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Bankfull Geomorphic Relationships and HEC-RAS Assessment in Small Catchments of the Cumberland Plateau Ecoregion

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To the Graduate Council:

I am submitting herewith a thesis written by Ryan Lee Hodges entitled "Bankfull Geomorphic Relationships and HEC-RAS Assessment in Small Catchments of the Cumberland Plateau Ecoregion." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

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Bankfull Geomorphic Relationships and HEC-RAS Assessment in Small Catchments of the Cumberland Plateau Ecoregion

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ryan Lee Hodges

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ABSTRACT

There is a great need for state governments to have effective watershed restoration and mitigation efforts to return degraded ecosystems to a stable, healthy condition. Given the growing investment in stream restoration efforts, there is an urgent need for tools to assess and improve the effectiveness of restoration efforts at local, state, and nationwide scales. In 2000 there was less than ten stream restoration permits provided by the state of Tennessee and has increased each year with almost forty permits issued in 2013. To better achieve successful stream restoration, appropriate channel designs must be used that reflect the hydraulic conditions of streams in the appropriate ecoregion. Regional curves describe the relations of stream channel conditions to watershed drainage. Robust design curves that span the spatial scale of restoration efforts in terms of drainage area do not currently exist for the Appalachian Plateaus region of Tennessee. The objectives of this study were to 1) develop regional curves for low-order stream geometry in the Cumberland Plateau ecoregion of Tennessee, 2) compare the developed regional curve relationships for the Cumberland Plateau of Tennessee with similar relationships developed for neighboring ecoregions and, 3) validate the application of combining shear stress modeling and the modified Shield’s diagram for predicting bed substrate size in restoration of low-order streams in the Cumberland Plateau of Tennessee. Regional curves for the Tennessee Cumberland Plateau ecoregion were develop and compared with the regional curves of Alabama Cumberland Plateau, North Carolina Piedmont, and Tennessee Western Ridge and Valley ecoregions. Statistical analysis on the regional curves determined that there is a significant difference between some curves at the 0.05 confidence level. Using HEC-RAS and the modified Shield’s Diagram, the predicted D50 was five to ten times greater than the field measured D50 and D84.

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CHAPTER I: Introduction

Over the course of history, civilizations have developed proximate to streams and rivers for convenient access to stable sources of food, water, transportation, and commerce. Consequently, the pragmatic nature of humans to live near flowing water has driven people to search for methods of defining, understanding and predicting relations among hydraulic parameters of the river, such as discharge, width, depth, and velocity (Williams, 1978). Streams transport water, sediment and energy while providing habitat for aquatic and terrestrial organisms, but development has placed restrictions on how efficiently stream systems can transport water, sediment, and nutrients. Each river basin produces a range of discharges and sediment loads that are products of a number of variables interacting within a watershed, such as climate, geology, soils, vegetation, land use, topography, and valley morphology (Knighton, 1998). Due to urbanization, discharges from developing watersheds have been affected and channel geomorphology has changed as a response. According to the Tennessee 305(b) report, about 48 percent of the stream miles assessed for recreational use failed to meet the criteria assigned to that use. Approximately 40 percent of the assessed stream miles failed to meet fish and aquatic life criteria (Denton, 2014). Section 404 of the Clean Water Act determined that disturbances to our nation's water resources could not persist, and that restoration is needed to offset the impacts. Restoration has been becoming more popular in Tennessee each year. In the year 200 there was less than 10 permits approved by the Tennessee Department of Environment and Conservation, and that number has increased each subsequent year with almost 40 permits issued in 2013. The size of these restoration projects can range from less than one square mile to over 50 square miles. However, almost 75% of the restoration projects approved were for streams with watersheds less than 3 square miles. Figures 1 and 2 below show the sizes and location of restoration projects in Tennessee. Figure 2 shows the county lines, HUC-

8 watershed boundaries, and the drops represent the location and size of the project. Often times the only reference to watershed size in stream restoration permits are the HUC-8 watershed. This discrepancy in scale between the HUC-8 management unit and the actual restoration size shows the need for tools to work in small catchment scales such as the streams chosen for this project.

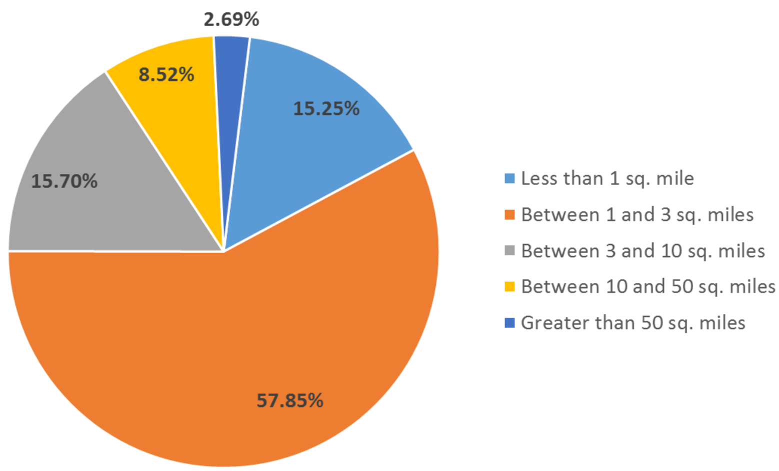

Figure 1. Stream Restoration Watershed Size for Permits (2000-2013)

Figure 2. Restoration Permit Map of Tennessee (2000-2013)

Restoration and rehabilitation of urban streams is a priority for many federal, state, and local government agencies and nonprofit groups. Many practitioners strive to restore stability to disturbed streams by rebuilding natural stream characteristics by using various methods including the use of reference reaches, design curves, modeling software, and many others. Stability is achieved when the stream has developed a stable dimension, pattern, and profile such that, over time, channel features are maintained and she stream system neither aggrades nor degrades (Rosgen, 1998). Better restoration approaches rely on the accurate identification of the bankfull channel dimension and discharge. Hydraulic geometry relationships that relate bankfull stream channel dimensions and discharge to watershed drainage area are therefore useful tools for stream restoration design (Doll et al., 2002a). Stream restoration, using natural channel design, has led the way in recent years to ameliorate adverse channel geomorphic response and ecosystem deterioration (McPherson, 2011). One thing that makes natural channel design different than other restoration techniques are the use of regional curves. Regional curves illustrate the hydraulic and geomorphic relationships between watershed area and channel morphological dimensions of width, cross sectional area, discharge, bankfull width, and bankfull depth. Regional curves are often used in natural channel design to aide in the validation of design channel dimensions, pattern, and profile for the stream system. Regional curves are also often used to confirm field indicators of bankfull channels. As channel-forming conditions are specific for ecoregions, regional curves vary for different ecoregions. Therefore, it is very important to use reference reaches in specific ecoregions to develop regional curves. Reference reach is a stream segment that represents a stable channel within a particular ecoregion. Some areas must rely on regional curves from nearby physiographic regions.

Ecoregions are delineated as areas of similar climate, geology, physiography, soils, vegetation, hydrology, wildlife, and land use (Griffith et al., 1997b). There are different levels for ecoregions, but level III ecoregions are often used because it integrates many channel-forming variables such as precipitation, vegetation, geology, physiography and soils into spatial framework for assessment, research monitoring and management (Griffith et al., 1997b). Castro and Jackson (2001) were able to distinguish ecoregions from climatic patterns and physiography as being the most statistically significant variable affecting the hydraulic geometry of stream channels, which is why they are typically completed specifically for regional curves. In 1992, the National Research Council developed a national aquatic ecosystem restoration strategy that targeted restoration using ecoregions as the geographic unit. Figure 3 is a map of ecoregions in Tennessee (Ecosystems--Science et al., 1992).

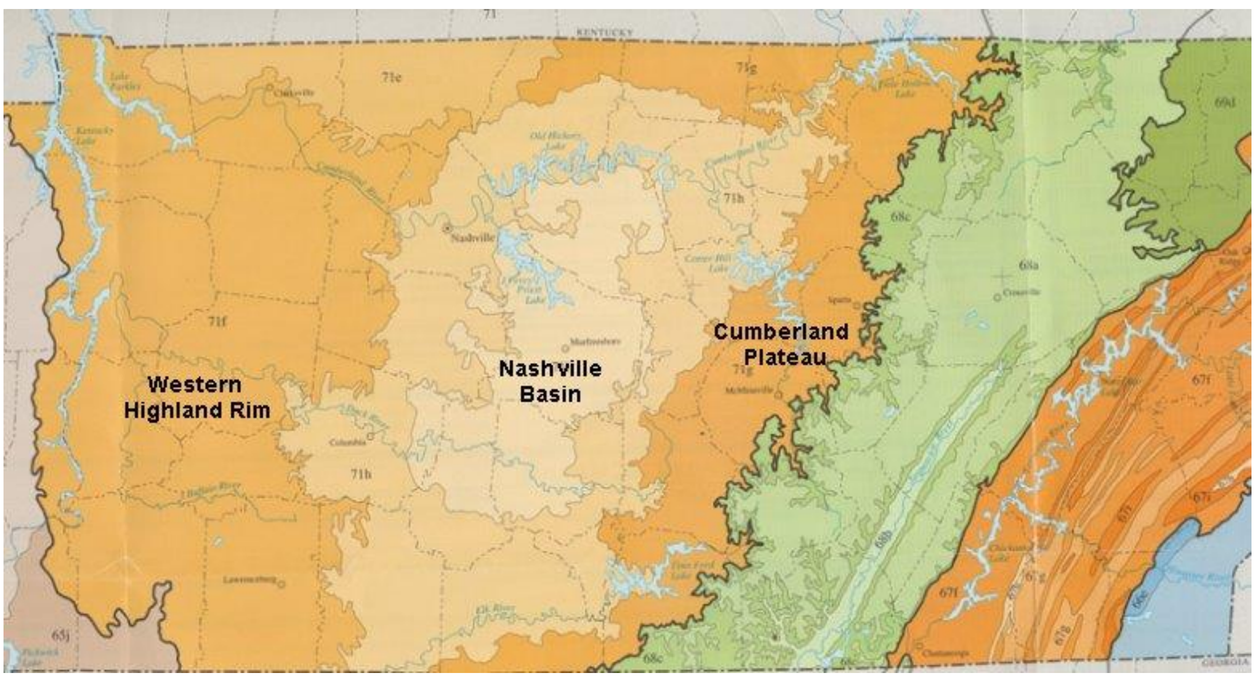

Figure 3. Ecoregions of Tennessee (swantrust.org)

It is often of interest to determine sediment transport characteristics of a channel at bankfull conditions since bankfull is the channel-forming discharge condition. Sediment transport is frequently related to the fluid shear stress in excess of a critical shear stress for a specified particle size (Johnson and Heil, 1996). There are multiple ways to determine shear stress, but one of the more common methods is to use computer modeling software such as the Hydrologic Engineering Centers River Analysis System (HEC-RAS). It is important to determine the mean diameter of the substrate when considering restoration because using the wrong D_{50} could result in a failed stream. Failed streams can be caused by human impacts or nature. Streams are dynamic systems that adjust to the tectonic, climatic and environmental changes imposed upon them (Dollar, 2000). The reasons streams adjust are to maintain a steady state of equilibrium between the flow of the water and the transport of the sediment and the resisting forces. For example, a stream may respond to an increased flow rate caused by upstream urbanization by adjusting its morphology and floodplain in order to return to a steady state. Sometimes the adjustment is so great that the stream will fail and start to buildup sediment (aggradation) or erode (degradation), and will not be able to return to a state of equilibrium. When a stream fails, restoration measures such as natural channel design may be necessary. The Objectives of this study were to; 1) develop regional curves for low-order stream geometry in the Cumberland Plateau ecoregion of Tennessee, 2) compare the developed regional curve relationships for the Cumberland Plateau of Tennessee with similar relationships developed for the Cumberland Plateau of Alabama and neighboring ecoregions and, 3) validate the application of combining shear stress modeling and the modified Shield's diagram for predicting bed substrate size in restoration of low-order streams in the Cumberland Plateau of Tennessee. The expected outcomes from this effort were to provide design tools for stream restoration projects in small catchments in the Cumberland Plateau Ecoregion of Tennessee.

CHAPTER II: Literature Review

Fluvial Geomorphology

The current practice of natural channel design is largely based on the science of fluvial geomorphology, which focuses on how land forms are shaped by moving water (Brookes and Shields, 1996). More specifically fluvial geomorphology is the study of landforms and the process that shape them by the transport of water and sediment through a fluvial system. Fluvial forms are the structural patterns of landforms at various spatial scales, from watersheds to channel bedforms. Fluvial processes are the actions when a hydraulic force from moving water induces a landform change by transporting sediment and depositing sediment. These hydraulic forces are dependent on landform\channel roughness influencing local degradation and aggradation. There are key contributions that fluvial geomorphology can make to the engineering profession. Fluvial geomorphology promotes recognition of vertical and downstream connectivity in the fluvial system and the inter-relationships between river planform, profile, and cross-section (Gilvear, 1999). When considering design, the practitioner needs to stress the importance of understanding fluvial history and chronology over a range of time scales, and recognize the significance of active landforms and deposits as indicators of levels of landscape stability (Gilvear, 1999). A couple other aspects of fluvial geomorphology in engineering are to highlight the sensitivity of geomorphic systems to environmental disturbances and change, the dynamics of the natural systems, and to demonstrate the importance of landforms and process in controlling and defining fluvial biotopes to promote ecologically acceptable engineering (Gilvear, 1999).

Ecoregions

North America has been divided into 15 level I ecological regions. These 15 regions highlight major ecological areas and provide the broad framework to the ecological mosaic of the continent. There are 50 level II ecological regions and provide a more detailed description of the large ecological areas nested within level I. Level III mapping describes smaller areas nested within the level II ecoregions. There are currently 182 level III ecoregions and these smaller divisions help enhance environmental monitoring, assessment, reporting, and decision-making. The delineation of level III ecoregions group landforms with similar climate, geology, physiography, soils, vegetation, hydrology, wildlife, and land use (Griffith et al., 1997b). Since a lot of these are channel forming feature, regional curves often use level III ecoregions. In recommending a national aquatic ecosystem restoration strategy for the United States, the National Research Council stated that restoration goals and assessment strategies should be established for each ecoregion (Omernik and Bailey, 1997). Tennessee contains 8 separate level III ecoregions and the ecoregion used for this study is the Interior Plateau ecoregion.

Approaches to Stream Restoration Design

a. Natural Channel Design

Many states require that impacts to streams from urbanization be mitigated based on the implementation of section 404 of the Federal Clean Water Act. Restoration can be defined as a measurable improvement to channel stability, water quality, habitat, and overall function of a degraded stream (Babbit, 2005). A popular method to stream restoration is using natural channel design. Natural channel design is defined as design intended to restore an impaired stream reach to a state such that the stream can transport the current sediment load and runoff provided to it from upstream without excessive aggradation or degradation while maintaining habitat and aesthetics consistent with that found in an unimpaired reach within an area of similar physiography (Cinotto, 2003). Natural channel design has been the most prevalent method for stream restoration used by biologists, fluvial geomorphologists, and engineers throughout the United States (Doll, 1999). Natural channel design incorporates the bankfull discharge, as previously discussed, and uses it as a base for channel dimensions.

One other component of natural channel design is the utilization of a reference reach. Many river engineering methods rely on clear water discharge, rigid boundaries, uniform flow, and channel materials (Chow, 1959). These requirements are not often observed in nature due to urbanization and can lead to poor channel design. Empirically derived 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 relationship had been developed (Rosgen, 1998). Most studies to develop regional curves use power relationships for drainage area to the bankfull hydraulic dimensions. Power relationships transform the data to log scale but statistical analysis can be done to validate the model. So often the natural channel design can be a failure if using streams from different physiographic regions or designing after unhealthy streams.

b. Reference Reaches

Using 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 (McPherson, 2011). The use of reference reaches provide the engineer with measurements that are similar to a healthy stream and have characteristics to target in a stream restoration design. Measured channel characteristics are presented as dimensionless ratios, such as width/depth ratio, are extrapolated to the project site for incorporation into the restoration design (White, 2001). The reference reach provides the dimensionless ratios specifically for riffle, run, pool habitat units, which are important for healthy streams, and other measurements.

By incorporating these dimensionless ratios that characterize a stable stream reach into the natural channel design, engineers assume the newly designed reach will function as effectively as the reference reach at transporting discharge and sediment (White, 2001). Some other commonly used methods for determining reference reaches include that the stream must be free to adjust channel boundaries, have gauge station data, must be stable and in equilibrium, and have consistent bankfull indicators. Reference reaches selected for use in natural channel design are assumed to be stable or in equilibrium with the sediment and water inputs from their drainage basin, they also interact frequently with the floodplain. There is no universally accepted set for criteria for determining whether all of part of a system is in equilibrium (Knighton, 1998). However a stream can become stable if they are disturbed they will return approximately to their previous state according to the channel evolution model. Equilibrium can be defined as a state of grade, in which, over a period of years the 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 (Mackin, 1948). Depending on the ecoregion there may or may not be available reference reaches for the development of regional curves and use of natural channel design. If not, extrapolation can be done but for the best results a variety of drainage areas and bankfull dimensions will have better results from each ecoregion.

c. Ecoregional Curves for Channel Design

Regional curves are graphical representations of stream channel bankfull hydraulic geometry as a function of basin drainage area within a specific ecoregion or physiographic province (Harman et al., 1999). Regional curves are the product of regression analysis performed on the relationships of bankfull discharge, width, mean depth, and cross sectional area (Cinotto, 2003). The bankfull discharge, width, and mean depth can be measured from geomorphic surveys of the reference streams selected. An example of a regional curve can be seen in figure 4. Figure 4 shows the geomorphic relationship between mean depth and drainage area. The regional curve in figure 4 was developed for the Southwestern Appalachians of Tennessee and has sites with very large drainage areas. Regional curves for this project are focusing on drainage areas less than 10 square miles to better represent what is commonly seen in practice. These regional curves can be developed by using the survey data and drainage area to form a log-log plot.

The principal reason for developing regional curves is to assist in identifying bankfull stage and channel dimensions in ungauged watersheds and to validate bankfull dimensions and discharge for stream restoration designs (Rosgen, 1994). Bankfull calibration is conducted at USGS gaging stations in which the field-determined stage is referenced to the stage discharge table (Rosgen, 1994). More recently, there has been an increasing interest in developing regional curves for different physiographic regions.

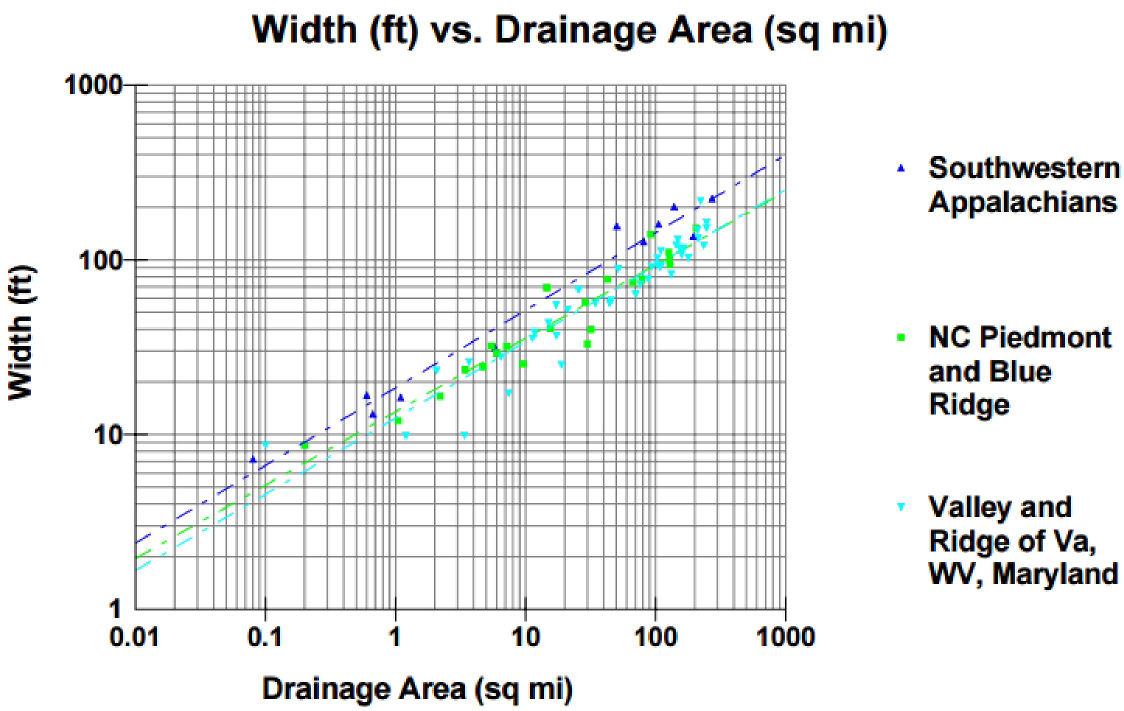

Figure 4. Bankfull Width vs. Drainage Area (Babbit, 2005)

One benefit of regional curves is using them to help watershed planners evaluate physical impacts of channel alteration and aid in predicting channel adjustments as a results of those modifications (Smith and Turrini-Smith, 1999). Another benefit is using regional curves to provide preliminary data on existing stream conditions. They can be useful tools in facilitating the decision making progress for both watershed planning and regulatory permitting (Smith and Turrini-Smith, 1999). Stream restoration is an important aspect in the increasing environmental actions due to the mandate by the EPA to identify the total maximum daily loads for streams in compensatory mitigation promulgated by the clean water act (Babbit, 2005). Establishing bankfull geomorphic relationships are important for validating natural channel design projects. The regional curves assist in guiding field determination of bankfull stage for streams that are difficult to determine as well.

d. Computational Design Models

Complex flow patterns generated by irregular channel topography, such as boulders, submerged large woody debris, riprap and spur dikes, provide unique habitat and stream structures but modeling these structures can be challenging. Modeling these flow features that are important in assessing stream conditions have been becoming more of an interest to practitioners. Recently, they have begun examining the usefulness of two-dimensional hydrodynamic models to attain this objective (Crowder and Diplas, 2000). Current modeling practices consider relatively long channel sections with their bathymetry represented in terms of large topographic features. The smaller features that create the smaller complex flow patterns are typically not considered in the modeling process. Instead, the overall effects of these flow obstructions are captured through increased values in channel roughness parameters (Crowder and Diplas, 2000). Even though the modeling software cannot provide details about the complex flow patterns, using two-dimensional modeling allows one to accurately predict average depth and velocity values. Two-dimensional hydrodynamic modeling with moving boundaries by the finite element approach overcomes many limitations related to classical one-dimensional modeling (Leclerc et al., 1995). Some of the important benefits of two-dimensional modeling include: the spatial resolution of the model can be adapted to scale, the areas frequently uncovered because of flow regime are correctly taken into account through the drying-wetting capability, and the flow resistance variables are more accurate in two-dimensions because they can be specified as functions of the local substrate conditions or lateral shear stresses (Leclerc et al., 1995).

e. Sediment Transport in Stream Restoration Design

Sediment transport is an important and difficult to predict process in fluvial environments. The complexity of the problem has resulted in a number of methods for predicting the threshold of bed sediment movement being proposed. These are normally presented in the form of equations or graphs and relate different critical flow characteristics (velocity, shear stress, stream power, and water discharge), associated with the initiation of bed sediment transport, to some parameters (Shvidchenko and Pender, 2000). One of the fundamental aspects of sediment transport has to deal with the critical condition for incipient motion of sediment. One of the most widely used criterions dealing with sediment transport is the Shield's diagram. The Shield's diagram establishes a relationship between the critical Shield's parameter and the shear Reynolds number (Cao et al., 2006). For a specific set of fluid and sediment parameters, one has to resort to a trial and error procedure or iterations to find the critical bed shear stress (Mantz, 1977). This makes the application more difficult but using modeling software such as HEC-RAS the shear stress is obtainable. HEC-RAS was developed by the US Army Corps of Engineers and is commonly used to calculate variables that could be difficult without it such as the energy slope, discharges, and floodplain management. Comparing the HEC-RAS outputs with the field results could yield different results and be very important in helping to understand the accuracy of using empirical models such as the modified Shield's diagram.

CHAPTER III: Bankfull Geomorphic Relationships and HEC-RAS Assessment in Small Catchments of the Cumberland Plateau Ecoregion

Introduction

Over the course of history, civilizations have developed proximate to streams and rivers for convenient access to stable sources of food, water, transportation, and commerce. Consequently, the pragmatic nature of humans to live near flowing water has driven people to search for methods of defining, understanding and predicting relations among hydraulic parameters of the river, such as discharge, width, depth, and velocity (Williams, 1978). Streams transport water, sediment and energy while providing habitat for aquatic and terrestrial organisms, but development has placed restrictions on how efficiently stream systems can transport water, sediment, and nutrients. Each river basin produces a range of discharges and sediment loads that are products of a number of variables interacting within a watershed, such as climate, geology, soils, vegetation, land use, topography, and valley morphology (Knighton, 1998). Due to urbanization, discharges from developing watersheds have been affected and channel geomorphology has changed as a response. According to the Tennessee 305(b) report, about 48 percent of the stream miles assessed for recreational use failed to meet the criteria assigned to that use. Approximately 40 percent of the assessed stream miles failed to meet fish and aquatic life criteria (Denton, 2014). Section 404 of the Clean Water Act determined that disturbances to our nation's water resources could not persist, and that restoration is needed to offset the impacts. Restoration has been becoming more popular in Tennessee each year. In the year 200 there was less than 10 permits approved by the Tennessee Department of Environment and Conservation, and that number has increased each subsequent year with almost 40 permits issued in 2013. The size of these restoration projects can range from less than one square mile to over 50 square miles. However, almost 75% of the restoration projects approved were for streams with watersheds less than 3 square miles. Often times the only reference to watershed size in stream restoration permits are the HUC-8 watershed. This discrepancy in scale between the HUC-8 management unit and the actual restoration size shows the need for tools to work in small catchment scales such as the streams chosen for this project.

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Materials and Methods

a. Selection and Description of Reference Streams

Fifteen reference streams were selected in the Cumberland Plateau Ecoregion of Tennessee, including three with gauging stations. Streams selected met the reference criteria previously discussed thus were assumed to be representative of channels in the ecoregion. The streams also represented a range of drainage areas, which were targeted in order to develop a robust relationship between drainage area and bankfull dimensions. The sites selected were also easily accessible by foot, easy to survey, and were not controlled by bed rock or the karst geography commonly found in the ecoregion. The majority of the sites were around the Catoosa Wildlife Management Area in Crossville, Tennessee and the Big South Fork National River Recreation Area. The watersheds were delineated using watershed tools in ArcMap and also checked using the interactive program developed by the United States Geological Survey (USGS) , Streamstats (USGS, 2008). Figure 5 below shows two of the streams selected to have reference conditions and were used in the development of the regional curves. Figures 6 through 8 show the locations of the reference sites used, as well as the maps for the delineated watersheds. Table 1 summarizes the results and lists the names of all the reference streams.

Figure 5. Otter Creek, Drainage Area of 16.9 Sq. Miles (above) and Black House Branch, Drainage Area of 2.05 Sq. Miles (below)

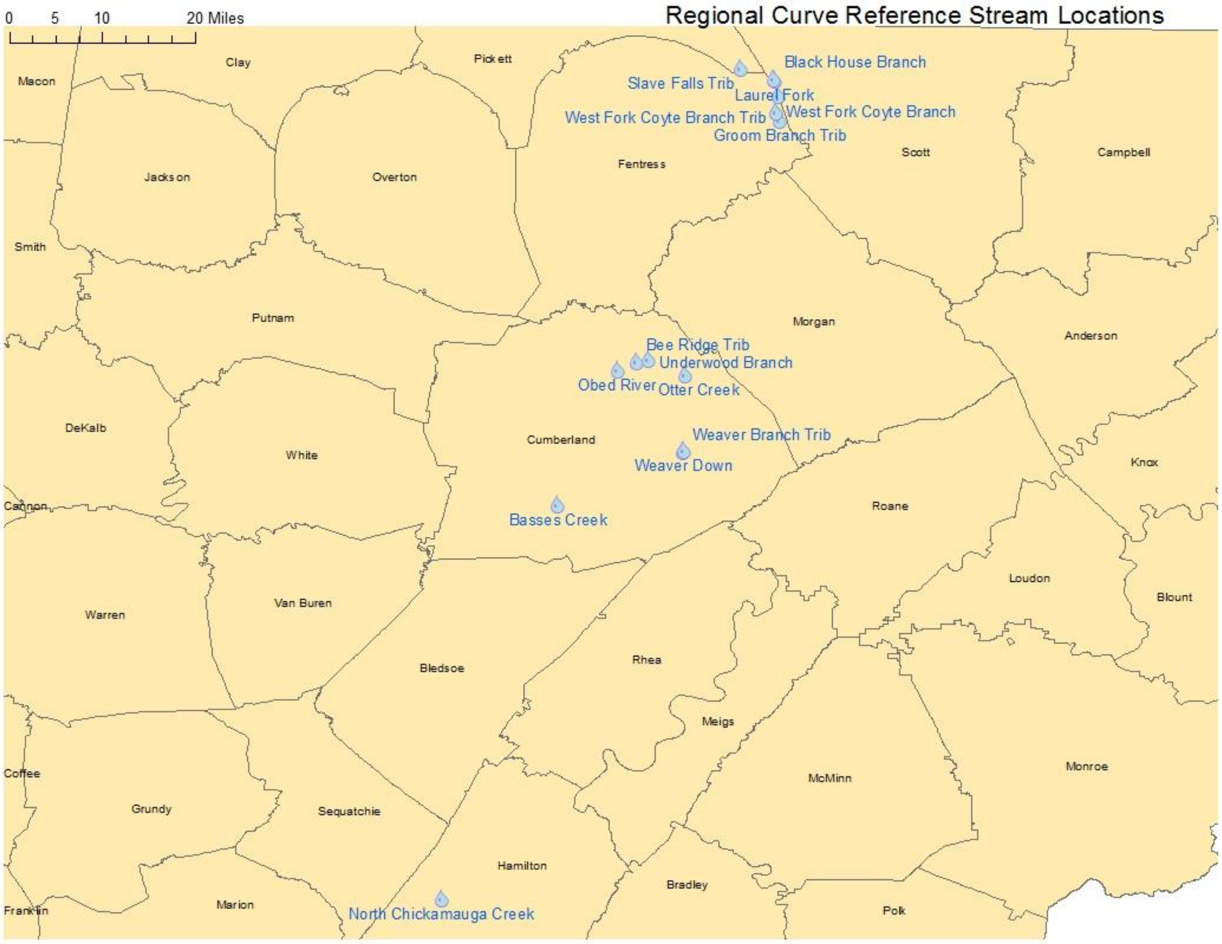

Figure 6. Reference Site Locations for Big South Fork Locations (North), Obed Area Locations (Middle), and Gauging Station (South) Used to Develop Regional Curves

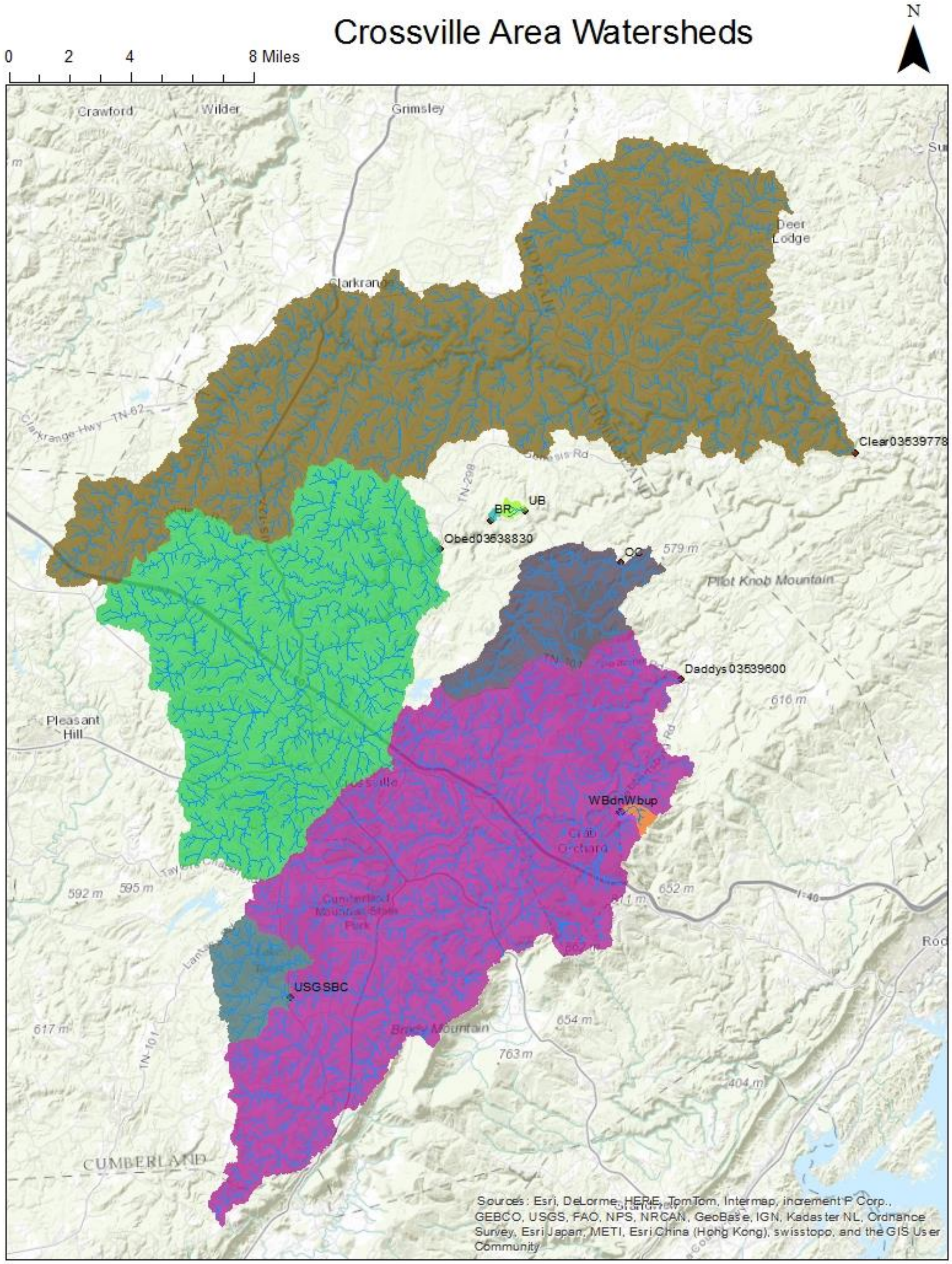

Figure 7. Delineated Watersheds for Crossville Area

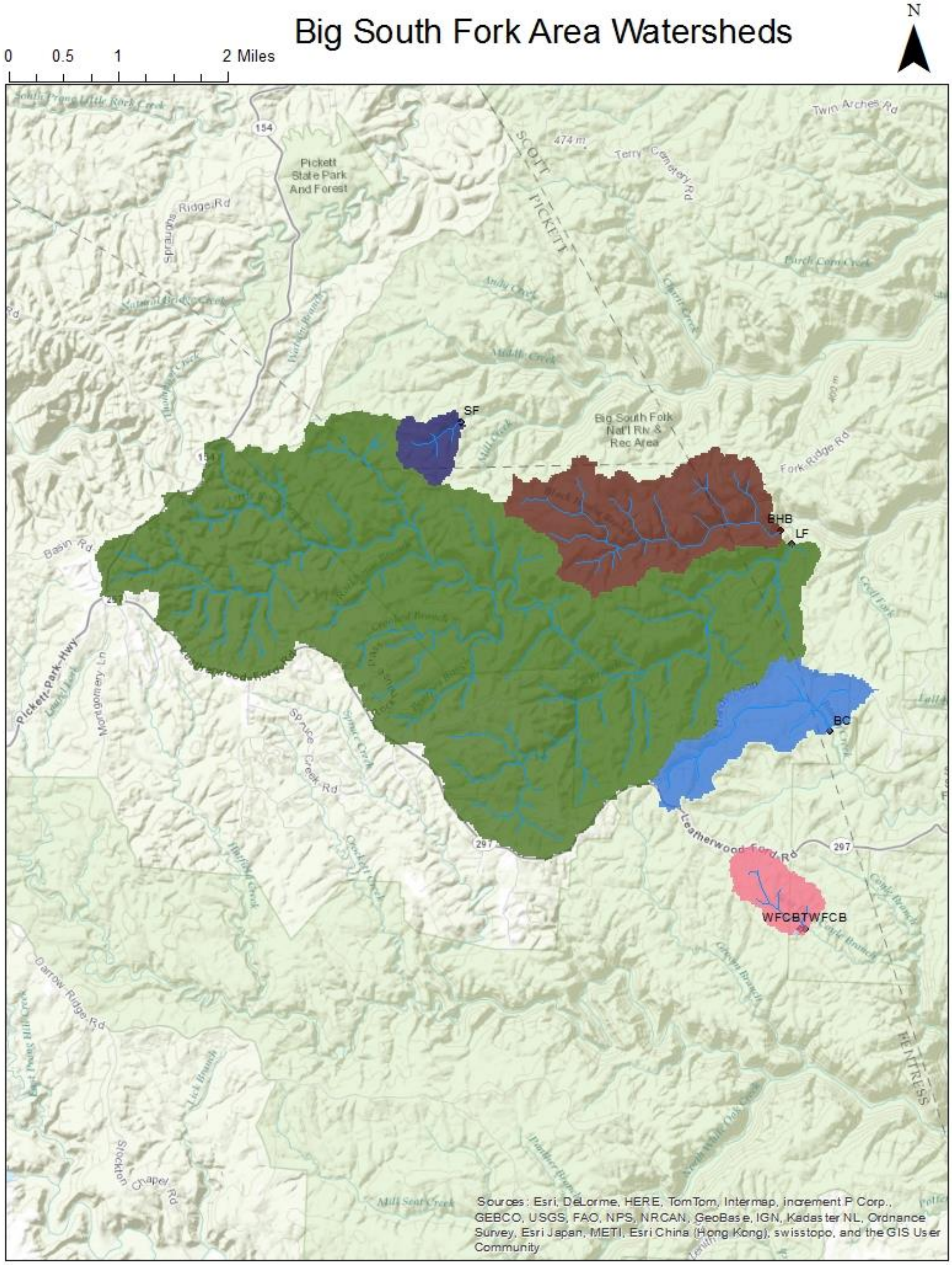

Figure 8. Delineated Watersheds for Big South Fork Area

Table 1. Reference Streams Summary

Site No.	Site Name	Latitude	Longitude	State	GIS ID	Drainage Area (mi^2)
1	Groom Branch Trib	36.449872	-84.708111	TN	GBT	0.05
2	West Fork Coyte Branch Trib	36.463306	-84.714556	TN	WFCBT	0.08
3	West Fork Coyte Branch	36.463139	-84.714583	TN	WFCB	0.43
4	Bandy Creek	36.489056	-84.710028	TN	BC	0.76
5	Laurel Fork	36.513783	-84.715431	TN	LF	12.7
6	Black House Branch	36.515389	-84.716944	TN	BHB	2.05
7	Slave Falls Trib	36.531368	-84.769519	TN	SF	0.29
8	Bee Ridge Trib	36.075083	-84.931611	TN	BR	0.11
9	Underwood Branch	36.079056	-84.911972	TN	UB	0.34
10	Otter Creek	36.053528	-84.856222	TN	OC	16.9
11	Obed River	36.061667	-84.961389	TN	Obed03538830	91.8
12	North Chickamauga Creek	35.238333	-85.235556	TN	USGSCC03566525	60.6
13	Basses Creek	35.850833	-85.054722	TN	na	8.07
14	Weaver Branch Trib	35.934432	-84.859921	TN	WBup	0.09
15	Weaver Down	35.936126	-84.857636	TN	WBdn	0.51

b. Topographic Surveying

The method of data collection for developing the regional curves followed the level II protocol commonly used in designing bankfull geomorphic relationships (Rosgen and Silvey, 1996). Level II protocol gathers quantitative information regarding stream channel morphological description and enables the designer to classify a stream based on those measurements. The level II criteria describe stream channel width, mean depth, cross-sectional area, longitudinal profile, and dominant material measured in the field. The geomorphic measurements were surveyed at bankfull for each site. Bankfull was determined in the field by a combination of field observations such as a change in sediment or benches, and validated with the cross-section plots. The survey was done using a Nikon DTM-322 and a TDS Nomad handheld (Figures 9 and 10). Cross sectional surveying was completed at locations on the stream that represented slope-forming features, such as riffles. The topographic survey data was then analyzed and graphed using power curves to illustrate the existing stream channel and level II criteria. The regional curves will then be the product of regression analysis performed on the relationships of the level II criteria to drainage area. A summary table for the survey data collected at each site can be found in appendix d.

Stream Substrate Size was determined using a modified Wolman's Pebble count (Wolman, 1954). Wolman's pebble count procedure recommends 100 samples but for this study only 50 randomly selected pebble measurements were collected along riffle and pool transects to represent the entire reach. Some sites had large substrate so a visual estimate of D_{50} was measured. The b-axis was measured using a ruler and the particle size class was recorded in the field. After data was collected, it was plotted by size class (log scale) and frequency to determine distributions. The modified Wolman's pebble count particle distribution charts and histograms can be found in appendix b.

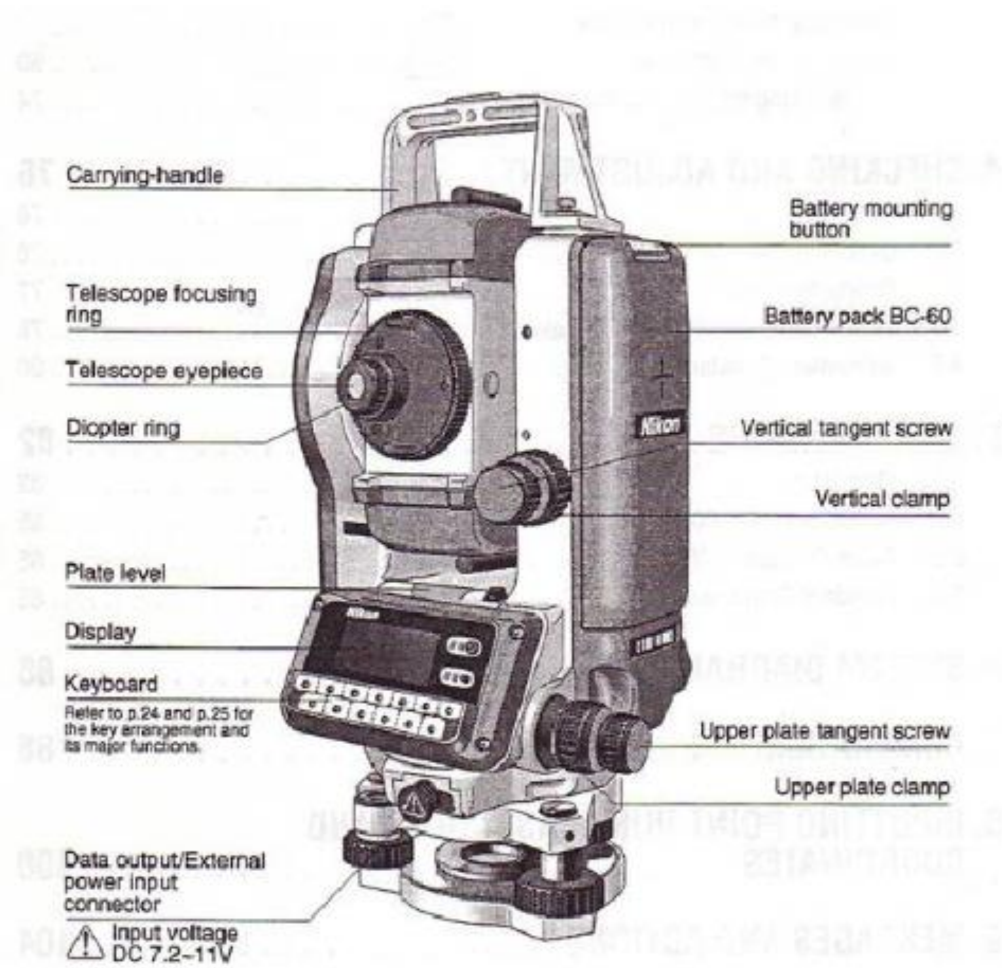

Figure 9. Nikon DTM-322 Total Station (landsurveyorsunited.com)

Figure 10. Handheld Trimble Using Survey Pro

c. Regional Curve Comparison

The resulting regional curves were analyzed using JMP. Since power equations for regional curve relationships are often developed in excel, the resulting equations use transformed data. The first analysis was to compare how well the developed power curve could predict the bankfull geomorphic relationships in the 95% confidence interval of the untransformed data. The next analysis was to compare the regional curves of the Tennessee section of the Cumberland Plateau to the Alabama curves of the Cumberland Plateau. Lastly, the Cumberland Plateau curves were compared to the curves from the North Carolina Piedmont Ecoregion and the Western Ridge and Valley Ecoregion of Tennessee. A test for significance was done to analyze the difference for mean, slope, and intercept at each bankfull geomorphic relationship. The 95% confidence interval was used for each analysis to account for environmental data.

d. HEC-RAS Modeling

HEC-RAS, (Hydraulic Engineering Center – River Analysis System) version 4.1 was used to model selected sites that were dominated by gravel substrate, easily accessible, and met the reference reach criteria to be used with the regional curves as well. HEC-RAS is a one-dimensional computer program that models the flow of water through channels, meaning that there is no direct modeling of the hydraulic effect of cross section shape changes, bends, and other two- and three-dimensional aspects of flow. Input data for the model include the topographic survey data, discharge rate (bankfull for this study), and Manning's roughness factor (*n*). Bankfull discharge was calculated using the Manning's equation (Equation 1), using channel dimensions associated with field indicators of bankfull. The calculated discharge was then compared to the 2-year flow events determined with the StreamStats program because the bankfull, or channel forming discharge, is found to have a return period of 1.15 to 1.40 years on the annual series (Pickup and Warner, 1976). Therefore the calculated discharge is expected to be lower than the StreamStats output, but since StreamStats can have errors 30 to 50% multiple models were used with different discharges.

The Manning's Equation is calculated as follows:

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

Where:
Q = Flow Rate, (ft^3 s^{-1})
v = Velocity, (ft s^{-1})
A = Flow Area, (ft^2)
n = Manning's Roughness Coefficient
R = Hydraulic Radius, (ft)
S = Channel Slope, (ft ft^{-1})

Manning's n was selected for specific channel and floodplain conditions using field pictures at each cross section and using accepted Manning's *n* values for channels (Tables 2 and 3) from Chow (1959). For the models initial boundary condition, normal depth was used. Since all inputs such as Manning's n, survey data, and discharge are used at bankfull the bankfull depth was used as normal depth for each site.

A variety of flowrates and inputs were used for the HEC-RAS analysis. There were three analysis for Weaver Down and two analysis for Weaver Trib. Low, middle, and high represent the range of characteristics input for the model. The low test used the minimum Manning's n value for the stream and floodplain. The low test also used the lowest flowrate, either calculated from StreamStats or Manning's method. The middle test used the middle Manning's n values and the middle flowrate. And since Weaver Down was large enough to have a period of record, the high test done for that site included the max flowrate from StreamStats. Since there are a variety of ways to calculate Manning's n and flowrate, the multiple tests were done to show a range of results based on the characteristics used.

Table 2. Manning's n for Main Channels (Chow, 1959)

Main Channels	Minimum	Normal	Maximum
clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
same as above, but more stones and weeds	0.030	0.035	0.040
clean, winding, some pools and shoals	0.033	0.040	0.045
same as above, but some weeds and stones	0.035	0.045	0.050
same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
same as "d" with more stones	0.045	0.050	0.060
sluggish reaches, weedy, deep pools	0.050	0.070	0.080
very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150

Table 3. Manning's n for Floodplains(Chow, 1959)

Floodplains	Minimum	Normal	Maximum
Pasture, no brush			
1.short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160
Trees			
1. dense willows, summer, straight	0.110	0.150	0.200
2. cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. same as 4. with flood stage reaching branches	0.100	0.120	0.160

The HEC-RAS output of energy slope was used to obtain a predicted D_{50} using the shear stress equation (equation 2) to determine the shear stress acting on the stream bed.

The shear stress is calculated as follows:

$$\tau = \gamma DS \qquad (2)$$

Where:
τ = shear stress, (lb ft^{-2})
γ = specific weight of water, (lb ft^{-3})
D = bankfull depth, (ft)
S = energy slope from HEC-RAS, (ft ft^{-1})

The specific weight of water at 32° Fahrenheit was used and the mean depth used was the average bankfull depth of the reach on each cross section. Once shear stress was calculated, the modified Shield's diagram and critical shear stress equation (equation 3) was used to predict a D_{50}.

The unitless shear stress for the modified Shield's Diagram is calculated as follows:

$$\tau_{*c} = \frac{\tau_c}{(\gamma_s - \gamma)d_{50}} \qquad (3)$$

Where:
τ_{*c} = unitless critical shear for Julien's modified Shield's diagram
τ_c = shear stress calculated from equation 2, (lb ft^{-2})
$(\gamma_s - \gamma)$ = difference in specific weight of sediment and water, (lb ft^{-3})
d_{50} = mean substrate size, (ft)

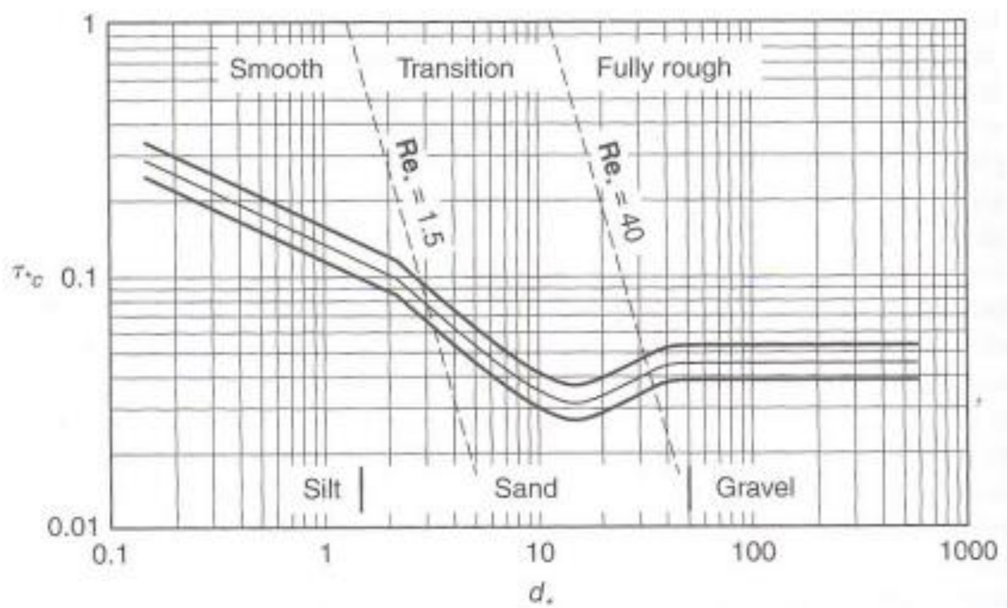

Figure 11. Modified Shield's Diagram After Julien (1994)

The Modified Shield's Diagram was used with two assumptions. The first assumption is that the site has a gravel bed. The Wolman's pebble count was used to confirm that the dominant substrate size was indeed gravel. This assumption is also checked using equation 4 below for the unitless particle size d_* which is the x-axis on the Shield's diagram. In a gravel bed, τ_{*c} will always be 0.045. The other assumption is that the shear stress calculated in equation 2 is critical shear stress. The critical shear stress is the shear stress required to mobilize the sediments delivered to the channel. Using this assumption will mean that our resulting D_{50} will be the substrate that is mobile at bankfull flow.

The unitless particle size for the modified Shield's Diagram is calculated as follows:

$$d_* = \left(\frac{Rgd_{50}{}^3}{v^2}\right)^{\frac{1}{3}} \qquad (4)$$

Where:
d_* = unitless particle size for Julien's modified Shield's diagram
R = constant for US units, 1.65
d_{50}= mean substrate diameter, (ft)
v = viscosity, ($ft^2\ s^{-1}$)

Results and Discussion

Data gathered at each site yielded cross section plots, grain size distributions, and result summaries for each site. Details of each of these are included in Appendices a, b, and d respectively.

a. Regional Curves

The first objective of this study was achieved by developing bankfull and hydraulic geometry relationships for small catchments (drainage area less than 20 mi^2) in the Cumberland Plateau Ecoregion of Tennessee. The resulting power curves are shown in figures 12 through 14. Since the power relationships developed use transformed data, the 95% confidence interval for the non-transformed data is plotted as well. The power relationship for bankfull cross-section area and depth fall almost completely within the 95% confidence interval. However, the bankfull cross-section width is not within the confidence area between drainage areas of one to 10 square miles. It should be considered that using the power model from transformed data for a design bankfull depth in the Tennessee Cumberland Plateau Ecoregion may not be as accurate within that range. Using a regional curve model from non-transformed data or developing a model using streams of a matching order as the design stream may be alternative methods. Figures 15 through 17 include regional curves associated with the Tennessee Plateau and the neighboring ecoregions of the Alabama Plateau (unpublished data from on-going federally-funded project), Western Ridge and Valley of Tennessee (McPherson, 2011), and the Piedmont Ecoregion of North Carolina (Doll et al., 2002b). Table 4 below is a summary table for the Cumberland Plateau Ecoregion of Tennessee regional curves.

Table 4. Cumberland Plateau Ecoregion Regional Curves Summary Where the Geomorphic Dimension is a Function of Drainage Area (x)

Dimension	Power Curve	R Squared
Area	$y = 20.88x^{0.7098}$	0.98
Depth	$y = 1.3305x^{0.3469}$	0.90
Width	$y = 15.708x^{0.3627}$	0.96

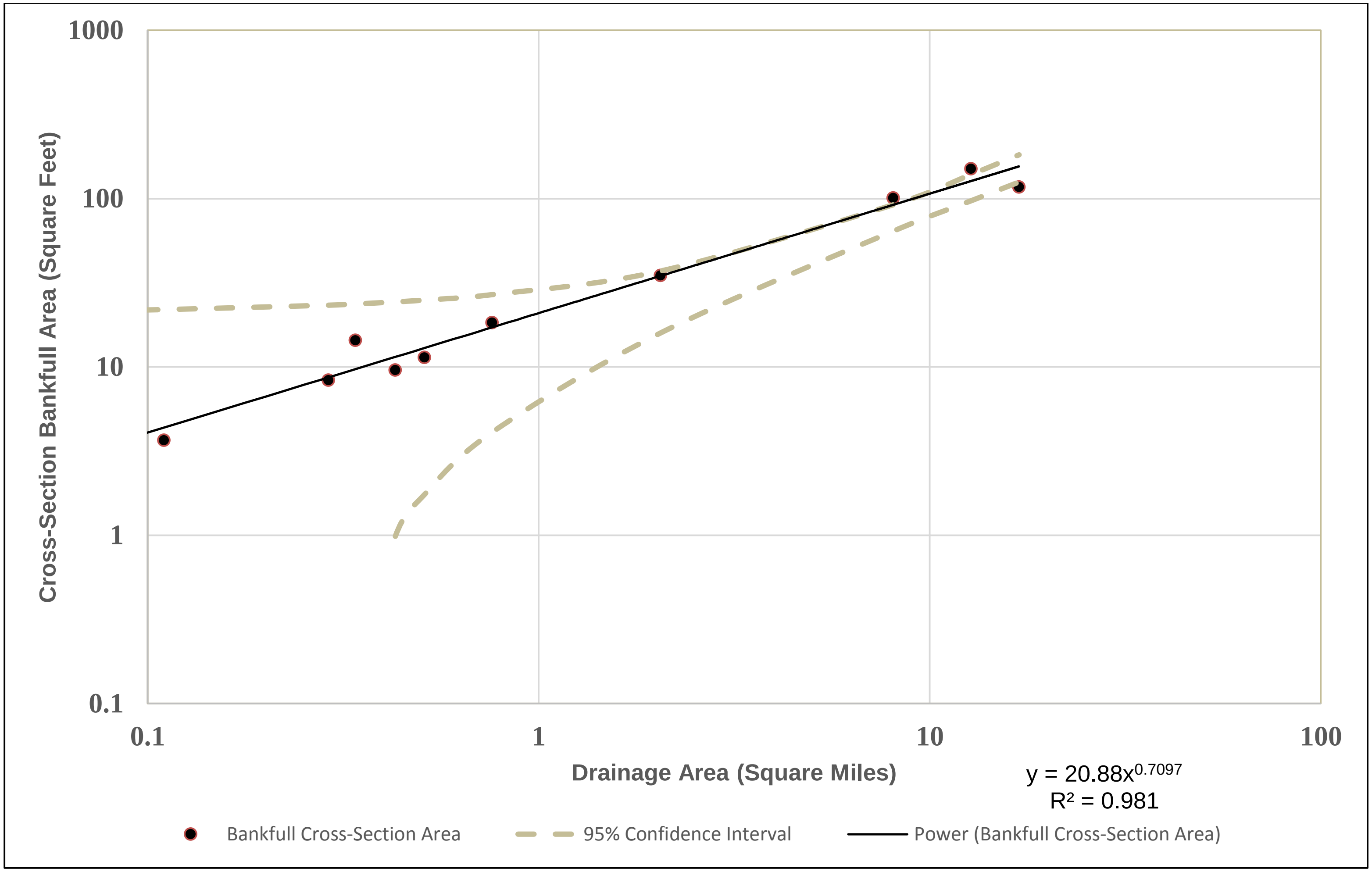

Figure 12. Cumberland Plateau Ecoregion of Tennessee Cross-Section Area Regional Curve and 95% Confidence Interval

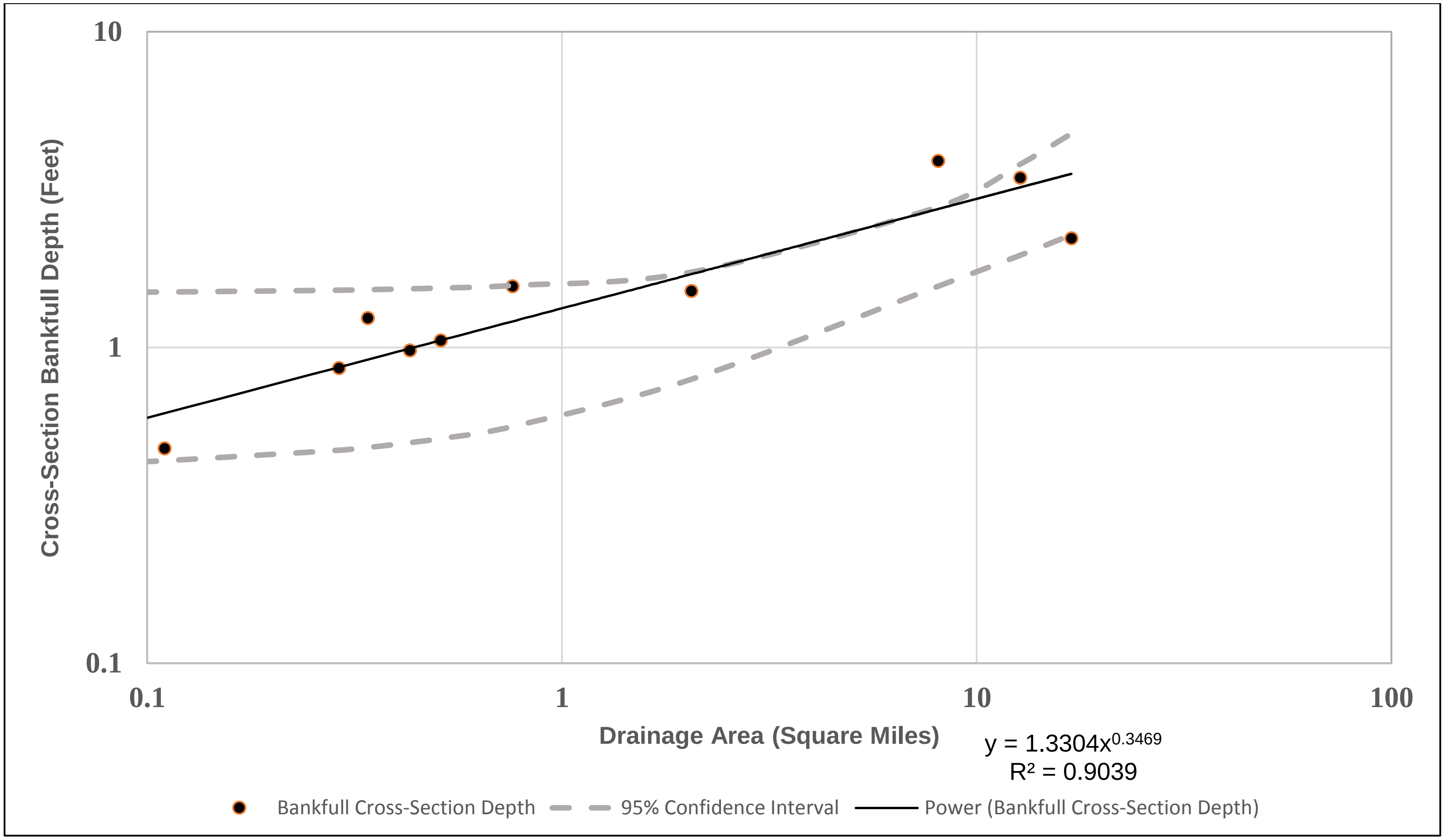

Figure 13. Cumberland Plateau Ecoregion of Tennessee Cross-Section Depth Regional Curve and 95% Confidence Interval

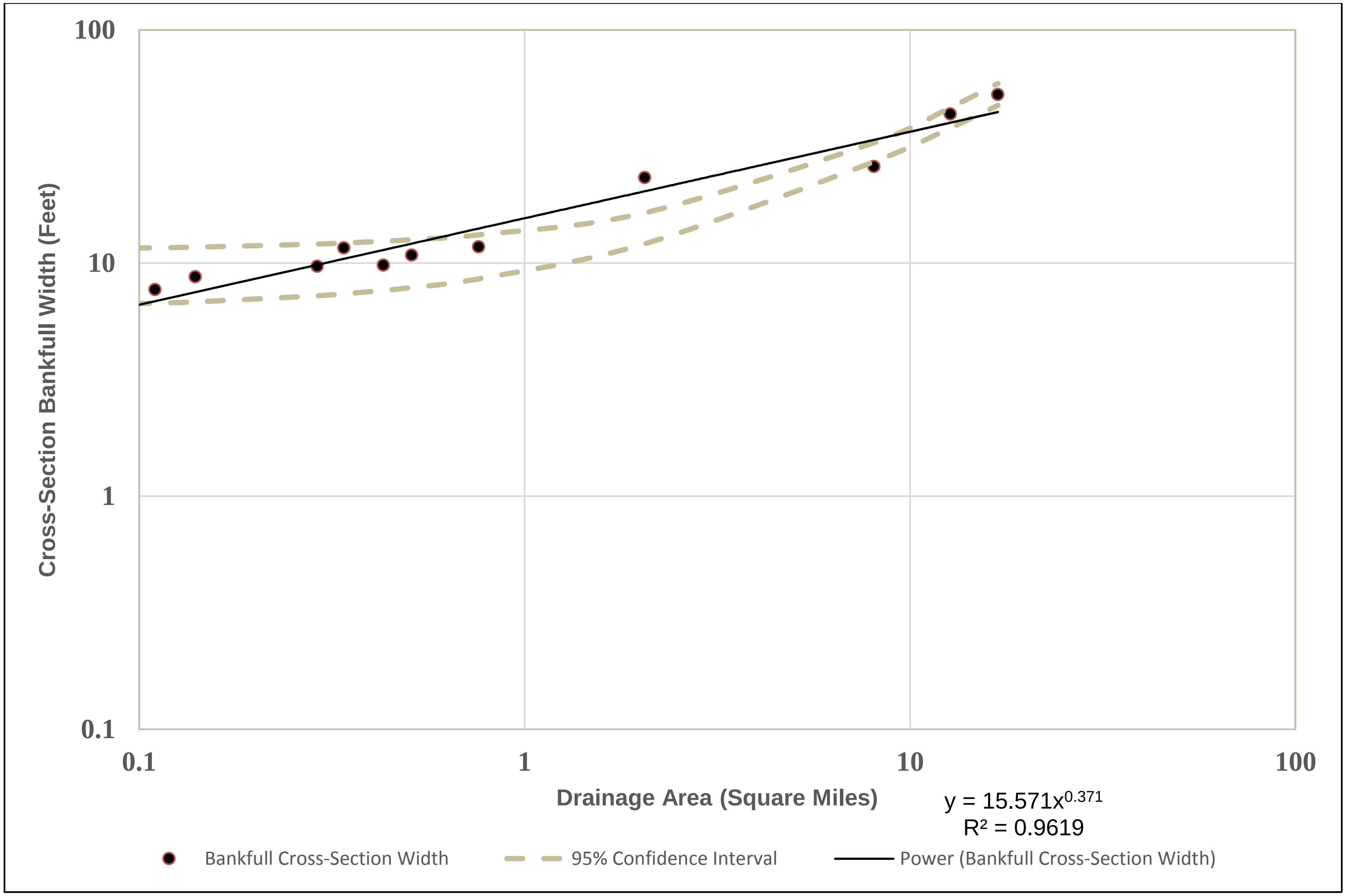

Figure 14. Cumberland Plateau Ecoregion of Tennessee Cross-Section Width Regional Curve and 95% Confidence Interval

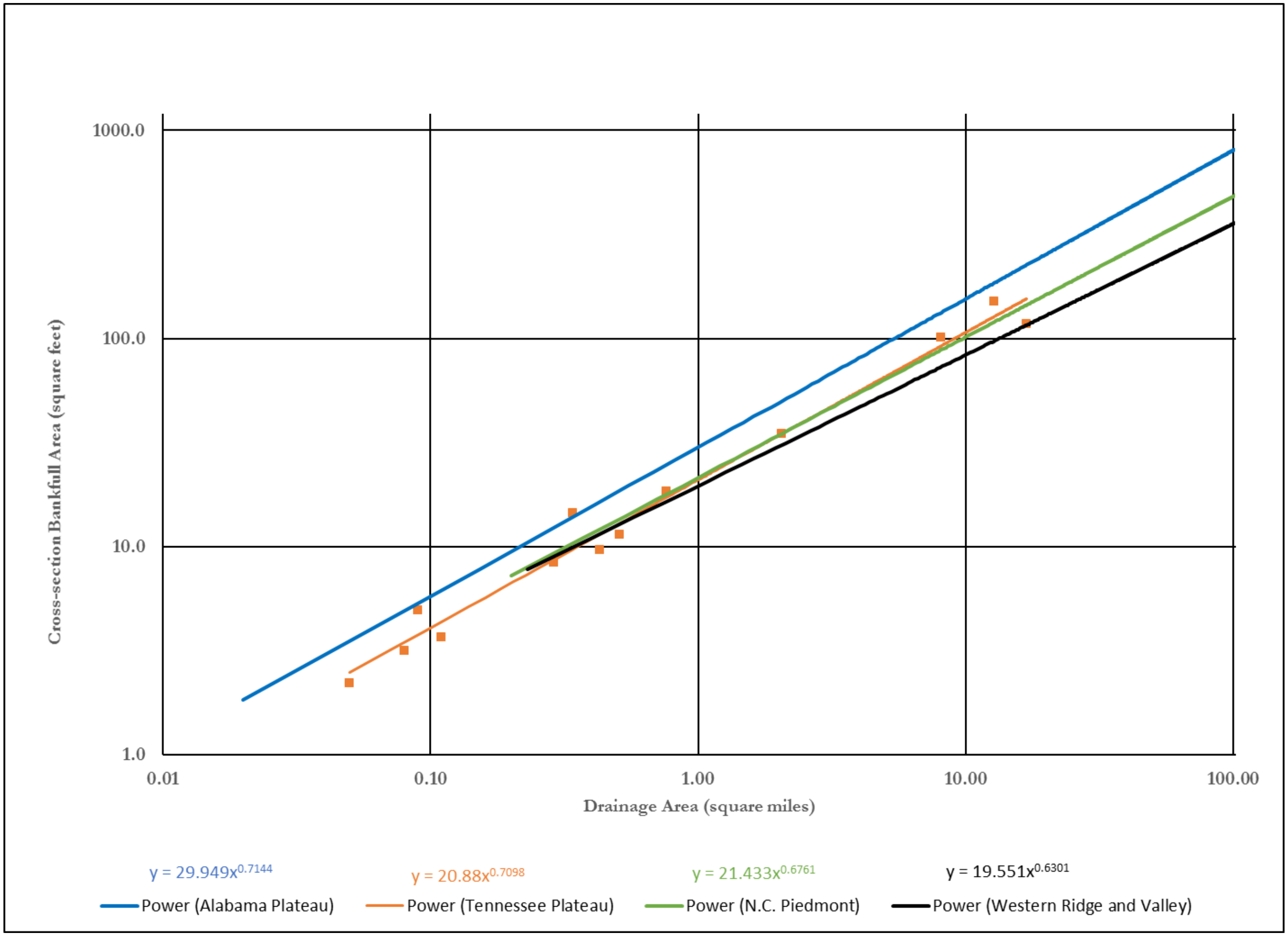

Figure 15. Bankfull Channel Cross-sectional Area Regional Curves for Tennessee Plateau and Neighboring Ecoregions.

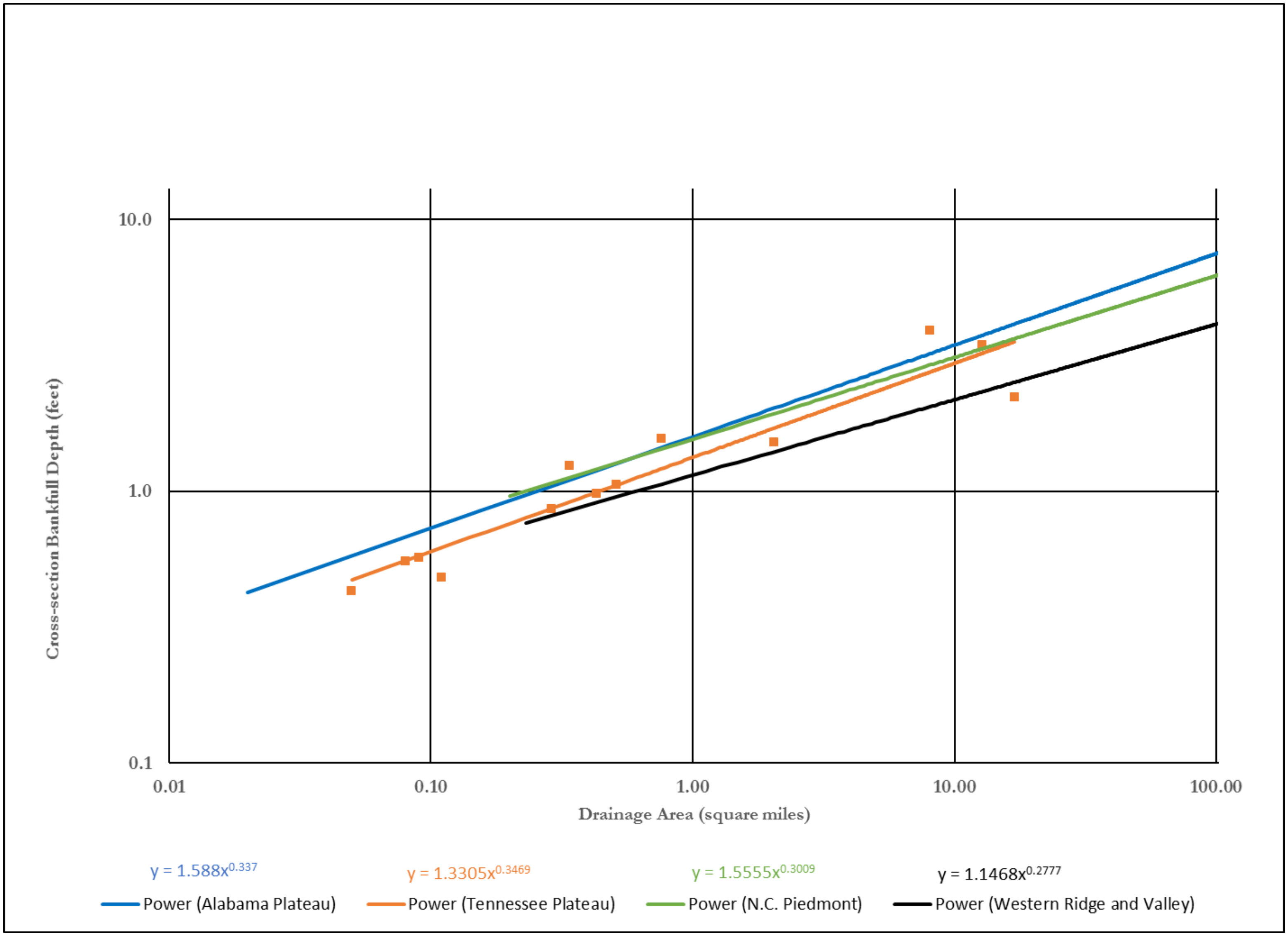

Figure 16. Bankfull Channel Depth Regional Curves for Tennessee Plateau and Neighboring Ecoregions.

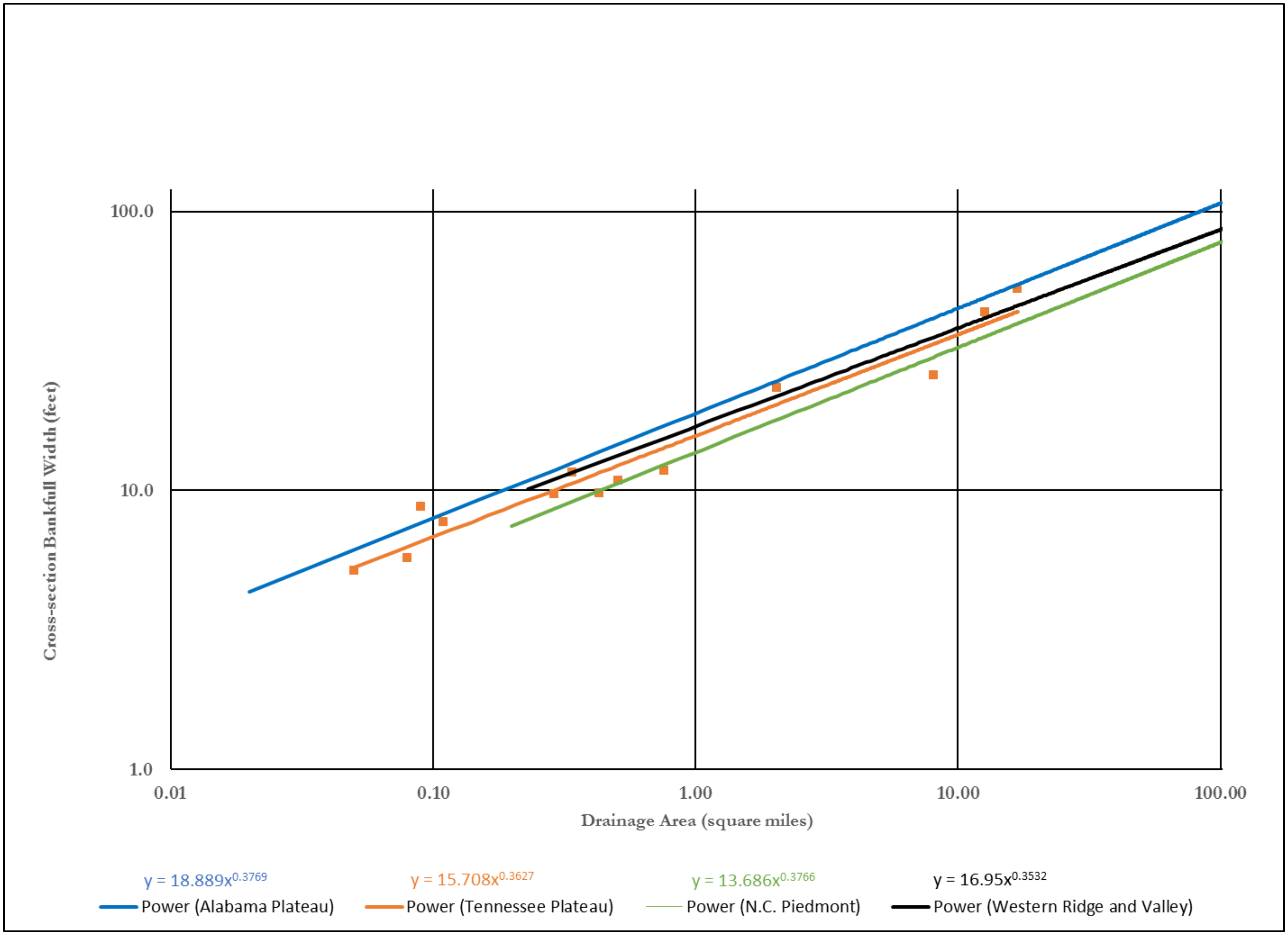

Figure 17. Bankfull Channel Width Regional Curves for Tennessee Plateau and Neighboring Ecoregions.

b. Regional Curve Comparison

The second objective of this study was to compare the regional curves of the Tennessee Cumberland Plateau Ecoregion to that of neighboring ecoregions. The resulting regional curves above show a difference in each ecoregion, which could be a result of many factors. Previous studies have determined that there is no significant difference in regional curves between neighboring ecoregions. McPherson (2011) stated that his sites, the Western Ridge and Valley, showed no statistical difference at the 0.05 significance level compared to neighboring ecoregions used for comparison. A 2008 a study on a statistical comparison for physiographic provinces in the Eastern US concluded that regional equations and their associated data showed that the majority of the equations are similar within their respective physiographic provinces (Johnson and Fecko, 2008). However, the study used a majority of drainage areas far above the size commonly used in natural channel design with some drainage areas exceeding 1000 square miles. For this study, JMP (JMP, 1989-2007) was used to compare the regional curves developed from the data collected within the Tennessee Cumberland Plateau Ecoregion to that of data collected in the same manner in the Alabama Cumberland Plateau Ecoregion (unpublished data accessed as part of the larger study). Additionally, the Cumberland Plateau Ecoregion as a whole was compared to neighboring ecoregions of Western Ridge and Valley and the North Carolina Piedmont. Analysis of covariance is often used to evaluate whether the population means of a dependent variable (bankfull dimensions) are equal across levels of a categorical independent variable (ecoregion). However, this analysis assumes that the compared regressions have equal slopes, since the regional curves do not meet that assumption and drainage area also needs to be accounted for an indicator-variable regressions was used. Indicator variable regression allowed to test the bankfull relationships for statistical differences in mean, slope, and intercept. For each study the null hypothesis is that for each variable (mean, slope, intercept) there is no statistical difference for the bankfull relationships between ecoregions. All analysis were completed at the 95% confidence level to account for natural variability in environmental data. The first analysis was the regional curves for Tennessee Cumberland Plateau compared to the curves for the Alabama Cumberland Plateau and the results are shown in table 5.

Table 5. Indicator Variable Regression for Tennessee and Alabama Cumberland Plateau Ecoregion, P-Value 0.05

Cumberland Plateau Ecoregion Statistical Analysis (Tennessee and Alabama)						
Bankfull Dimension	**Slope**	**Slope t**	**Mean**	**Mean t**	**Intercept**	**Intercept t**
Cross-Section Area	Reject	0.0002	Accept	0.1050	Accept	0.7642
Cross-Section Depth	Accept	0.1471	Accept	0.7233	Accept	0.3492
Cross-Section Width	Accept	0.1613	Accept	0.8457	Accept	0.6651

The Tennessee data set was compared to the Alabama data set to evaluate whether there existed a difference in the relationship between geomorphic channel dimensions and drainage area. The null hypothesis was rejected in the analysis of cross-section area, showing that there is a significant difference in the rate of change in cross-section area with respect to increasing drainage area between the two areas within the ecoregion (alpha = 0.05). For all other variables, the hypothesis regarding effects of area within the ecoregion was not rejected (or accepted), therefore there was no evidence that the variables are significantly different. The results for the same analysis combining the Cumberland Plateau Ecoregion and comparing to the neighboring ecoregions is in table 6.

Table 6. Indicator Variable Regression for Cumberland Plateau Ecoregion and Neighboring Ecoregions

Ecoregion Statistical Analysis (Cumberland Plateau, Western Ridge and Valley, and N.C. Piedmont)						
Bankfull Dimension	**Slope**	**Slope t**	**Mean**	**Mean t**	**Intercept**	**Intercept t**
Cross-Section Area	Reject	<0.0001	Accept	0.0985	Reject	0.0169
Cross-Section Depth	Reject	<0.0001	Reject	0.0158	Reject	<0.0001
Cross-Section Width	Reject	<0.0001	Reject	0.0028	Reject	<0.0001

In the comparison between the Cumberland Plateau Ecoregion, Western Ridge and Valley of Tennessee Ecoregion, and North Carolina Piedmont Ecoregion the null hypothesis was rejected for every variable and every bankfull dimension besides the means of cross-section area. Rejecting the null at a p value of 0.05 shows that there is a significant difference between cross-section depth, area, and width for each variable besides the mean previously mentioned. The statistical differences between ecoregions is greater than the statistical differences between the Alabama and Tennessee sections of the Cumberland Plateau which agrees with some previous studies that the equations are more similar within the physiographic provinces.

These findings show that a portion of regional curves are statistically different from regional curves in neighboring ecoregions. In Figure 17, for example, at one square mile the cross sectional width could range from 14 to 19 feet depending on which curve is used. Variability within the bankfull hydraulic geometry relationships may be attributed to differences in regional land uses, and presumably water surface gradients, quantity of instream debris and bank vegetation, and underlying geology that affects water storage capacity within a given watershed (Sweet and Geratz, 2003). The geology of the Cumberland Plateau Ecoregion is distinctly different from the coastal plain sands and alluvial deposits to the west, and elevations are lower than the Appalachian ecoregions to the east. Mississippian to Ordovician-age limestone, chert, sandstone, siltstone and shale compose the landforms of open hills, irregular plains, and tablelands. The natural vegetation is primarily oak-hickory forest, with some areas of bluestem prairie and cedar glades (Griffith et al., 1997a). The Western Ridge and Valley Ecoregion has relatively low-lying, but diverse ecoregion is sandwiched between generally higher, more rugged mountainous regions with greater forest cover. As a result of extreme folding and faulting events, the region is characterized by roughly parallel ridges and valleys having a variety of widths, heights, and geologic materials, including limestone, dolomite, shale, siltstone, sandstone, chert, mudstone, and marble. Springs and caves are relatively numerous. Present-day forests cover about 50% of the region (Griffith et al., 1997a).

There are many differences between these ecoregions, such as: elevation, vegetation, geology, and land type, and both ecoregions are in the same state. Another factor influencing the regional curves may be precipitation. Figure 18 below shows the total precipitation that was predicted for 2014. A change in annual precipitation aligns with the ecoregion boundary between Ridge and Valley, Cumberland Plateau, and North Carolina Piedmont, which likely causes a change in runoff and recharge sources, and as a result, in bankfull channel dimensions.

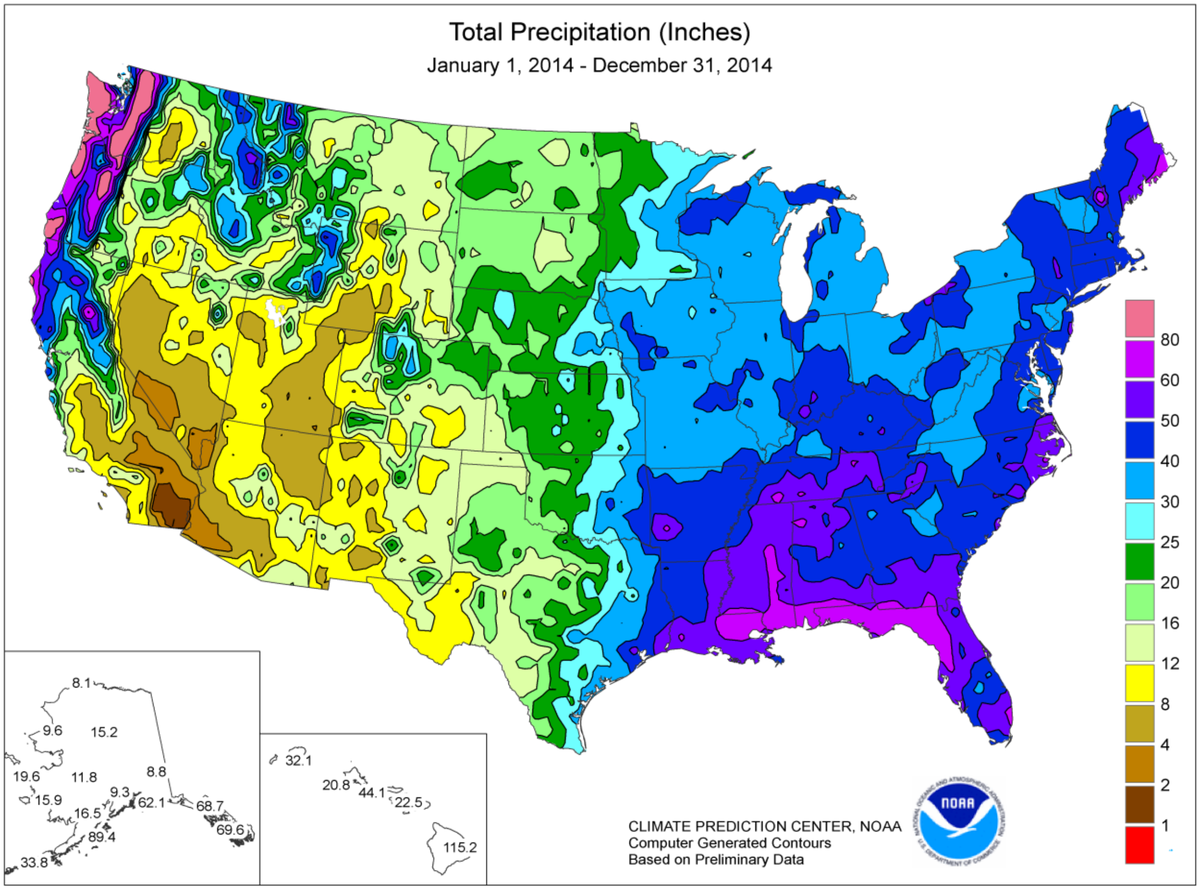

Figure 18. NOAA Prediction for 2014 Total Precipitation (http://www.wpc.ncep.noaa.gov/)

c. HEC-RAS Results

Channel hydraulics were modeled at two sites using HEC-RAS. Both sites were located within the Weaver Branch catchment, one site downstream (weaver down) and the other site an upstream tributary (weaver trib). Both sites are gravel bed systems with drainage areas of less than one square mile (0.51 mi^2 and 0.09 mi^2 respectively). The summary tables and results are shown below in tables 7 and 8 respectively. (Note that the D_{50} in the table are changed to mm, as commonly used in practice).

Table 7. HEC-RAS Results Summary Weaver Down

Inputs	Slope (ft ft^{-1})	Shear Stress (lb ft^{-2})	Predicted D_{50} (mm)	Measured D_{50} (mm)	Measured D_{84} (mm)
Low	0.0092	0.5543	36.47	7.43	13.64
Middle	0.0101	0.6034	39.69		
High	0.0107	0.6443	42.39		

Table 8. HEC-RAS Results Summary Weaver Trib

Inputs	Slope (ft ft^{-1})	Shear Stress (lb ft^{-2})	Predicted D_{50} (mm)	Measured D_{50} (mm)	Measured D_{84} (mm)
Low	0.0133	0.8001	52.64	6.21	13.39
Middle	0.0187	1.1215	73.78		

Comparing the D_{50} calculated from HEC-RAS and using the modified Shield's diagram based on the predicted shear stress to that of the grain size distribution created from field measurements shows that the predicted D_{50} size is larger than the measured values found in the field at both sites. Since the assumption that the shear stress calculated is the critical shear stress, which is the magnitude of shear stress required to move the particle, and the model predicted such a larger D_{50} value means the predicted D_{50} is mobile. There are many explanations for such a large difference between predicted and field measurements. One reason could be the way the Shield's Diagram was developed. The Shield's Diagram was obtained from experiments conducted in a narrow set of flume conditions and often fail to produce accurate incipient motion results in natural streams (Marcus et al., 1992). The fact that flume conditions are not the same as reference stream conditions such as the ones used in this project could cause a difference. One common problem with flume studies is scaling issues. A change in physical scale does not create an equal change in dynamic and kinematic scales. A flume experiment can scale the substrate to whatever is needed but the Reynolds number (turbulent versus laminar flow) and Froude number (supercritical flow vs subcritical flow) will not scale (Tinkler and Wohl, 1998). Also with flumes, problems with poorly sorted gravel, recycled sediment, and using planar beds instead of riffled beds similar to those in reference streams could cause differences. There is most likely less energy loss in a flume and less variables that are hard to account for in the natural streams. Using the Shield's curve for the computation of the particle size at bankfull flow is a common practice. However, by definition of the Shield's value, solving the Shield's equation for a critical particle size and using bankfull flow is based on the inherent assumption that bankfull flow entrains the bed D_{50} size. As a consequence, the Shield's curve τ^*c is only valid in streams that transport their bed surface d_{50} size at bankfull flow (Marcus et al., 1992). D_{84} is considered to be the largest particle size that could be moved by the channel. Since the HEC-RAS calculated D_{50} substrate size greater than both the D_{50} and D_{84} measured in the field, alternative methods from those used in this study should be considered for stream design.

Conclusions and Future Work

Regional curves and the Shield's Diagram are two commonly used tools for natural channel design and other restoration techniques. More projects are relying on regional curves and eventually curves should be developed for every ecoregion. Using popular methods for developing bankfull geomorphic relationships, regional curves were developed in the Tennessee Cumberland Plateau Ecoregion of Tennessee for bankfull cross-section area, width, and depth. Since popular methods use power relationships, the model is developed from transformed data. The power relationships were validated using the 95% confidence interval from untransformed data and the results determined that using the regional curve for bankfull cross-section width could predict incorrectly. Engineers and practitioners should consider the possibility of error when using regional curves. While developing and comparing the regional curves, clumping of sites was noticed. The sites that were more similar and closer together could be an effect of stream order. Futures studies could further specialize regional curves by developing relationships for a specific stream order to use for specific stream order designs.

Using independent variable analysis, the regional curves for the Tennessee Cumberland Plateau Ecoregion were compared to the regional curves for the Alabama Cumberland Plateau Ecoregion to test for significant difference in the slopes, mean, and intercept for each bankfull relationship. The two ecoregions in the same physiographic region were not significantly different for any test besides the slope for bankfull cross-section area. The same analysis was done comparing the Cumberland Plateau Ecoregion to the neighboring ecoregions of the Western Ridge and Valley in Tennessee and the North Carolina Piedmont area. The three different ecoregions were significantly different at the 95% confidence level for every test besides mean bankfull cross-section area. The independent variable analysis was a unique approach to show that regional curves in the same physiographic region are more similar statistically than regional curves in different ecoregion. There is a need to better understand the driving environmental factors that control channel morphology and how those factors would be expected to change across ecoregions. Many studies compare regional curves but do not discuss in detail the differences in geomorphic relationships. In future studies in the topic area, there should be more emphasis placed on why these geomorphic relationships vary, whether its slope, elevation, or even precipitation, and it may be easier to create curves for each ecoregion and minimize field surveying efforts.

Using the modified Shields diagram along with HEC-RAS, a designed D_{50} was compared to a field measured D_{50} at two sites and was predicted to be five to 10 times greater than the measured D_{50}. Many design projects use the Shield’s Diagram to determine a D_{50} for their designed reach. If these projects use regional curves to develop their bankfull dimensions, then using the same techniques used in this research may result in an over prediction of the actual D_{50} value. This could result in stream failure and a loss of economic resources as a result. The streams failure may be caused by aggradation or the entire food chain of a stream system being compromised because macroinvertebrates often use detritus of a specific particle size for food (Culp et al., 1983). The Shield’s Diagram relies on the assumption that the mean substrate size is mobile and there have been studies to develop and compare different Shield’s curves (Marcus et al., 1992). Possibly doing a similar study using different empirical thresholds similar to the Shield’s diagram would have results more similar to the field measured D_{50}. There is also a gap in the science and practice that future studies should be done to possibly develop a regional curve for D_{50}. Since most studies that develop the bankfull geomorphic relationships measure the particle size distribution, there could be a relationship between drainage area and D_{50} or D_{84} that would be useful for natural channel design.

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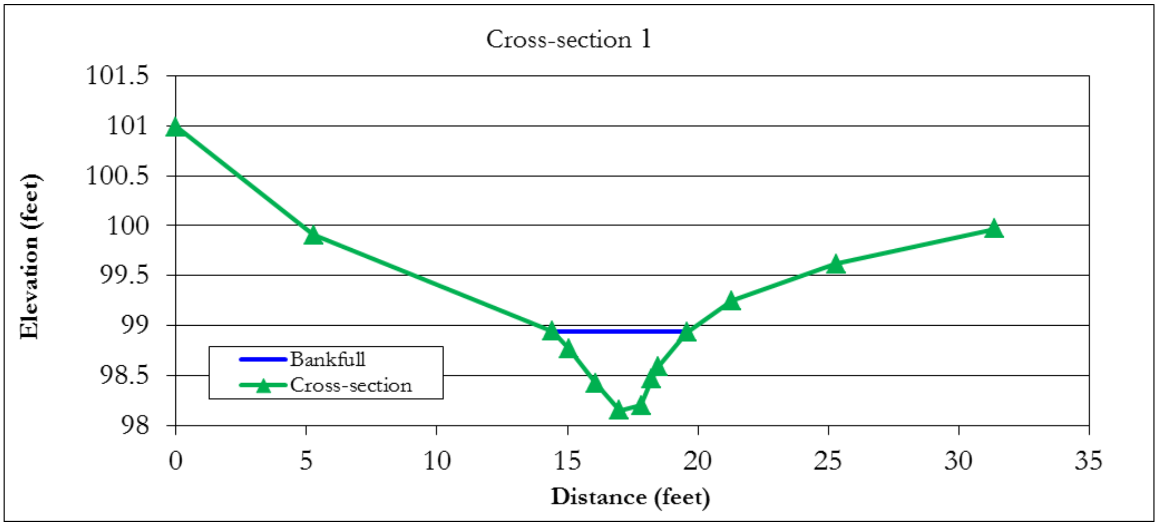
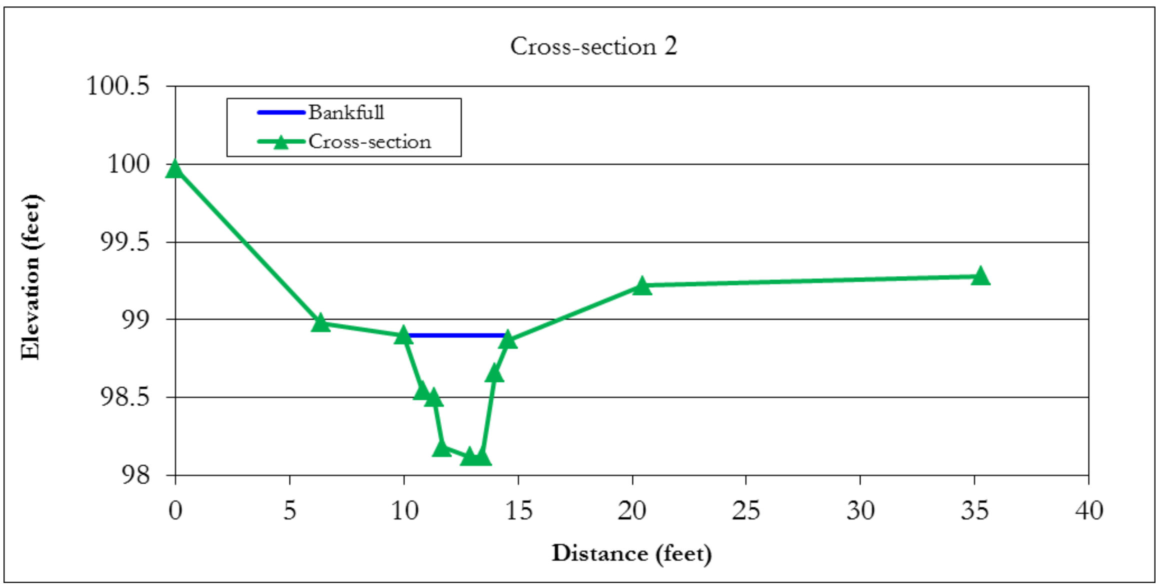
Appendices

a. Cross-Sections and Longitudinal Profiles

Figure 19. Site 1 – Groom Trib Cross Sections 1 - 3





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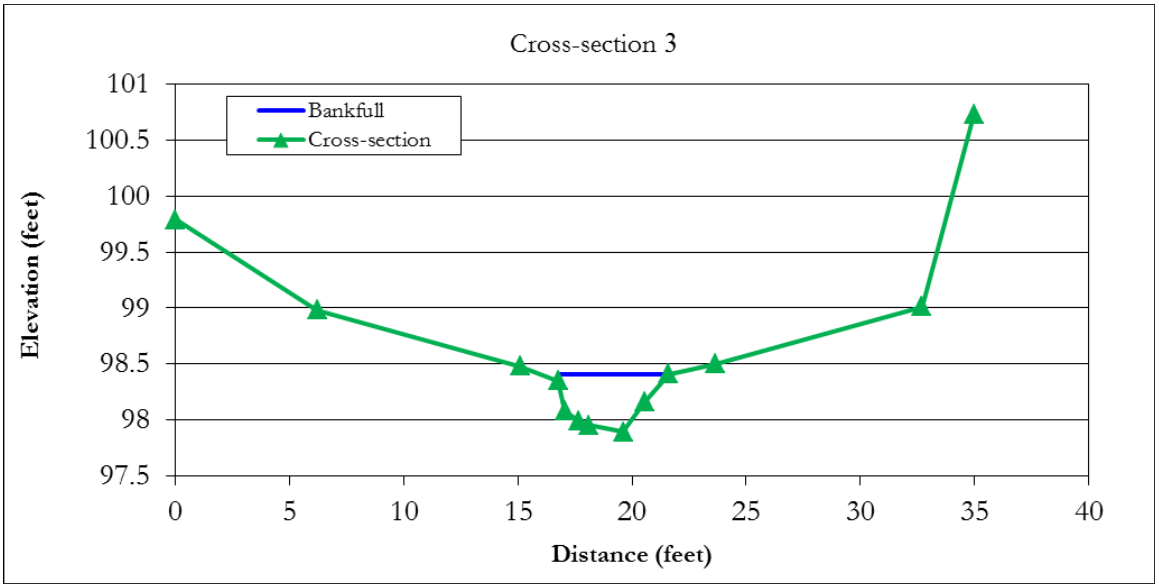

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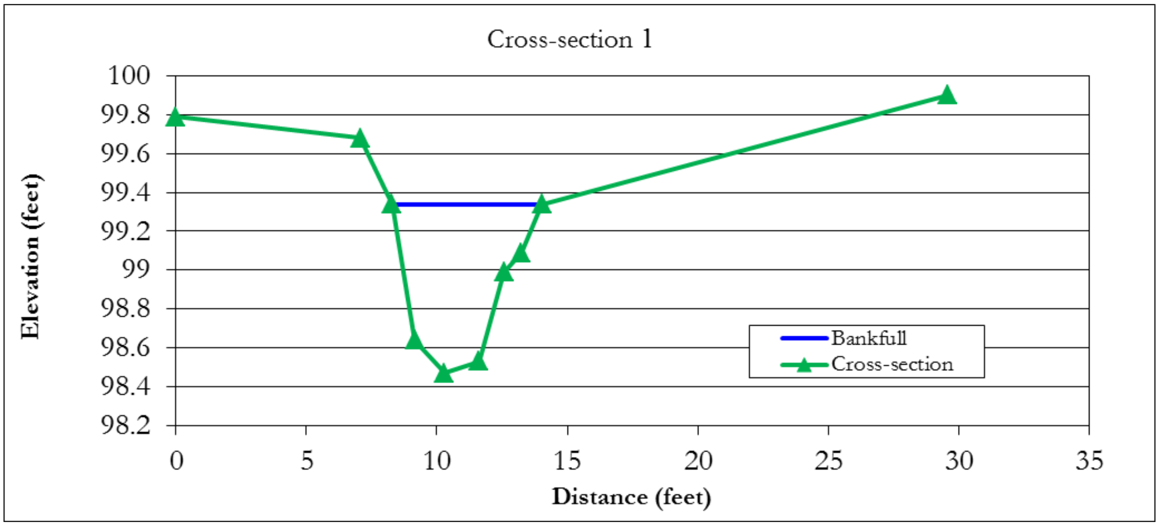


Figure 20. Site 2 - West Fork Coyte Branch Trib Cross Section 1

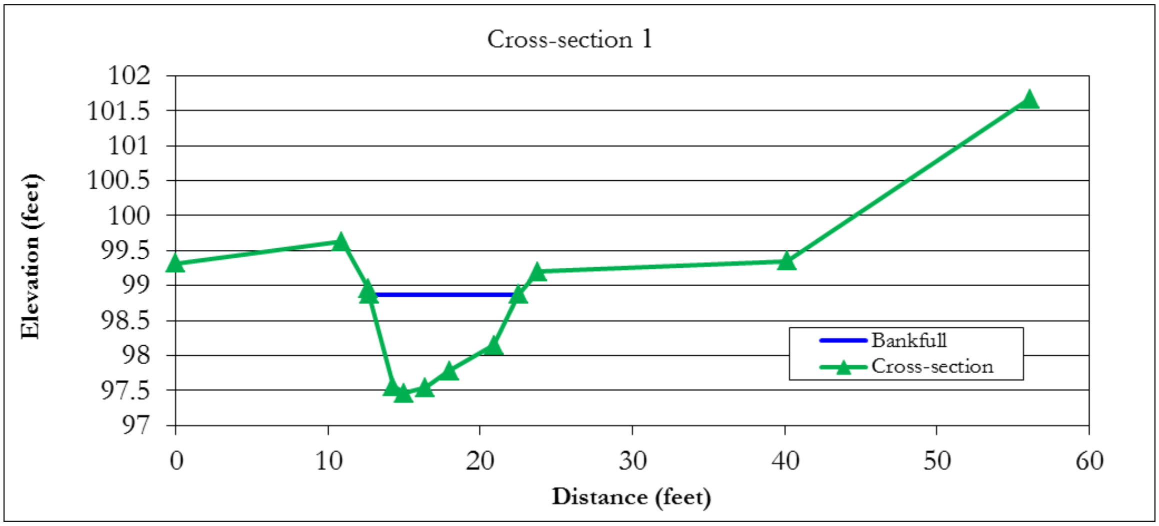


Figure 21. Site 3 - West Fork Coyte Branch Cross Section 1

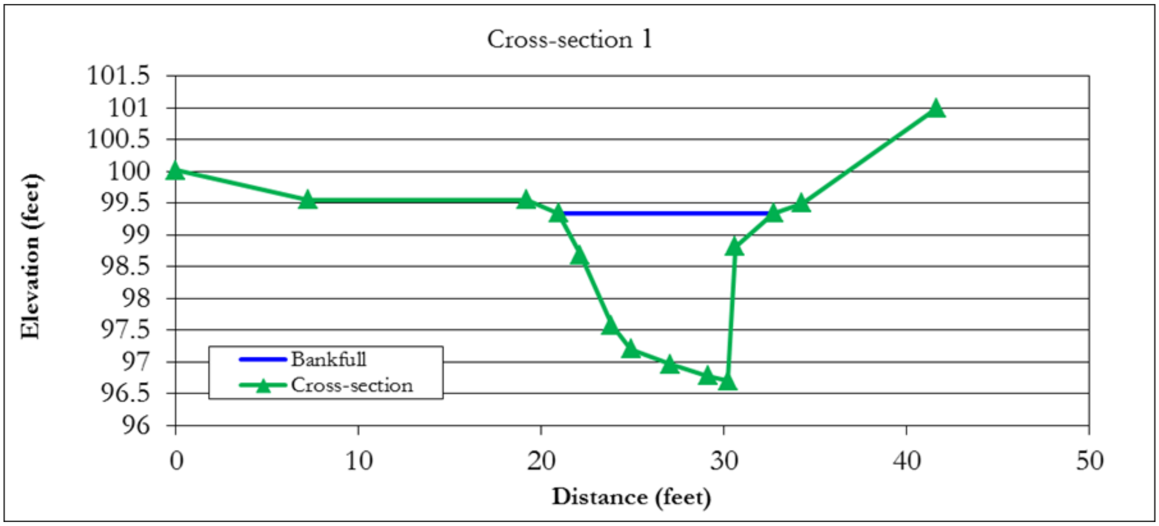


Figure 22. Site 4 - Bandy Creek Cross Section 1

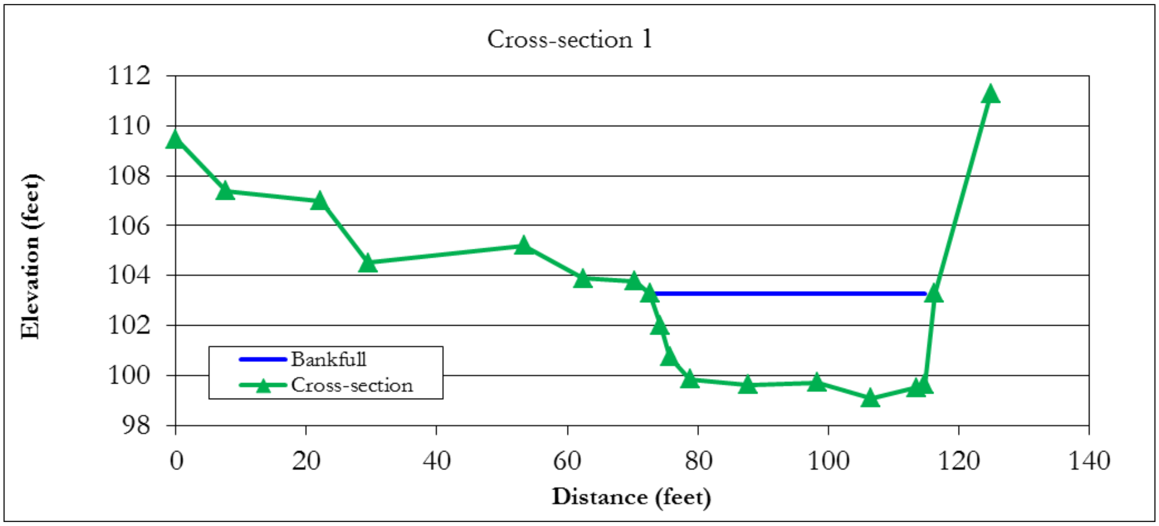
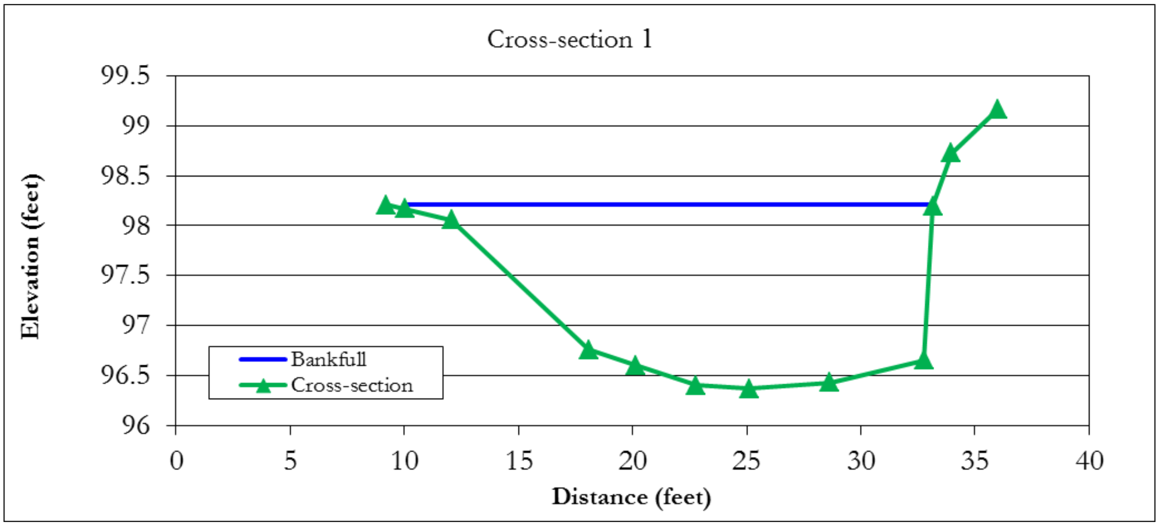


Figure 23. Site 5 – Laurel Fork Cross Section 1



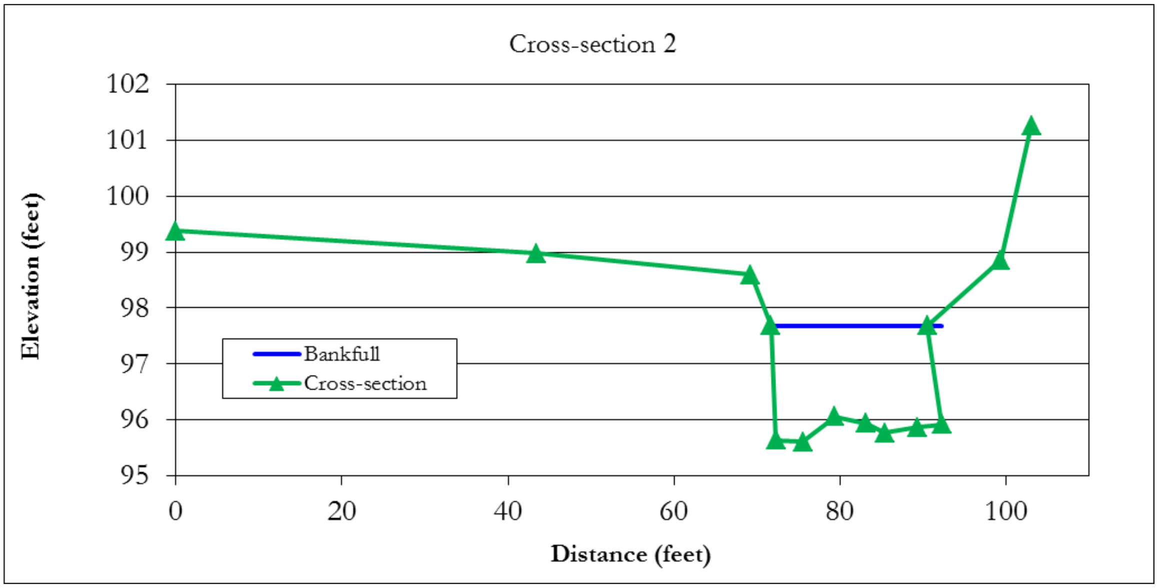


Figure 24. Site 6 - Black House Branch Cross Sections 1 - 2

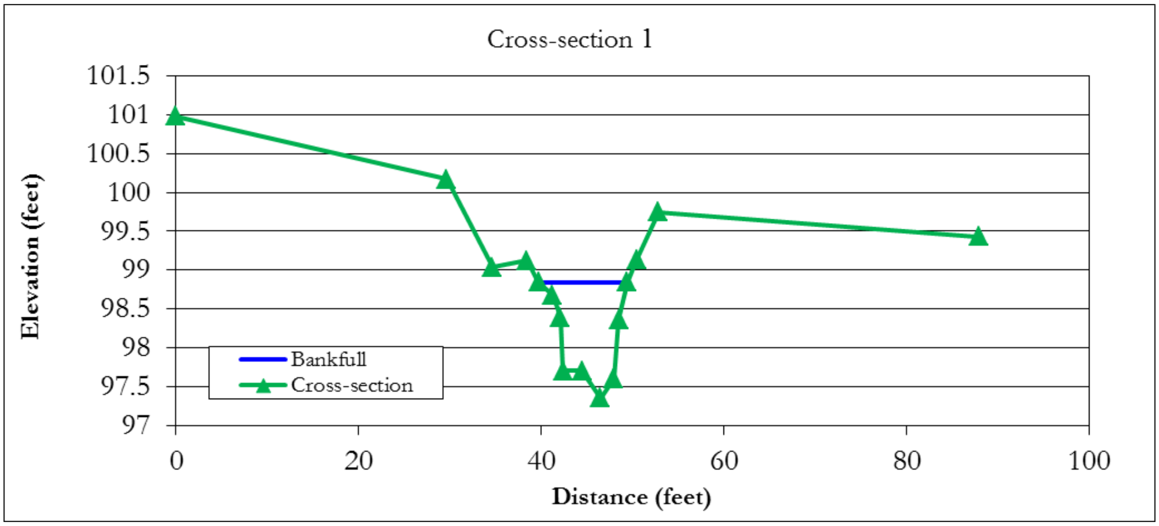
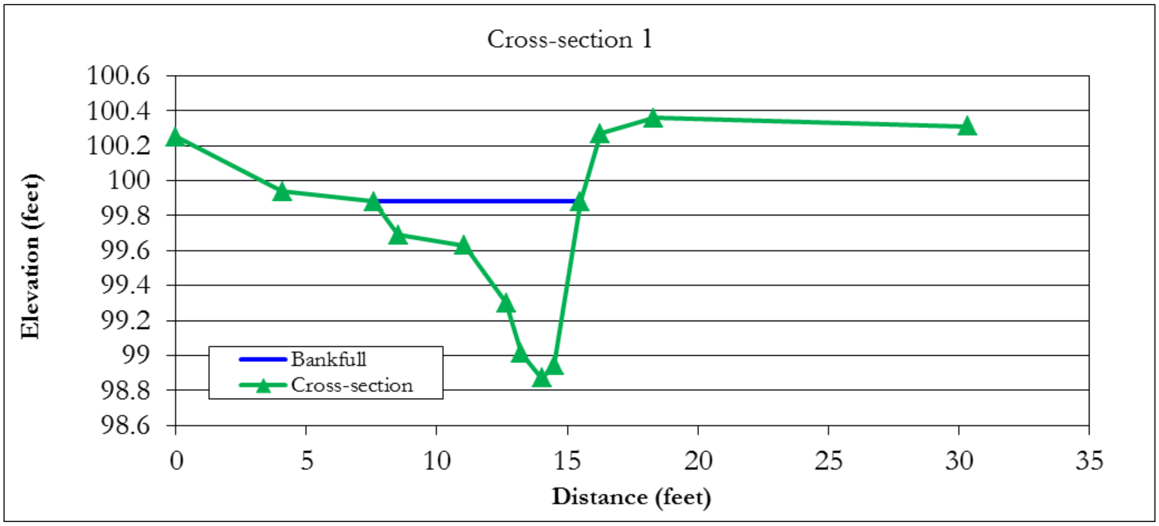


Figure 25. Site 7- Slave Falls Trib Cross Section 1



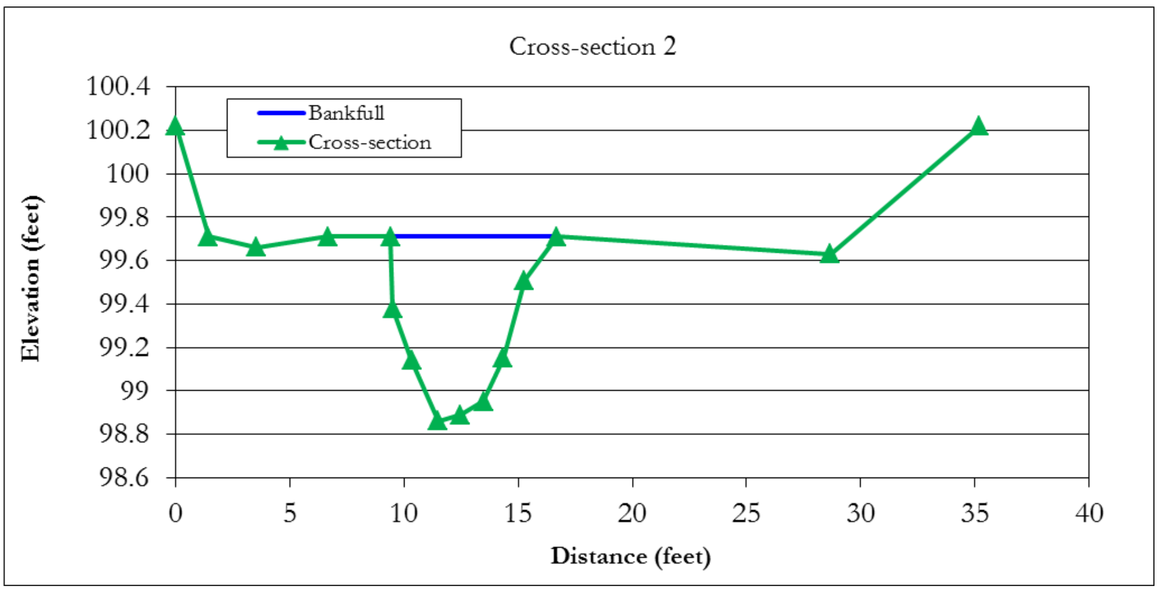


Figure 26. Site 8 - Bee Ridge Trib Cross Sections 1 - 2

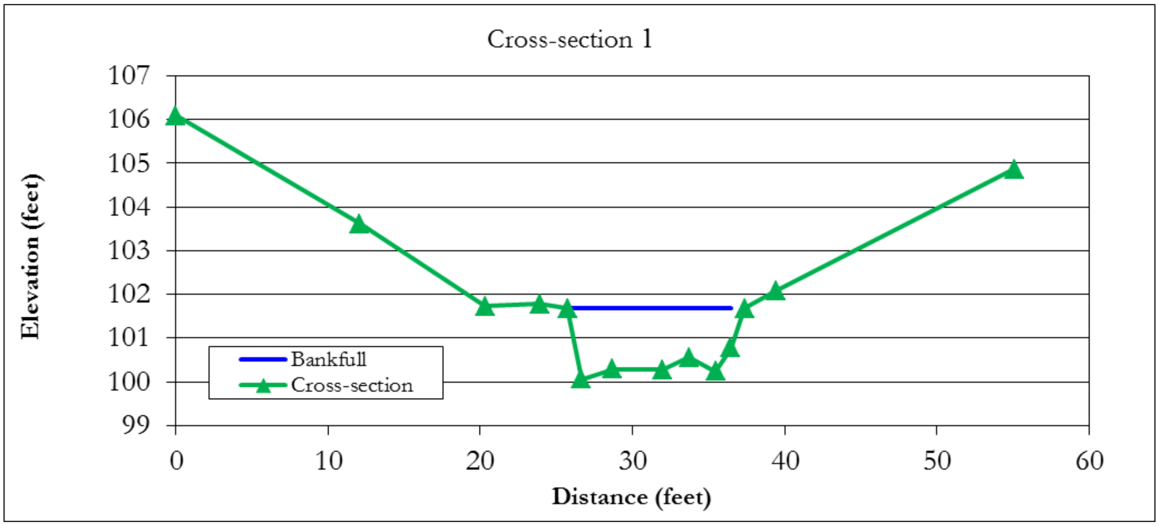


Figure 27. Site 9 - Underwood Branch Cross Section 1

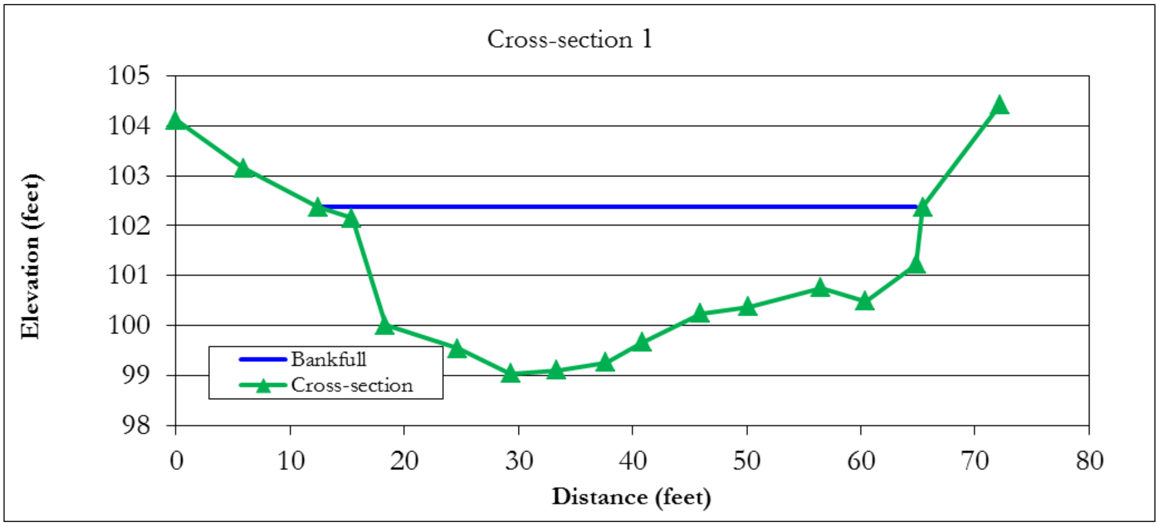


Figure 28. Site 10 - Otter Creek Cross Section 1

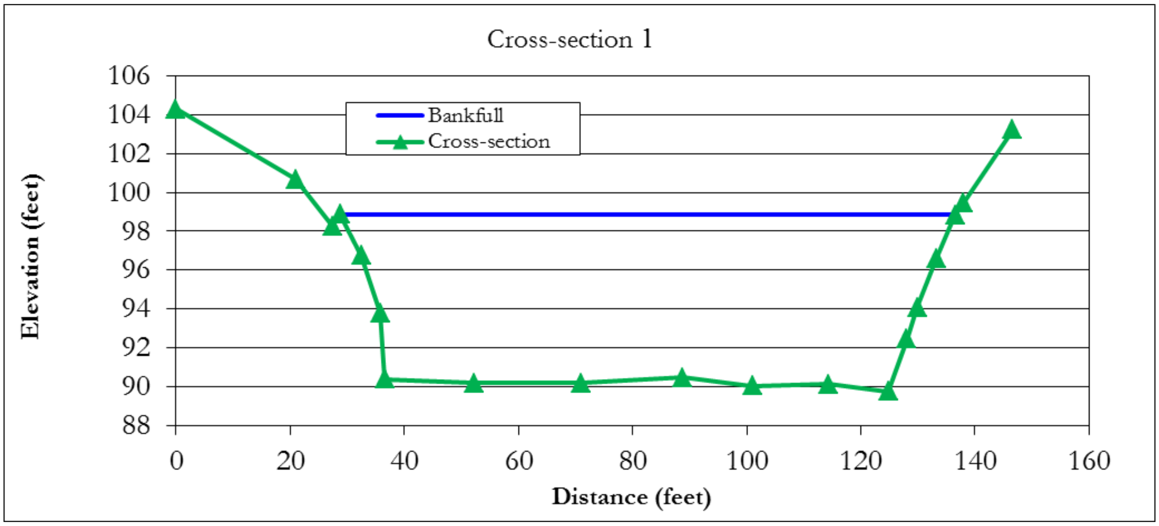


Figure 29. Site 11 - Obed River Cross Section 1

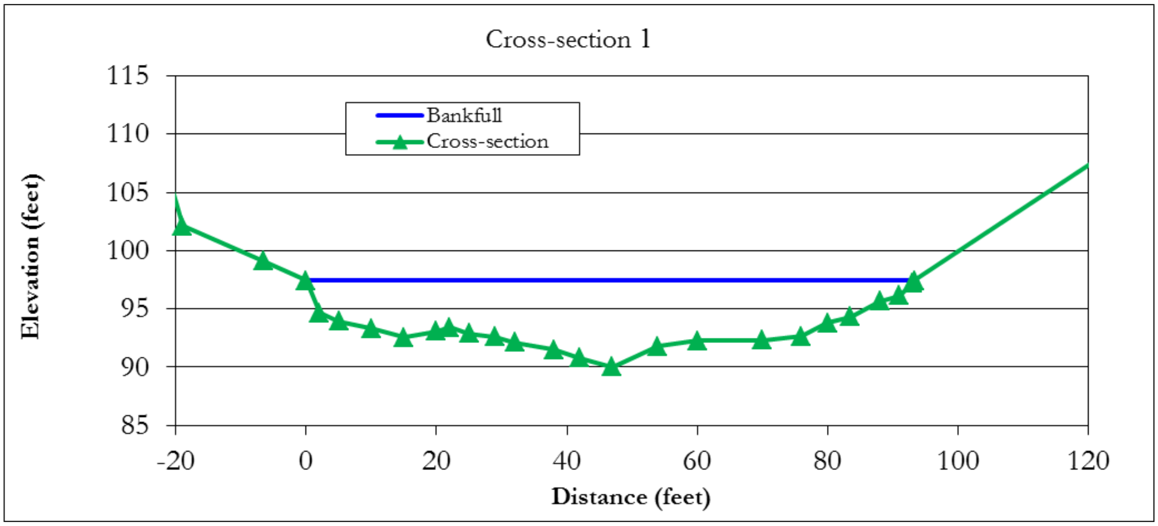


Figure 30. Site 12 - North Chickamauga Creek Cross Section 1

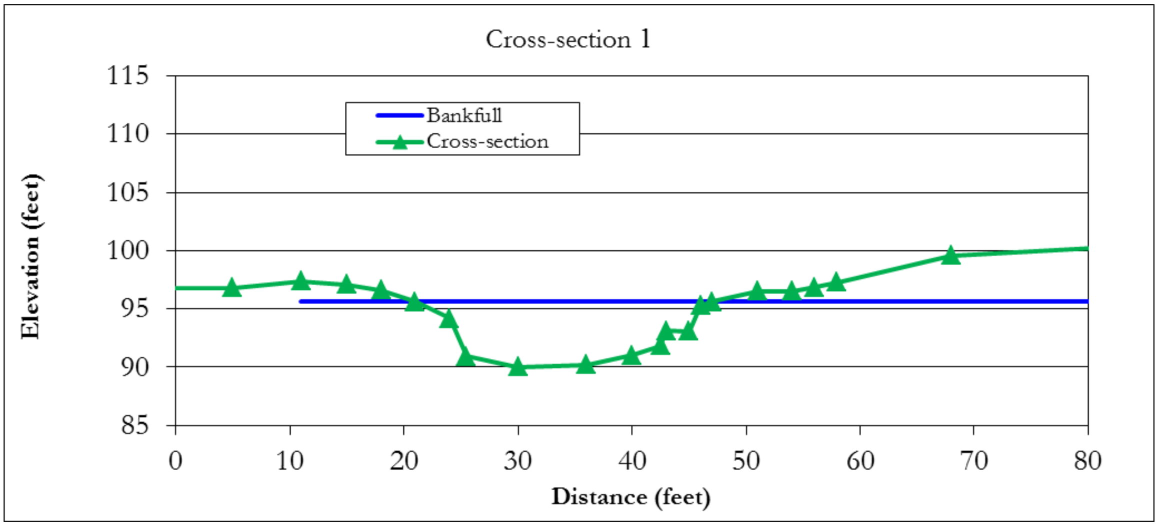
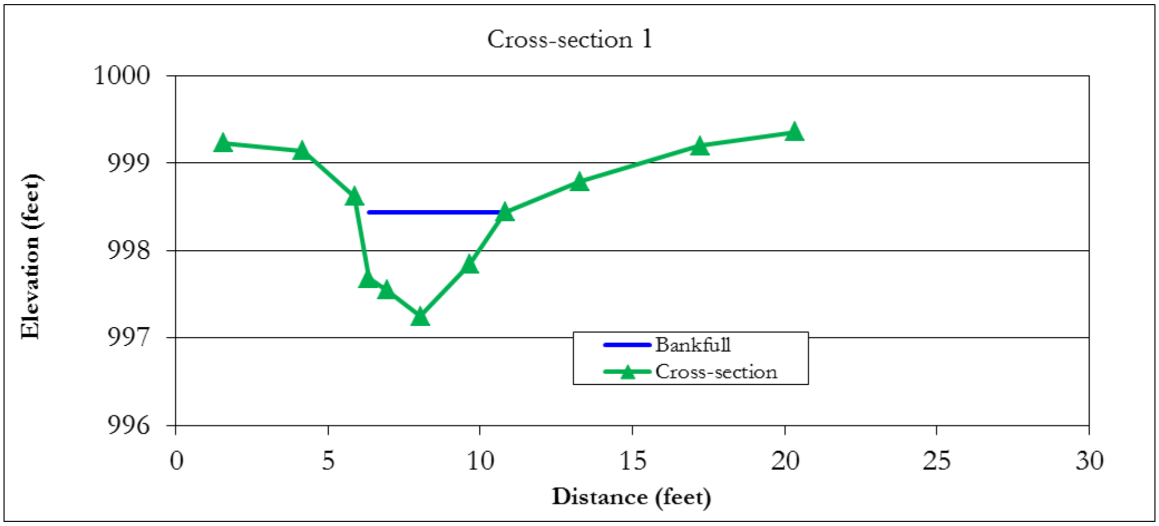
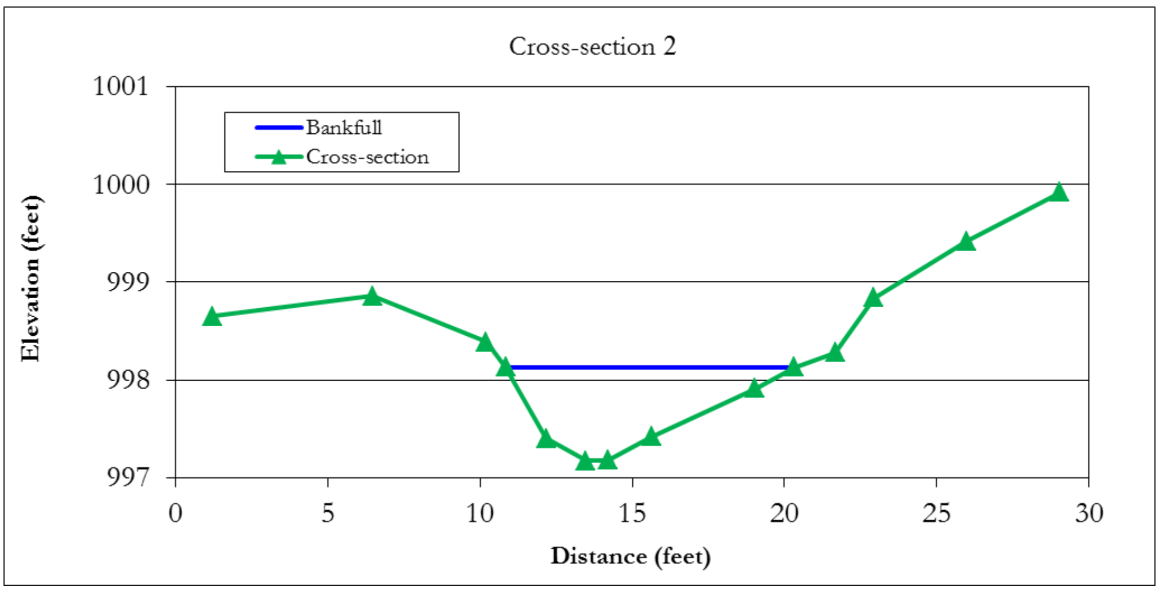


Figure 31. Site 13 - Basses Creek Cross Section 1

Figure 32. Site 14 - Weaver Trib. Cross Sections 1 - 3





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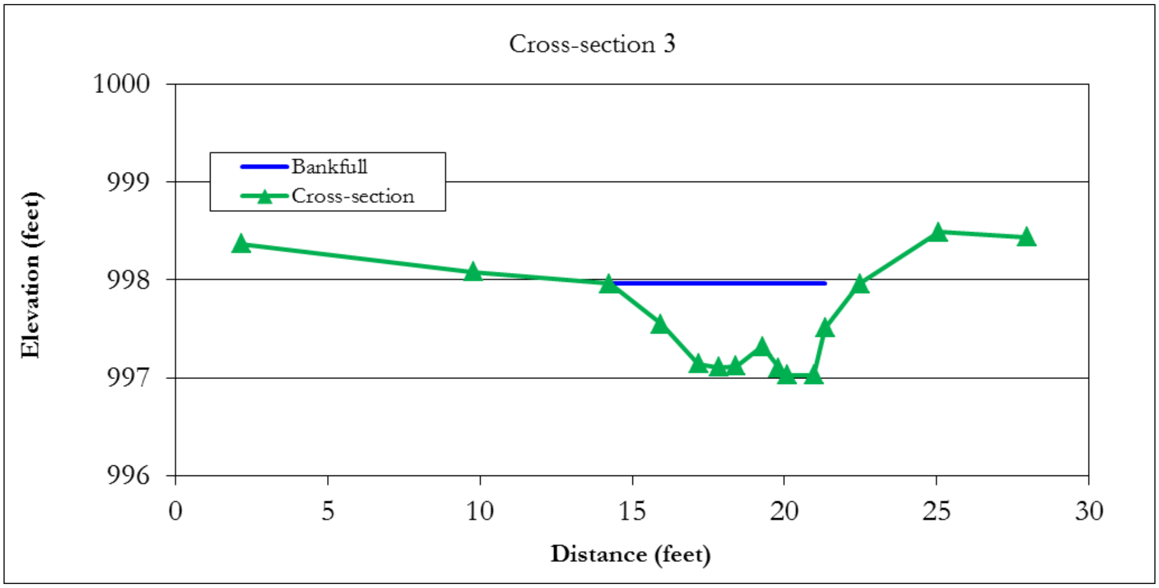
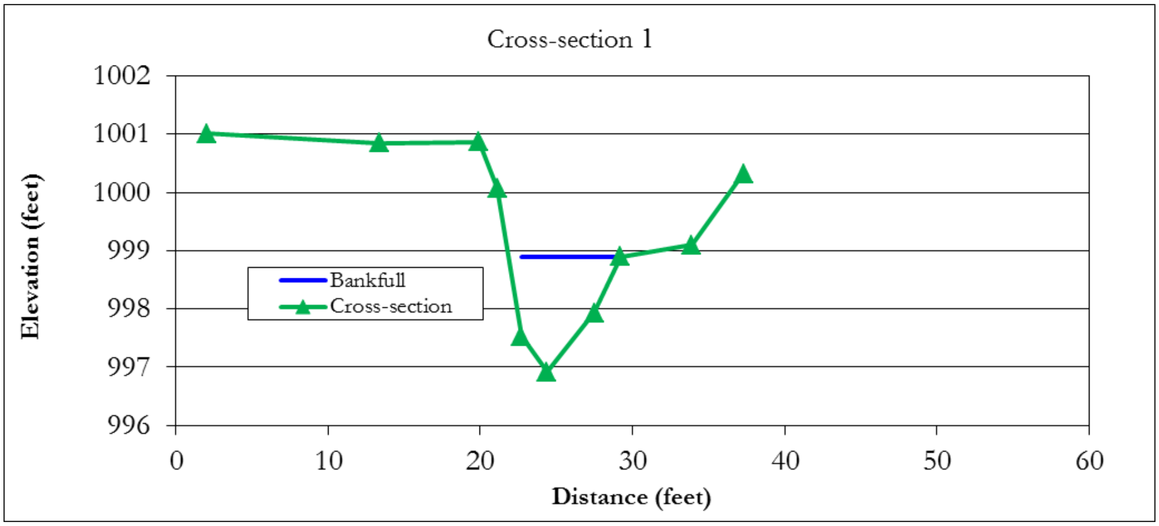
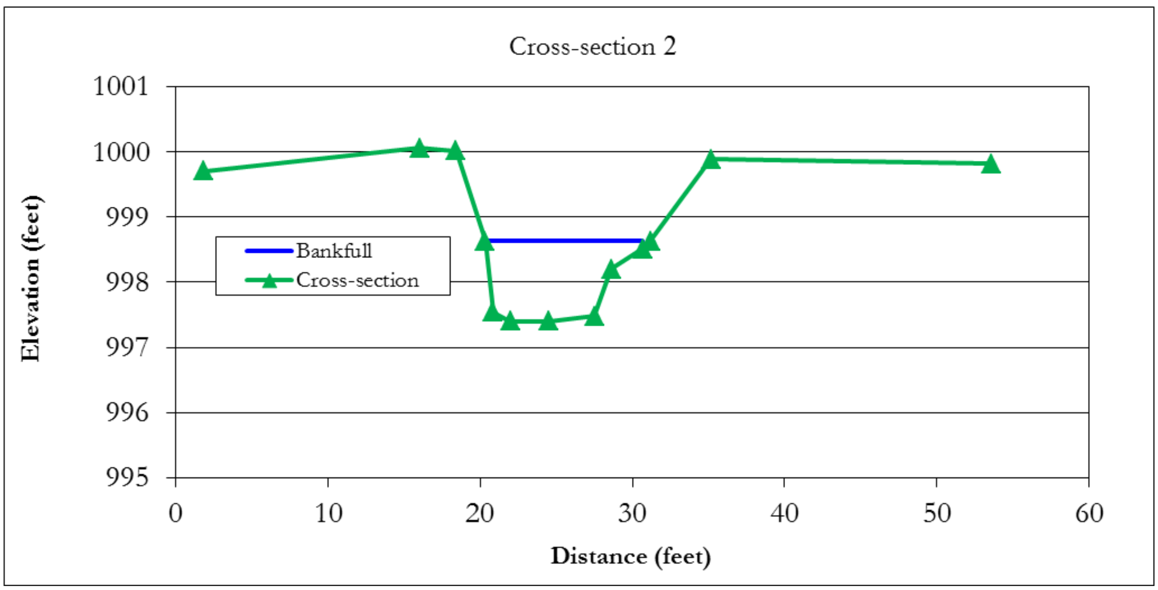


Figure 32 Continued

Figure 33. Site 15 - Weaver Down Cross Sections 1 - 4





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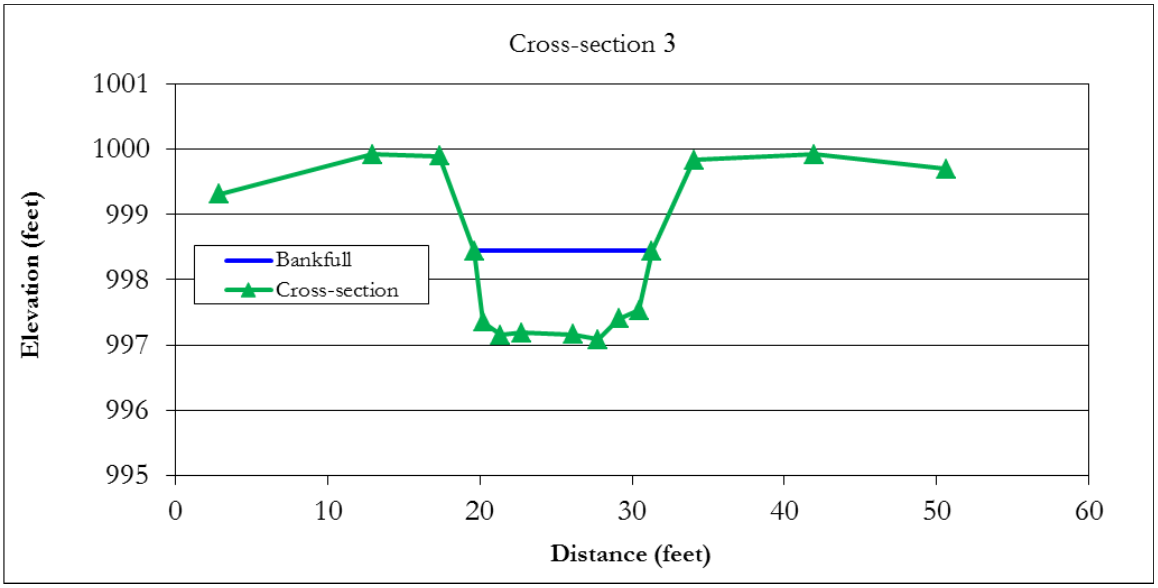

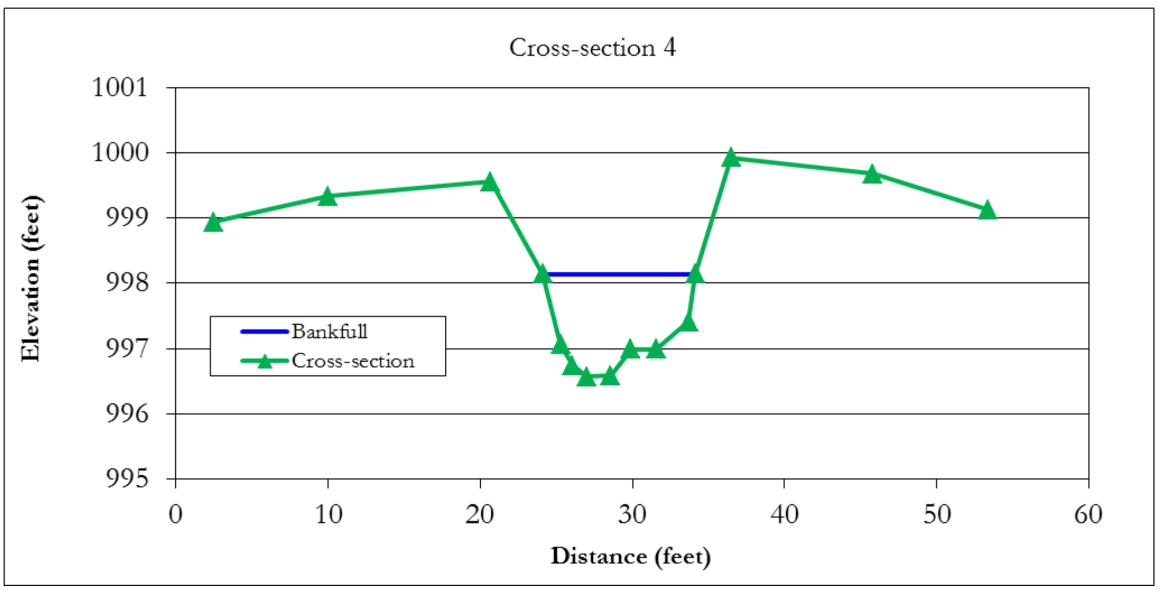

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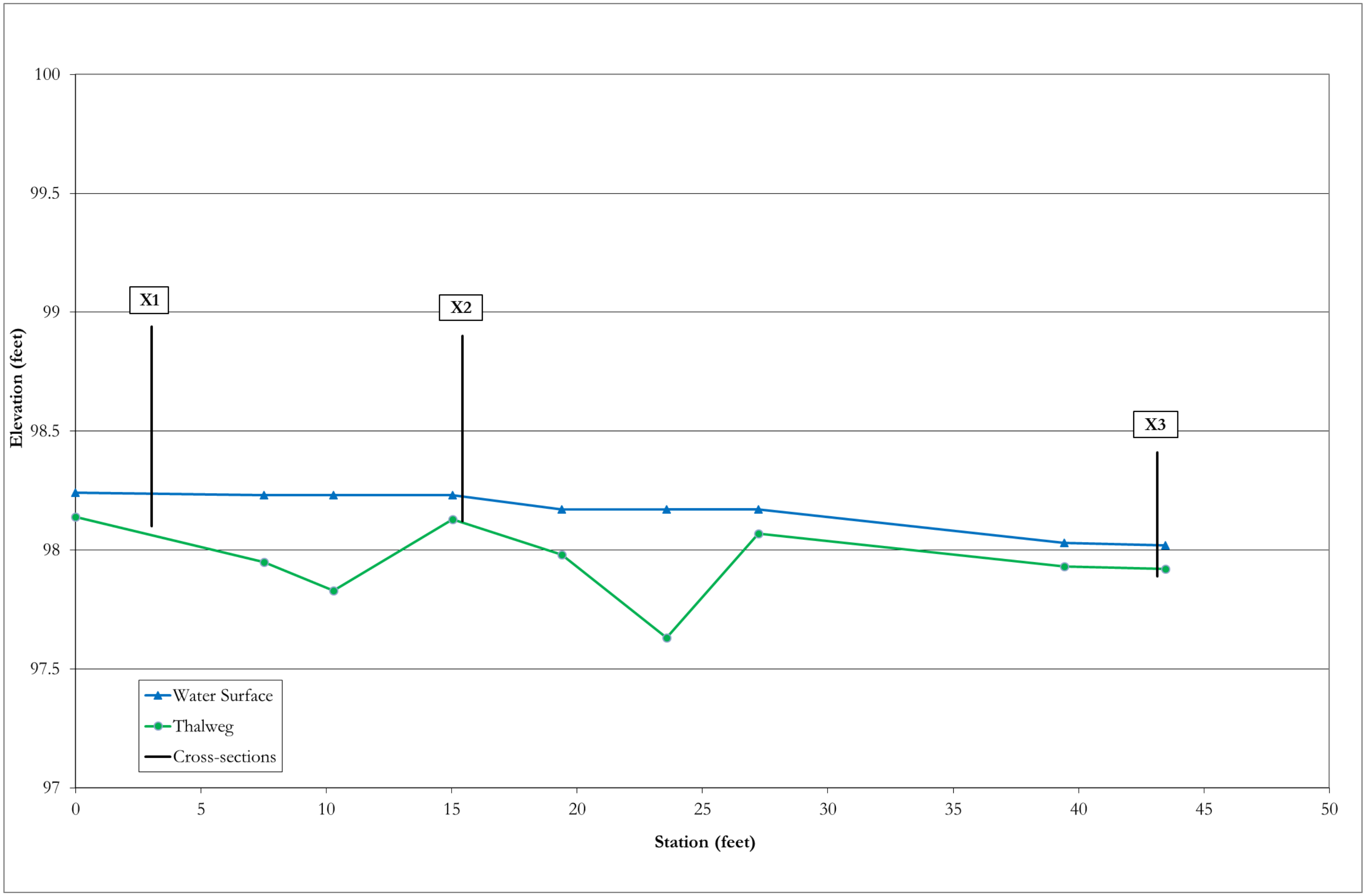


Figure 34. Site 1 – Groom Branch Trib Longitudinal Profile

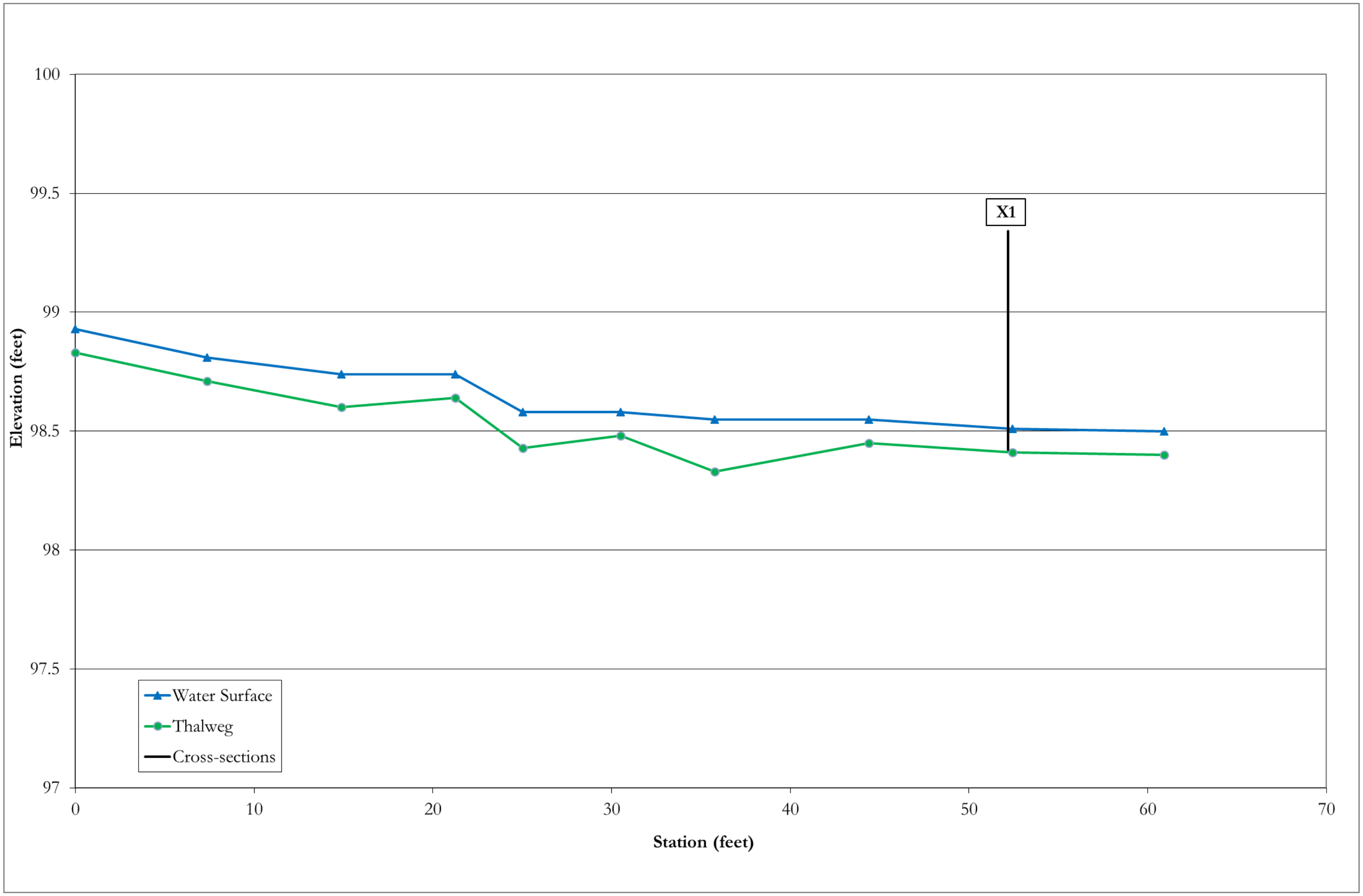


Figure 35. Site 2 - West Fork Coyte Trib Longitudinal Profile

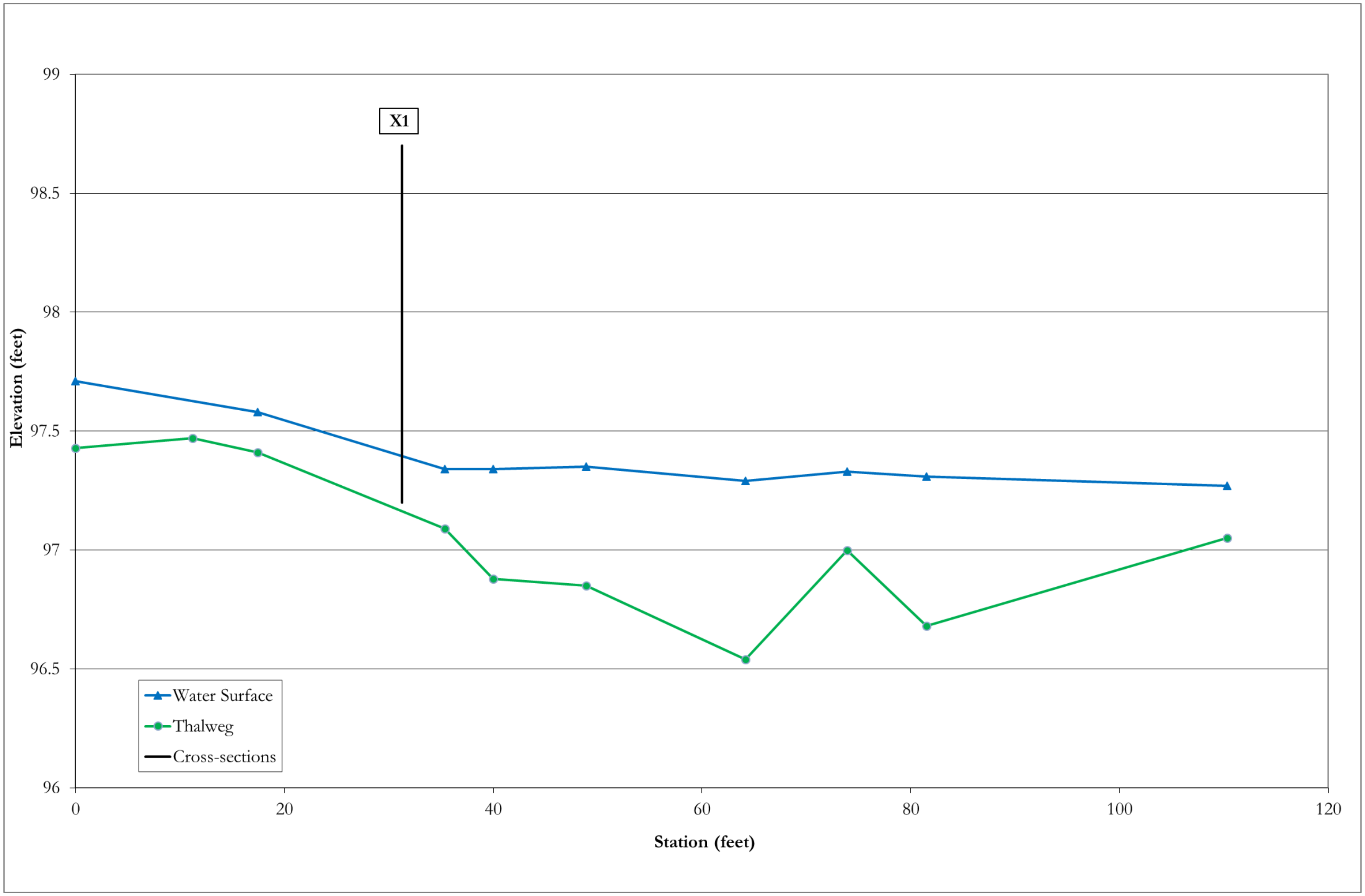


Figure 36. Site 3 – West Fork Coyte Branch Longitudinal Profile

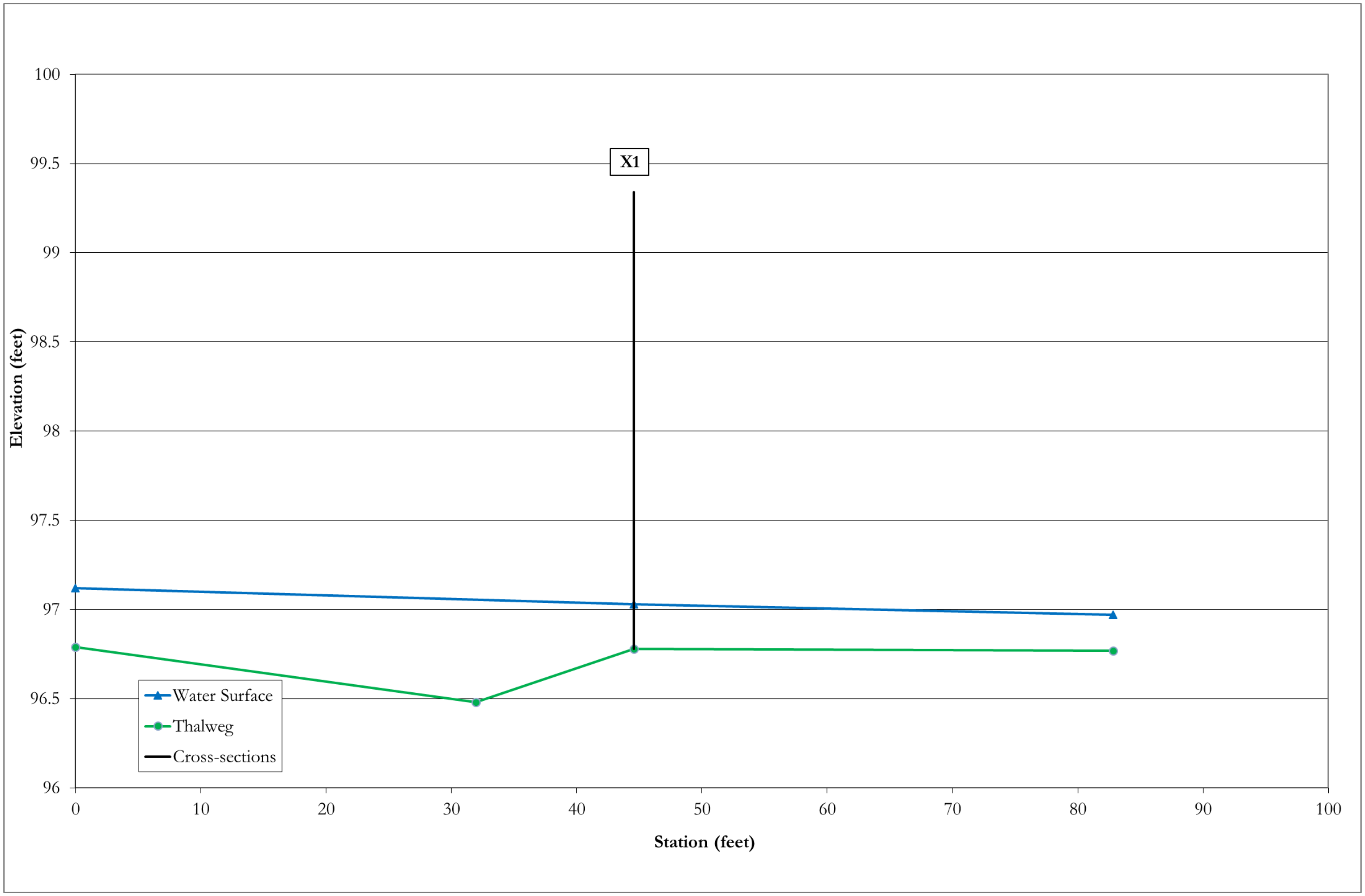


Figure 37. Site 4 - Bandy Creek Longitudinal Profile

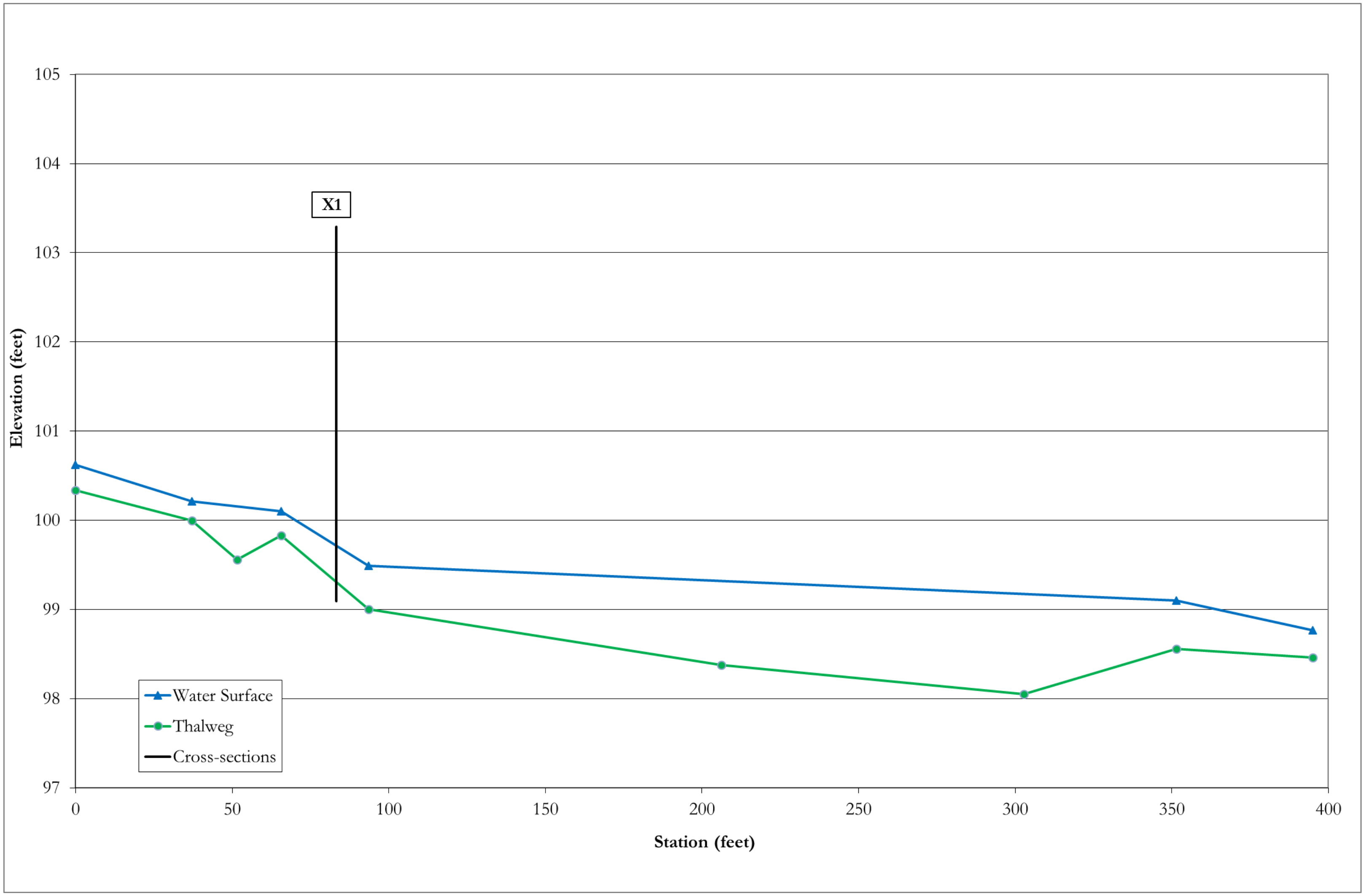


Figure 38. Site 5 – Laurel Fork Longitudinal Profile

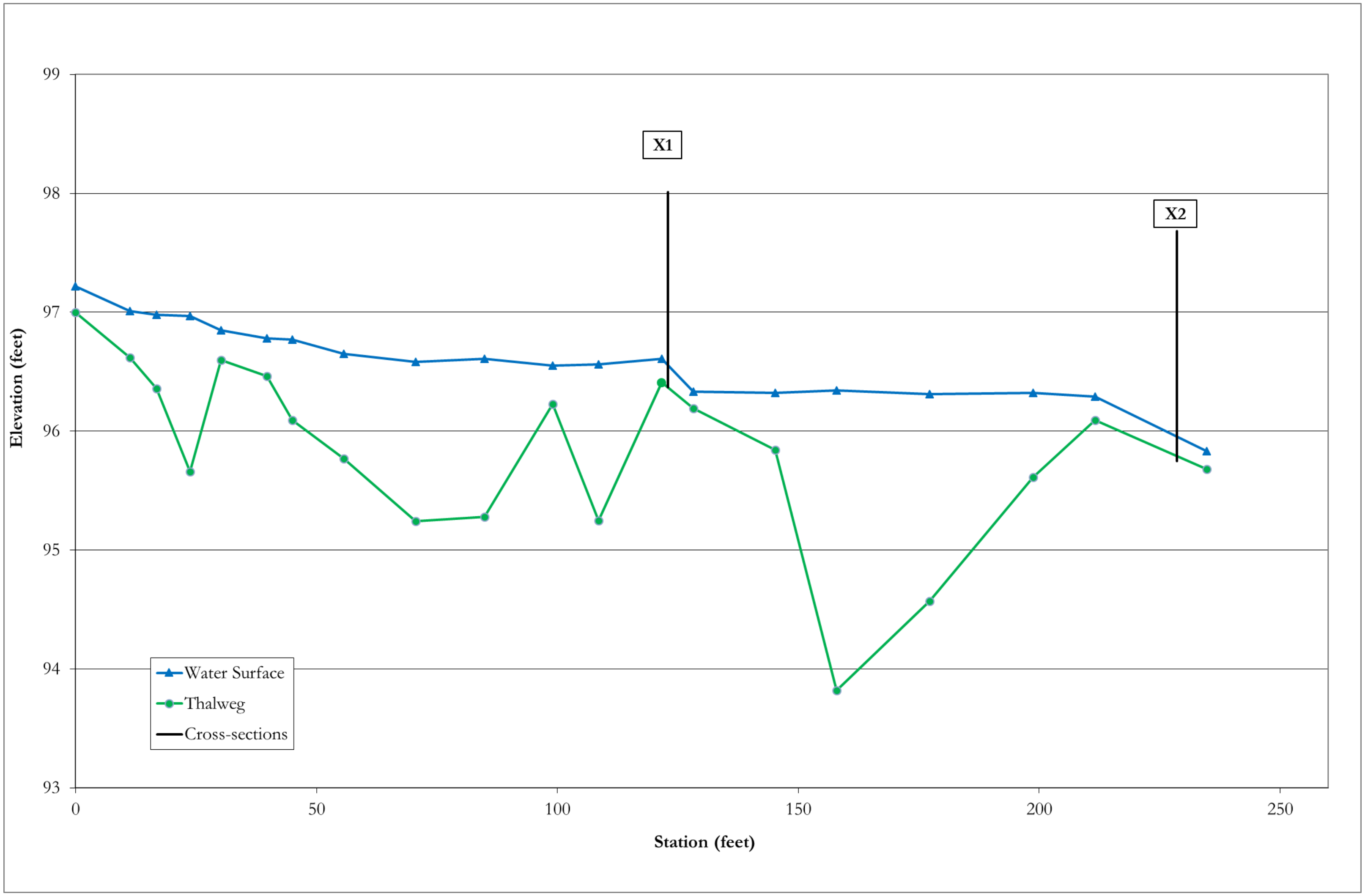


Figure 39. Site 6 - Black House Branch Longitudinal Profile

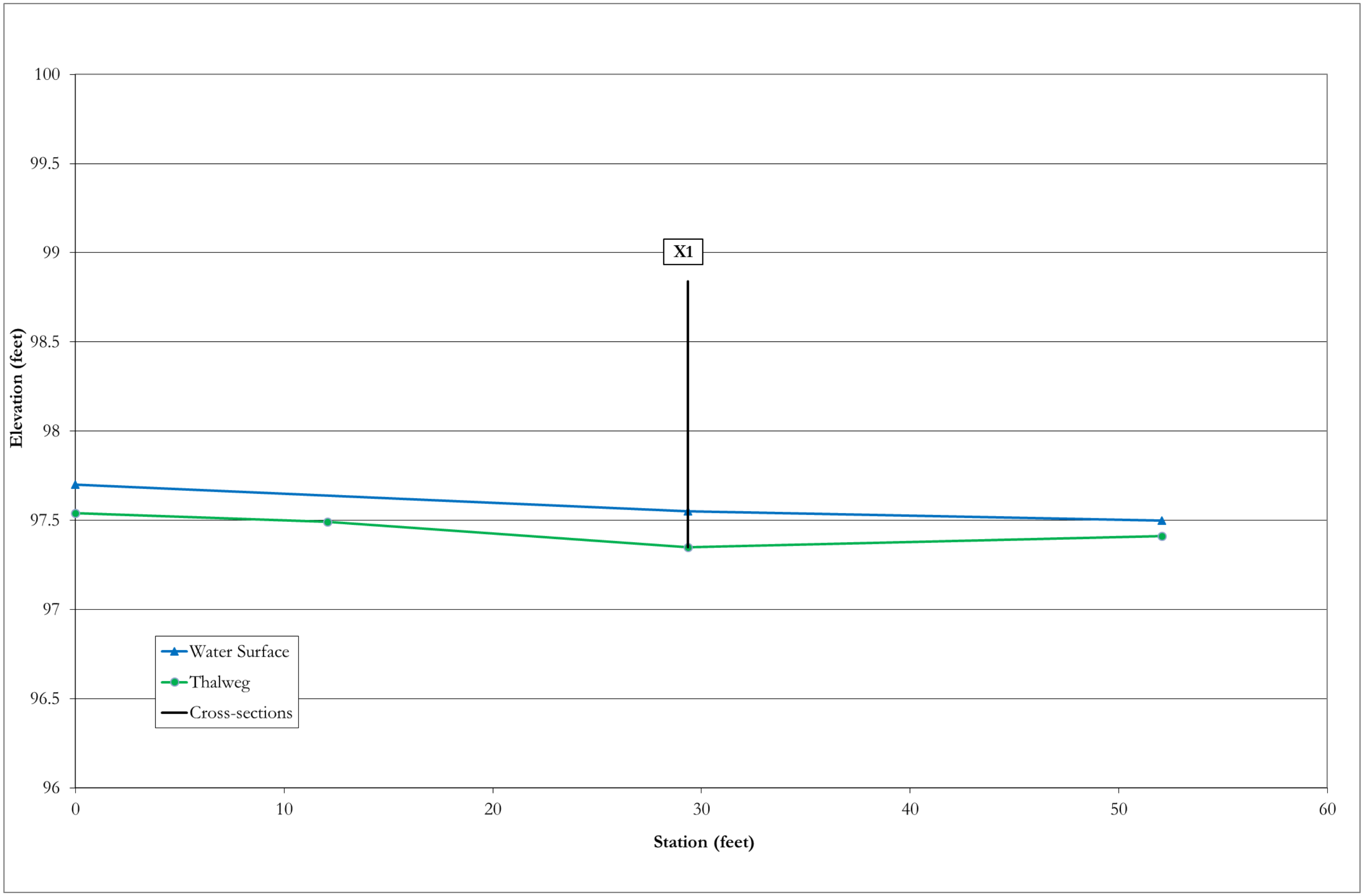


Figure 40. Site 7 - Slave Falls Longitudinal Profile

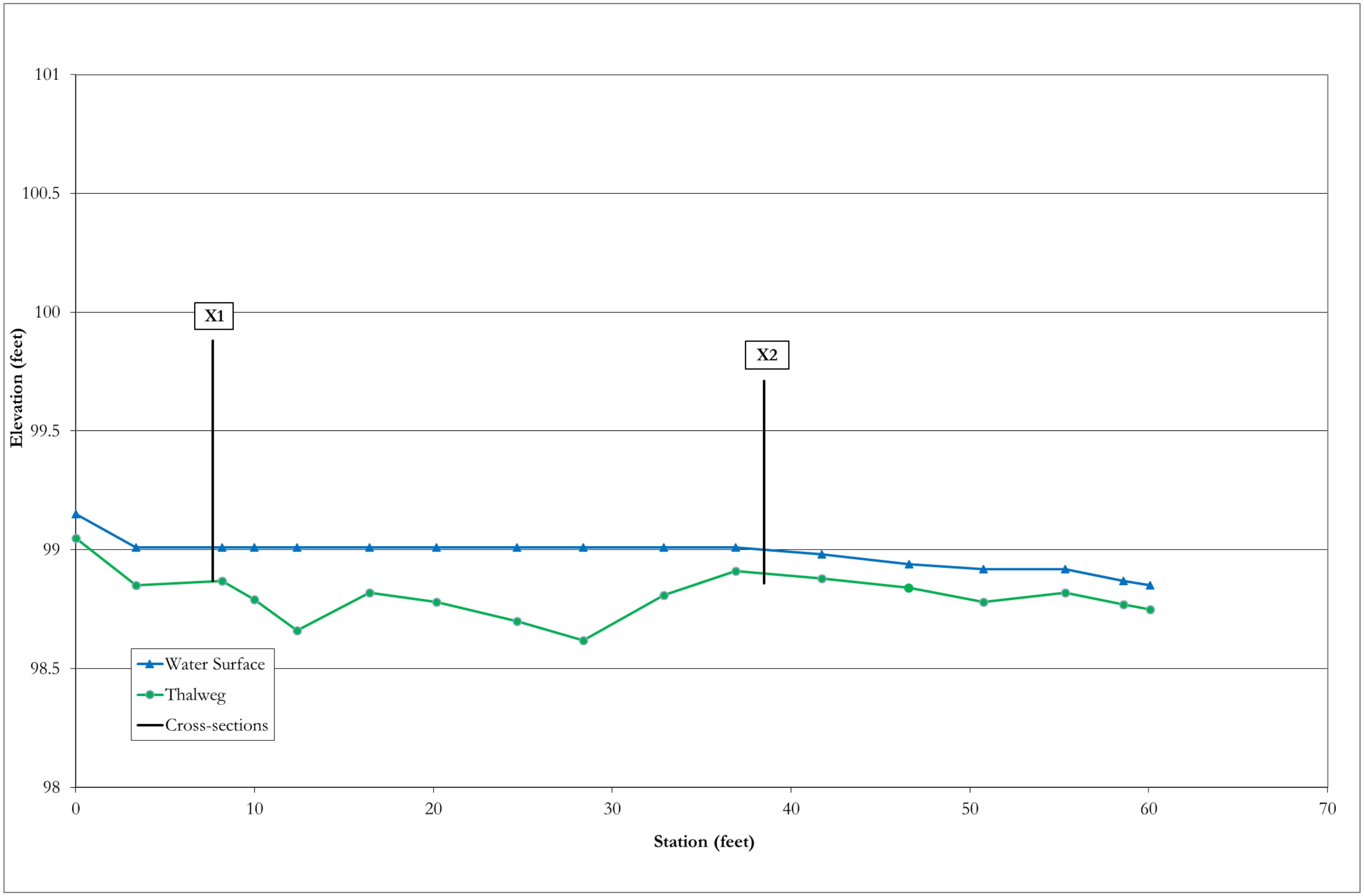


Figure 41. Site 9 - Underwood Longitudinal Profile

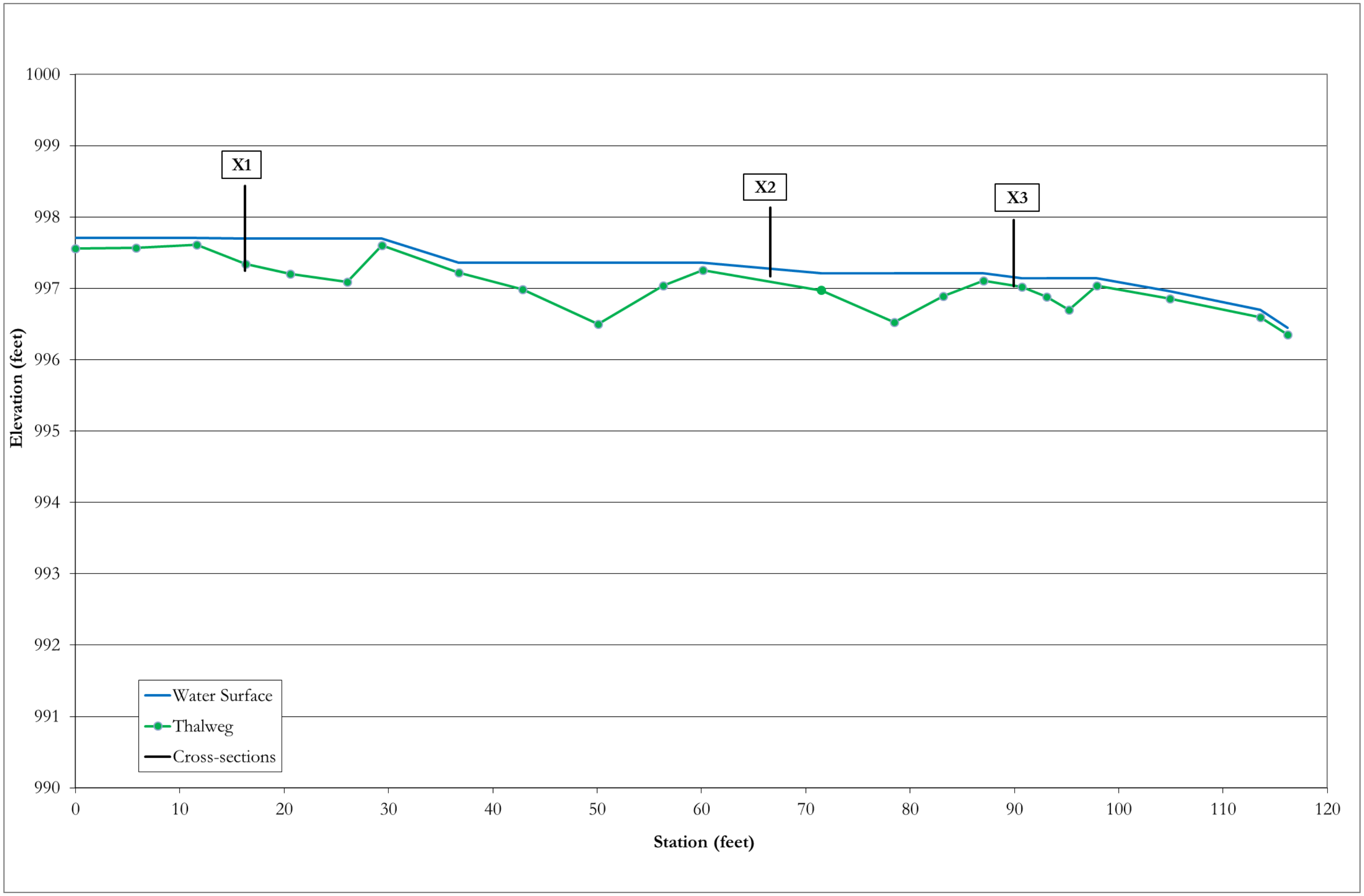


Figure 42. Site 14 - Weaver Trib Longitudinal Profile

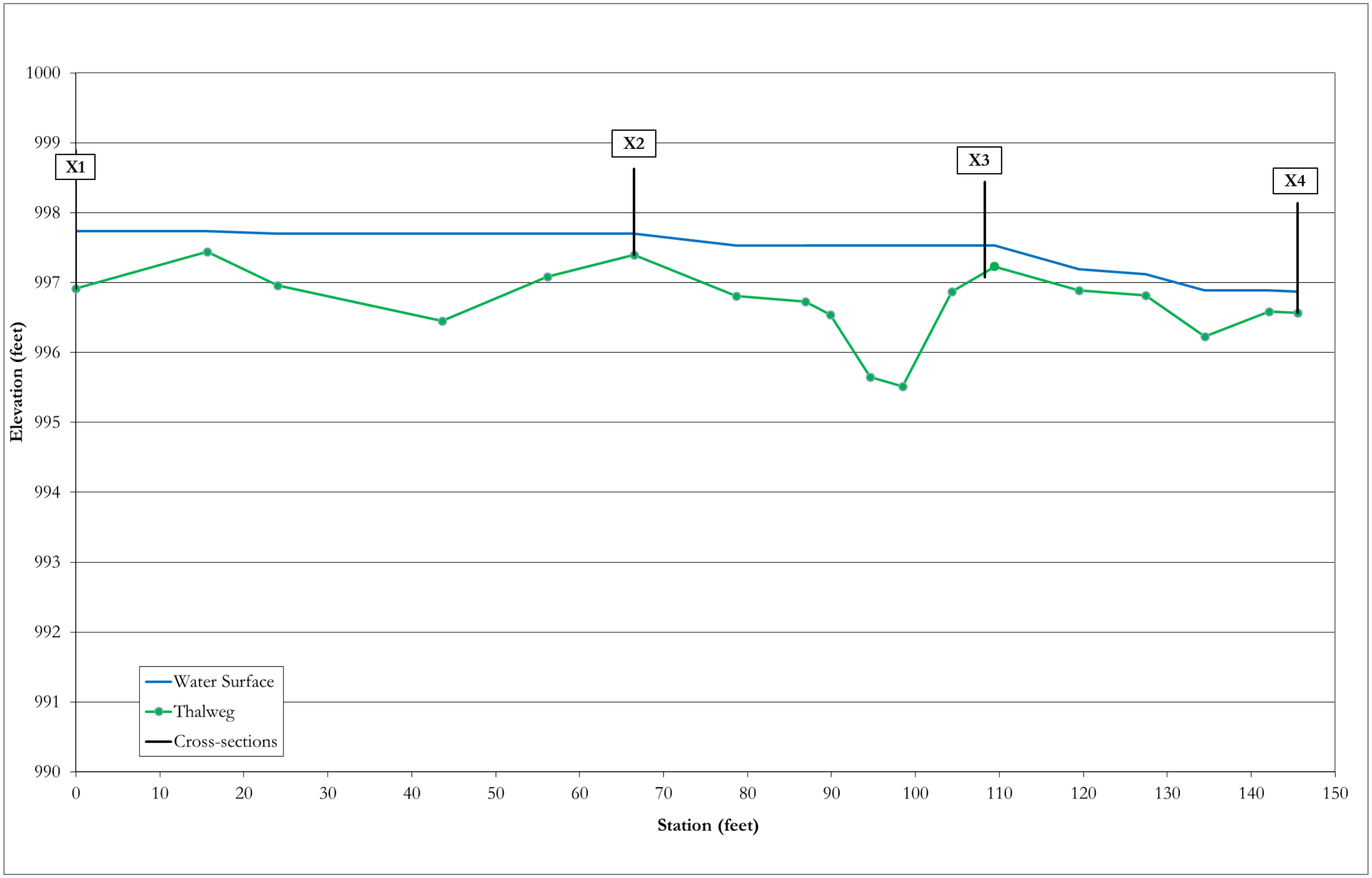


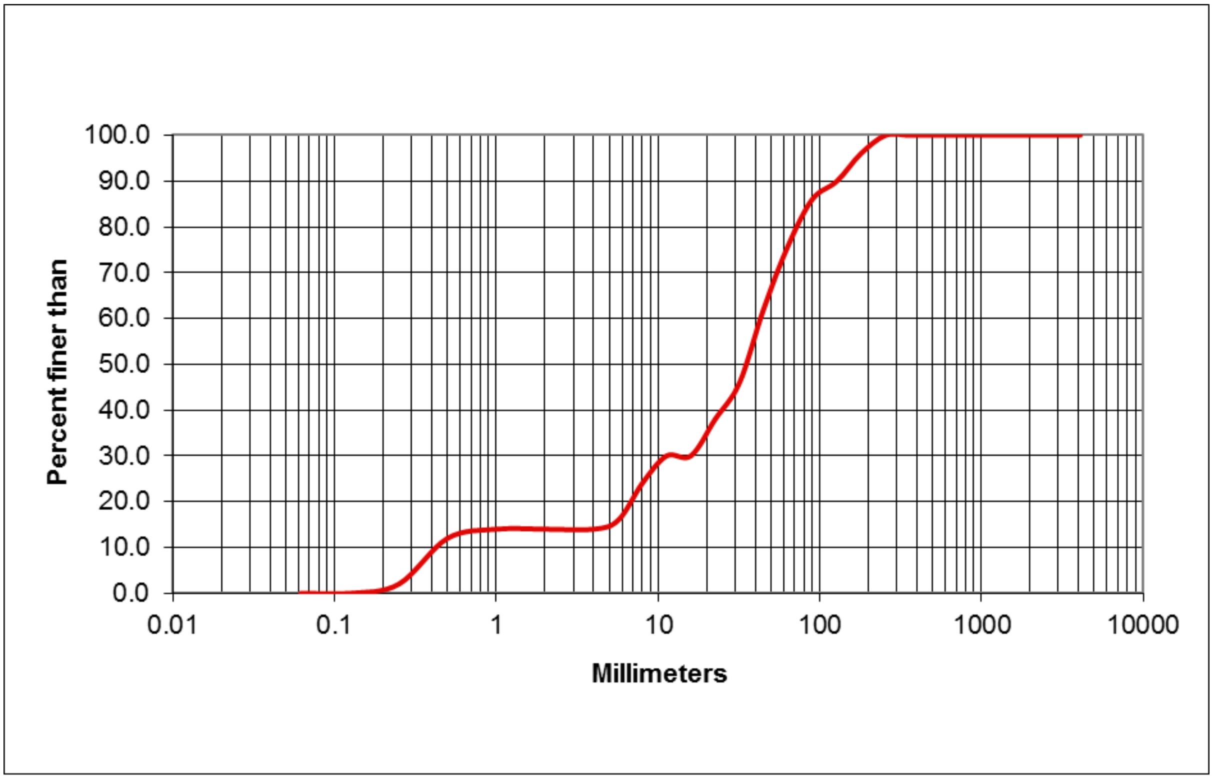
Figure 43. Site 15 - Weaver Down Longitudinal Profile

b. Pebble Count Results

Pebble counts for Tennessee steams are below. Some streams had a visual estimate for pebble counts while others had a Wolman's pebble count.

Table 9. Site 5 - Laurel Fork Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	0	0
Very Fine Sand	0.062 - 0.125	0	0
Fine Sand	0.125 - 0.25	1	2
Medium Sand	0.25 - 0.5	5	12
Coarse Sand	0.5 - 1.0	1	14
Very Coarse Sand	1.0 - 2.0	0	14
Very Fine Gravel	2.0 - 4.0	0	14
Fine Gravel	4.0 - 5.7	1	16
Fine Gravel	5.7 - 8.0	4	24
Medium Gravel	8.0 - 11.3	3	30
Medium Gravel	11.3 - 16.0	0	30
Coarse Gravel	16.0 - 22.6	4	38
Coarse Gravel	22.6 - 32	4	46
Very Coarse Gravel	32 - 45	8	62
Very Coarse Gravel	45 - 64	7	76
Small Cobble	64 - 90	5	86
Small Cobble	90 - 128	2	90
Large Cobble	128 - 180	3	96
Large Cobble	180 - 256	2	100
Small Boulder	256 - 362	0	100
Small Boulder	362 - 512	0	100
Medium Boulder	512 - 1024	0	100
Large Boulder	1024 - 2048	0	100
Bedrock	>2048	0	100
	Totals	50	



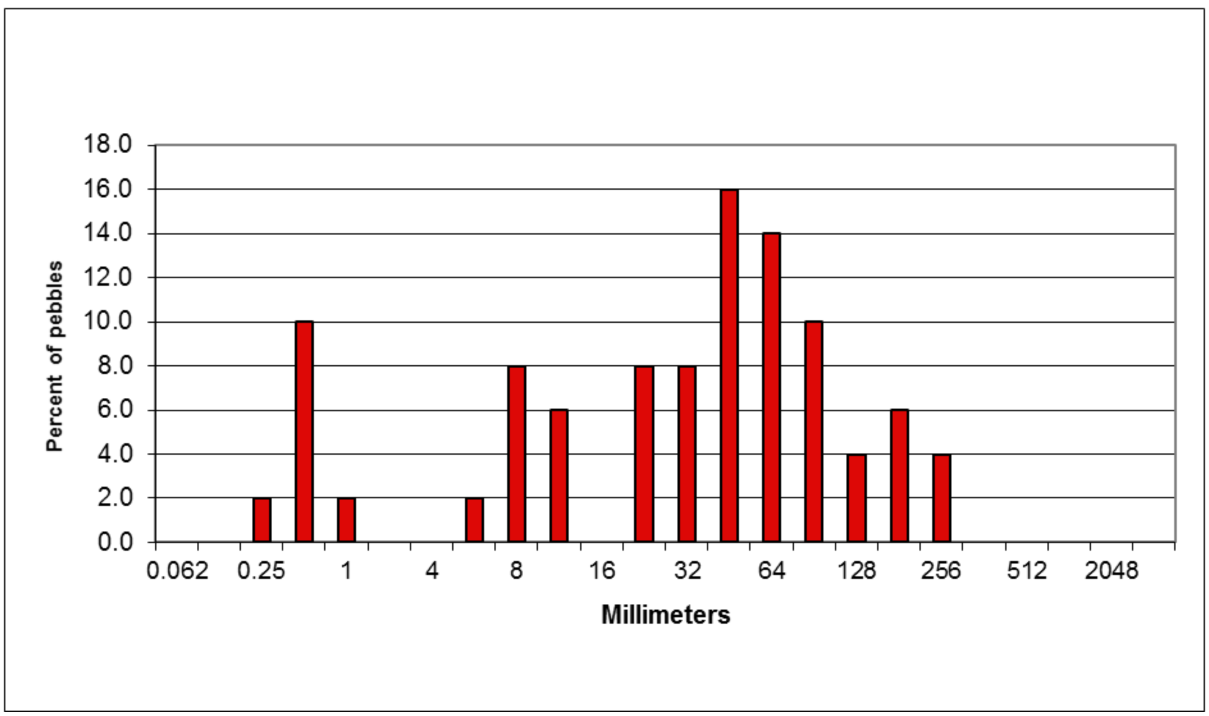
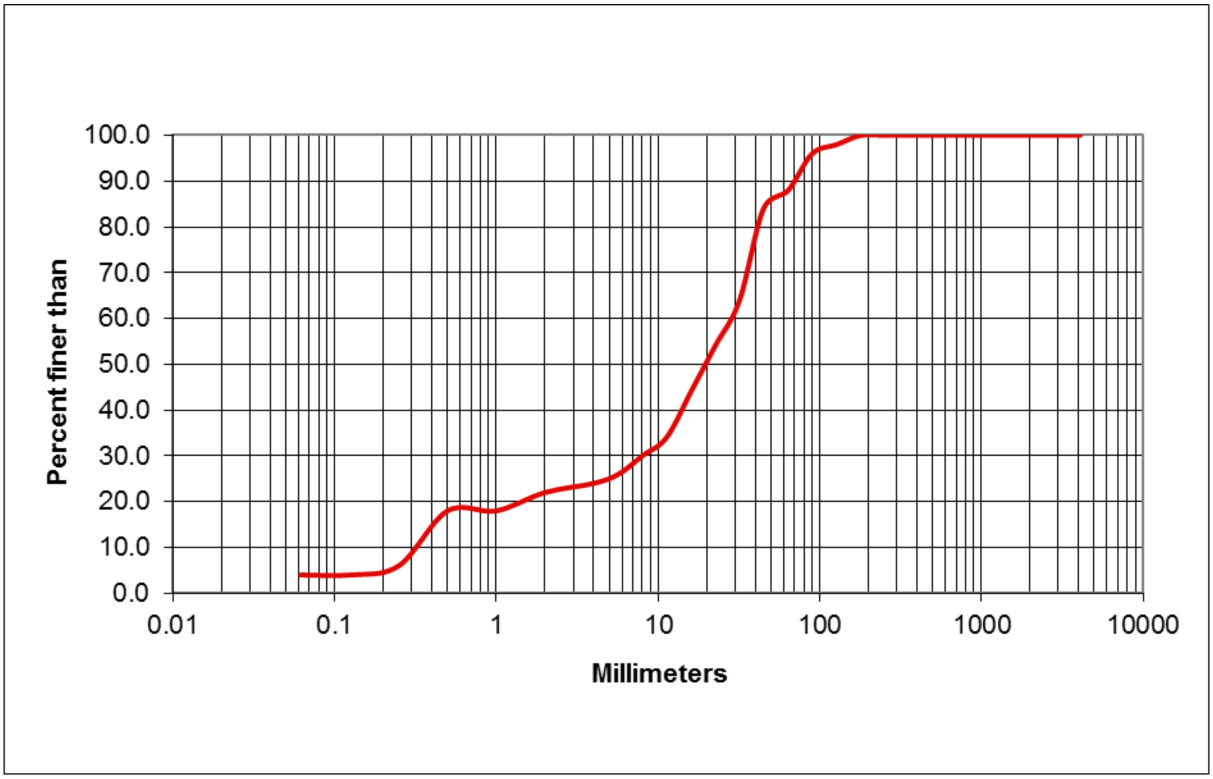


Figure 44. Site 5 – Laurel Fork Particle Size Distribution Chart and Histogram

Table 10. Site 6 – Black House Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	2	4
Very Fine Sand	0.062 - 0.125	0	4
Fine Sand	0.125 - 0.25	1	6
Medium Sand	0.25 - 0.5	6	18
Coarse Sand	0.5 - 1.0	0	18
Very Coarse Sand	1.0 - 2.0	2	22
Very Fine Gravel	2.0 - 4.0	1	24
Fine Gravel	4.0 - 5.7	1	26
Fine Gravel	5.7 - 8.0	2	30
Medium Gravel	8.0 - 11.3	2	34
Medium Gravel	11.3 - 16.0	5	44
Coarse Gravel	16.0 - 22.6	5	54
Coarse Gravel	22.6 - 32	5	64
Very Coarse Gravel	32 - 45	10	84
Very Coarse Gravel	45 - 64	2	88
Small Cobble	64 - 90	4	96
Small Cobble	90 - 128	1	98
Large Cobble	128 - 180	1	100
Large Cobble	180 - 256	0	100
Small Boulder	256 - 362	0	100
Small Boulder	362 - 512	0	100
Medium Boulder	512 - 1024	0	100
Large Boulder	1024 - 2048	0	100
Bedrock	>2048	0	100
	Totals	50	



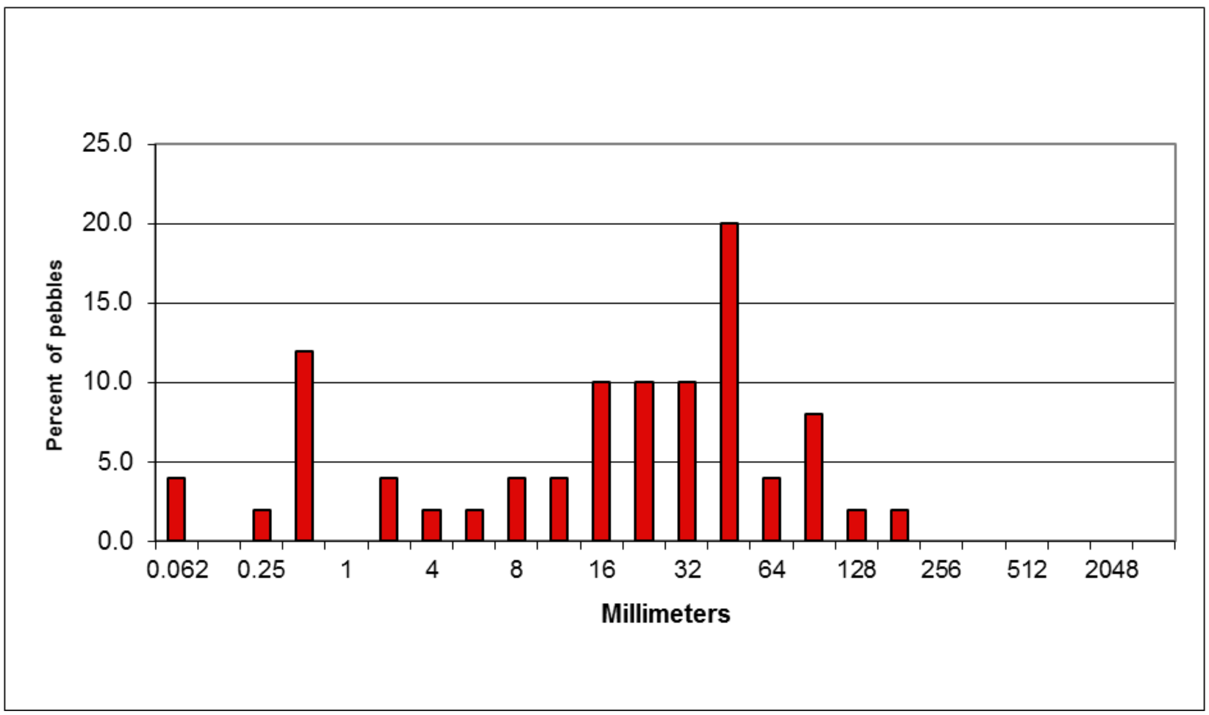
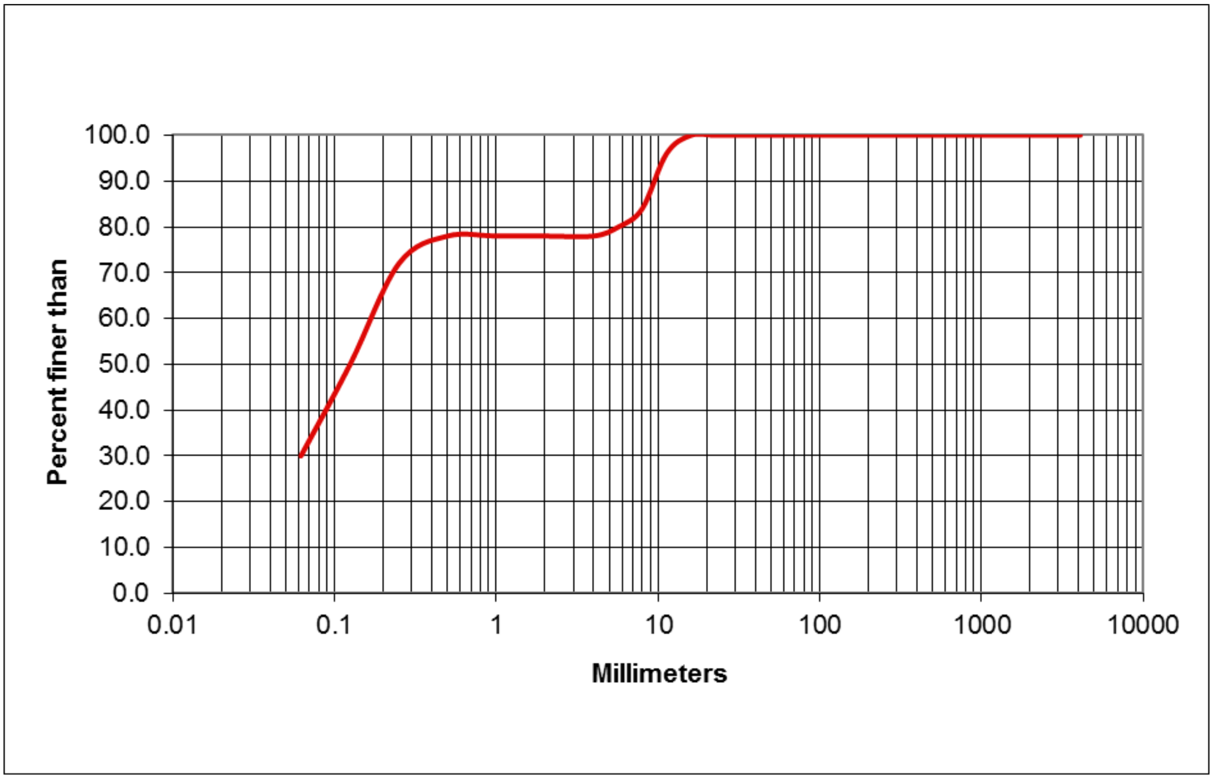


Figure 45. Site 6 – Black House Particle Size Distribution Chart and Histogram

Table 11. Site 8- Bee Ridge Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	15	30
Very Fine Sand	0.062 - 0.125	10	50
Fine Sand	0.125 - 0.25	11	72
Medium Sand	0.25 - 0.5	3	78
Coarse Sand	0.5 - 1.0	0	78
Very Coarse Sand	1.0 - 2.0	0	78
Very Fine Gravel	2.0 - 4.0	0	78
Fine Gravel	4.0 - 5.7	1	80
Fine Gravel	5.7 - 8.0	2	84
Medium Gravel	8.0 - 11.3	6	96
Medium Gravel	11.3 - 16.0	2	100
Coarse Gravel	16.0 - 22.6	0	100
Coarse Gravel	22.6 - 32	0	100
Very Coarse Gravel	32 - 45	0	100
Very Coarse Gravel	45 - 64	0	100
Small Cobble	64 - 90	0	100
Small Cobble	90 - 128	0	100
Large Cobble	128 - 180	0	100
Large Cobble	180 - 256	0	100
Small Boulder	256 - 362	0	100
Small Boulder	362 - 512	0	100
Medium Boulder	512 - 1024	0	100
Large Boulder	1024 - 2048	0	100
Bedrock	>2048	0	100
	Totals	50	



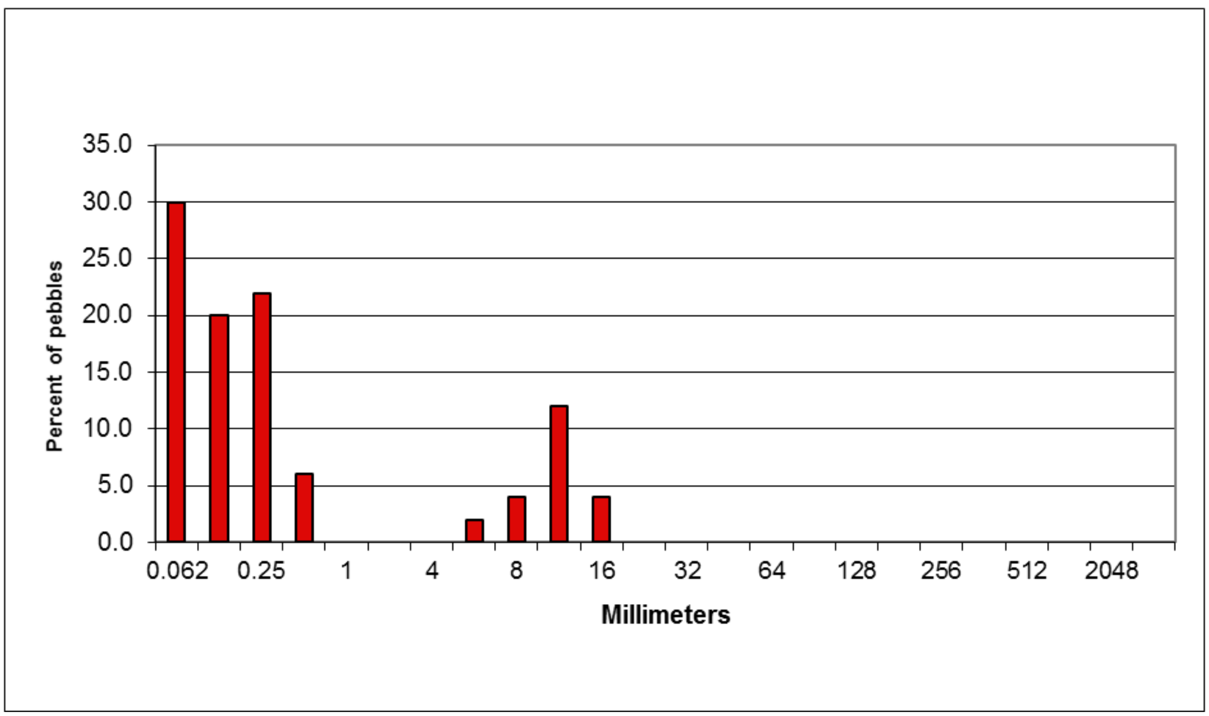
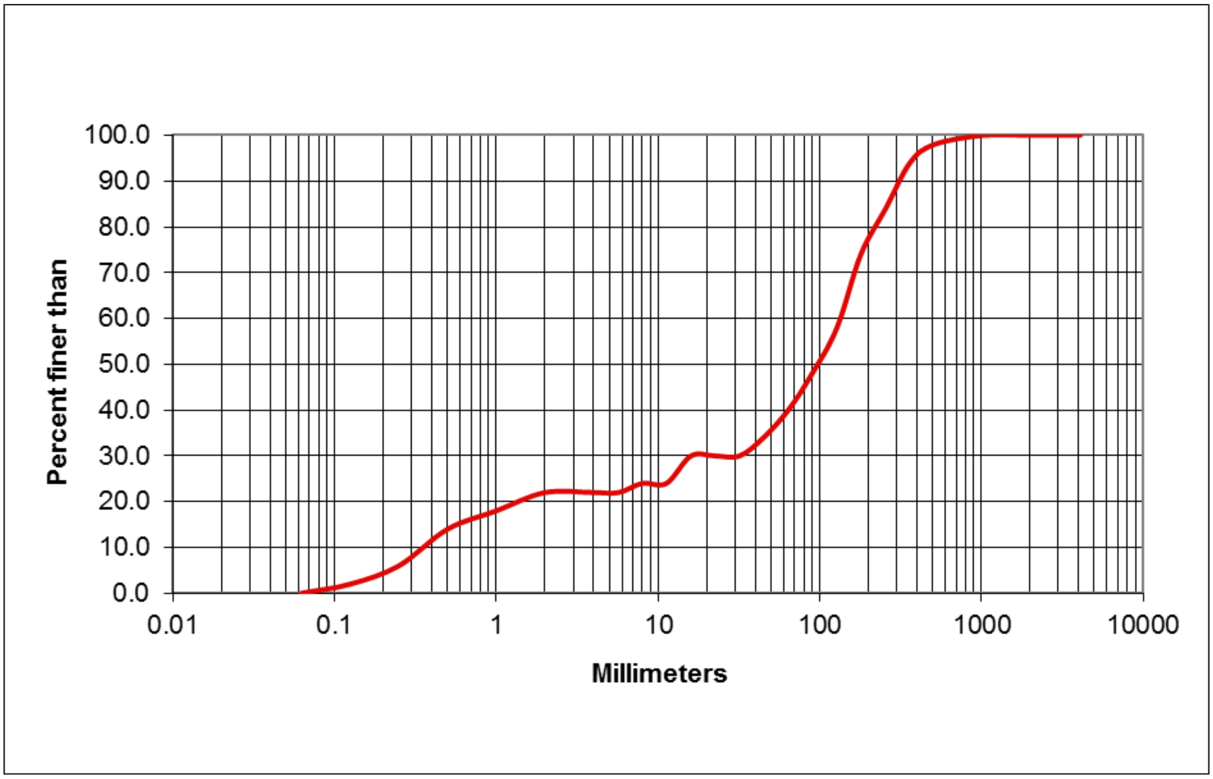


Figure 46. Site 8 –Bee Ridge Particle Size Distribution Chart and Histogram

Table 12. Site 9 - Underwood Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	0	0
Very Fine Sand	0.062 - 0.125	1	2
Fine Sand	0.125 - 0.25	2	6
Medium Sand	0.25 - 0.5	4	14
Coarse Sand	0.5 - 1.0	2	18
Very Coarse Sand	1.0 - 2.0	2	22
Very Fine Gravel	2.0 - 4.0	0	22
Fine Gravel	4.0 - 5.7	0	22
Fine Gravel	5.7 - 8.0	1	24
Medium Gravel	8.0 - 11.3	0	24
Medium Gravel	11.3 - 16.0	3	30
Coarse Gravel	16.0 - 22.6	0	30
Coarse Gravel	22.6 - 32	0	30
Very Coarse Gravel	32 - 45	2	34
Very Coarse Gravel	45 - 64	3	40
Small Cobble	64 - 90	4	48
Small Cobble	90 - 128	5	58
Large Cobble	128 - 180	8	74
Large Cobble	180 - 256	5	84
Small Boulder	256 - 362	5	94
Small Boulder	362 - 512	2	98
Medium Boulder	512 - 1024	1	100
Large Boulder	1024 - 2048	0	100
Bedrock	>2048	0	100
	Totals	50	



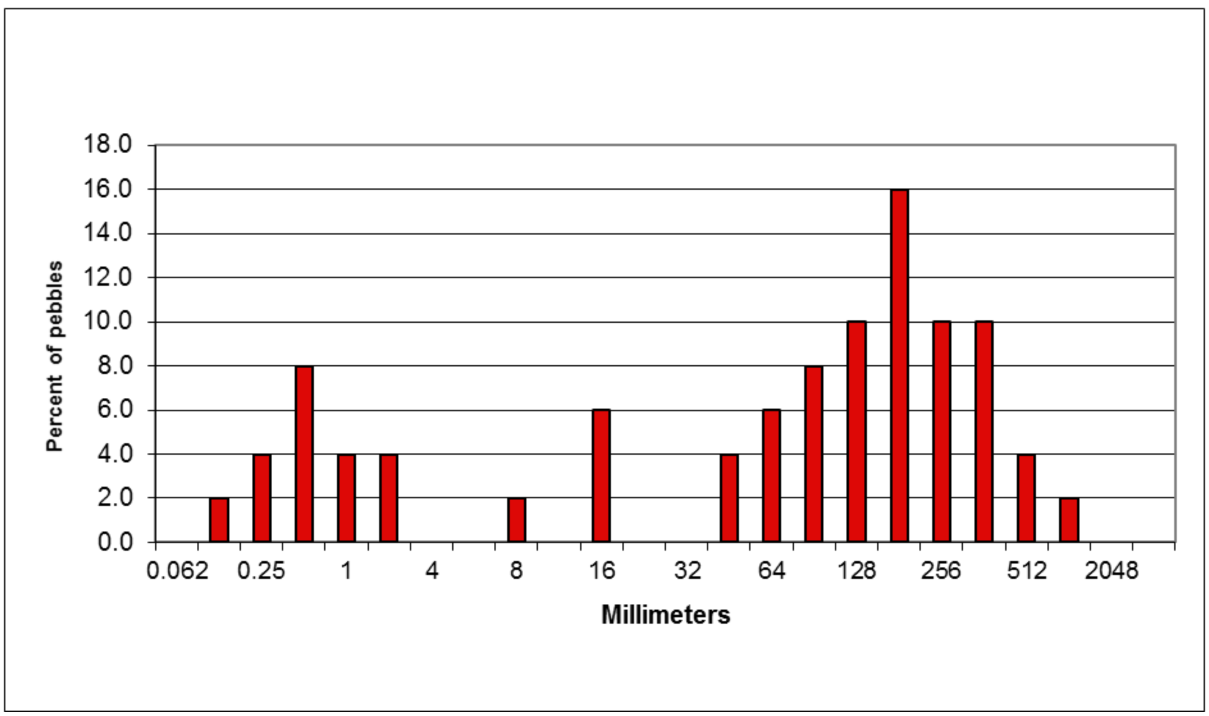
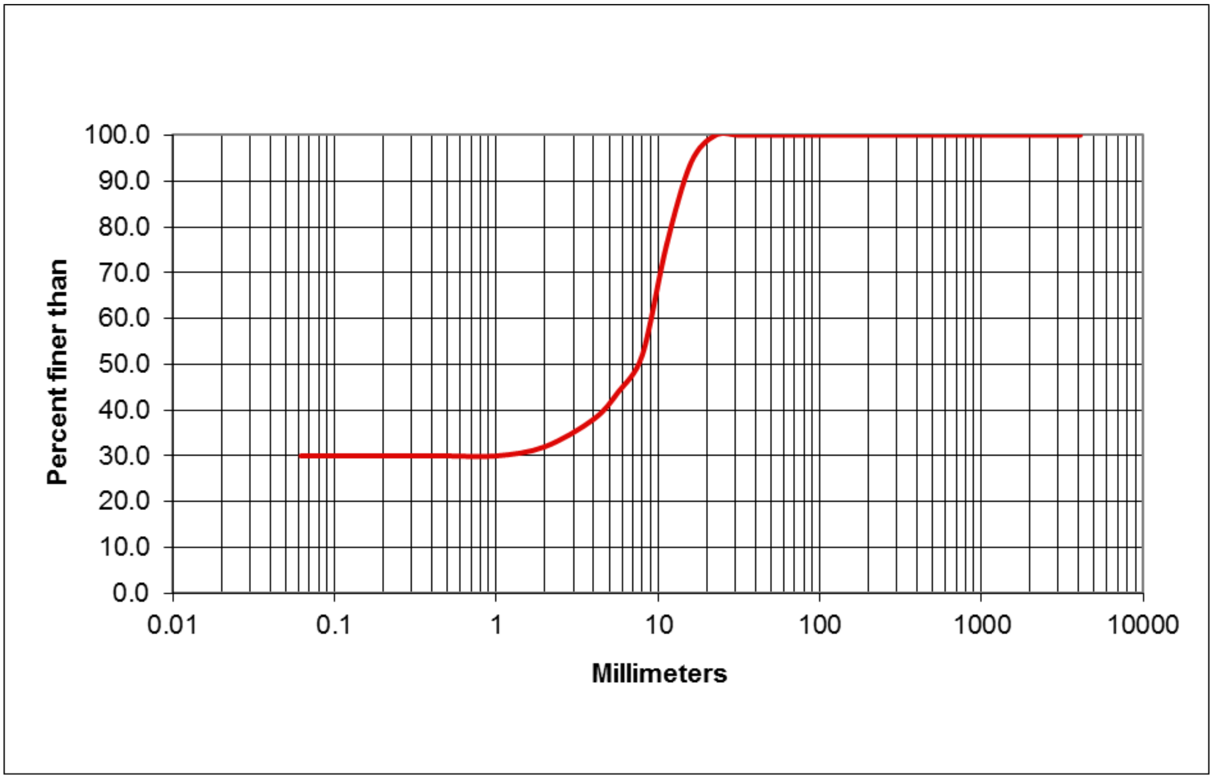


Figure 47. Site 9 - Underwood Particle Size Distribution Chart and Histogram

Table 13. Site 14 – Weaver Trib Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	15	30
Very Fine Sand	0.062 - 0.125		30
Fine Sand	0.125 - 0.25		30
Medium Sand	0.25 - 0.5		30
Coarse Sand	0.5 - 1.0		30
Very Coarse Sand	1.0 - 2.0	1	32
Very Fine Gravel	2.0 - 4.0	3	38
Fine Gravel	4.0 - 5.7	3	44
Fine Gravel	5.7 - 8.0	4	52
Medium Gravel	8.0 - 11.3	12	76
Medium Gravel	11.3 - 16.0	9	94
Coarse Gravel	16.0 - 22.6	3	100
Coarse Gravel	22.6 - 32		100
Very Coarse Gravel	32 - 45		100
Very Coarse Gravel	45 - 64		100
Small Cobble	64 - 90		100
Small Cobble	90 - 128		100
Large Cobble	128 - 180		100
Large Cobble	180 - 256		100
Small Boulder	256 - 362		100
Small Boulder	362 - 512		100
Medium Boulder	512 - 1024		100
Large Boulder	1024 - 2048		100
Bedrock	>2048		100
	Totals	50	



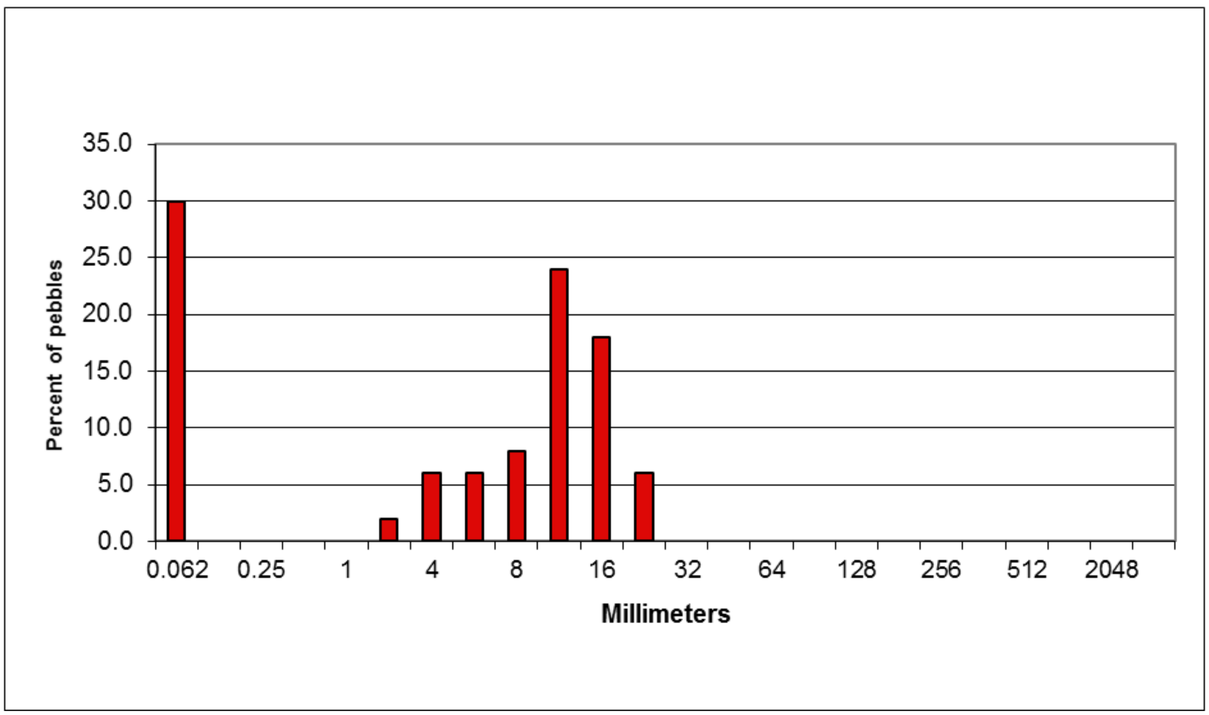
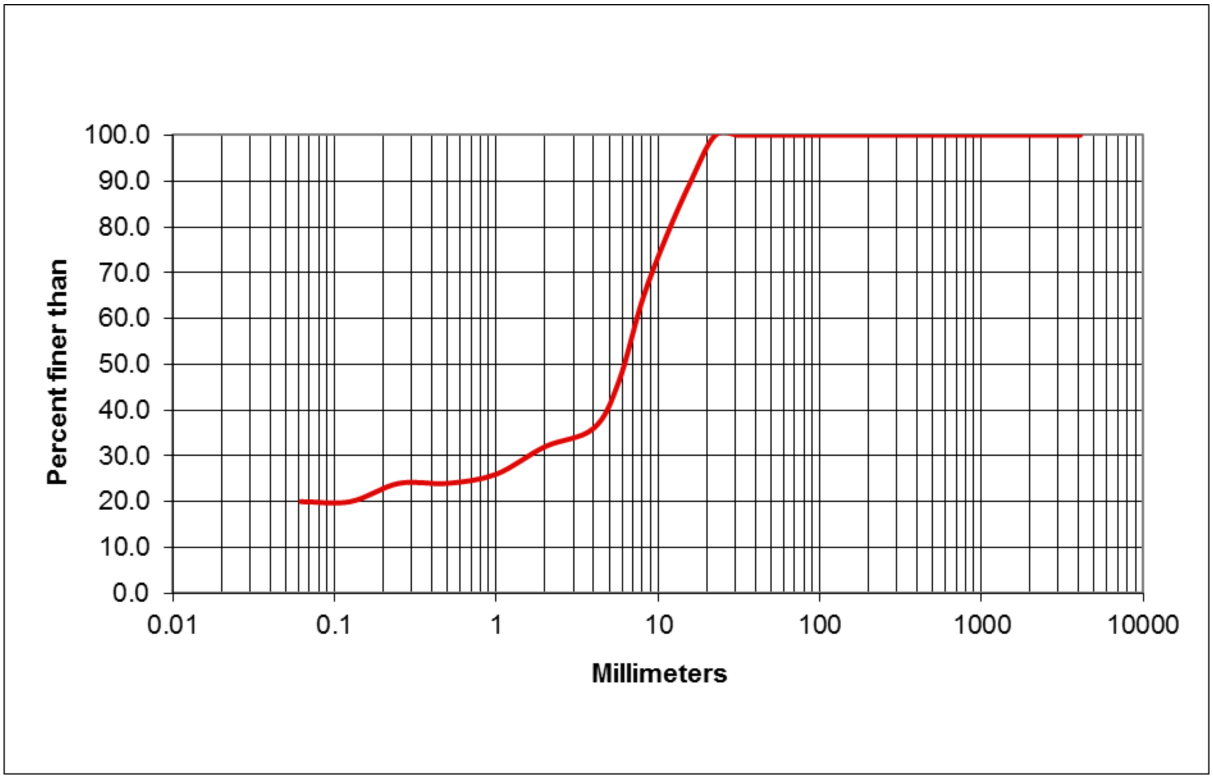


Figure 48. Site 14 – Weaver Trib Particle Size Distribution Chart and Histogram

Table 14. Site 14 - Weaver Down Wolman's Pebble Count Results

Class Name	Particle Size Class (mm)	Total	Cumulative %
Silt/Clay	<0.062	10	20
Very Fine Sand	0.062 - 0.125		20
Fine Sand	0.125 - 0.25	2	24
Medium Sand	0.25 - 0.5		24
Coarse Sand	0.5 - 1.0	1	26
Very Coarse Sand	1.0 - 2.0	3	32
Very Fine Gravel	2.0 - 4.0	2	36
Fine Gravel	4.0 - 5.7	5	46
Fine Gravel	5.7 - 8.0	9	64
Medium Gravel	8.0 - 11.3	7	78
Medium Gravel	11.3 - 16.0	6	90
Coarse Gravel	16.0 - 22.6	5	100
Coarse Gravel	22.6 - 32		100
Very Coarse Gravel	32 - 45		100
Very Coarse Gravel	45 - 64		100
Small Cobble	64 - 90		100
Small Cobble	90 - 128		100
Large Cobble	128 - 180		100
Large Cobble	180 - 256		100
Small Boulder	256 - 362		100
Small Boulder	362 - 512		100
Medium Boulder	512 - 1024		100
Large Boulder	1024 - 2048		100
Bedrock	>2048		100
	Totals	50	



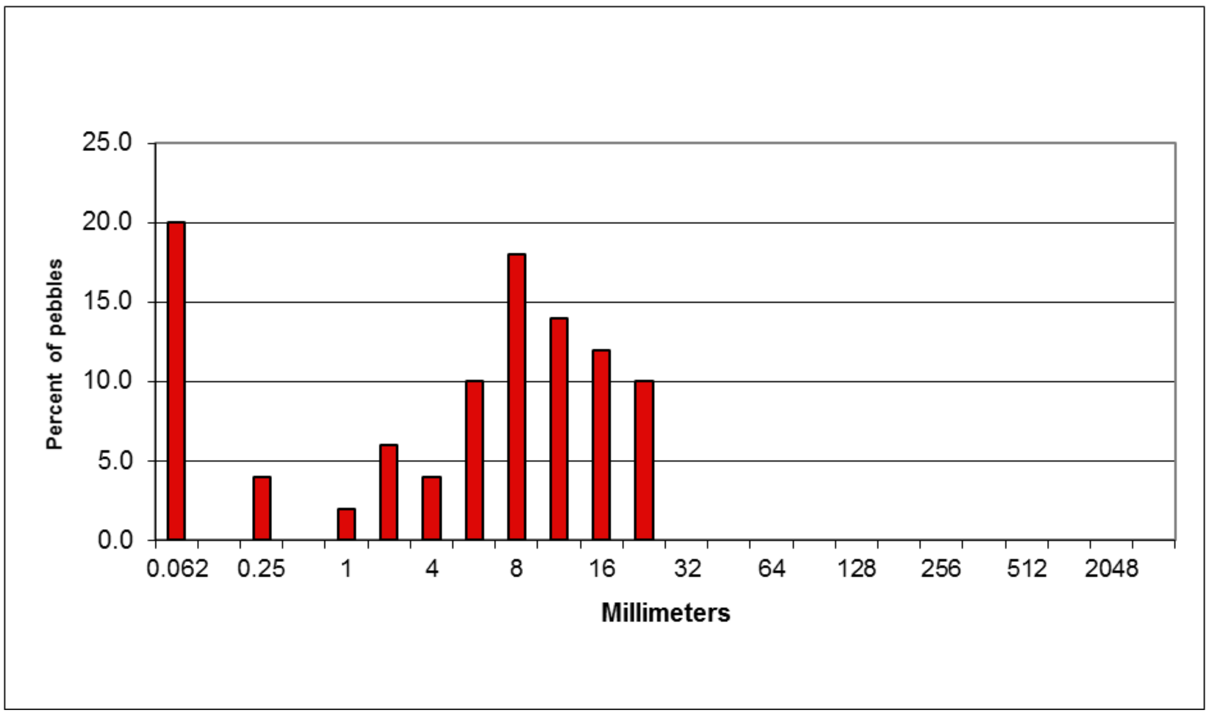


Figure 49. Site 15 - Weaver Down Particle Size Distribution Chart and Histogram

c. Survey Data Summary

Table 15. Survey Data for Sites 1 - 5

Measurement	**1. UT Groom**		**2. UT W Fork Coyte**	**3. W Fork Coyte**	**4. Bandy**	**5. Laurel**
	x1	**x2**	**x1**	**x1**	**x1**	**x1**
Area	2.2	2.2	3.2	9.6	18.4	150.5
Width	5.2	5.1	5.7	9.8	11.8	43.6
Depth	0.4	0.4	0.6	1.0	1.6	3.4
dmax	0.8	0.8	0.9	1.4	2.6	4.2
W/d	12.3	11.6	10.4	10.0	7.5	12.6
Wfpa	20.2	33.4	29.6	46.6	41.6	113.3
ER	3.9	6.5	5.2	4.8	3.5	2.6
S	0.005		0.007	0.004	0.002	0.005
d50	sand		sand	sand	sand	gravel
Type	E5		E5	E5	E5	C4

Table 16. Survey Data for Sites 6 - 10

Measurement	6. Black House		7. UT Slave Falls	8. UT Bee Ridge		9. Underwood	10. Otter
	x1	**x2**	**x1**	**x1**	**x2**	**x1**	**x1**
Area	30.5	39.4	8.3	3.5	3.9	14.4	117.5
Width	23.9	22.6	9.7	8.1	7.3	11.6	53.0
Depth	1.3	1.7	0.9	0.4	0.5	1.2	2.2
dmax	1.8	2.1	1.5	1.0	0.8	1.6	3.3
W/d	18.8	13.0	11.3	19.1	13.7	9.4	23.9
Wfpa	120.0	120.0	64.0	40.3	35.2	32.8	152.0
ER	5.0	5.3	6.6	5.0	4.8	2.8	2.9
S	0.004		0.004	0.005		0.028	0.007
d50	gravel		sand	sand		cobble	cobble
Type	C4		E5	C5		E3b	C3

Table 17. Survey Data for Sites 11 - 15

Measurements	11. Obed	12. N Chickamauga	13. Basses	14. Weaver Trib		15. Weaver Down		
	x1	**x1**	**x1**	**x1**	**x2**	**x1**	**x2**	**x3**
Area	835.4	432.9	101.2	5.2	4.8	9.7	13.2	11.3
Width	107.8	93.3	26.0	9.3	8.2	10.9	11.7	10.0
Depth	7.8	4.6	3.9	0.6	0.6	0.9	1.1	1.1
dmax	9.1	7.5	5.6	1.0	0.9	1.2	1.4	1.6
W/d	13.9	20.1	6.7	16.7	14.2	12.1	10.3	8.9
Wfpa	197.0	133.0	167.0	28.0	29.0	17.0	16.5	16.0
ER	1.8	1.4	6.4	3.0	3.5	1.6	1.4	1.6
S	0.0006	0.0311	0.0012	0.011		0.0067		
d50	cobble	boulder	gravel	gravel		gravel		
Type	F3	B2	E4	C4		B4c		

Vita

Ryan Hodges was born in Maryville, TN, to the parents of Vicky and Joe Hodges. He is the youngest to his sister Rachel Hodges. He attended William Blount High School in Maryville, TN from 2004 – 2008. After graduation, he headed to the University of Tennessee where he was introduced to the Biosystems Engineering and Soil Science Department. Ryan worked for various professors in the department in the 5 years he was there and was motivated to continue his education. He obtained a Bachelor's of Science degree from the University of Tennessee in May 2013 in Biosystems Engineering with a minor in Biosystems Engineering Technology. He accepted a graduate research assistantship at the University of Tennessee, Knoxville, in the Biosystems Engineering Department working for Dr. Andrea Ludwig. Ryan graduated with his Masters of Science degree in Biosystems Engineering and a minor in Watershed in December 2015. He is currently living in Chattanooga, TN applying his experience to the world of engineering seeking to gain his engineering license.