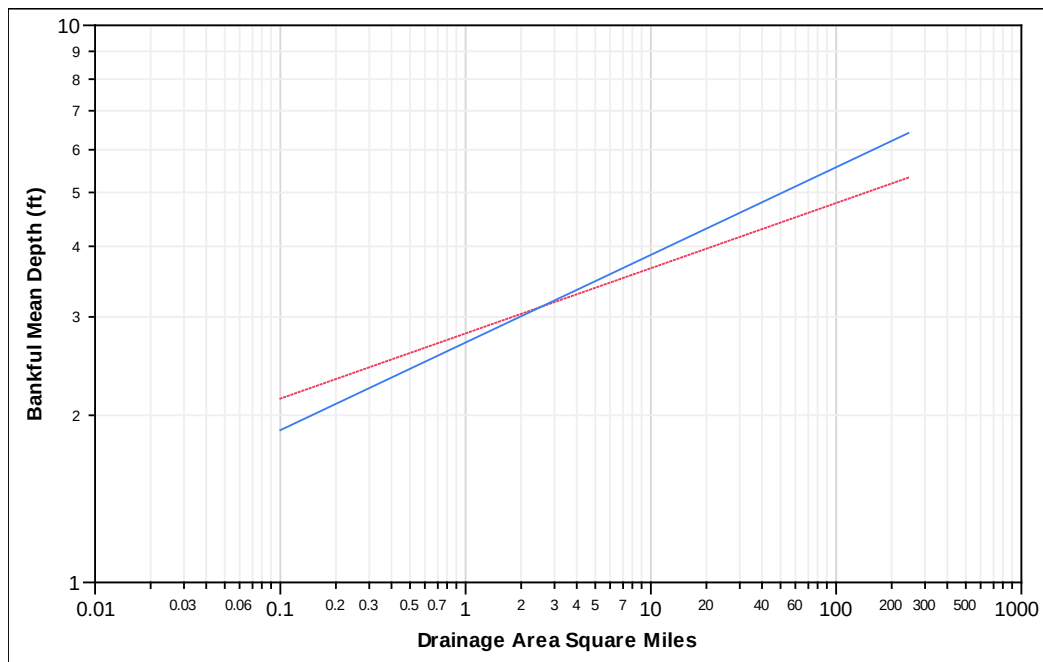


Figure 5-14. Bankfull mean depth for study sites in the southern Ridge and Valley compared to the Ridge and Valley of Virginia, West Virginia and Maryland. Dashed line = Keaton *et al.*, 2005. Solid line = McPherson, 2011.

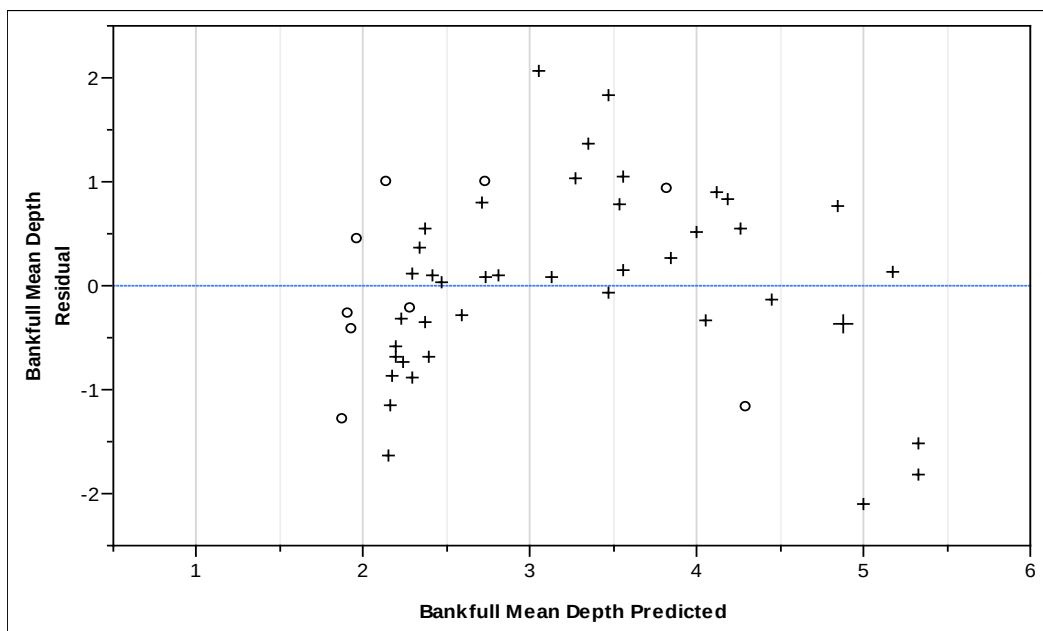


Figure 5-15. Analysis of Covariance residual plot for bankfull mean depth. O = McPherson, (2011)
+ = Keaton *et al.*, (2005).

Discharge (cfs) vs. Drainage Area (mi²)

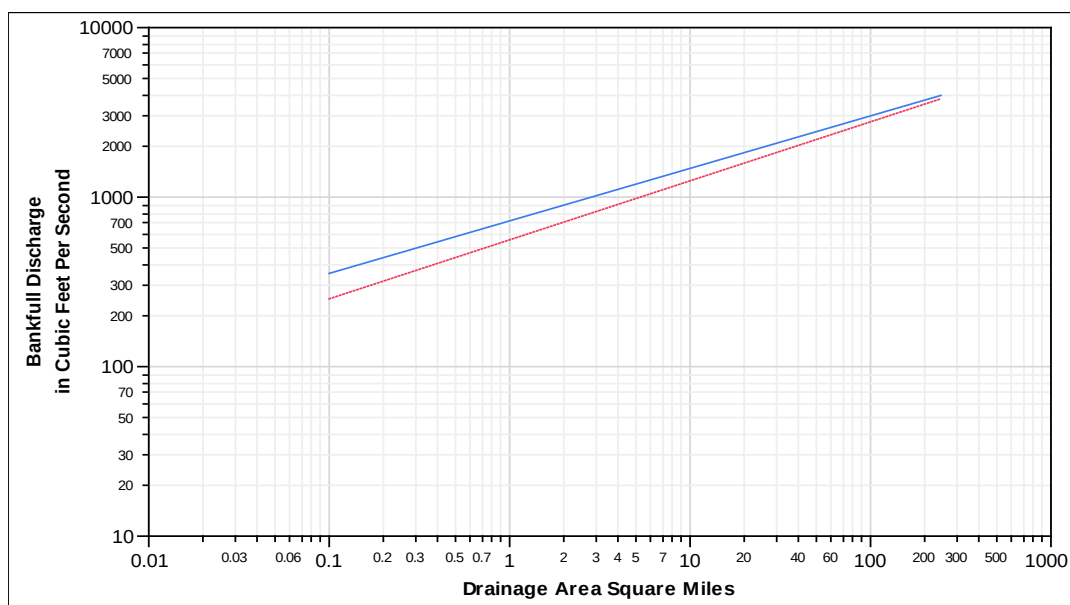


Figure 5-16. Bankfull discharge for study sites in the southern Ridge and Valley compared to the Ridge and Valley of Virginia, West Virginia and Maryland. Dashed line = Keaton *et al.*, 2005. Solid line = McPherson, 2011.

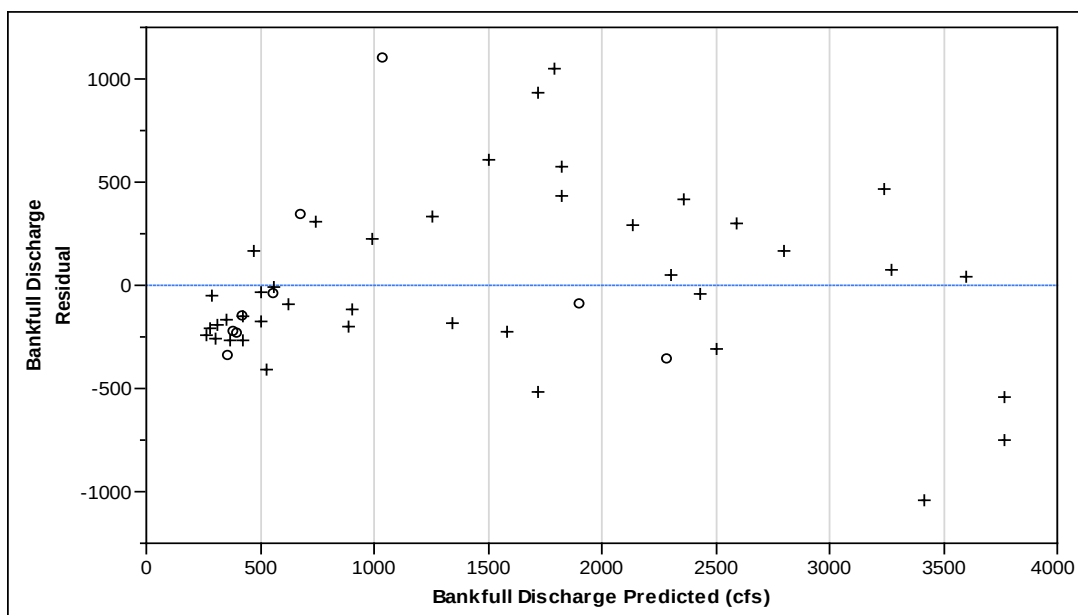


Figure 5-17. Analysis of Covariance residual plot for bankfull discharge. O = McPherson, (2011)
+ = Keaton *et al.*, (2005).

Table 5-6. Comparison of P values for Null Hypothesis of Equal Slopes and Intercept

Dependent Variable	Slope	Intercept
Bankfull Cross Sectional Area (ft ²)	0.9377	0.9695
Bankfull Width (ft)	0.9731	0.8788
Mean Bankfull Depth (ft)	0.4339	0.6962
Bankfull Discharge (cfs)	0.8875	0.5081

P value > 0.05 = Fail to Reject Null Hypothesis

Reference Reach Study Results

Reference Reach Site Selection

A total of seven stream reaches were determined suitable for survey (Figure 5-18). Most streams were located using the Tennessee Ecoregion Project (Arnwine *et al.*, 2000). One reach (Unnamed Tributary to Big Creek) chosen for a reference reach geomorphic survey was upstream of a discontinued USGS gage, but no stage discharge relations could be made because the benchmarks had been destroyed. “UT to Big Creek” was not a Tennessee Ecoregion Project reference site. It was determined that this was a suitable site for reference survey due to landowner permission not being granted at another more appropriate site from the Tennessee Ecoregion Project (Arnwine *et al.*, 1997).

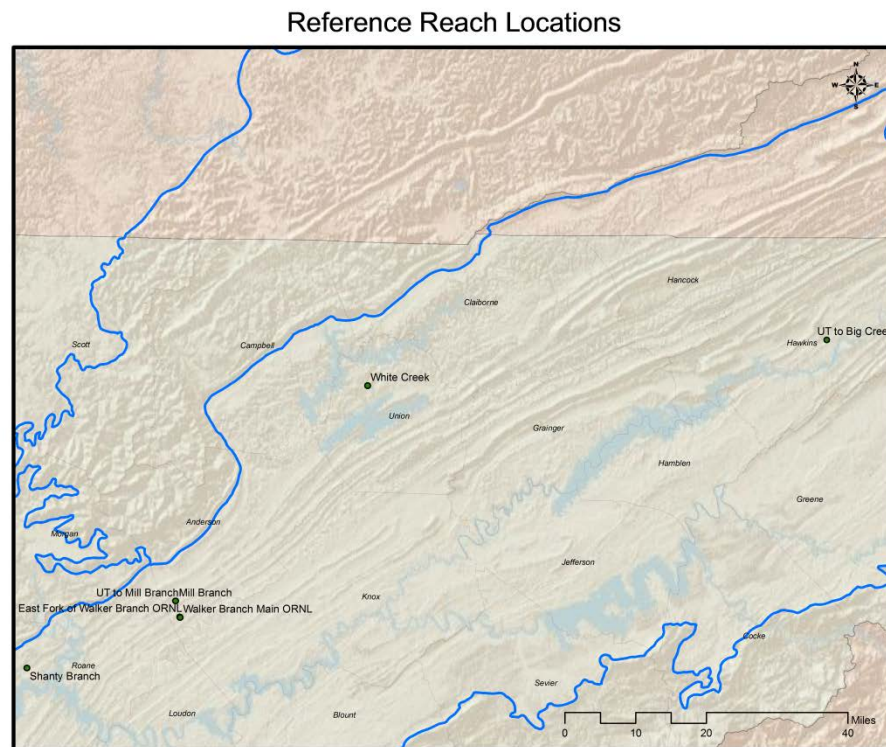


Figure 5-18. Geographic distribution of Reference Reaches in the Level III Ecoregion 67.

Reference Reach Database

The fourth objective of this study was to develop a reference reach database for streams draining the Level III Ecoregion 67 Ridge and Valley of Tennessee. This was achieved by filtering the Tennessee Ecoregion Project reaches and selecting seven streams as close to reference quality as possible, stratifying them by stream and valley type, surveying the bankfull dimensions at the reference bankfull stage, and calculating the appropriate dimensionless channel geometry ratios. Bankfull stream channel characteristics and dimensionless channel geometry ratios for each reference reach can be viewed in the appendices in Tables A-1 to A-6.

Comparison of Regional Curve Relationships to Reference Reach Sites

The fifth objective of this study was to compare the reference reach bankfull channel geometry measurements and bankfull discharge calculations to those computed from the regional power function equations to validate reference reach bankfull stage (Table 5-7). The measurements for bankfull cross sectional area proposed by the regional equations had a mean absolute difference of 27 percent. The measurements for bankfull width and bankfull mean depth proposed by the regional equations had mean absolute differences of 13 and 21 percent, respectively. Bankfull discharge estimations computed with Manning's Equation had a mean absolute difference of 118 percent from the regional equation proposed discharge values. Discharge estimates from Manning's equation were validated with HEC-RAS. Bankfull flow was successfully modeled in HEC RAS for all reaches except White Creek. Had there been more cross sections surveyed and the bed surface better represented, the program may have been able to balance the energy equations used to determine subcritical flow within the reach with less error, providing more confidence in the modeled bankfull discharge.

Table 5-7. Reference Reach & Regional Curve Bankfull Stream Characteristic Comparison

Stream Name	Drainage Area (mi ²)	Bankfull Area (ft ²)	Regional Curve	Percent Difference %	Bankfull Width (ft)	Regional Curve	Percent Difference %	Bankfull Mean Depth (ft)	Regional Curve	Percent Difference %	Bankfull Discharge (cfs)	Regional Curve	Percent Difference of Curve	HEC RAS Bankfull Discharge (cfs)
UT to Mill Branch	0.2	7.9	6.2	-21.7	9.8	8.9	-9.3	0.8	0.7	-15.7	33.7	15.8	-113.6	34
East Fork Walker Branch	0.2	6.1	7.7	20.7	10.4	10.1	-3.2	0.6	0.8	25.0	24.3	20.8	-16.8	23
Walker Branch	0.4	12.9	10.6	-17.9	10.7	12.0	12.3	1.0	0.9	-12.4	94.0	30.7	-206.0	44
Mill Branch	0.4	10.6	11.5	8.7	15.3	12.6	-17.7	0.9	0.9	7.0	59.6	34.1	-74.9	32
Shanty Branch	1.0	35.1	19.3	-45.1	19.9	16.8	-15.5	1.4	1.1	-18.4	190.0	64.5	-194.4	164
White Creek	1.3	36.2	22.9	-36.8	17.7	18.5	4.6	2.0	1.2	-38.4	257.0	79.8	-222.0	120
UT to Big Creek	2.0	21.3	29.9	40.4	16.4	21.5	31.2	1.9	1.4	-27.0	114.0	111.3	-2.5	112

Bankfull Discharge Estimated with Mannings's Equation

Yellow Fill Indicates Percent Difference from Regional Power Function Equations

Two Cross Sections Averaged in Discharge Calculations

Chapter V

Discussion

Regional Curves

Bankfull discharge and hydraulic geometry regional curves for the Level III Ecoregion 67 of the Ridge and Valley in East Tennessee were a challenge to determine due to the lack of available stream flow gaging stations that met the selection criteria. An initial list of 47 USGS peak streamflow gaging stations was investigated. Every available stream gage site had been impacted by some form of human manipulation. Many stations had been discontinued and the associated reference point or benchmarks destroyed due to road construction. Agriculture also placed many constraints on waterways in the Ridge and Valley physiographic province of East Tennessee by altering the hydrographs, geomorphically disturbing the channels, reducing riparian widths, or introducing excess sediment to the systems. A total of six USGS gaging stations were found within the state boundaries that met the selection criteria. Another site was located within the Department of Energy Oak Ridge National Laboratory Walker Branch Experimental Watershed (Mulholland, 2010). These seven out of the nine streams selected had drainage areas of less than 50 square miles. The scope of the project designated streams draining areas less than 50 square miles as being critical, since restoration is usually implemented on first and second order streams in this size range. However, streamflow gaging stations with larger drainage areas were necessary to construct complete regional curves. It was found that in East Tennessee there were no large streams that had been monitored for peak flow data that had not been regulated to some extent, so the study considered streams draining the Southern Ridge and Valley portion of Virginia available for survey. Two additional sites were selected, (Copper Creek and the Middle Fork of the Holston River); both were less than 35 miles from the Tennessee state line and well within the Level III Ecoregion 67 of the Ridge and Valley.

The primary bankfull indicator observed in this study was the active floodplain connection, which is the incipient point of flooding. This bankfull indicator was in agreement with other researchers who have completed similar studies in the eastern U.S. (Harman *et al.*, 1999; Keaton *et al.*, 2005). Although the active floodplain connection was the primary indicator observed, at some sites it was observed that inflection points or a depositional bench represented the bankfull stage. Scour and fine sediment deposition often coincided with the bankfull level represented by the active floodplain connection along the reach.

The study failed to reject the null hypothesis of equal slopes and intercepts when comparing the regional curves developed to those created by Keaton *et al.*, (2005), providing insufficient evidence to validate having separate regional curves for the two areas in the Ridge and Valley Physiographic Province. The similarities that were observed in the two studies can be explained by the similarities of the basin level features that dictate channel form, such as climate, geology, soils, vegetation, land use, topography, and basin morphology.

The underlying geology and physiography of the study area in this analysis also provided insight into the comparisons being made. The majority of the Ridge and Valley province was formed from folding and thrust faulting of Cambrian and Ordovician carbonate rocks resulting in the many parallel and even crested ridges seen today. The similar underlying strata and rather homogenous patterns of topographic relief throughout the province lead the way to similar colluvial and alluvial deposits in the valley bottoms where soils are formed, vegetation grows and drainage ways persist. The parameters of bankfull width and mean depth are most affected by the composition of the bed and bank material and its resistance to erosion (Knighton, 1987), as well as the bank vegetation (Smith, 1976). It appears the similarity of bank materials and vegetation in the Ridge and Valley province lead to the close association of the bankfull width relations compared in this study.

Channel morphology is affected by local geomorphic factors such as reach sediment supply, bedrock positioning, composition of bed and bank materials, and vegetation. The channel morphology can vary a great deal throughout a reach because these geomorphic factors are continually changing in intensity of exposure and concentration, but it appears that these driving factors of channel form are dynamically consistent throughout the two study areas and explain the statistically insignificant differences observed in the comparisons made for the bankfull width, mean depth, cross sectional area, and discharge relations.

In addition, all streams included in the study had evidence of some degree of bedrock exposure. The areas of exposure were variable; I observed outcrops in various places in the stream bed or bank, as well as a bedrock dominated stream. Bedrock control is characteristic of streams draining the Ridge and Valley province. Many streams change morphological character by altering shallow spreads of alluvial and colluvial deposits above layers of bedrock, but large flows may be controlled by the underlying rock. Bedrock streams behave much differently than fully alluvial channels (Shields *et al.*, 2003). Some cut and fill can occur in bedrock channels, but there is not a permanent balance on the geologic time scale as in alluvial channels (Tinkler and Wohl, 1998).

Big Creek was a bedrock dominated channel with greater than 50% bedrock substrate, but it did contain alluvium in the riffles. Stream channels composed primarily of bedrock are forced to migrate laterally over time and thus have more variable bankfull widths (Tinkler and Wohl, 1998). This created a condition where discharge was very sensitive to the stage of the stream. Big Creek was also located within a confined valley that made determining the bankfull stage difficult because multiple levels of scour lines were evident from past discharges. Channel geometry measurements made for Big Creek were the largest outlier in the regression relations, as it was the most different geomorphically. The influence of Big Creek would not have been as severe if the study had included a larger sample size.

The first objective of the study was to determine if the bankfull return interval of streams draining the Level III Ecoregion 67 of the Ridge and Valley of East Tennessee was between 1 and 2 years. The study determined that the bankfull return interval ranged from 1.1 to 1.76 years, agreeing with work completed in other areas of the eastern United States and that of Keaton *et al.*, (2005). The second and third objectives were to develop the bankfull discharge and hydraulic geometry relationships for the Ridge and Valley and compare them to those developed for the Ridge and Valley of Maryland, Virginia and West Virginia (Keaton *et al.*, 2005). The resulting power function equations and coefficients of determination were calculated and reported for the relationships of drainage area to bankfull discharge and the associated hydraulic geometry, but should not be extrapolated to drainage areas outside the 0.2 to 132 square mile range. Drainage area explained from 84 to 96 percent of the variation in the relationships. Regional relationships were compared to those of Ridge and Valley in Maryland, Virginia and West Virginia with the use of an analysis of covariance. Means were compared at a drainage area of 79.68 square miles, and no statistically significant differences were found between the datasets for slopes or intercepts. This provided evidence that supported future merging of the datasets to provide more explanatory power when estimating the bankfull channel geometry conditions that approximate equilibrium in a degraded system. Although no statistically significant differences were found, some caution should be used when interpreting these regional curves. One of the underlying assumptions of regression is that the errors are independent or the residuals are randomly distributed. Relations of bankfull cross sectional area and bankfull discharge to drainage area both showed signs of lack of fit when estimating values for smaller drainage areas. Relations of bankfull mean depth to drainage area were the most acutely heteroscedastic and could have increased the possibility of rejecting the null hypothesis of equal slopes and intercepts (McDonald, 2009). This could have caused the more dramatic differences in the regression relations as indicated by the ANCOVA plot. Caution should also be used when applying the bankfull discharge and cross sectional area regional

curves to stream restoration projects with smaller drainage areas, as they may have a tendency to over-predict smaller values. Regional curves for bankfull mean depth should also be used with caution, taking into consideration the degree of bedrock exposure and location of the stream in the drainage basin.

The curves compared in the study utilized drainage area as the sole explanatory term in the models. The drainage basin is considered the fundamental unit of the fluvial landscape, but many believe that basin characteristics other than drainage area alone could explain additional variability in the regional curves (Ritter *et al.*, 2002). Analysis of basin characteristics such as land cover, watershed slope, and percent carbonate of underlying bedrock may provide increased insight of the effects on channel geometry, should be considered by users of regional curves, and have been found to significantly affect the slope of the bankfull discharge relationship (Keaton *et al.*, 2005). The study of these effects on channel geometry and discharge were not in the scope of this project but may be analyzed in the future. It is also important to note that the curves should be used to assist in determining channel dimensions for natural channel design and should only be employed to validate bankfull stage (Babbitt, 2005; Cinotto, 2003).

USGS Site Comparison

The differences between measurements made for bankfull channel geometry, bankfull discharge and channel bed materials for this study and that of Keaton *et al.*, (2005) for the Middle Fork of the Holston River can be related to the riffle cross section locations, adjustments in flow data used for the flood frequency analysis, measurement variance, and the inherent subjectivity with which bankfull delineations are made. The prominent bankfull indicator observed in both surveys was the lateral depositional bench along the right banks. Similar return intervals and surveyed bankfull geometry (with differences of less than 25%) led me to believe that the surveys and measurements were implemented in the same repeatable manner.

Reference Reach

Another tool engineers and designers of restoration projects have used to estimate what channel conditions approximate equilibrium in a degraded system is the use of the reference reach. By locating a stream that is transporting its sediment and water inputs from its basin without severely aggrading or degrading and that has a similar basin form, sediment regime, and channel classification, a designer is able to extrapolate the channel geometry conditions that will allow a state of quasi equilibrium to exist to another degraded site. The detailed information acquired from the surveys of reference reaches provides habitat unit channel geometry information in the form of dimensionless ratios that aid in the reconstruction of stable and supporting stream features. The resulting reference reach database will aid in restoration implemented in this manner by providing detailed geometry information on reference quality streams stratified by valley and stream type draining the Level III Ecoregion 67 of the Ridge and Valley of East Tennessee. Care was taken to provide the most geomorphically stable and representative streams of the region, as previously described in Chapter 2.

Six out of the seven reference reach streams selected for this study drained narrow valley types and were of 1st or 2nd order (Strahler, 1952). Reference reaches draining the southern Ridge and Valley consisted of 3-C4, 2-E4, 2-B4 and a 1-B4c stream types (Figure 2-1). The physiographic and human development of the Ridge and Valley has created a situation where forested areas remained on steeper slopes and valley bottoms have been developed. As a result, two Rosgen (1994) valley types, VII and VIII, were observed during the reference reach study. Streams selected for survey had clear and consistent bankfull indicators, with the active floodplain connection being observed as the reference bankfull discharge at all sites. All streams included in the reference condition design database consisted of gravel sediment regimes. Bedrock was observed as a grade control in the downstream cross section at the East Fork of Walker Branch, which was the only B4c stream type and drained a steeper, more confined valley,

which is atypical of streams with bedrock influence. The downstream cross section morphology had increased its width as a response to the bedrock outcrop, but maintained nearly the same cross sectional area as the upstream cross section. At the remaining reference sites, bedrock was almost exclusively present in pool habitat units created by fluvial scour. This supports the thought that most streams in the Ridge and Valley persist near bedrock because they are currently in the erosional stage in the geologic timescale (Hack, 1960). All reference reaches except the Unnamed Tributary to Big Creek were located within primarily forested watersheds. The dimensionless ratios computed were still comparable to the reaches in forested watersheds and was considered acceptable for inclusion into the reference reach database. The dimensionless ratios can be found in the appendix (A-1 to A-7).

The fourth and fifth objectives of the study were to develop a reference reach database, and to compare bankfull channel geometry measurements and bankfull discharge estimations to the regional equations to validate the bankfull stage. By estimating the channel roughness through use of the equations developed by Hey (1979), calculating velocity using Manning's equation, and measuring cross sectional geometry I was able to determine bankfull discharge and the associated hydraulic geometry. Differences between measured reference reach bankfull geometry and bankfull discharge were found when compared to the proposed geometry and discharge suggested by the regional equations, but channel geometries were similar enough that I was confident in the estimated bankfull stages on which the dimensionless ratios were based.

The reference reach bankfull stage was validated by comparing the bankfull channel geometry measurements and bankfull discharge estimations with those proposed by the regional power functions developed for the second objective of this study. The mean absolute value percent differences for the bankfull channel geometry measurements lead me to believe that the bankfull stages chosen for the reference reaches are sufficiently accurate. The mean absolute value difference between the

computationally estimated reference reach bankfull discharges and their associated geometry with the discharges and geometry proposed by the regional relations are possibly the effect of having few streams with drainage areas between 0.2 and 2.23 square miles, the unknown degree of karst effects on bankfull streamflow in east Tennessee, and differences in form resistance contribution of structures, large woody debris, and sinuosity in small streams. Also, both the stage discharge ratings at USGS gages and Manning's equation both assume steady uniform flow that has assumes a one-to-one relationship between depth and discharge.

Conclusions

Regional curves and detailed channel geometry information in the form of dimensionless ratios gleaned from reference reach geomorphic surveys are helpful tools that can be used to estimate the bankfull stage and channel dimensions in degraded or altered stream systems. Dimensionless ratios are useful design tools because they can be obtained quickly and applied to streams of differing sizes and discharge while staying within the same stream type. Regional curve studies are useful because they describe a broad range of bankfull channel characteristics for a specific Level III Ecoregion. By including regional curve and reference reaches in this study that are stable and currently accommodating their drainage basin inputs of discharge and sediment, regional curves and the reference reach database for the Level III Ecoregion 67 Ridge and Valley in Tennessee will benefit the natural channel design methodology of stream restoration.

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Appendix

Table A-1. Reference Reach Bankfull Stream Characteristics

Stream Name	Drainage	Valley	Width/Depth Ratio	Entrenchment Ratio	Stream Type (Rosgen)	Velocity (ft/sec)	Bankfull	Bankfull	Bankfull	Bankfull ¹	Slope (ft/ft)
	Area (mi ²)	Type (Rosgen)					Area (ft ²)	Width (ft)	Mean Depth (ft)	Discharge (cfs)	
UT to Mill Branch	0.20	VIII	12.5	5.9	C4	4.0	8.5	10.3	0.8	34	0.009
East Fork Walker Branch	0.23	VII	18.3	1.8	B4	4.3	6.2	10.4	0.6	23	0.039
Walker Branch	0.38	VII	11.6	1.7	B4c	5.7	18.5	14.5	1.3	44	0.019
Mill Branch	0.40	VIII	18.4	5.2	C4	4.4	13.6	16.1	0.9	32	0.012
Shanty Branch	0.98	VIII	6.6	6.6	C4	4.2	40.9	32.2	1.3	164	0.006
White Creek	1.30	VII	5.4	5.4	E4	6.4	40.0	19.0	2.1	120	0.011
UT to Big Creek	2.00	VIII	9.8	9.8	E4	5.5	20.5	11.9	1.7	112	0.010

¹ Bankfull Discharge estimated in HEC-RAS (Brunner, 2001).

Table A-2. Channel Pattern Characteristics

Stream Name	Planform			Longitudinal Profile Geometry										Dimensionless Geometry Ratios								
	Valley Length (ft)	Stream Length (ft)	Sinuosity	Pool Length (ft)			Pool to Pool Spacing (ft)			Riffle Length (ft)			Riffle Width (ft)	Pool Length/Riffle Width			Pool to Pool Spacing/Riffle Width			Riffle Length/Riffle Width		
				Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
UT to Mill Branch	99.5	136.0	1.37	12.5	7.0	16.0	21.2	12.0	31.0	7.0	4.0	14.0	10.3	1.2	0.7	1.6	2.1	1.2	3.0	0.7	0.4	1.4
Mill Branch	200.0	246.0	1.23	27.3	16.0	33.0	73.3	49.0	113.0	17.8	10.0	31.0	15.9	1.7	1.0	2.1	4.6	3.1	7.1	1.1	0.6	1.9
East Fork Walker Branch	129.1	133.9	1.04	8.9	3.8	14.9	27.2	17.3	37.1	11.1	10.3	12.3	10.4	0.9	0.4	1.4	2.6	1.7	3.6	1.1	1.0	1.2
Walker Branch	130.3	132.6	1.02	16.8	11.0	21.3	20.0	17.2	34.0	11.0	5.8	18.6	14.5	1.2	0.8	1.5	1.4	1.2	2.3	0.8	0.4	1.3
White Creek	256.0	275.1	1.07	17.5	8.1	25.9	56.0	44.3	76.0	26.0	14.5	35.5	17.3	1.0	0.5	1.5	3.2	2.6	4.4	1.5	0.8	2.1
UT to Big Creek	173.6	177.0	1.02	20.3	12.0	34.0	44.3	36.0	56.0	19.5	10.0	29.0	14.3	1.4	0.8	2.4	3.1	2.5	3.9	1.4	0.7	2.0
Shanty Branch	366.0	518.0	1.42	51.0	16.0	89.0	82.2	61.0	114.0	26.0	18.0	39.0	22.7	2.2	0.7	3.9	3.6	2.7	5.0	1.1	0.8	1.7

Valley length calculated as the straight line distance between the start and end points of the long profile survey.

Sinuosity calculated as stream length divided by valley length

Riffle width calculated as average of upstream and downstream riffle cross section widths

Table A-3. Channel Substrate Percent Compositions (%)

Stream Name	Silt/ Clay		Sand		Gravel		Cobble		Boulder		Bedrock	
	Reach	Riffle	Reach	Riffle	Reach	Riffle	Reach	Riffle	Reach	Riffle	Reach	Riffle
UT to Mill Branch	8	0	15	6	75	94	0	2	0	0	0	0
Mill Branch	4	0	15	2	72	97	1	1	0	0	8	0
East Fork Walker Branch	2	0	6	3	55	75	21	21	0	1	15	0
Walker Branch	0	0	6	4	64	63	30	33	0	0	0	0
White Creek	0	0	12	9	56	65	25	25	0	1	0	0
UT to Big Creek	0	0	1	0	93	83	4	17	0	0	2	0
Shanty Branch	0	1	5	0	69	91	9	8	0	0	17	0

Percent compositions for Riffle and Reach calculated from 100 samples collected using Wolman(1954) sampling method.

Table A-4. Feature Depths and Ratios

Stream Name	Feature Midpoint Depths (ft)													Dimensionless Depth Ratios																								
	Max Riffle Depth			Max Run Depth			Max Pool Depth			Max Glide Depth			Bankfull Depth (ft)	Max Riffle Depth/ Depth			Max Run Depth/Depth			Max Pool Depth/Depth			Max Glide Depth/Depth															
	d _{maxrif}			d _{maxrun}			d _{maxp}			d _{maxg}				d _{maxrif} /d _{bld}			d _{maxrun} /d _{bld}			d _{maxp} /d _{bld}			d _{maxg} /d _{bld}															
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	d _{bld}	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max													
UT to Mill Branch	0.18	0.13	0.27	0.18	0.16	0.19	1.01	0.65	1.10	-	-	-	1.30	1.30	0.14	0.14	0.10	0.10	0.21	0.21	0.13	0.13	0.12	0.12	0.15	0.15	0.78	0.78	0.50	0.50	0.85	0.85	-	-	-	-	-	-
Mill Branch	0.26	0.10	0.36	0.27	-	-	1.30	1.10	1.41	0.53	0.45	0.60	2.00	1.10	0.13	0.24	0.05	0.09	0.18	0.33	0.14	0.25	-	-	-	-	0.65	1.18	0.55	1.00	0.71	1.28	0.26	0.48	0.23	0.41	0.30	0.55
East Fork Walker Branch	0.40	0.24	0.51	0.20	0.13	0.28	0.60	0.29	0.77	0.49	0.41	0.56	0.90	1.60	0.44	0.25	0.27	0.15	0.57	0.32	0.22	0.13	0.14	0.08	0.31	0.18	0.67	0.38	0.32	0.18	0.86	0.48	0.54	0.31	0.46	0.26	0.62	0.35
Walker Branch	0.50	0.36	0.62	0.52	0.31	0.73	0.82	0.67	1.01	0.53	-	-	1.40	1.70	0.36	0.29	0.26	0.21	0.44	0.36	0.37	0.31	0.22	0.18	0.52	0.43	0.59	0.48	0.48	0.39	0.72	0.59	0.38	0.31	-	-	-	-
White Creek	0.40	0.38	0.50	0.40	0.36	0.57	0.90	0.53	1.02	0.62	-	-	2.40	2.60	0.17	0.15	0.16	0.15	0.21	0.19	0.17	0.15	0.15	0.14	0.24	0.22	0.38	0.35	0.22	0.20	0.43	0.39	0.26	0.24	-	-	-	-
UT to Big Creek	0.48	0.28	0.61	0.35	-	-	1.08	0.84	1.47	0.50	-	-	2.20	2.30	0.22	0.21	0.13	0.12	0.28	0.27	0.16	0.15	-	-	-	-	0.49	0.47	0.38	0.37	0.67	0.64	0.23	0.22	-	-	-	-
Shanty Branch	0.23	0.12	0.37	0.16	0.16	0.16	1.49	0.82	2.16	0.75	0.45	1.00	2.40	2.10	0.10	0.11	0.05	0.06	0.15	0.18	0.07	0.08	0.07	0.08	0.07	0.08	0.62	0.71	0.34	0.39	0.90	1.03	0.31	0.36	0.19	0.21	0.42	0.48

Minimum, maximum, and mean depths calculated as depth from water surface to thalweg. Pool measurements taken at max pool depth.

Shaded column indicates downstream riffle

(-) Limited number of features observed during survey.

Table A-5. Feature Facet Slopes and Ratios

Stream Name	Facet Slopes (%)												Dimensionless Slope Ratios													
	Riffle			Run Slope			Pool Slope			Glide Slope			Avg. Water Surface Slope S _w	Riffle Slope/Slope			Run Slope/Slope			Pool Slope/Slope			Glide Slope/Slope			
	S _{rif}			S _{run}			S _p			S _g				S _{rif} /S _w			S _{run} /S _w			S _p /S _w			S _g /S _w			
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
UT to Mill Branch	2.0	0.0	4.4	1.5	1.5	1.6	0.2	0.0	0.8	-	-	-	0.9	2.2	0.0	4.7	1.6	1.6	1.7	0.2	0.0	0.9	-	-	-	
Mill Branch	2.8	1.4	4.1	2.5	-	-	0.1	0.0	0.4	0.3	-	-	1.2	2.4	1.2	3.5	2.2	-	-	0.1	0.0	0.4	0.2	-	-	
East Fork Walker Branch	6.0	3.1	8.3	5.0	2.5	8.0	0.6	0.0	1.8	1.3	1.0	1.5	3.1	2.0	1.0	2.7	1.6	0.8	2.6	0.2	0.0	0.6	0.4	0.3	0.5	
Walker Branch	4.2	2.0	5.7	2.3	1.2	3.4	0.5	0.4	0.8	0.5	-	-	1.9	2.2	1.1	3.0	1.2	0.6	1.8	3.0	0.2	0.4	0.3	-	-	
White Creek	2.1	1.4	3.2	0.7	0.1	2.2	0.2	0.0	0.6	0.2	-	-	1.0	2.0	1.4	3.1	0.7	0.1	2.1	0.2	0.0	0.6	0.2	-	-	
UT to Big Creek	1.9	1.9	2.0	3.1	-	-	0.0	0.0	1.1	1.0	-	-	1.0	1.9	1.9	2.0	3.0	-	-	0.0	0.0	1.1	0.9	-	-	
Shanty Branch	2.5	2.0	3.5	1.5	1.0	2.0	0.2	0.0	0.9	0.6	0.3	0.8	0.6	4.0	3.2	5.6	2.4	1.5	3.2	0.3	0.0	1.4	0.9	0.5	1.3	

(-) Limited number of habitat units observed during survey.

Table A-6. Riffle and Pool Cross Section Characteristics and Ratios

Stream Name	Riffle									Pool					Dimensionless Cross Section Ratios											
	Mean Depth (dbkf) (ft)		Width (Wbkf) (ft)		Area (Abkf) (ft)		Max Depth (dbkf) (ft)		Mean Depth (dbkfp) (ft)	Width (Wbkfp) (ft)	Area (Abkfp) (ft ²)	Max Depth (dmaxp) (ft)	Max Riffle Depth/ Mean Riffle Depth dmax/dbkf	Pool		Pool		Pool		Max Pool						
														Depth/Riffle		Width/Riffle		Area/Riffle		Depth/Riffle						
														Depth dbkf/dbkf	Depth	Width Wbkfp/Wbkf	Width	Area Abkfp/Wbkf	Area	Depth dmaxp/dbkf	Depth					
UT to Mill Branch	0.80	0.80	10.8	9.8	9.0	7.9	1.3	1.3	1.0	12.9	12.8	2.0	1.6	1.6	1.3	1.3	1.2	1.3	1.4	1.6	2.5	2.5				
Mill Branch	0.98	0.68	17.0	15.2	16.7	10.5	2.0	1.1	1.4	15.9	22.3	2.2	2.0	1.6	1.4	1.4	0.9	1.0	1.3	2.1	2.2	3.2				
East Fork Walker Branch	0.76	0.46	7.7	13.2	5.9	6.1	0.9	0.6	1.3	9.2	11.7	1.6	1.2	1.3	1.7	2.8	1.2	0.7	2.0	1.9	1.8	2.7				
Walker Branch	1.10	1.39	11.6	17.4	12.8	24.2	1.4	1.7	0.8	10.7	8.3	1.2	1.3	1.2	0.7	0.6	0.9	0.6	0.6	0.3	0.9	0.7				
White Creek	2.00	2.20	17.6	20.3	36.2	43.8	2.4	2.6	2.2	14.0	25.1	2.6	1.2	1.2	1.1	1.0	0.8	0.7	0.7	0.6	1.1	1.0				
UT to Big Creek	1.60	1.80	11.5	12.4	18.2	22.8	2.2	3.1	1.5	17.8	26.1	2.5	1.4	1.7	0.9	0.8	1.5	1.4	1.4	1.1	1.1	0.8				
Shanty Branch	1.80	1.60	19.9	25.1	35.1	41.1	2.4	2.0	1.4	23.3	31.8	3.1	1.3	1.3	0.8	0.9	1.2	0.9	0.9	0.8	1.3	1.6				

Two riffle cross sections surveyed at each site. Shaded columns indicates downstream riffle.

Stream Channel Classification

Stream Name: Unamed Tributary to Mill Branch
 Drainage Area: 0.2
 State: Tennessee
 County: Anderson
 Latitude: 39 59 8
 Longitude: 84 17 17

Classification Data

Valley Type: VII
 Width: 10.3 ft
 Mean Depth: 0.8 ft
 Flood Prone Width: 60.3 ft
 Channel Material D_{50} : 9.5 mm
 Water Surface Slope: 0.0094 ft/ft
 Sinuosity: 1.40
 Discharge: 38 cfs
 Velocity: 4.1 fps
 Cross Sectional Area: 8.5 ft²
 Entrenchment Ratio: 5.90
 Width to Depth Ratio: 12.50
 Rosgen Classification: C4

The Unamed Tributary to Mill Branch is located in Oak Ridge near the Department of Energy National Laboratory boundaries. The tributary is located within a completely forested watershed and has an extensive riparian buffer on either side. The stream was gravel dominated with large and small woody debris present in multiple places above and in the bankfull channel. The primary bankfull indicators were the tops of point bars and the lowest point of inflection on the banks. The reach was meandering with pool-riffle sequences. Access to the site is gained from Tuskegee Avenue. Approximately 300 feet from the road a capped rebar survey datum was installed at the confluence of Mill Branch and the Unamed Tributary for reference.



Figure A-1. Unamed Tributary to Mill Branch.

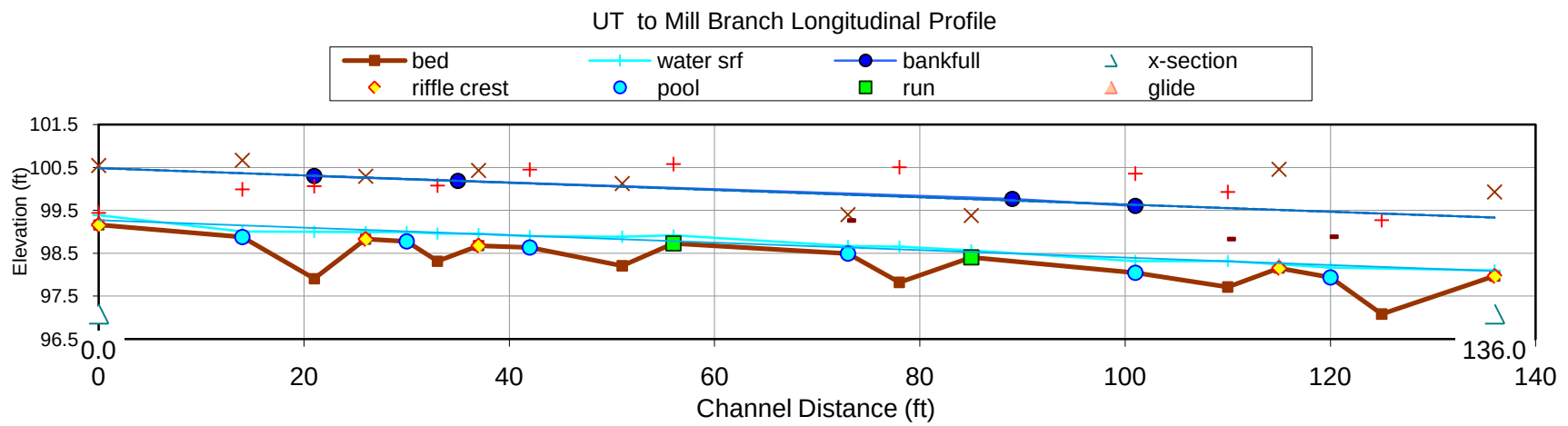
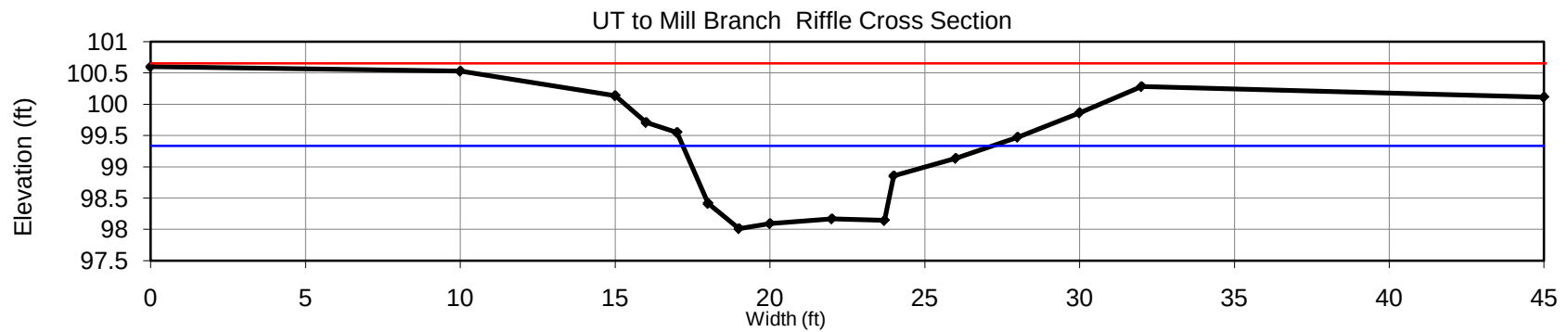
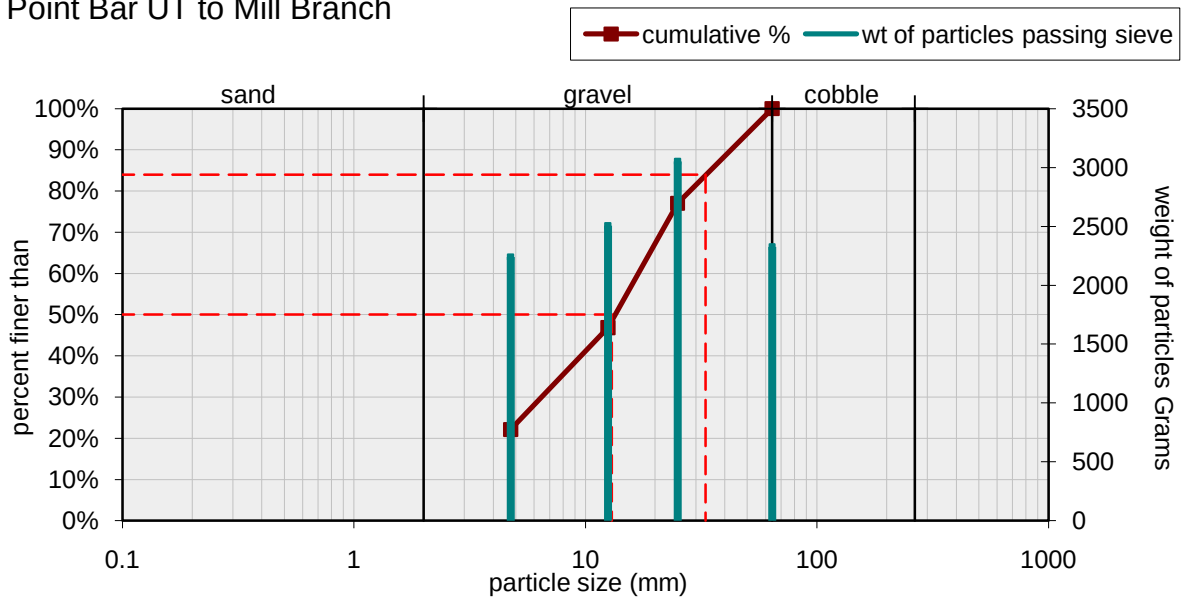


Figure A-1. Unnamed Tributary to Mill Branch.

Point Bar UT to Mill Branch



Bed Surface Pebble Count, UT to Mill Branch

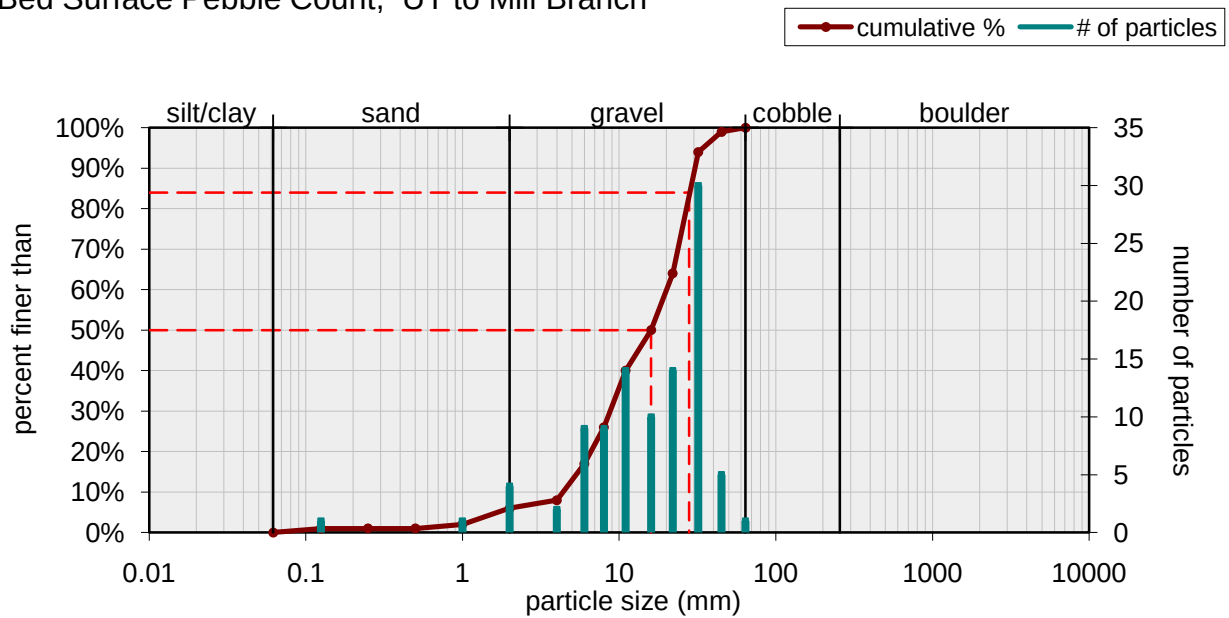


Figure A-1. Unnamed Tributary to Mill Branch.

Stream Channel Classification

Stream Name: East Fork of Walker Branch
Drainage Area: 0.2
State: Tennessee
County: Anderson

Classification Data

Valley Type: II
Width: 10.3 ft
Mean Depth: 0.57 ft
Flood Prone Width: 19.1 ft
Channel Material D_{50} : 25 mm
Water Surface Slope: 0.031 ft/ft
Sinuosity: 1.00
Discharge: 23 cfs
Velocity: 3.9 ft/sec
Cross Sectional Area: 6 ft²
Entrenchment Ratio: 1.80
Width to Depth Ratio: 18.30
Rosgen Classification: B4

The East Fork of Walker Branch is located within the Department of Energy Oak Ridge National Laboratory Experimental Watershed. The watershed has been protected and monitored for over 50 years. The channel is located within a narrow valley and had the steepest slope surveyed. The surveyed reach is located above the weir approximately 350 feet. Bedrock influence was observed in the lower half of the channel in the run, pool and riffle habitat units. The primary bankfull indicator is the connection with the small floodplain adjacent to the stream. Small and large woody debris and leaf packs were present in the channel. Some cobble was observed from colluvial deposits, but the reach was dominated by a gravel sediment regime.



Figure A-2. East Fork Walker Branch.

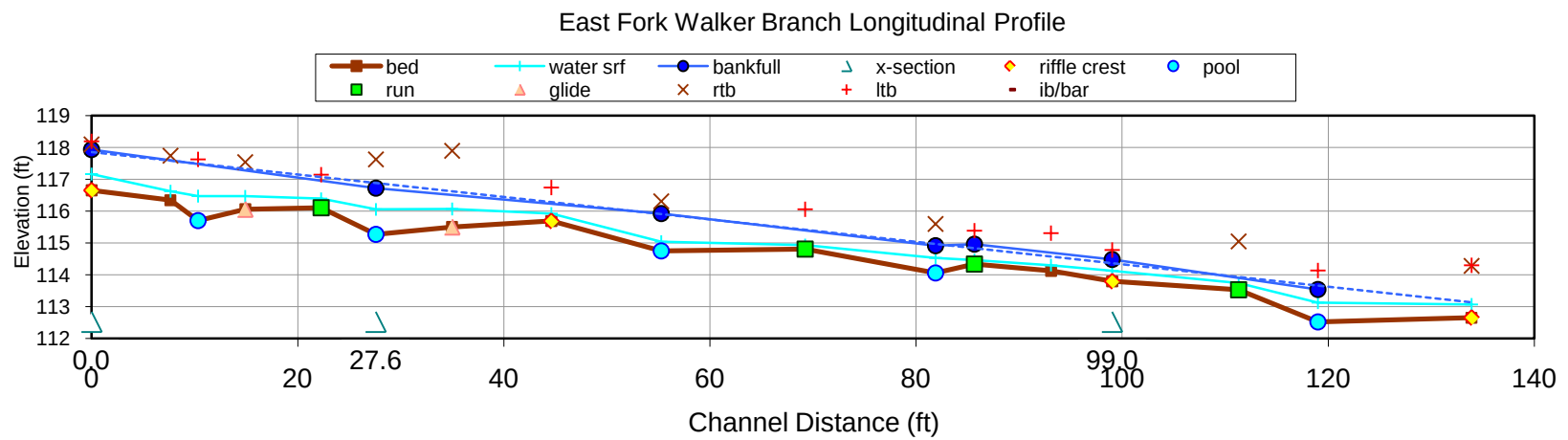
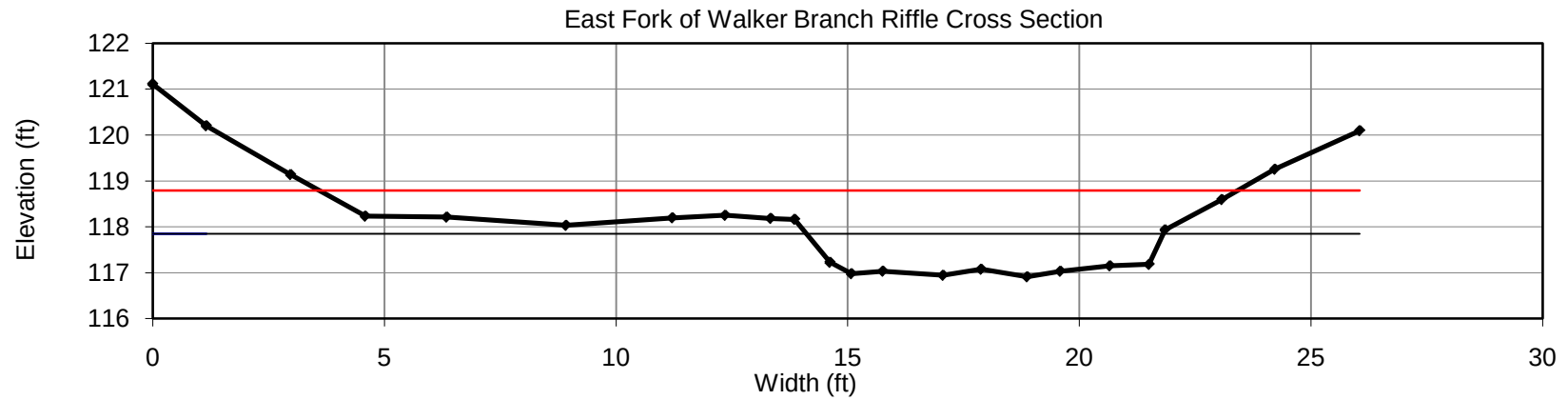
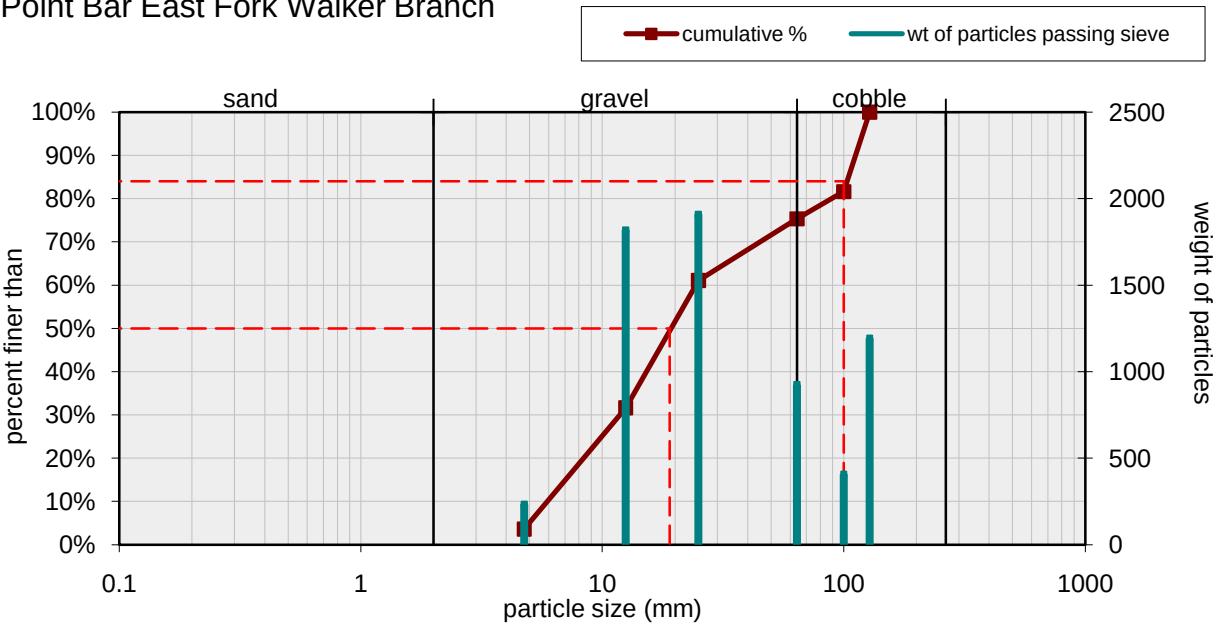


Figure A-2. East Fork of Walker Branch.

Point Bar East Fork Walker Branch



Bed Surface Pebble Count, East Fork Walker Branch

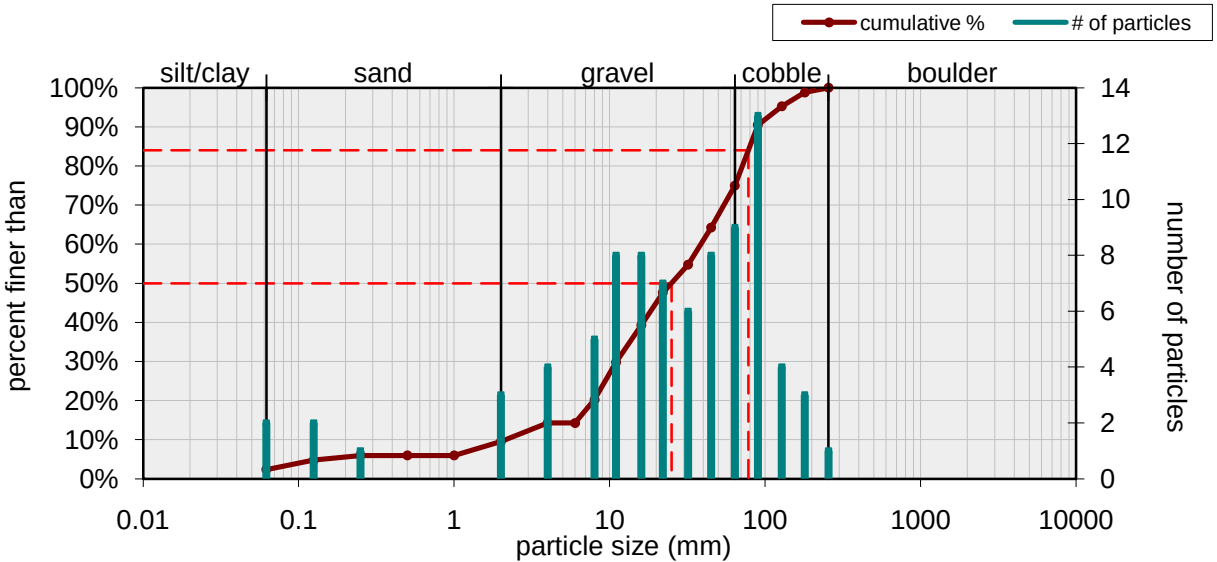


Figure A-2. East Fork Walker Branch.

Stream Channel Classification

Stream Name: Walker Branch
Drainage Area: 0.37
State: Tennessee
County: Anderson

Classification Data

Valley Type: II
Width: 14.3 ft
Mean Depth: 1.3 ft
Flood Prone Width: 23.9 ft
Channel Material D_{50} : 36 mm
Water Surface Slope: 0.019 ft/ft
Sinuosity: 1.00
Discharge: 44 cfs
Velocity: 5.4 ft/sec
Cross Sectional Area: 17.50
Entrenchment Ratio: 1.70
Width to Depth Ratio: 11.60
Rosgen Classification: B4c

The main stem of Walker Branch is located within the Department of Energy Oak Ridge National Laboratory Experimental Watershed. This watershed has been protected and monitored for over 50 years. The study reach is located directly downstream of the confluence of the East and West Forks. The bankfull indicator is the connection with the adjacent floodplain. Large and small woody debris were observed in the channel. Sediment regime was gravel with some large cobble in the riffles that had not moved in recent events. The B4c channel type was designated because of the mild slope observed. Pool riffle sequences were noted and the survey was continued until bedrock was observed at the downstream riffle.



Figure

A-3. Walker Branch.

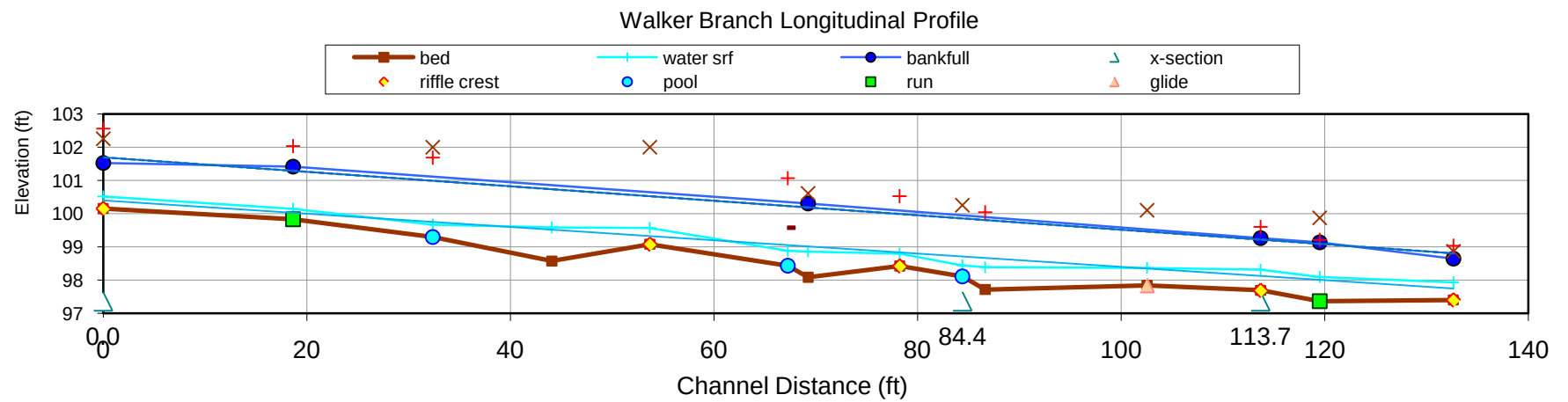
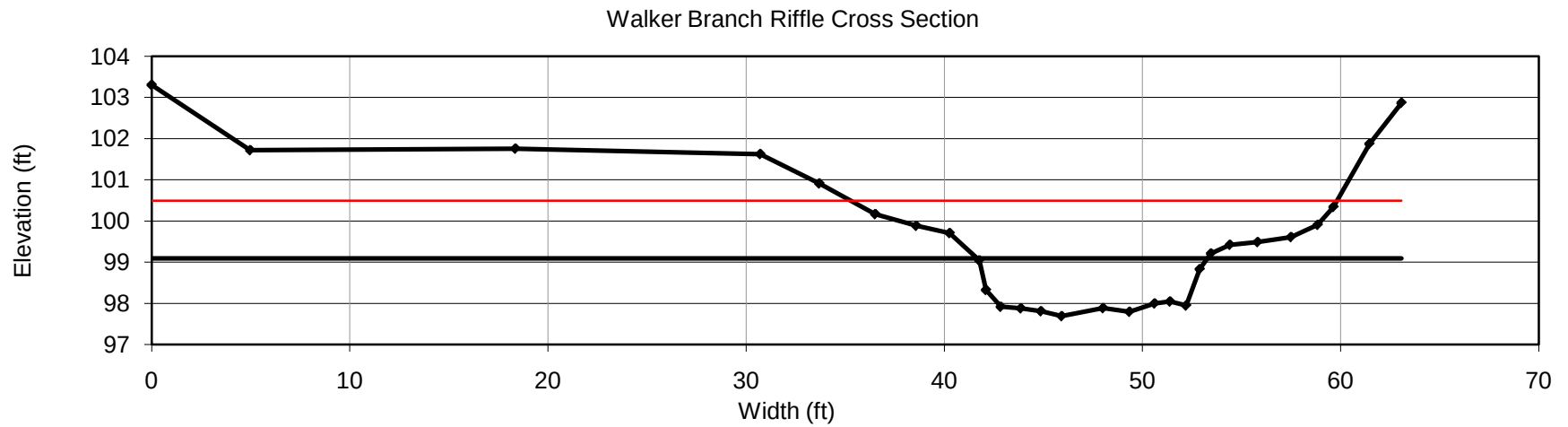
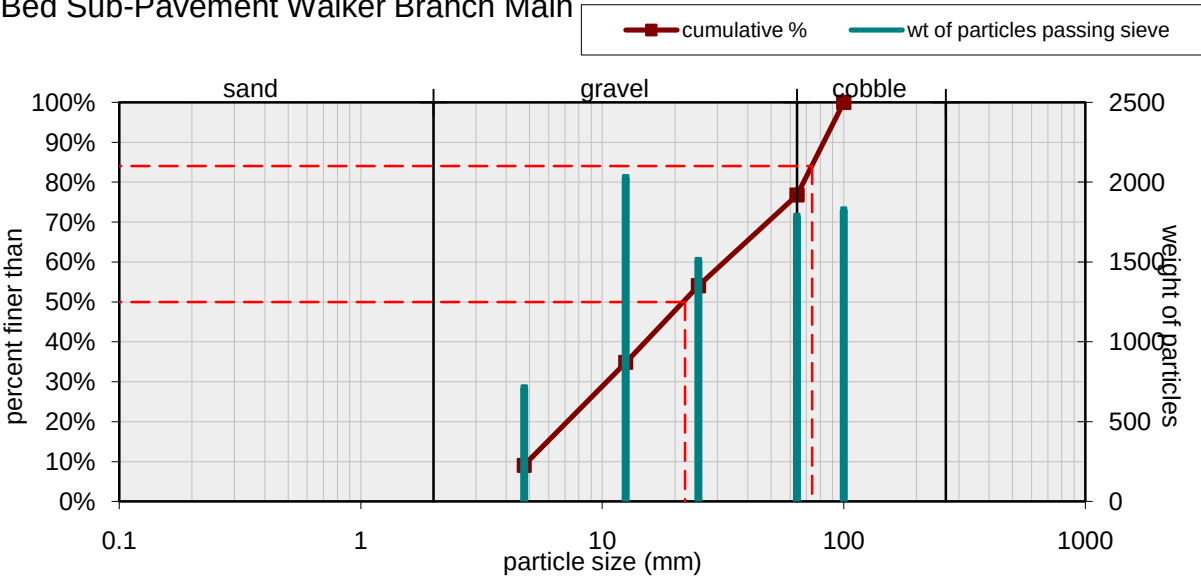


Figure A-3. Walker Branch.

Bed Sub-Pavement Walker Branch Main



Bed Surface Pebble Count, Walker Branch

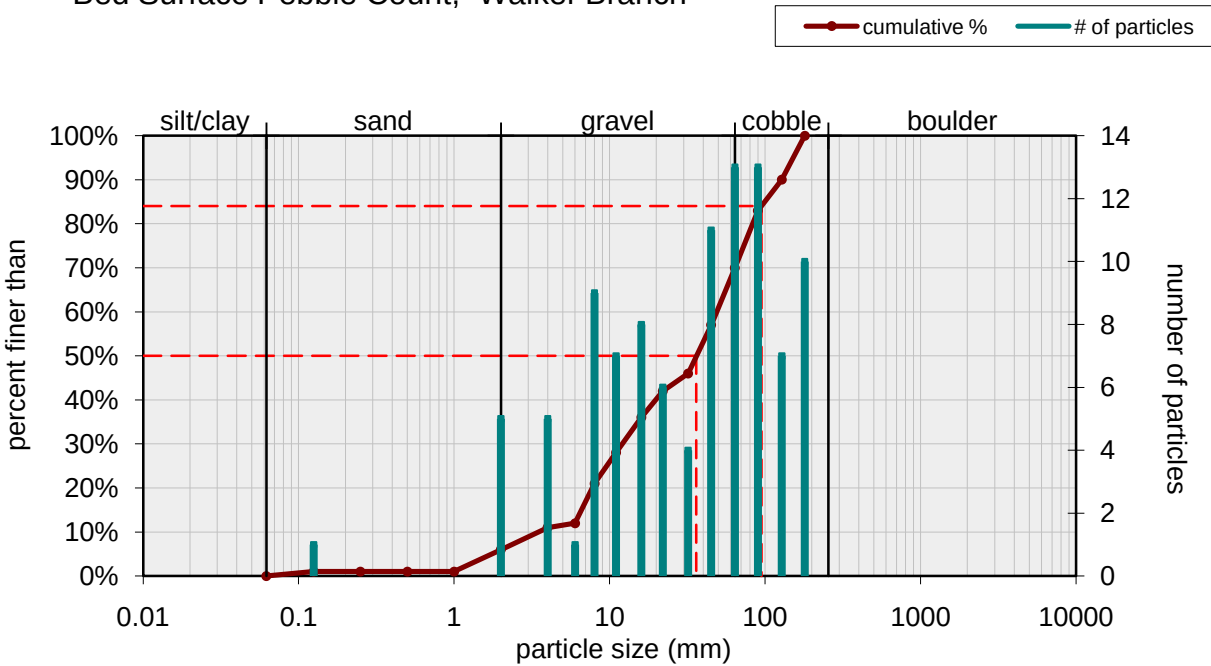


Figure A-3. Walker Branch.

Stream Channel Classification

Stream Name: Mill Branch
Drainage Area: 0.4
State: Tennessee
County: Anderson

Classification Data

Valley Type: VIII
Width: 15.9 ft
Mean Depth: 1.3 ft
Flood Prone Width: 83.1 ft
Channel Material D_{50} : 12 mm
Water Surface Slope: 0.012 ft/ft
Sinuosity: 1.20
Discharge: 32 cfs
Velocity: 5.4 ft/sec
Cross Sectional Area: 13.60
Entrenchment Ratio: 5.20
Width to Depth Ratio: 18.40
Rosgen Classification: C4

Mill Branch is located near the Oak Ridge National Laboratory boundaries. It drains a forested watershed and has an extensive riparian buffer on either side. Large and small woody debris are located in and above the bankfull channel. The primary bankfull indicator is the active connection to the floodplain with point bars supporting this elevation. The stream is sinuous and has a gravel sediment regime with pool, riffle, and run sequences. Bedrock can be found in the bottom of scour pools. Mill Branch is one of the highest quality TDEC reference streams in East Tennessee.



Figure A-4. Mill Branch.

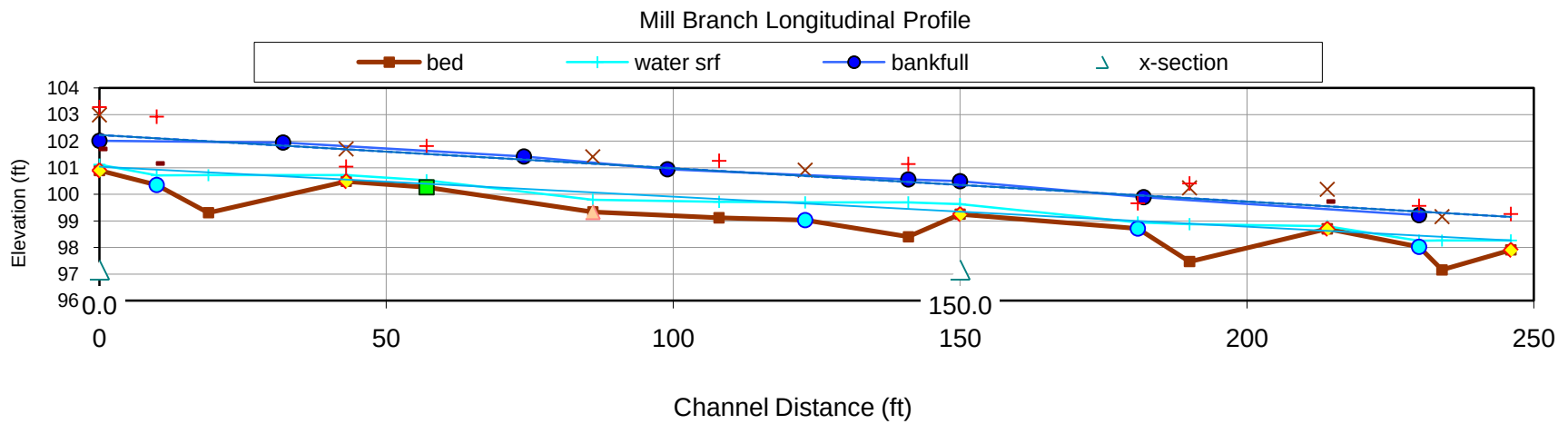
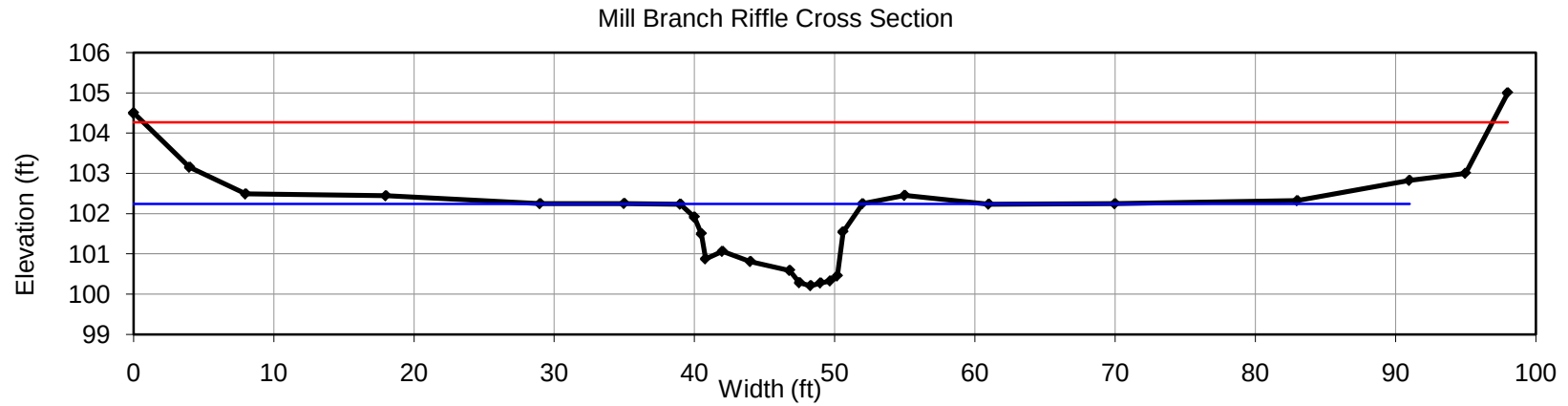


Figure A-4. Mill Branch.

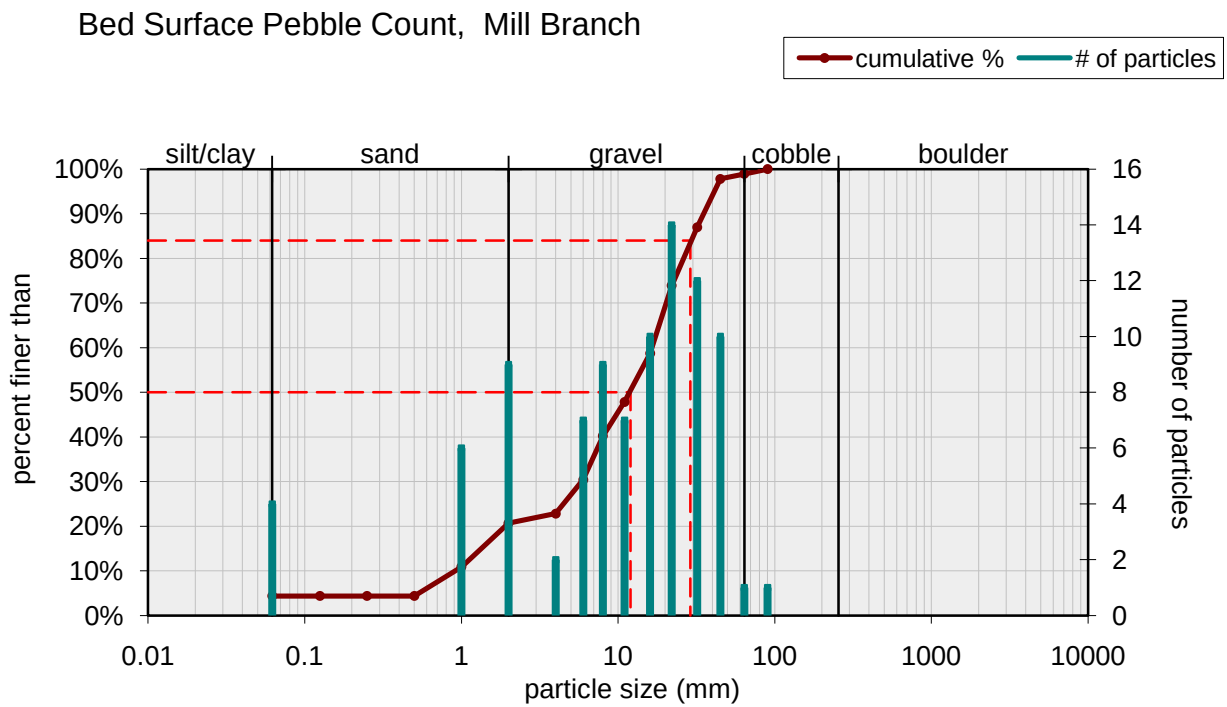
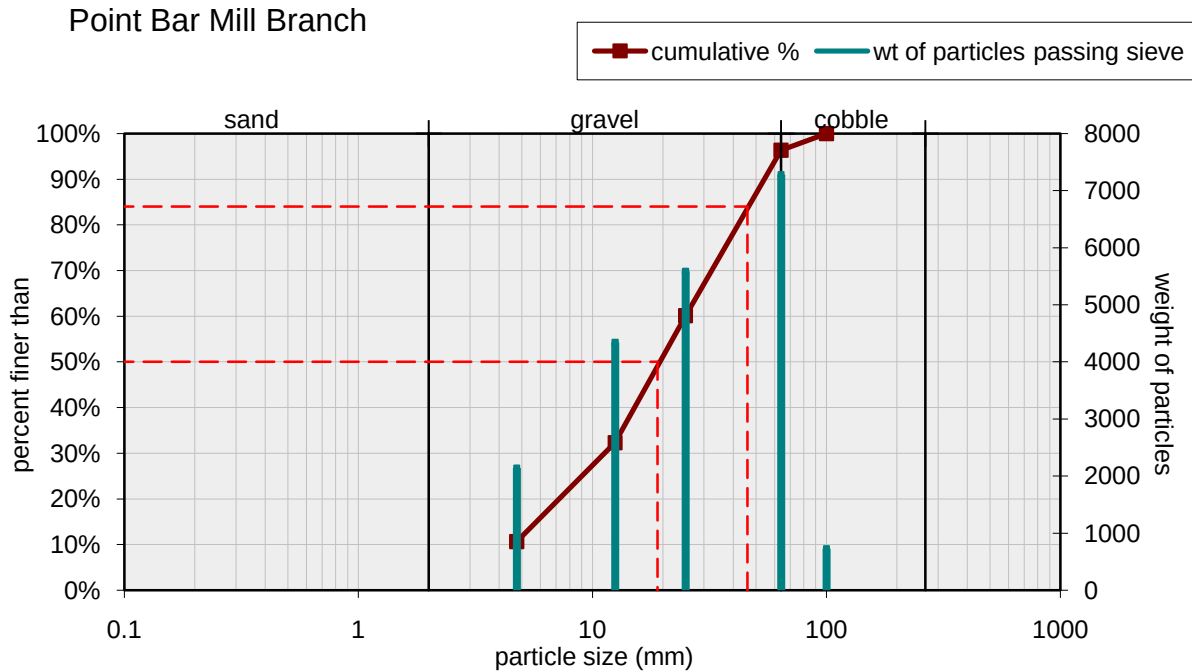


Figure A-4. Mill Branch.

Stream Channel Classification

Stream Name: Shanty Branch
Drainage Area: 1
State: Tennessee
County: Roane

Classification Data

Valley Type: VIII
Width: 22.7 ft
Mean Depth: 1.7 ft
Flood Prone Width: 149.7 ft
Channel Material D_{50} : 19 mm
Water Surface Slope: 0.0063 ft/ft
Sinuosity: 1.45
Discharge: 164 cfs
Velocity: 4.9 ft/sec
Cross Sectional Area: 38.5 ft^2
Entrenchment Ratio: 6.60
Width to Depth Ratio: 13.40
Rosgen Classification: C4

Shanty Branch is located in Roane County approximately 2 miles from the County Park on Poland Hollow Road. The Reach begins shortly before the stream crosses under the road and the survey datum can be found underneath an Ironwood tree 300 feet from the road. The reach has an extensive riparian buffer with large and small woody debris present above and in the bankfull channel. The reach is meandering with pool, riffle and run sequences. Pools are scoured to bedrock in some places and are maintained fluvially by large trees on the banks. The bankfull indicator is the active floodplain connection on either side of the stream.

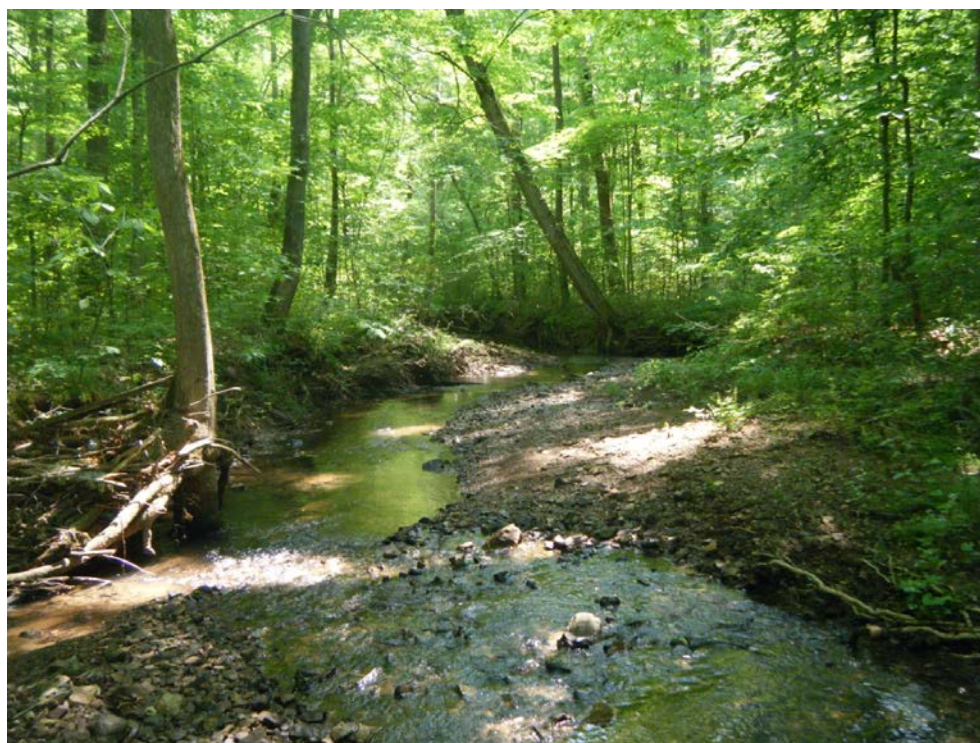


Figure A-5. Shanty Branch

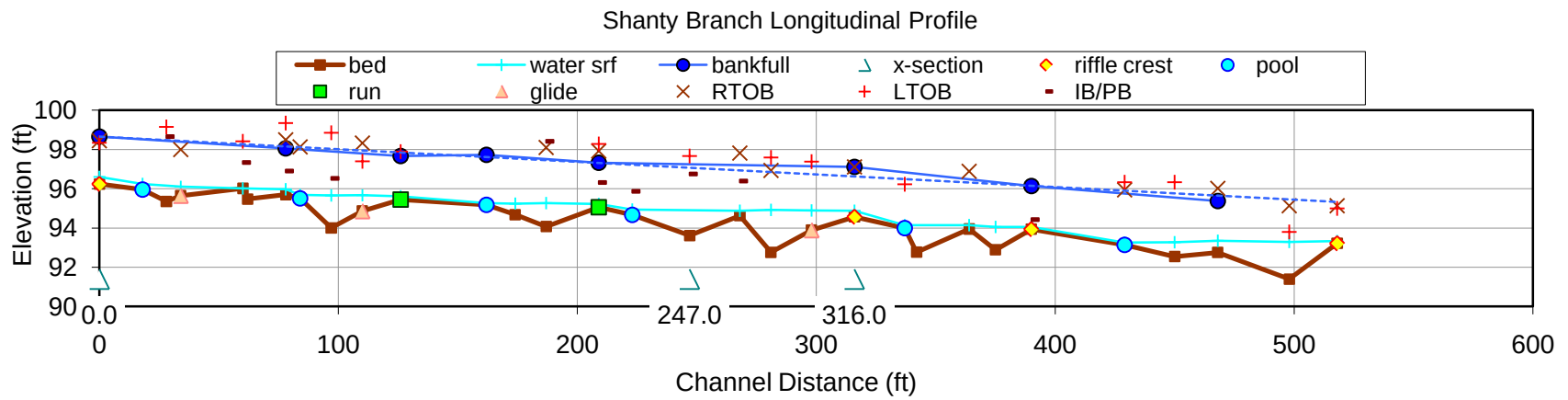
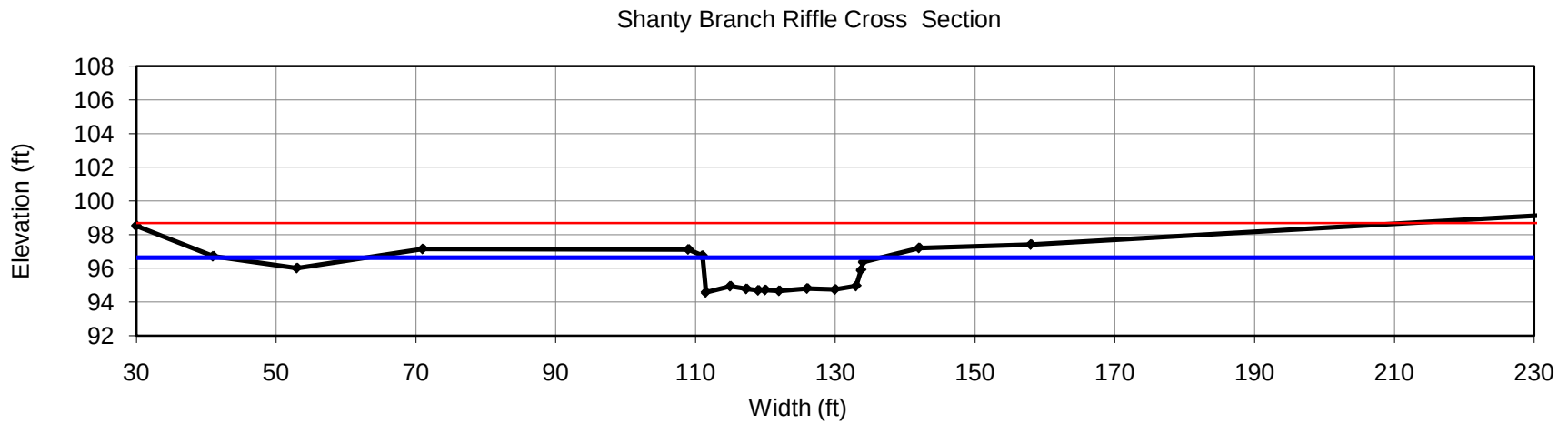


Figure A-5. Shanty Branch.

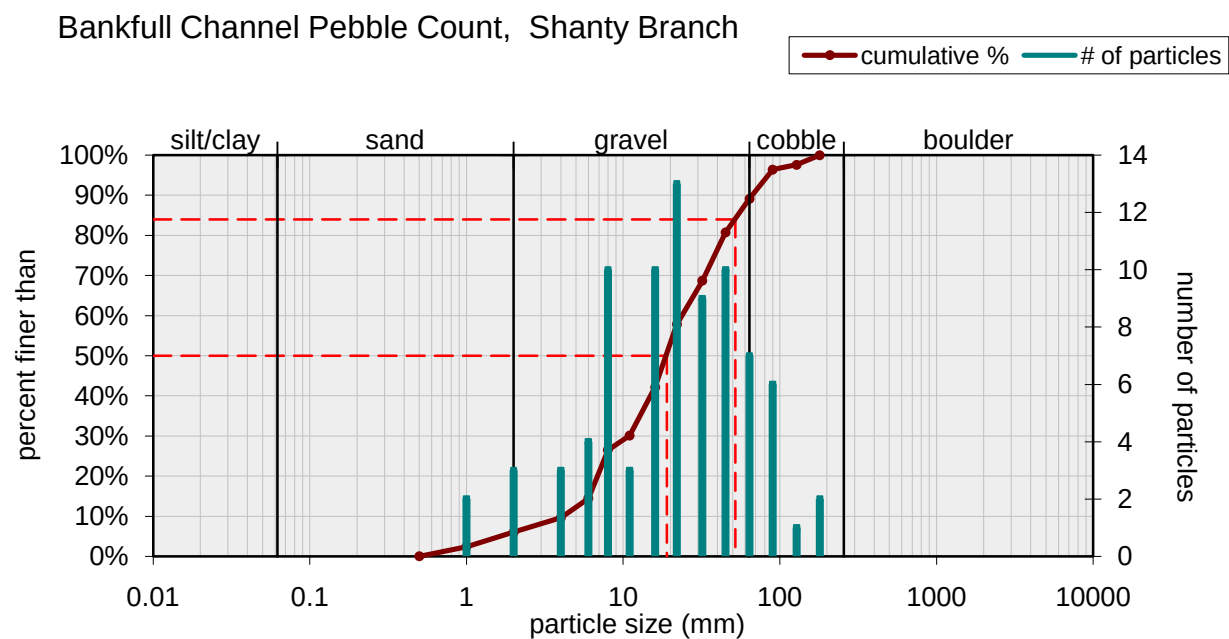
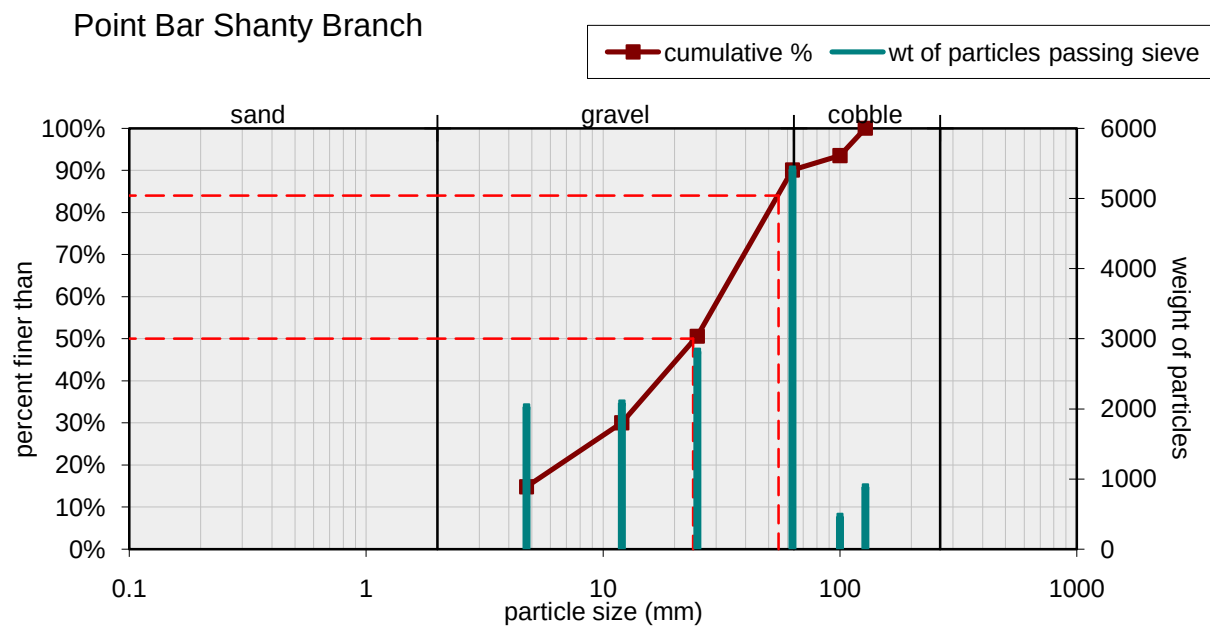


Figure A-5. Shanty Branch.

Stream Channel Classification

Stream Name: White Creek
Drainage Area: 1.3
State: Tennessee
County: Union

Classification Data

Valley Type: VII
Width: 17.30
Mean Depth: 2.0 ft
Flood Prone Width: 93 ft
Channel Material D₅₀: 31 mm
Water Surface Slope: 0.011 ft/ft
Sinuosity: 1.10
Discharge: 120 cfs
Velocity: 6.2 ft/sec
Cross Sectional Area: 35 ft²
Entrenchment Ratio: 5.40
Width to Depth Ratio: 8.60
Rosgen Classification: E4

White Creek is located within the Chuck Swan Wildlife Management Area. The reach is located upstream of the discontinued USGS streamflow gaging station. The main land use in the area is managed forestland. The reach runs parallel to the access road with a heavily vegetated riparian buffer. The reach has a gravel sediment regime with pool and riffle sequences. The floodplain access is on stream right and the active connection indicates the bankfull stage. Bedrock was observed in the bottom of the pool habitat units. At the downstream extent a debris jam had caused some gravel deposition and the channel was adjusting widening slightly but maintained similar cross sectional area.



Figure A-6. White Creek.

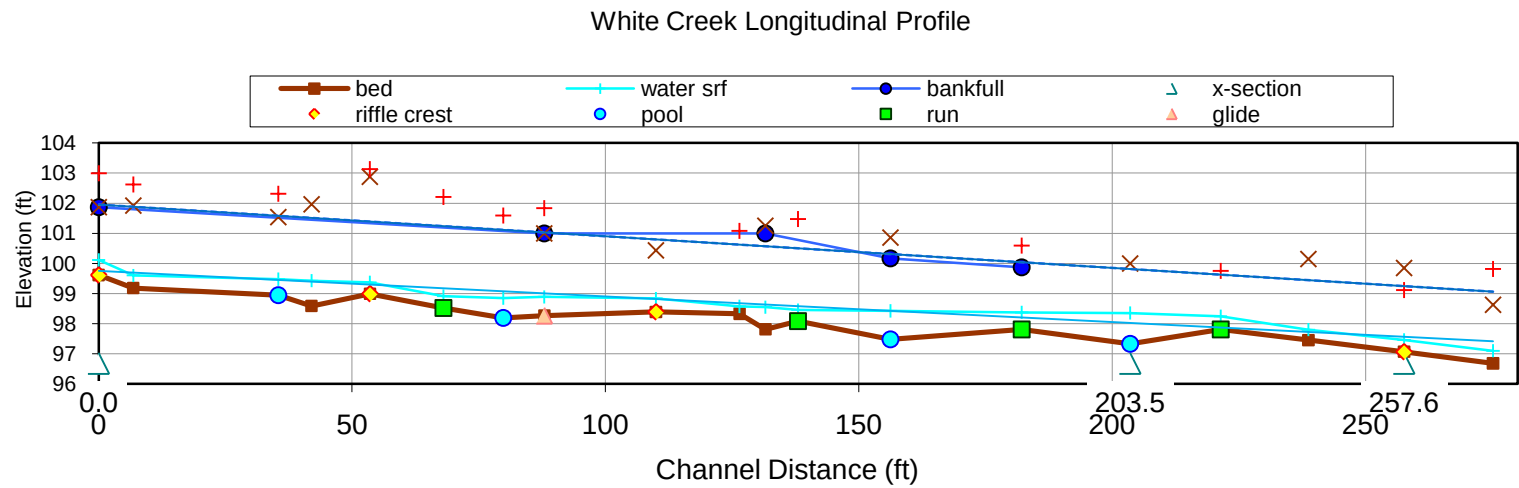
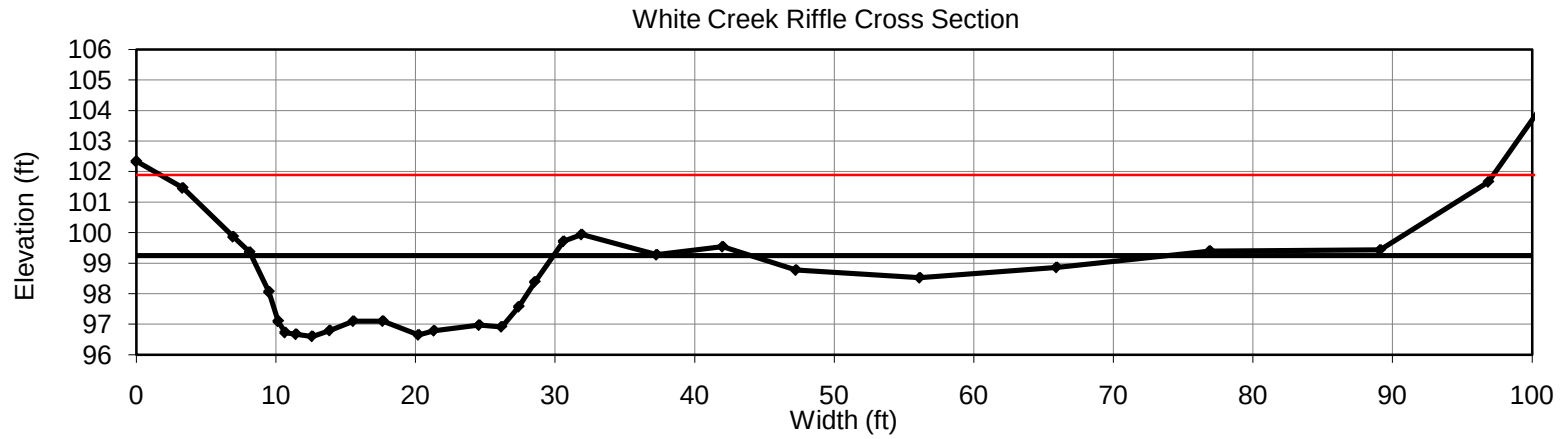
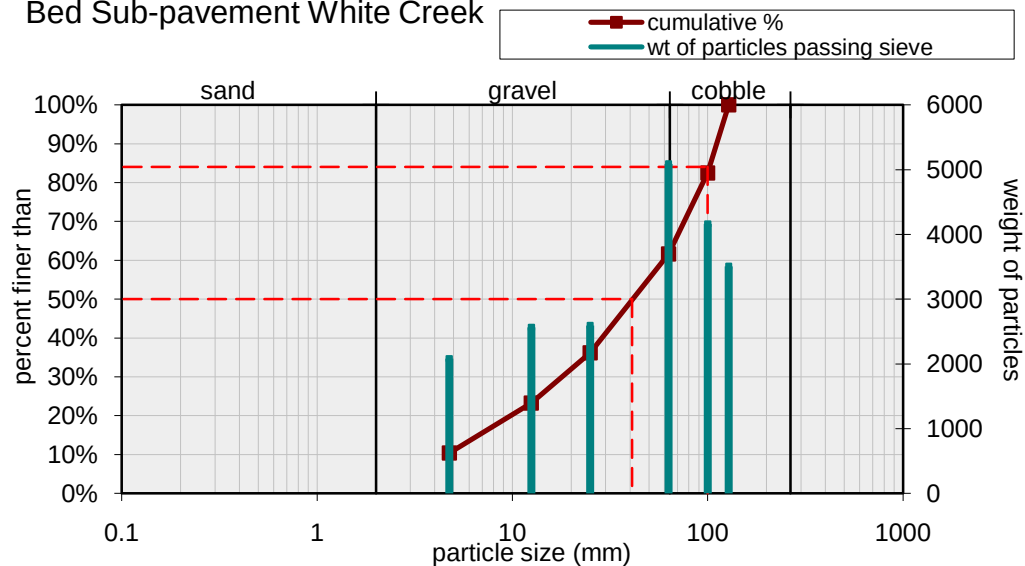


Figure A-6. White Creek.

Bed Sub-pavement White Creek



Bed Surface Pebble Count, White Creek

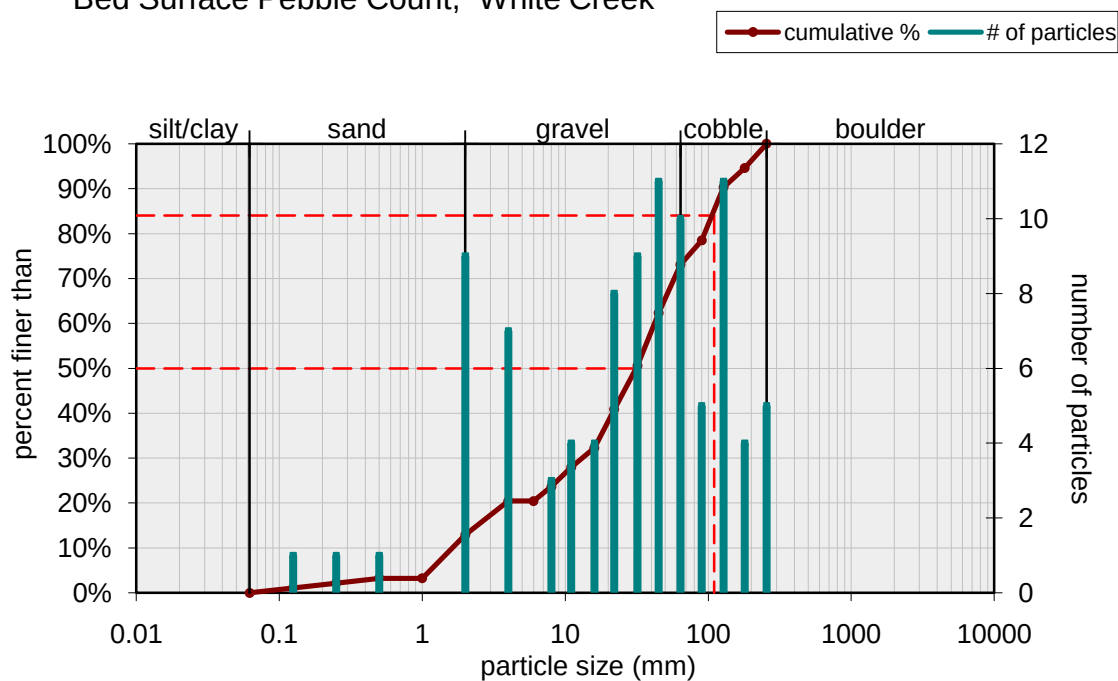


Figure A-6. White Creek.

Stream Channel Classification

Stream Name: Unnamed Tributary to Big Creek
Drainage Area: 2
State: Tennessee
County: Hawkins

Classification Data

Valley Type: VIII
Width: 14.0 ft
Mean Depth: 1.52 ft
Flood Prone Width: 137.3 ft
Channel Material D_{50} : 72 mm
Water Surface Slope: 0.01 ft/ft
Sinuosity: 1.00
Discharge: 112 cfs
Velocity: 5.2 ft/sec
Cross Sectional Area: 21.3 ft²
Entrenchment Ratio: 9.80
Width to Depth Ratio: 9.20
Rosgen Classification: E4

The reach of the unnamed tributary to Big Creek included in the study is located just upstream of the discontinued stream flow gaging station on Ebbing and Flowing Spring Road in Rogersville, TN. The reach exits a pasture used for cattle grazing and runs adjacent to the road for a length of approximately 250 feet. The reach has access to a large floodplain on stream right in a field and the bankfull stage is indicated by the active connection to this. The reach has pool riffle sequences with a gravel sediment regime. A bedrock step is located at the beginning of the run before the pool cross section. The riparian zone is little to absent with the exception of a narrow strip of vegetation between the field and the stream.



Figure A-7. Unnamed Tributary to Big Creek.

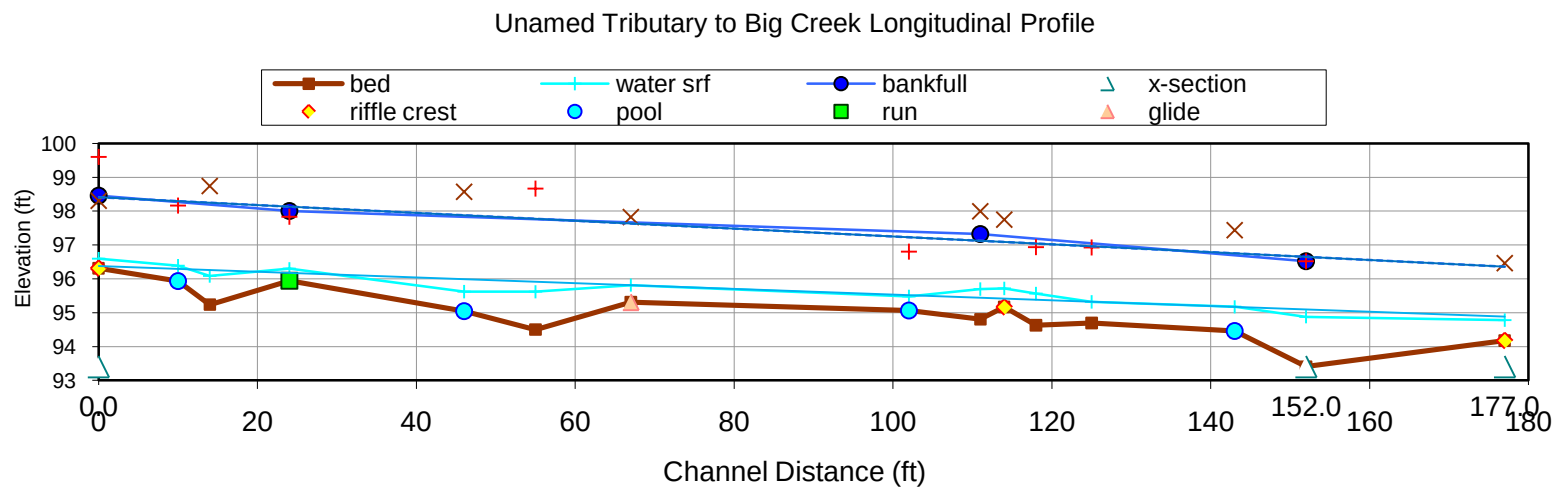
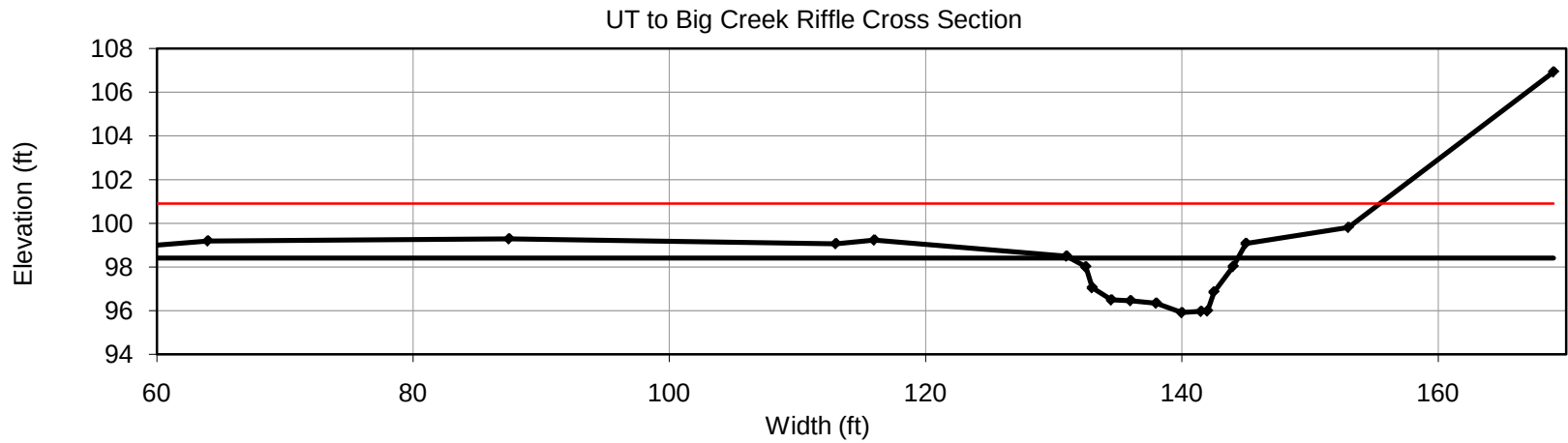
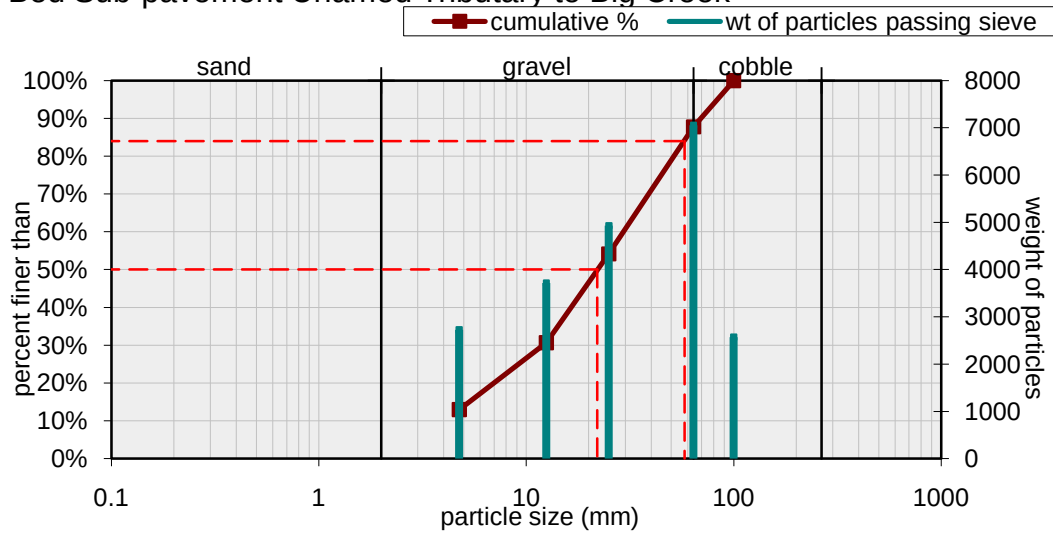


Figure A-7. Unnamed Tributary to Big Creek

Bed Sub-pavement Unnamed Tributary to Big Creek



Bed Surface Pebble Count, Unnamed Tributary to Big Creek

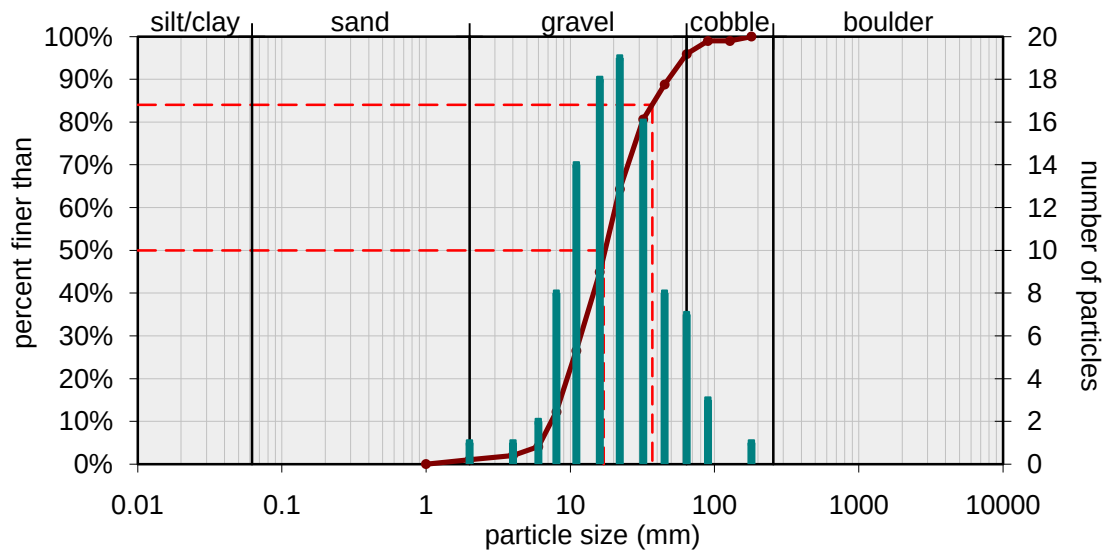


Figure A-7. Unnamed Tributary to Big Creek.

Stream Channel Classification

Stream Name: Crooked Creek
Drainage Area: 2.23
State: Tennessee
County: Union

Classification Data

Valley Type: VIII
Width: 29.90
Mean Depth: 1.64 ft
Flood Prone Width: 123 ft
Channel Material D₅₀: 22 mm
Water Surface Slope: 0.0092 ft/ft
Sinuosity: 1.50
Discharge: 161 cfs
Velocity: 6.3 ft/sec
Cross Sectional Area: 49ft²
Entrenchment Ratio: 18.20
Width to Depth Ratio: 4.10
Rosgen Classification: C4c

The reach of Crooked Creek surveyed for the regional curve study was located downstream of the USGS gage on Highway 170. The reach begins right above the property line marked by a barb wire fence and continues through a fallow field. The sediment regime was gravel with some larger cobble sized particles present. The bankfull indicator was the active connection to the floodplain on stream right with corresponding scour lines on stream left along the steeper bank. Bedrock was extensive throughout the surrounding area and was present in the pool and run habitat units.



Figure A-8. Crooked Creek.

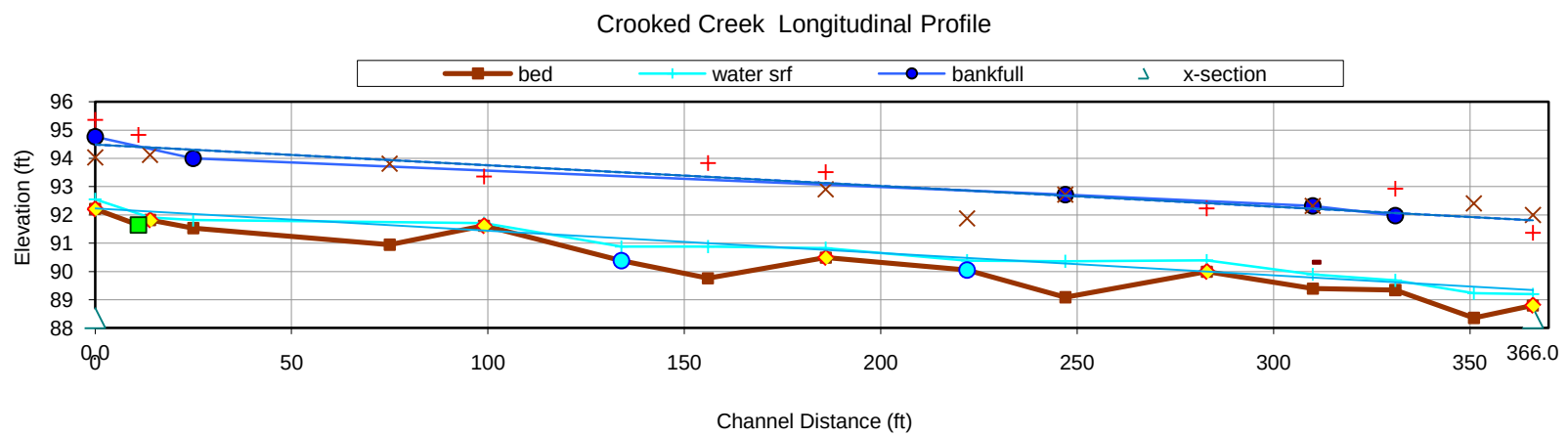
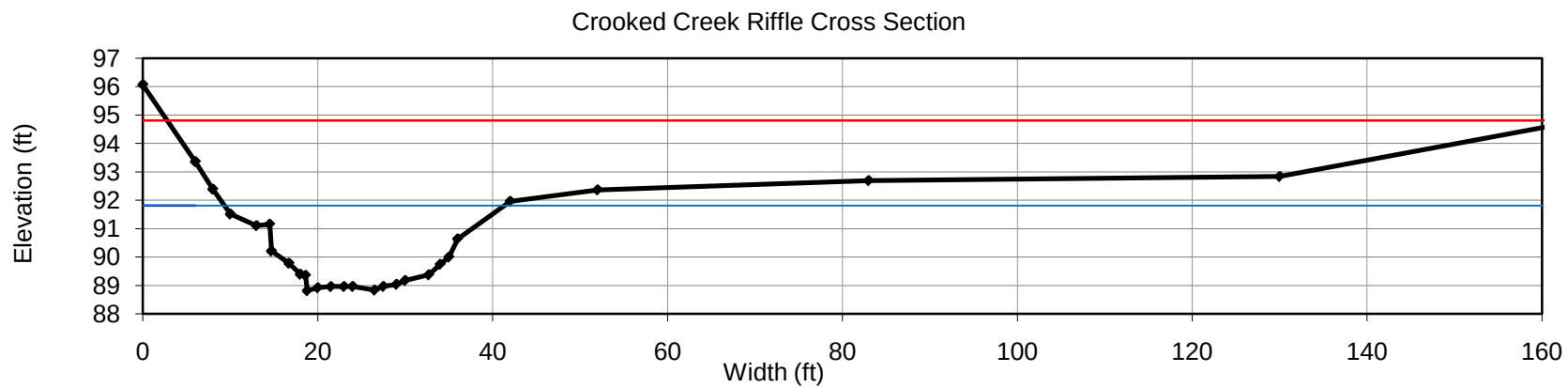


Figure A-8. Crooked Creek.

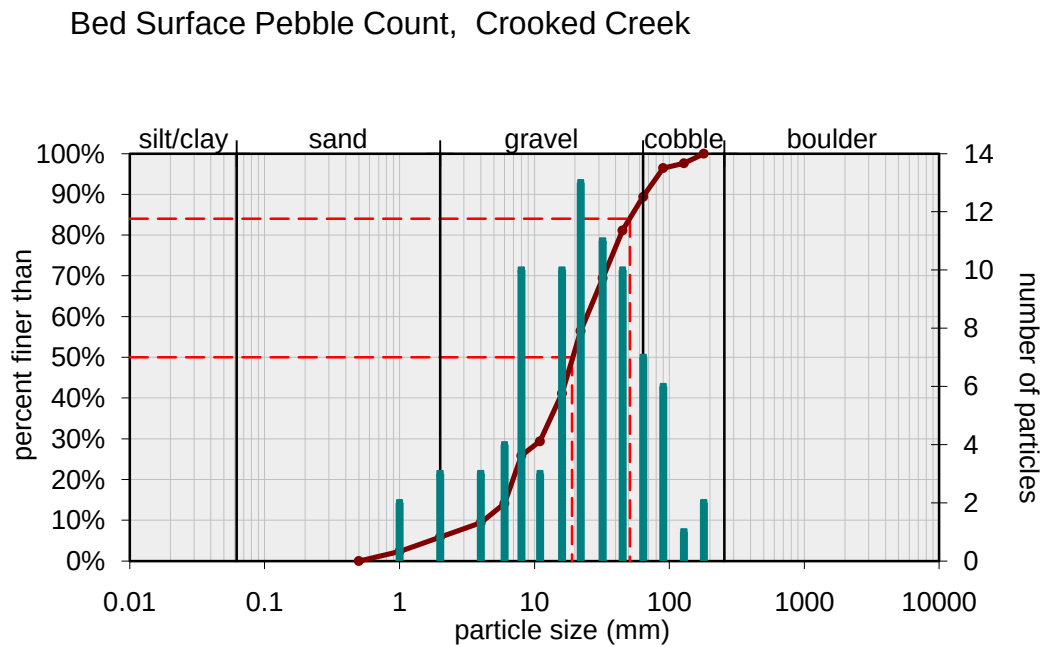
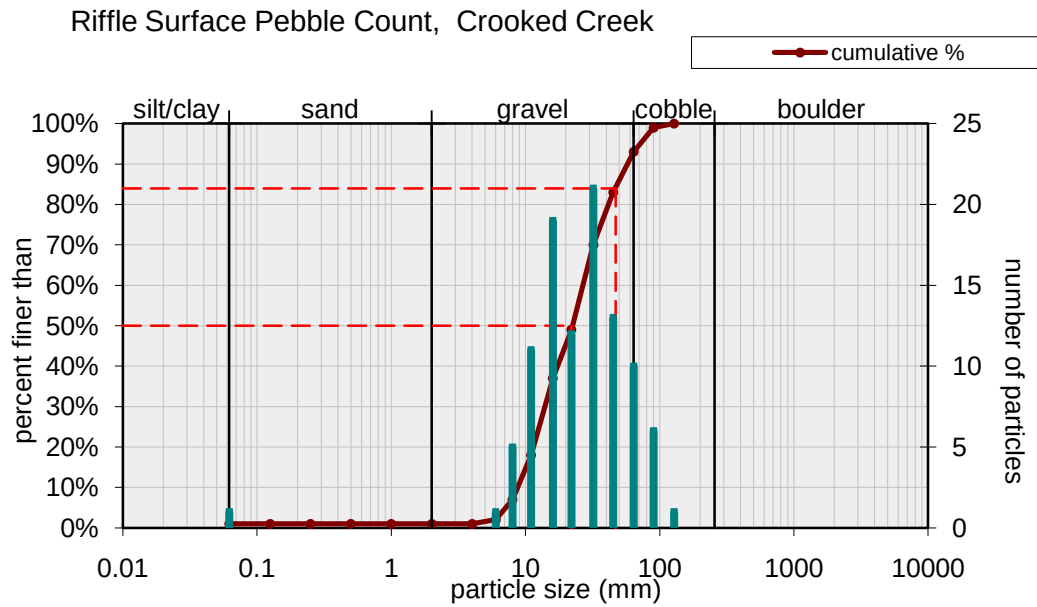


Figure A-8. Crooked Creek.

Stream Channel Classification

Stream Name: Willow Fork
Drainage Area: 3.23
State: Tennessee
County: Knox

Classification Data

Valley Type: VIII
Width: 20.1 ft
Mean Depth: 1.5 ft
Flood Prone Width: 409 ft
Channel Material D_{50} : 15 mm
Water Surface Slope: 0.0032 ft/ft
Sinuosity: 1.10
Discharge: 170 cfs
Velocity: 4.2 ft/sec
Cross Sectional Area: 30.5 ft²
Entrenchment Ratio: 20.40
Width to Depth Ratio: 13.30
Rosgen Classification: C4

The reach of Willow Fork included in the regional curve study is located directly downstream of the Quarry Road crossing. The reach had evidence of channelization above the road crossing. The reach lies in the center of a fallow field that is partially grazed by cattle. The reach continues to the property boundary marked by a barbwire fence. Bedrock is present in the surrounding area and in the stream channel bottom but alluvial riffles characterized the reach. The bankfull indicator was the active connection to the floodplain.



Figure A-9. Willow Fork.

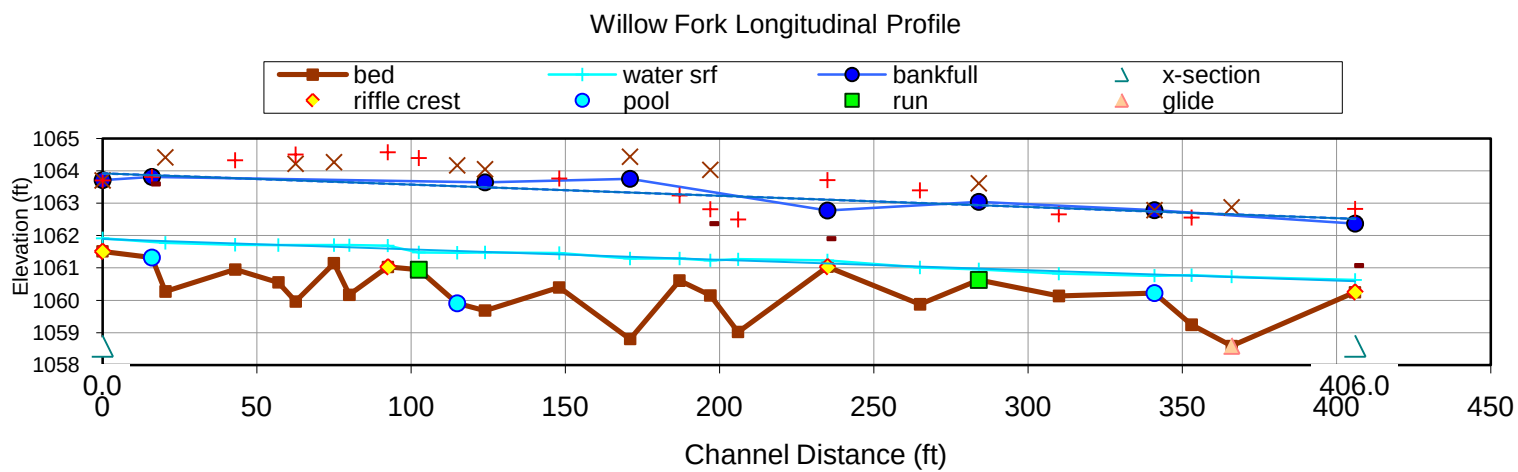
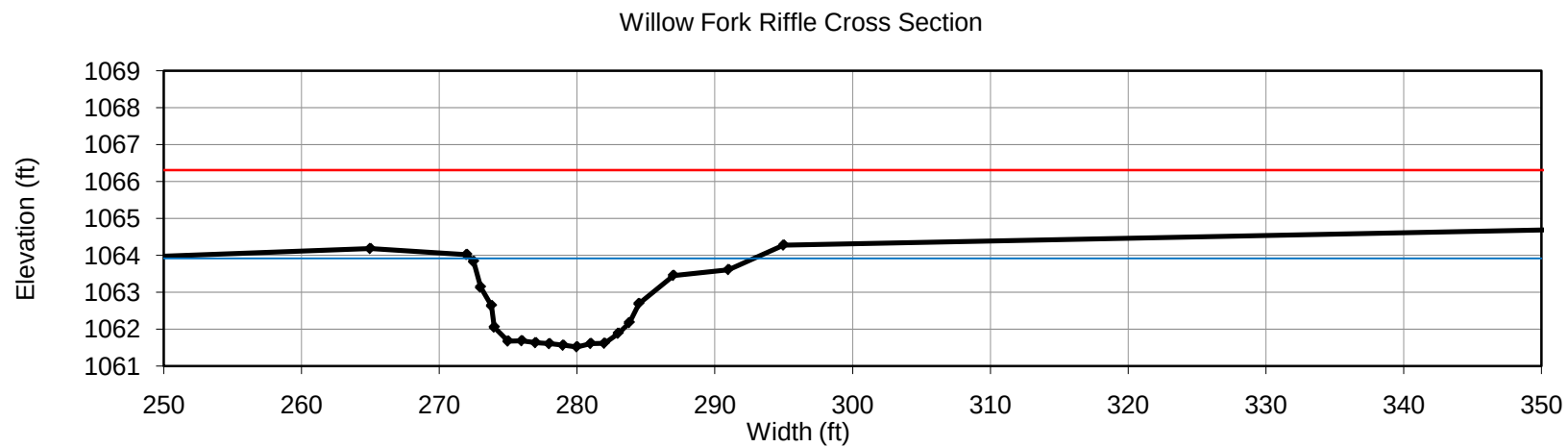


Figure A-9. Willow Fork.

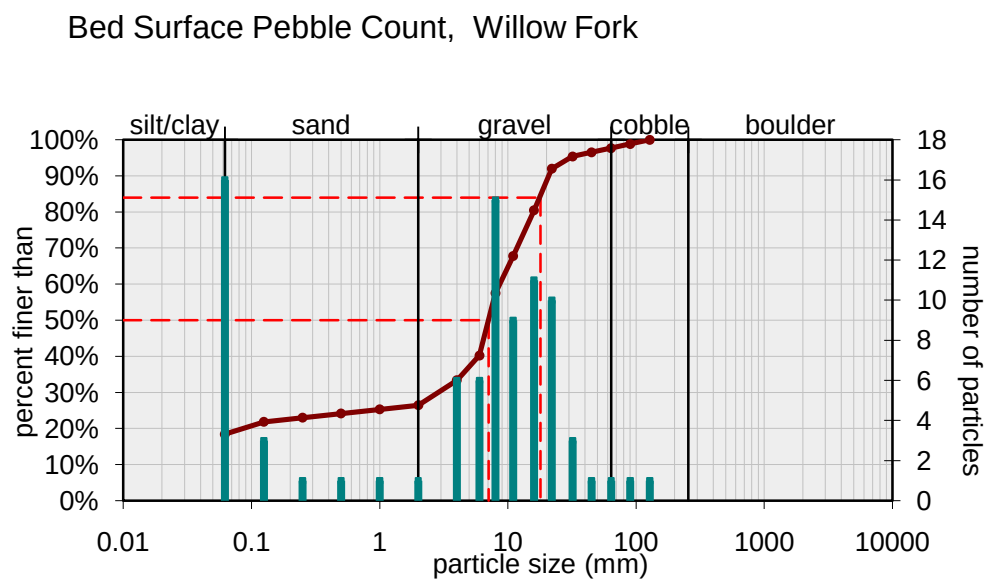
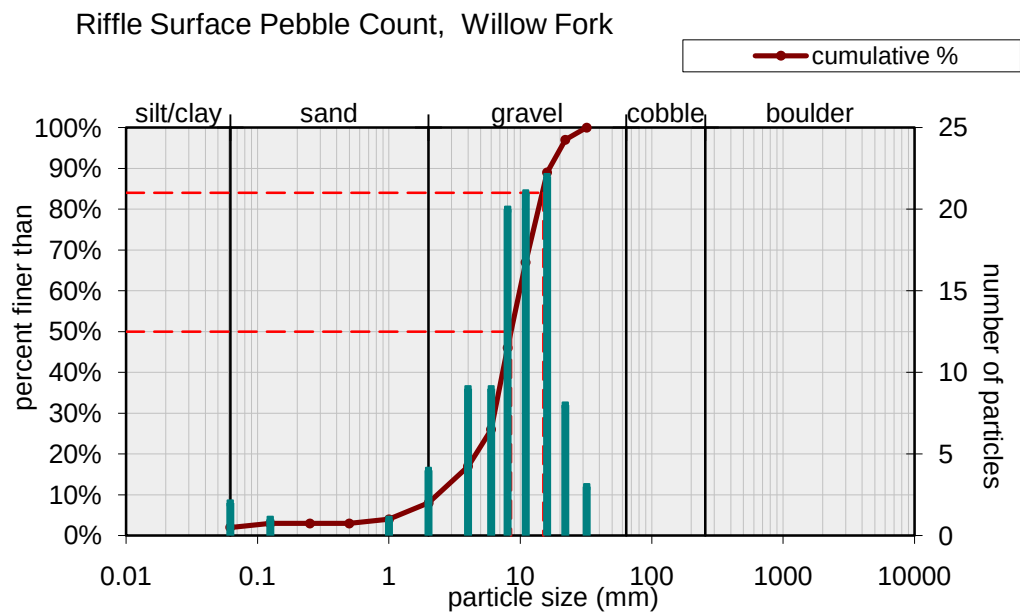


Figure A-9. Willow Fork

Stream Channel Classification

Stream Name: Crockett Creek
Drainage Area: 4.57
State: Tennessee
County: Hawkins

Classification Data

Valley Type: VIII
Width: 24.80
Mean Depth: 2.41 ft
Flood Prone Width: 134 ft
Channel Material D_{50} : 64 mm
Water Surface Slope: 0.0095 ft/ft
Sinuosity: 1.10
Discharge: 269.5 cfs
Velocity: 4.7 ft/sec
Cross Sectional Area: 59.7 ft²
Entrenchment Ratio: 5.40
Width to Depth Ratio: 10.30
Rosgen Classification: E4

The reach of Crockett Creek included in the regional curve study was located upstream of the existing USGS weir and gage. The reach began at the property line of the water treatment plant of Rogersville and stopped at the riffle crest before application of rip rap to the right bank of the channel. The bankfull indicator of the reach was the active floodplain connection and the sediment regime was gravel with some larger colluvial deposits from the adjacent ridge. The floodplain is extensive above the reach on stream right and it persists on stream left throughout the reach. Pool riffle sequences were present and bedrock was observed in the pool bottoms.



Figure A-10. Crockett Creek.

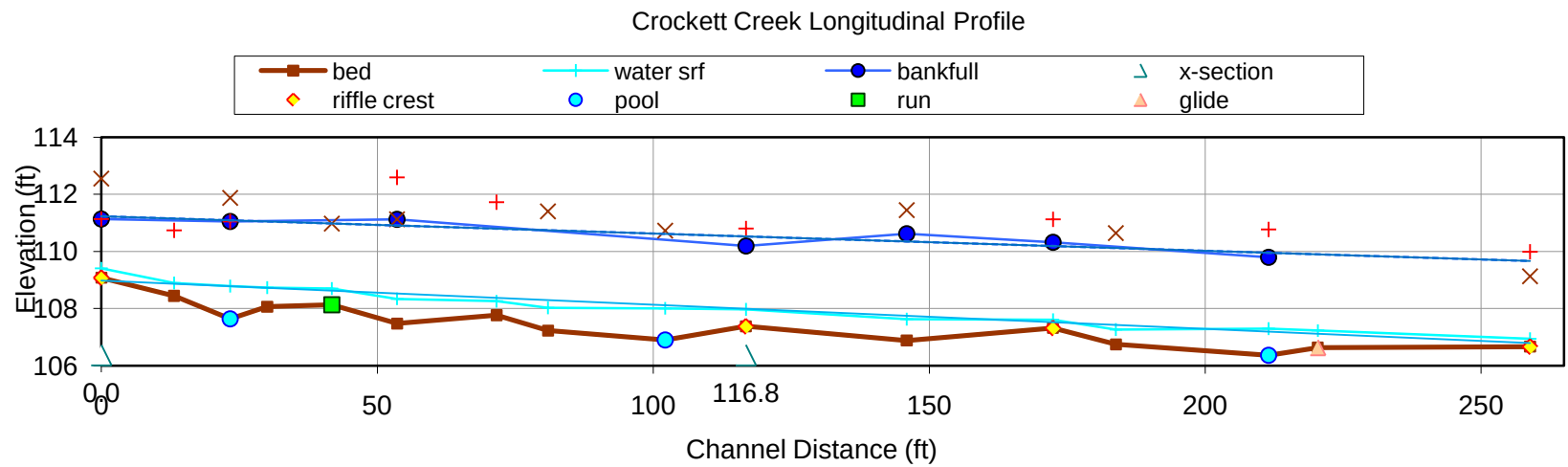
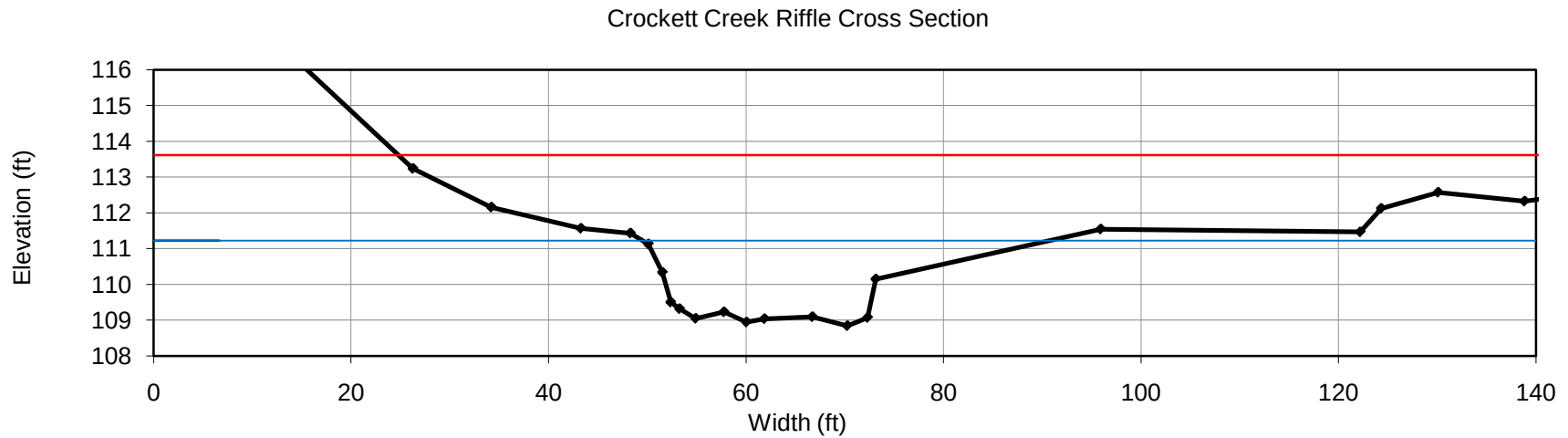


Figure A-10. Crockett Creek.

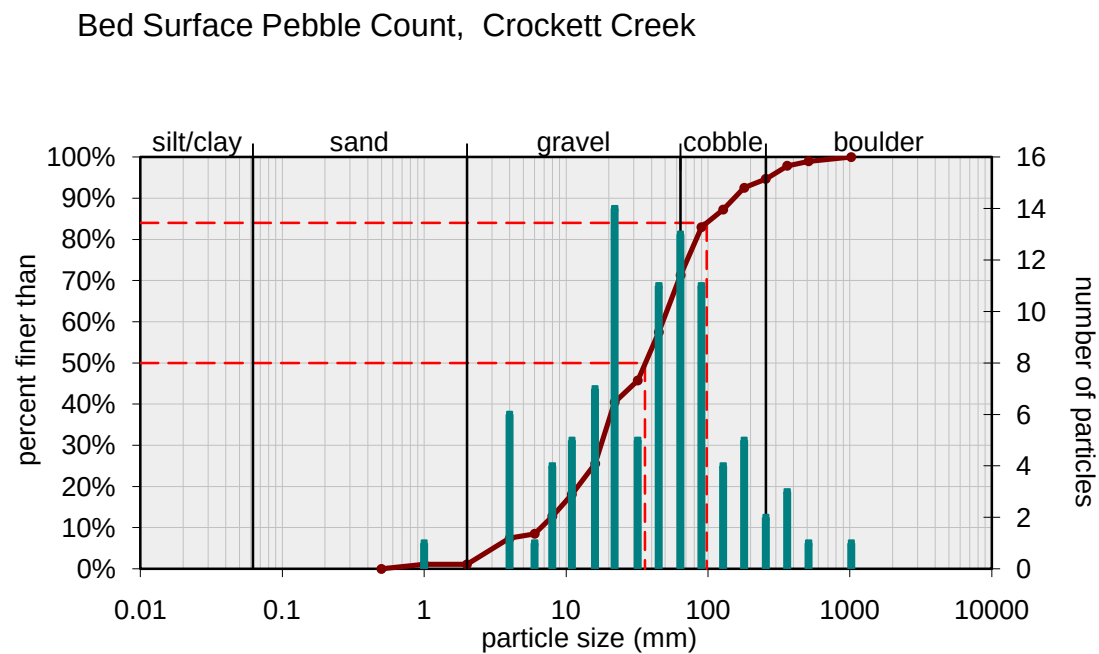
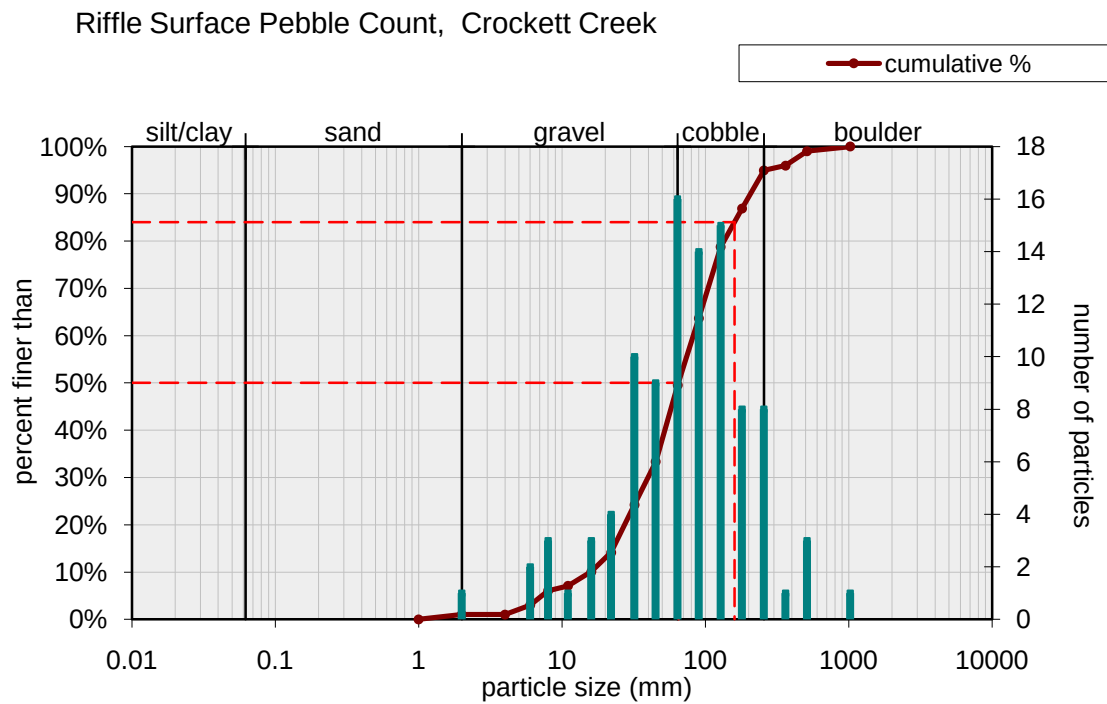


Figure A-10. Crockett Creek.

Stream Channel Classification

Stream Name: Robertson Creek
Drainage Area: 14.3
State: Tennessee
County: Hawkins

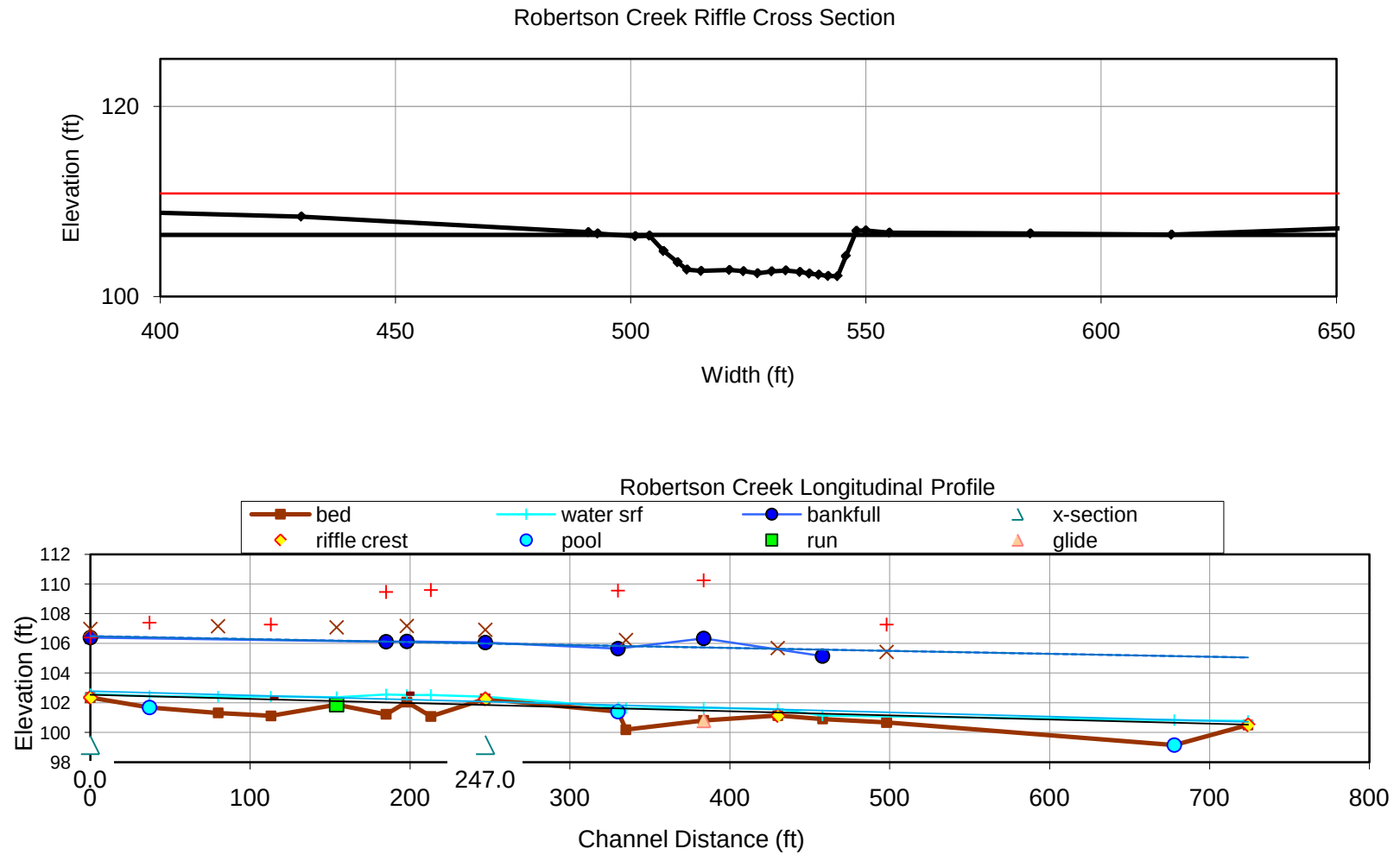
Classification Data

Valley Type: VIII
Width: 47.9 ft
Mean Depth: 3.13 ft
Flood Prone Width: 507 ft
Channel Material D_{50} : 37 mm
Water Surface Slope: 0.0025 ft/ft
Sinuosity: 1.20
Discharge: 518.8 cfs
Velocity: 4.4 ft/sec
Cross Sectional Area: 150 ft²
Entrenchment Ratio: 10.60
Width to Depth Ratio: 15.30
Rosgen Classification: C4

The reach of Robertson Creek included in the regional curve study was located above and below the USGS stream gage. The upstream extent begins approximately 700 feet above the stream gage. The reach has shale and gravel riffles with limestone and shale bedrock exposure throughout. The bottom half of the reach is characterized by a long glide-pool sequence through the gage. The bankfull indicator was the active floodplain connection on stream right. The watershed is mainly pasture used for grazing, but cattle are fenced out of the reach.



Figure A-11. Robertson Creek.



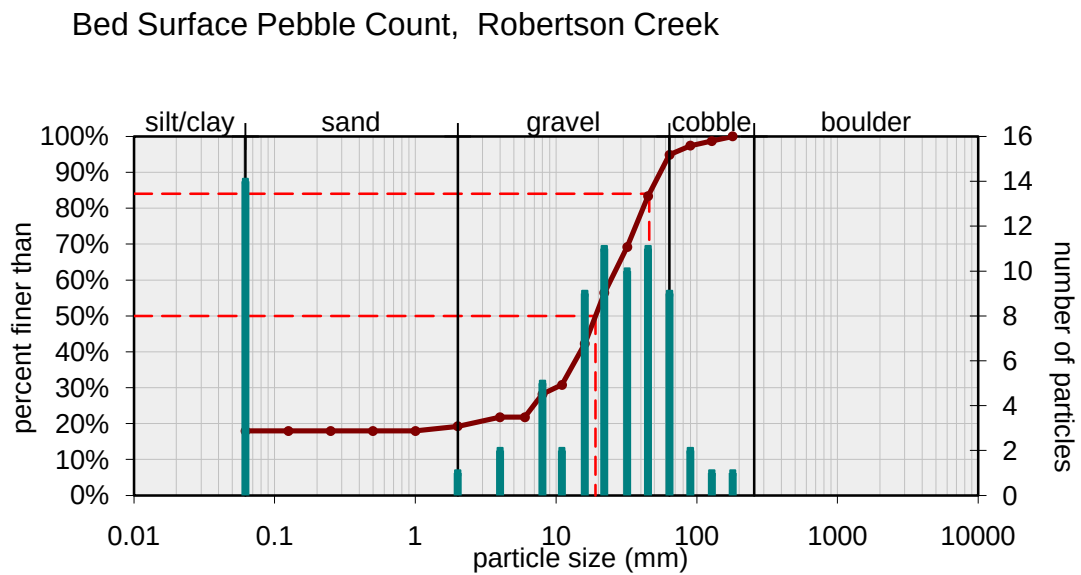
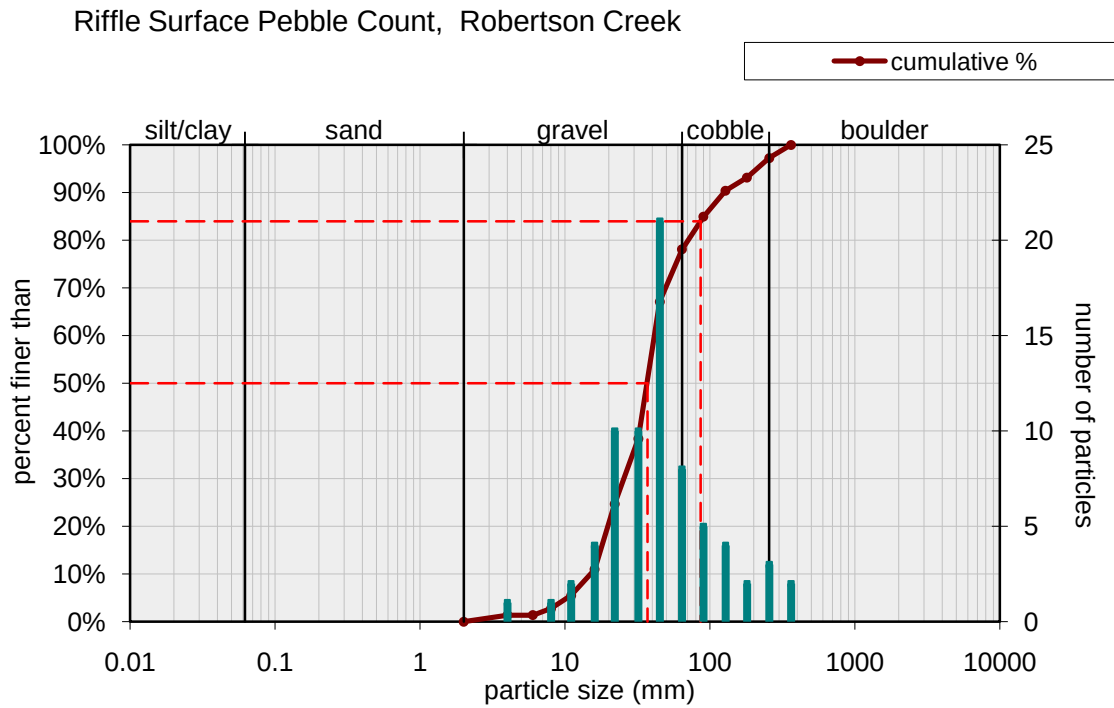


Figure A-11. Robertson Creek.

Stream Channel Classification

Stream Name: Big War Creek
Drainage Area: 22.3
State: Tennessee
County: Hancock

Classification Data

Valley Type: VI
Width: 38.4 ft
Mean Depth: 2.06 ft
Flood Prone Width: 75.4 ft
Channel Material D_{50} : 54 mm
Water Surface Slope: 0.0028 ft/ft
Sinuosity: 1.20
Discharge: 1018 cfs
Velocity: 3.2 ft/sec
Cross Sectional Area: 79.2 ft²
Entrenchment Ratio: 18.70
Width to Depth Ratio: 2.00
Rosgen Classification: B4c

The reach of Big War Creek included in the regional curve study was located upstream of the USGS gage between Highway 17 and Big War Creek Road. The stream is somewhat entrenched and the bankfull level is indicated by a prominent break in slope in the long floodplain connection. The floodplain on stream left is extensive. The reach has bedrock influence in the upstream riffle section where it runs adjacent to a ridge. Cattle graze the field, but the banks are stable and vegetated for the majority of the reach.



Figure A-12. Big War Creek.

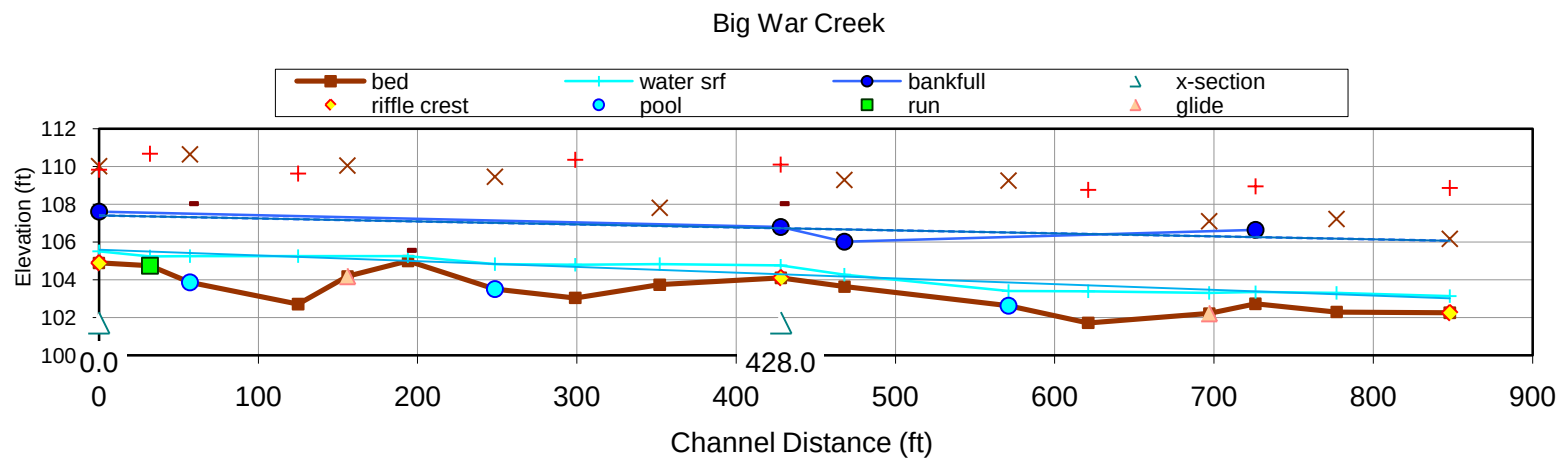
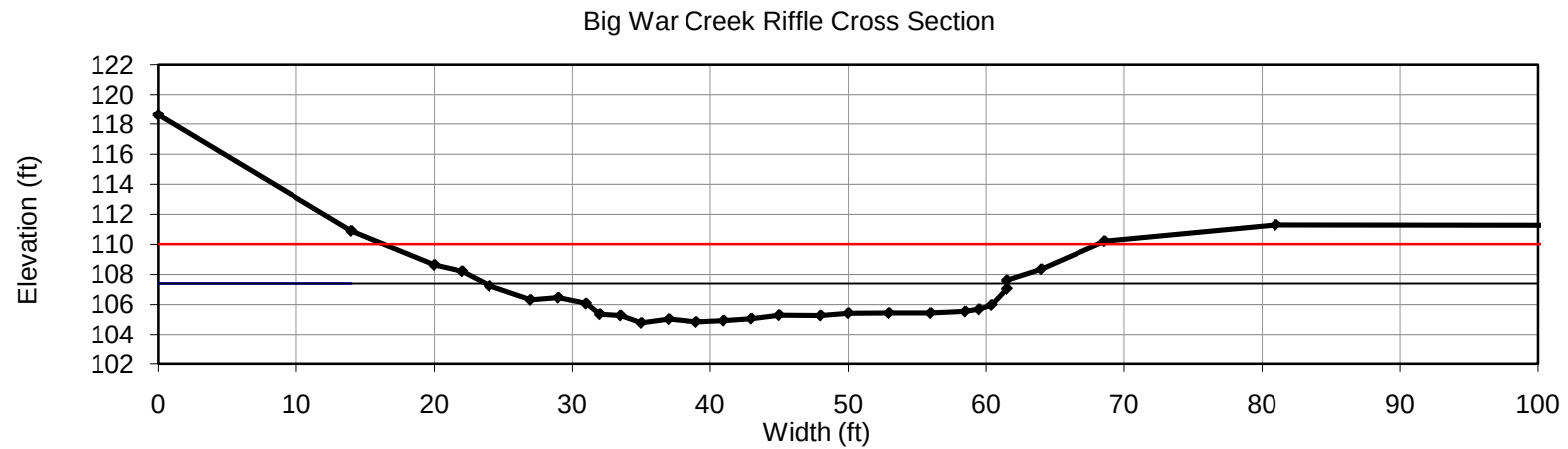
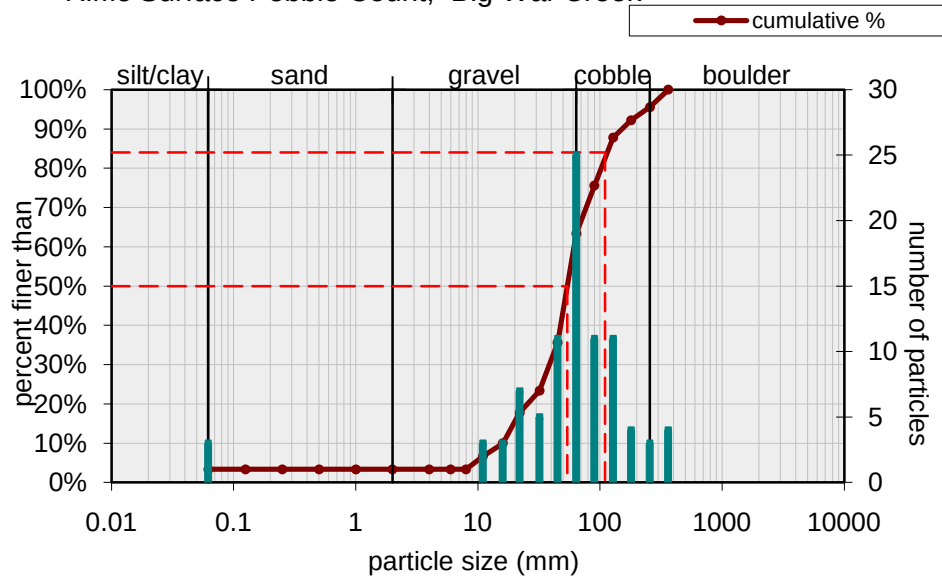


Figure A-12. Big War Creek.

Riffle Surface Pebble Count, Big War Creek



Bed Surface Pebble Count, Big War Creek

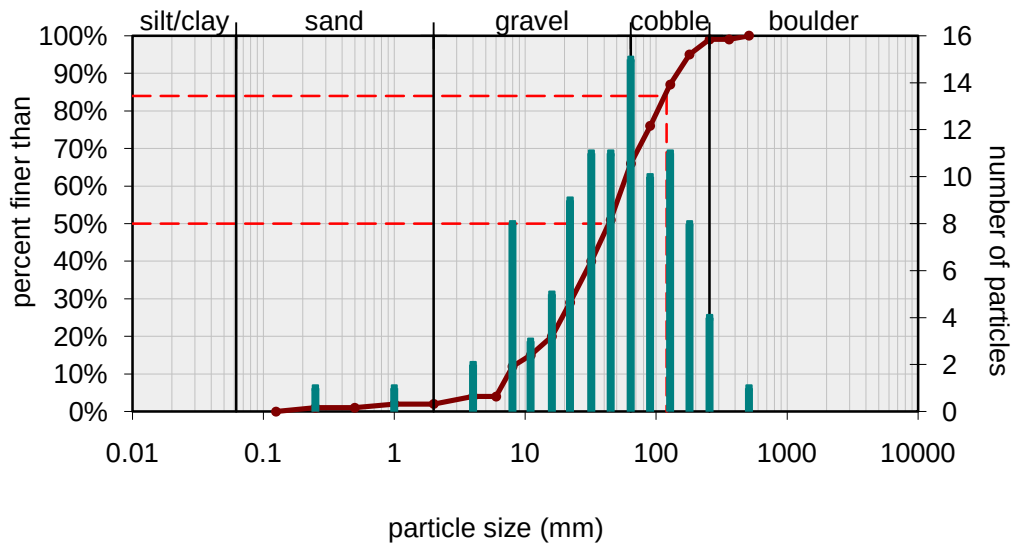


Figure A-12. Big War Creek.

Stream Channel Classification

Stream Name: Big Creek
Drainage Area: 47.9
State: Tennessee
County: Hawkins

Classification Data

Valley Type: II
Width: 94.90
Mean Depth: 3.7 ft
Flood Prone Width: 141 ft
Channel Material D_{50} : 15 mm
Water Surface Slope: 0.039 ft/ft
Sinuosity: 1.20
Discharge: 2144 cfs
Velocity: 5.6 ft/sec
Cross Sectional Area: 354 ft²
Entrenchment Ratio: 25.40
Width to Depth Ratio: 1.50
Rosgen Classification: B1c

The reach of Big Creek included in the regional curve study was located upstream of the existing USGS streamflow gaging station. The upstream extent of the reach began at the riffle downstream of a bedrock cascade. The reach was dominated by bedrock, but alluvial riffles were found. The reach was located within a confined valley type and the bankfull indicator was a break in slope of the valley wall and fine deposits. The reach had extensive riparian corridor on either side of the stream for the entire reach.



Figure A-13. Big Creek.

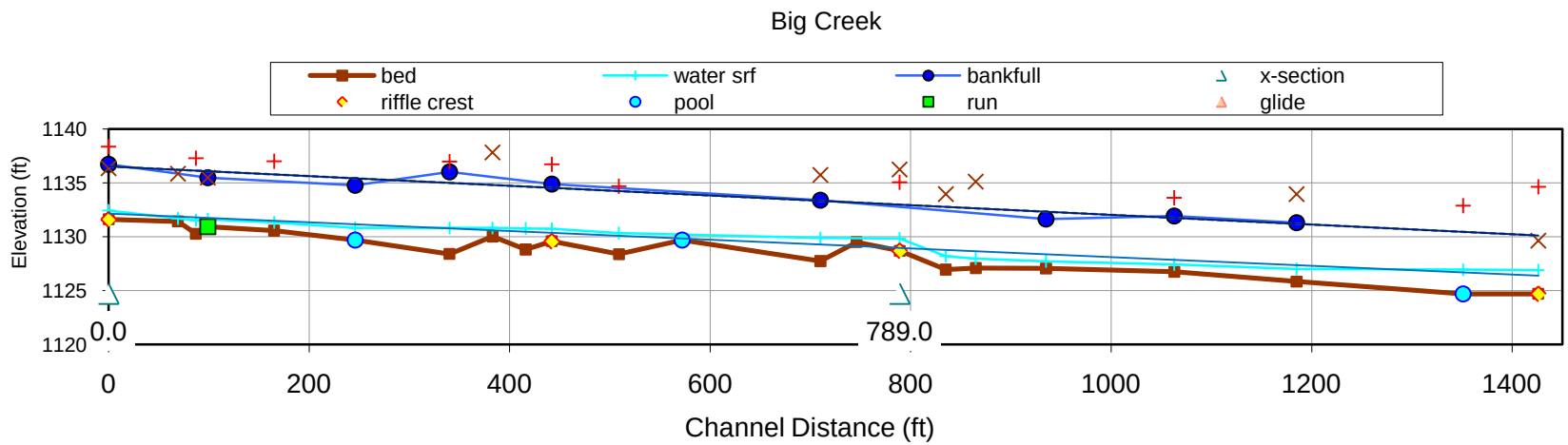
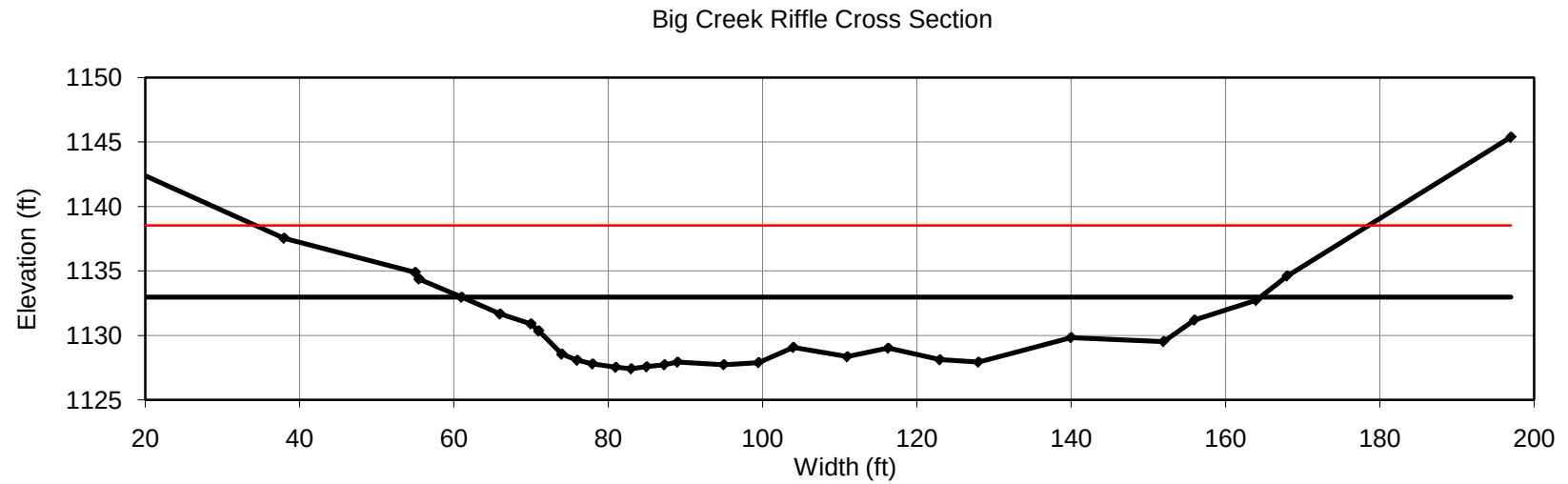
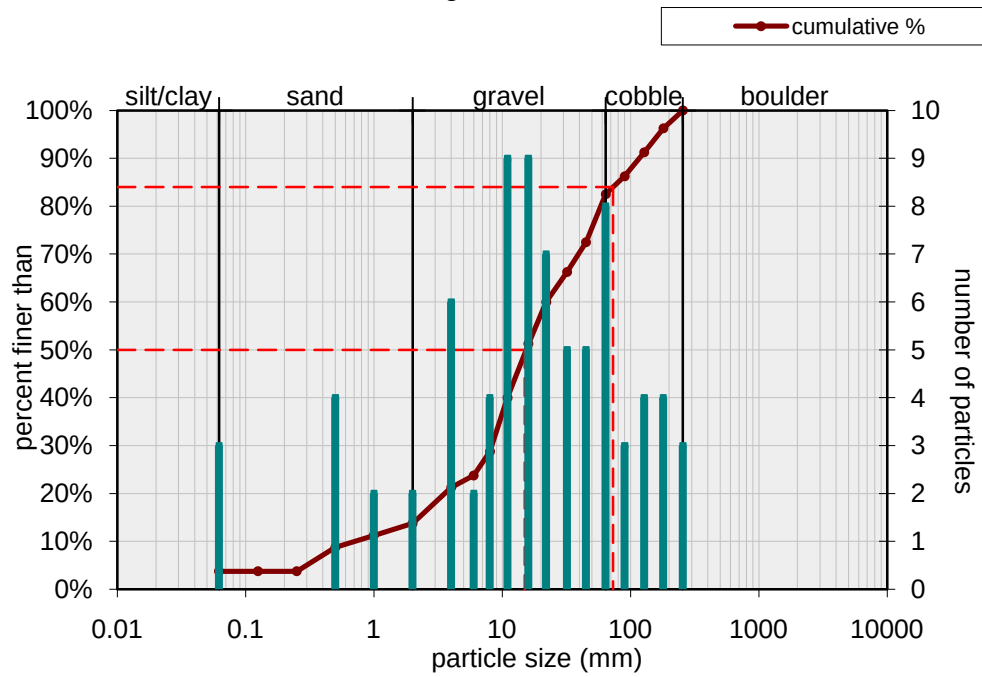


Figure A-13. Big Creek.

Riffle Surface Pebble Count, Big Creek



Bed Surface Pebble Count, Big Creek

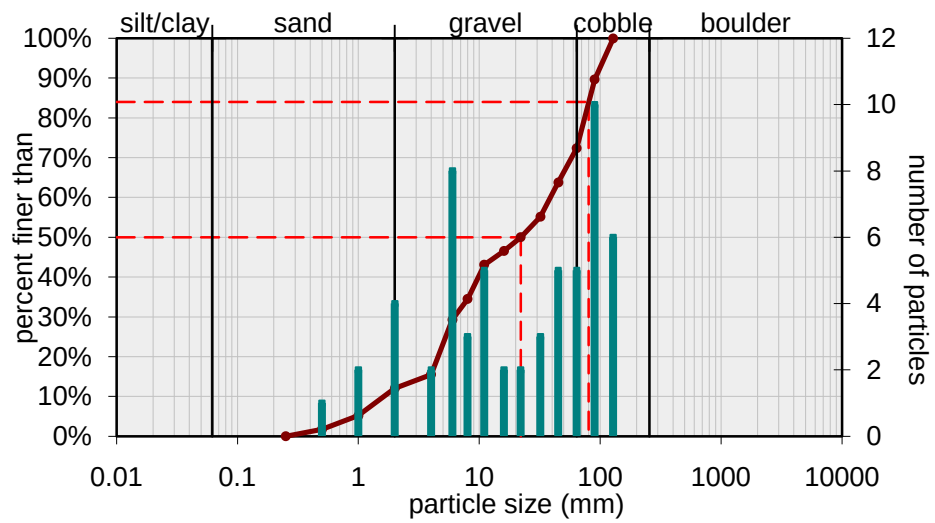


Figure A-13. Big Creek.

Stream Channel Classification

Stream Name: Copper Creek
Drainage Area: 106
State: Virginia
County: Scott

Classification Data

Valley Type: VI
Width: 86.60
Mean Depth: 4.75 ft
Flood Prone Width: 182.5 ft
Channel Material D_{50} : 25 mm
Water Surface Slope: 0.001 ft/ft
Sinuosity: 1.40
Discharge: 1820 cfs
Velocity: 4.2 ft/sec
Cross Sectional Area: 411.2 ft²
Entrenchment Ratio: 18.20
Width to Depth Ratio: 1.50
Rosgen Classification: C4

The reach of Copper Creek included in the regional curve study was located upstream of the existing USGS streamflow gaging station. The reach is adjacent to a steep ridge and has an extensive floodplain on stream right. The bankfull indicator is the active floodplain connection through the entire reach. The reach has a gravel sediment regime but some large boulders have been deposited colluvially from the adjacent ridge creating unique scour pools around them. Riparian vegetation is extensive on stream left, but less vegetation is present on stream right.



Figure A-14. Copper Creek.

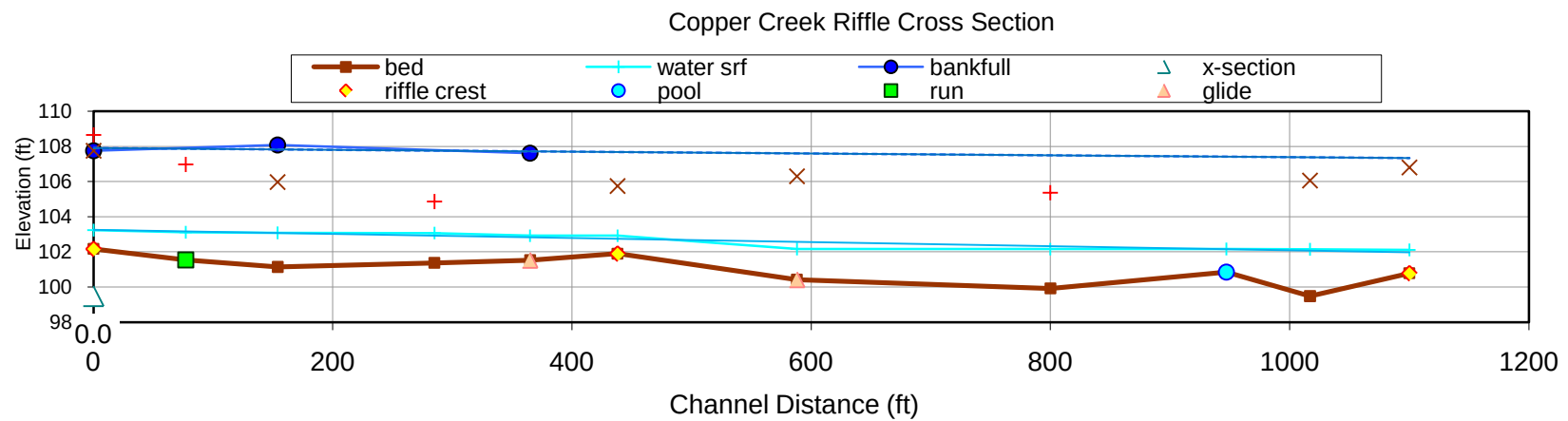
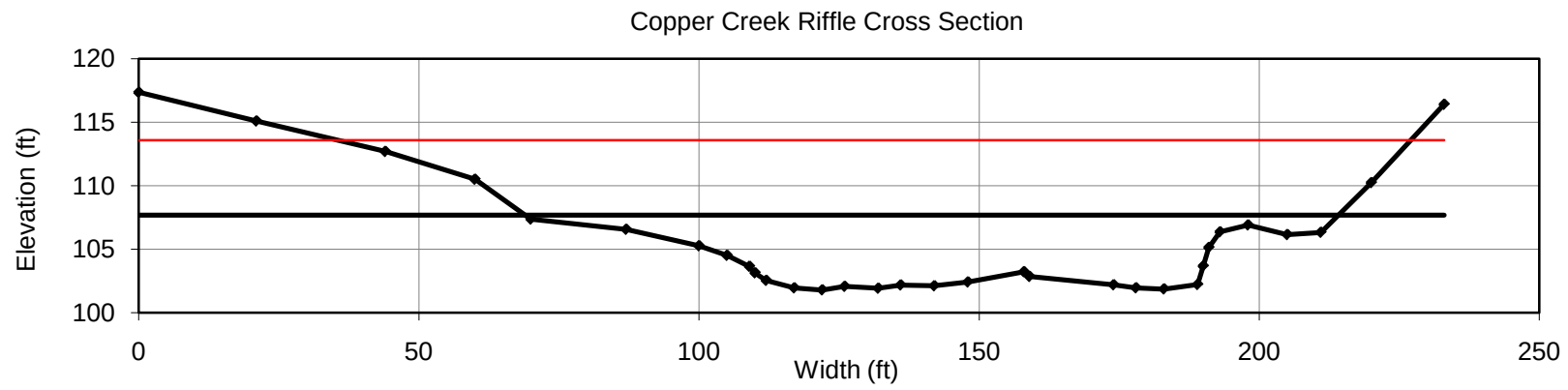
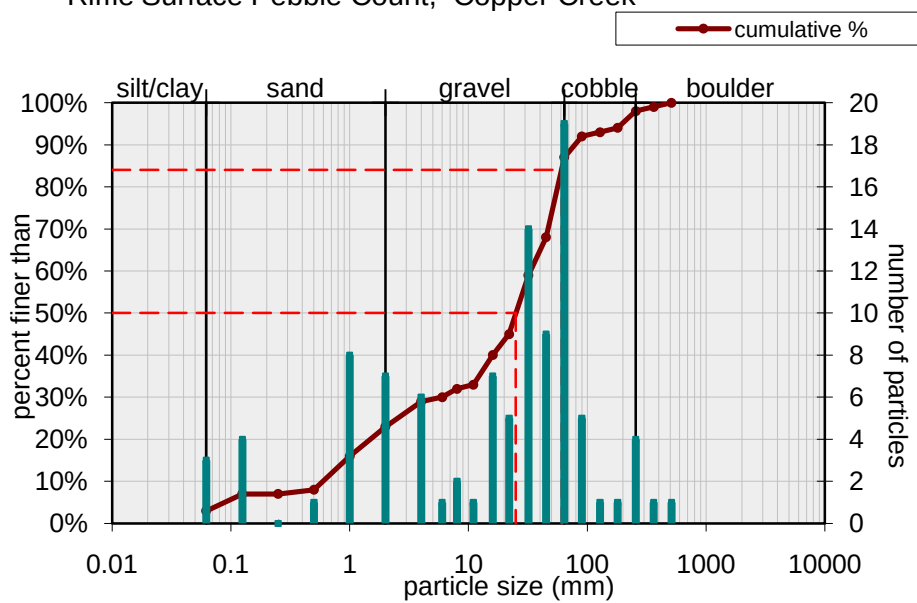


Figure A-14. Copper Creek.

Riffle Surface Pebble Count, Copper Creek



Bed Surface Pebble Count, Copper Creek

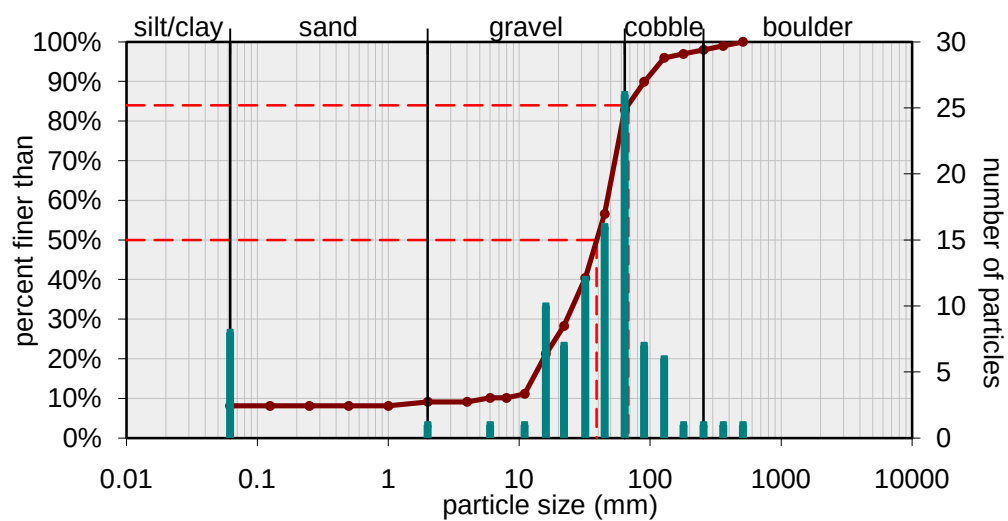


Figure A-14. Copper Creek.

Stream Channel Classification

Stream Name: Middle Fork of the Holston River
Drainage Area: 132
State: Virginia
County: Smyth

Classification Data

Valley Type: VIII
Width: 88.20
Mean Depth: 3.13 ft
Flood Prone Width: 212.5 ft
Channel Material D_{50} : 57 mm
Water Surface Slope: 0.0022 ft/ft
Sinuosity: 1.50
Discharge: 1930 cfs
Velocity: 4.2 ft/sec
Cross Sectional Area: 276.5 ft²
Entrenchment Ratio: 2.40
Width to Depth Ratio: 28.20
Rosgen Classification: C4

The reach of the Middle Fork of the Holston River that was included in the regional curve study was located downstream of the existing USGS streamflow gaging station. The survey was started below the installed weir downstream of the cascade. The bankfull indicator was a depositional bench on stream right throughout most of the reach. The reach had a gravel sediment regime with some evidence of bedrock in the pools. Residential development persisted on stream right and Interstate 81 bordered the reach on stream left. A low terrace was observed on stream right at the level of the old floodplain.



Figure A-15. Middle Fork of the Holston River.

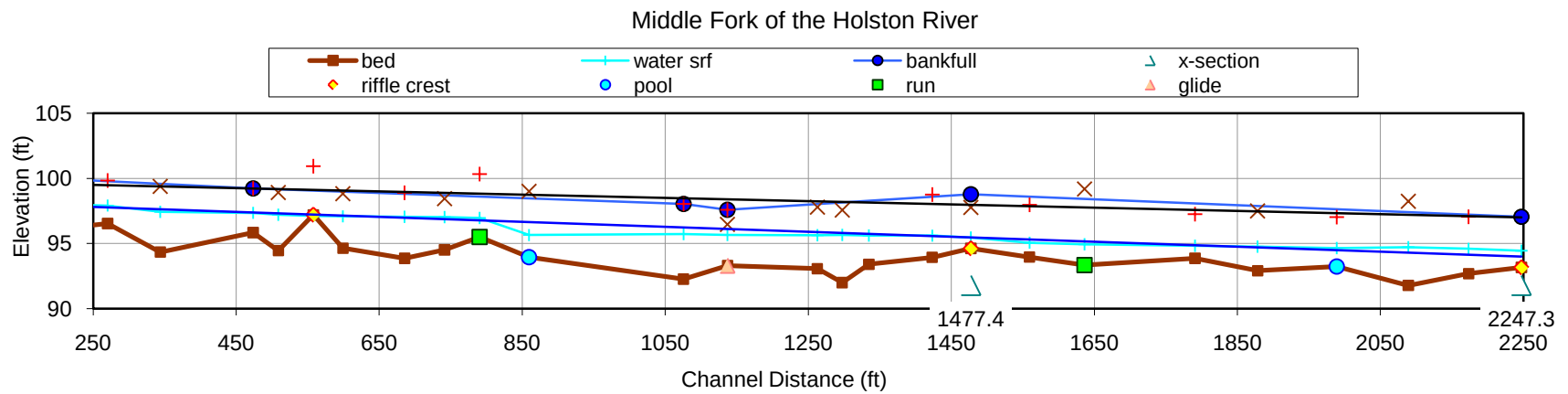
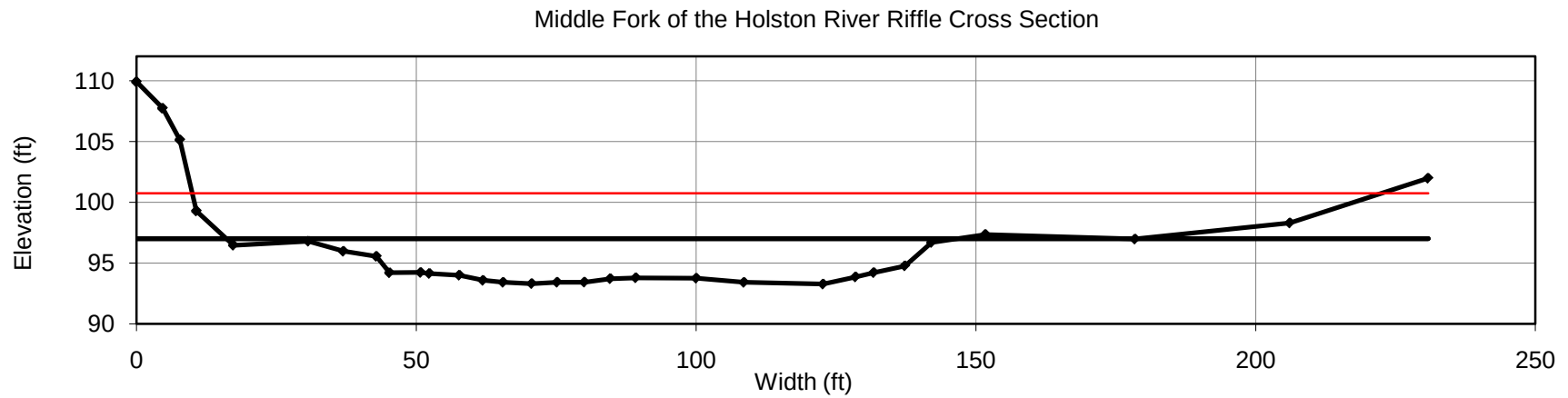


Figure A-15. Middle Fork of the Holston River.

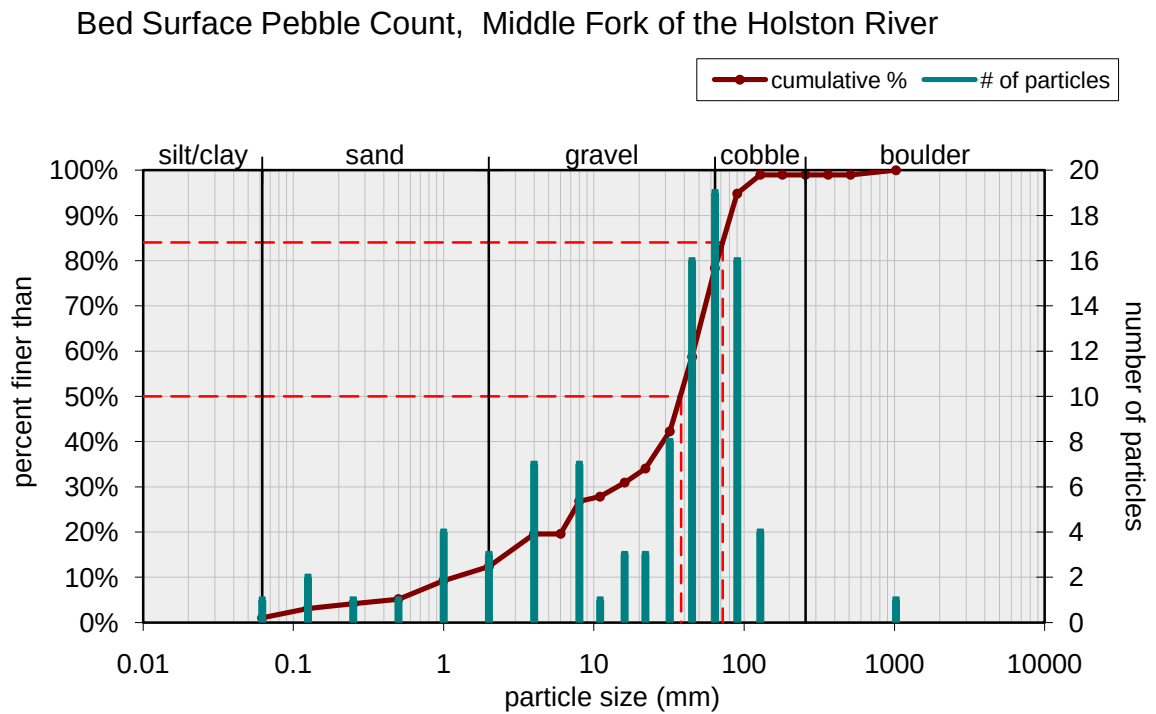
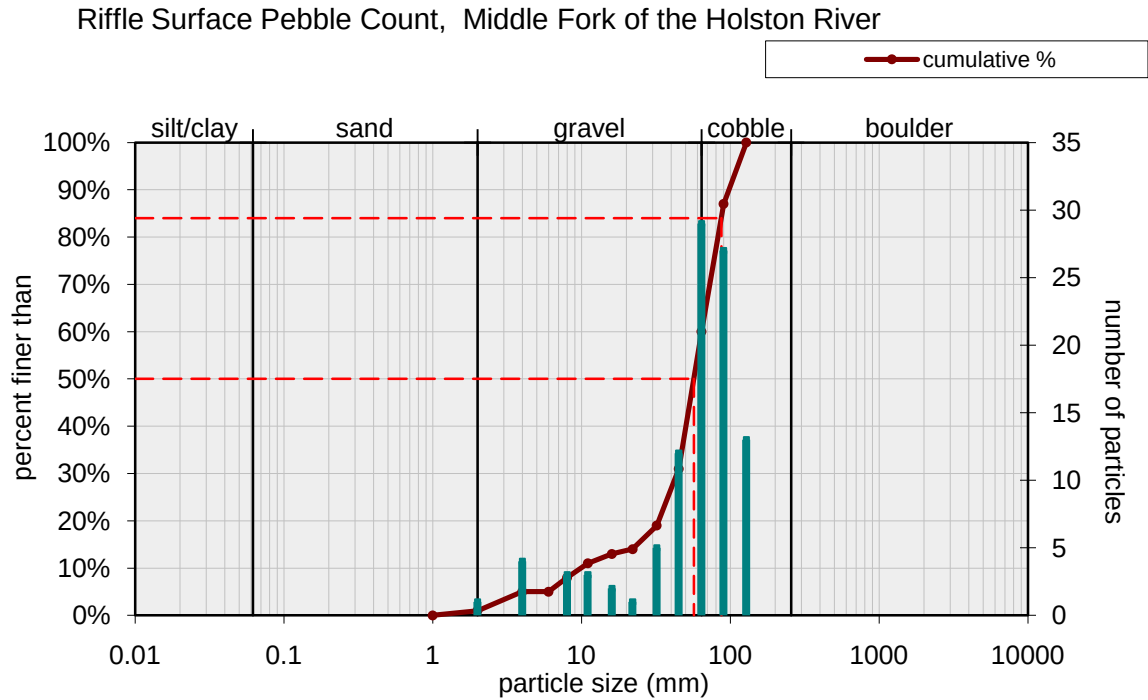


Figure A-15. Middle Fork of the Holston River.

Vita

James Brady McPherson was born in Searcy, Arkansas on September 10, 1985. He received elementary education in Pangburn, Arkansas before moving to White House, Tennessee. He graduated from White House High School in 2003 and in the fall of 2003 he enrolled at Cumberland University to study Biology. He transferred to Middle Tennessee State University in 2005 where he majored in Microbiology and Plant & Soil Science. Under the guidance of Dr. Warren Anderson he began working with rain gardens as means to treat urban runoff. Also, under the guidance of Terri Hogan, he began volunteering at the Stones River National Battlefield removing invasive exotics and replanting native species. In the summer of 2008 he began as an intern at the Tennessee Stream Mitigation Program in Nashville, Tennessee where he treated stream restoration riparian zones for invasive exotic species. In the May of 2009 he graduated with a Bachelor of Science degree in Microbiology and Plant & Soil Science. Following graduation he again interned with the Tennessee Stream Mitigation Program and continued to remove invasive exotics in restored riparian zones and performed maintenance on instream structures at stream restoration projects. In the fall of 2009 he was accepted into the Biosystems Engineering Technology program at the University of Tennessee. He held a Graduate Research Assistantship under Dr. John Steven Schwartz, completing this study for the Tennessee Stream Mitigation Program. In the summer of 2011 he will begin working for the Tennessee Stream Mitigation Program and will be identifying potential stream restoration and enhancement projects throughout the state of Tennessee.