# Stream Assessment and Design Report
# Sleepy Creek Near Smith Crossroads
# Morgan County, West Virginia

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## INTRODUCTION

Sleepy Creek is a large winding perennial stream located in the Eastern Panhandle of West Virginia. Sleepy Creek flows 42 miles north from near Bloomery, Virginia into the Potomac River at the village of Sleepy Creek, West Virginia. The creek is composed of the main branch, the middle fork, and the south fork, all of which join in the area of Stotlers Crossroads. Meadow Branch, which flows from the east, joins Sleepy Creek about three miles upstream from its confluence with the Potomac River. In additions to these four main Branches, another 194 smaller streams add up to a total of 320 miles of streambed. This network of streams drains approximately 93,000 acres (145 Square miles) of land in the Sleepy Creek watershed.

Approximately one-half of the Sleepy Creek watershed is forested, one-third is farmland, and the remaining area is homes and small businesses. Businesses are mainly located along the main transportation corridors on the north-south U.S. Route 522 or the east-west WV Route 9. The boundary of the watershed is made up of three mountain ranges and the Potomac River. Cacapon Mountain is located to the west. Sleepy Creek Mountain and Third Hill Mountain are located to the east, and the Potomac River is located to the north. The topography of the watershed is varying mountain heights and associated valleys. The Sleepy Creek watershed is situated within the valley and ridge physiographic province of Maryland, Virginia, and West Virginia.

**Figure 1** depicts the sub-watersheds in the Sleepy Creek Watershed.

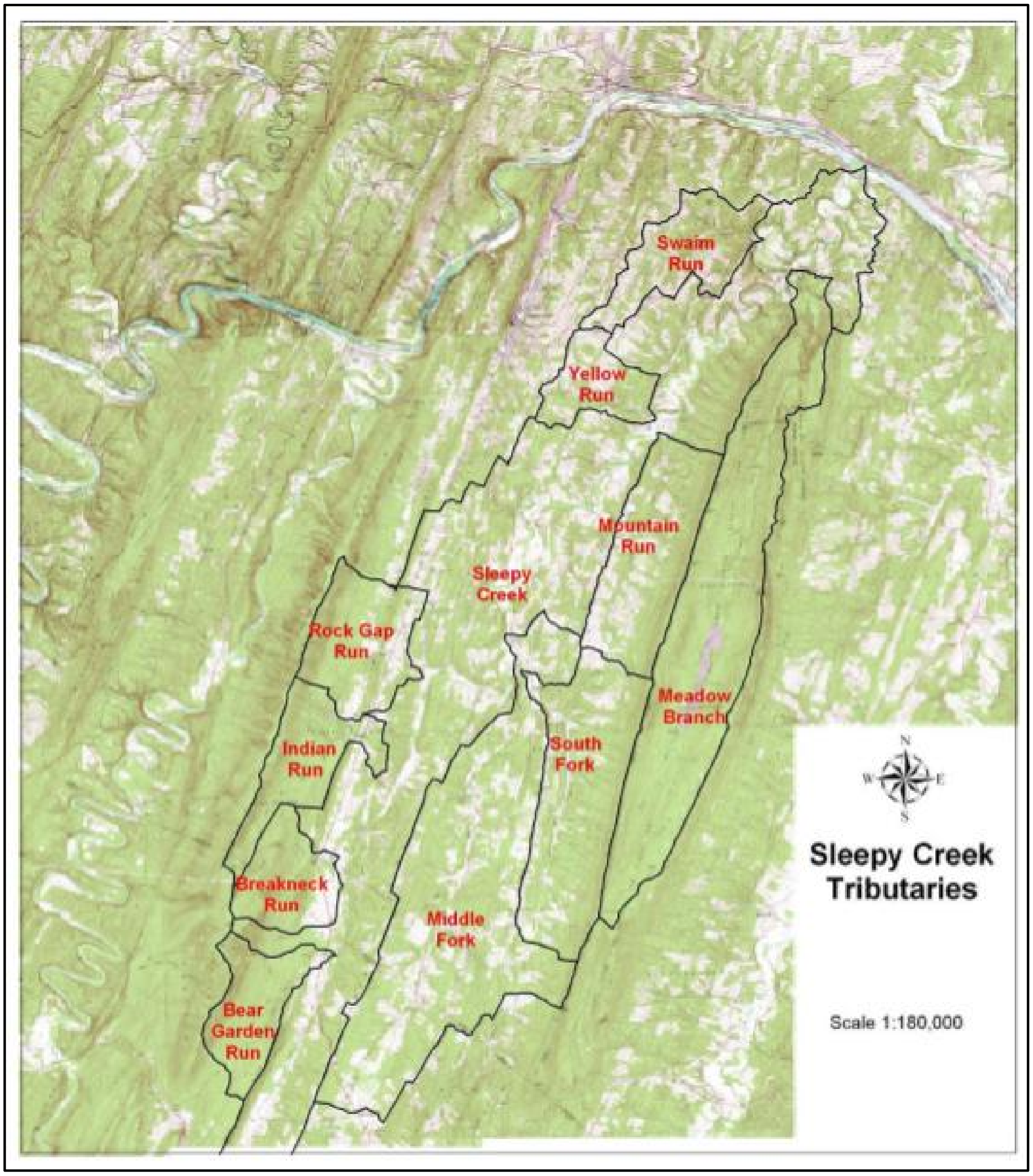
The Sleepy Creek Watershed Association, incorporated under West Virginia charter as a 501(c)(3) nonprofit organization, is a volunteer citizens group whose purpose is to protect and preserve Sleepy Creek and its watershed. A primary function of the organization is to educate and involve the public in the importance of the watershed and how to best protect it.

The major threat to the watershed is residential and commercial development that will lead to stream degradation. Agricultural practices that impact the riparian zone also contribute to stream degradation. As of 2006 the population of Morgan County was about 15,000 people with growth recorded at a pace of 24 percent for the 1990 to 2000 census period.

In the 2006 report entitled *Sleepy Creek Watershed Assessment*, eight resource concerns were identified; Riparian Zones, Biodiversity, Threatened and Endangered Species, Land Development, Stream Bank Erosion, Wetlands, Soil Erosion, and Water Quality.

The *Sleepy Creek Watershed Assessment* included the results of a *Stream Visual Assessment* that was completed in 2005. Sleepy Creek was surveyed on foot and by kayak to pinpoint critical areas of stream bank erosion, sedimentation, inadequate riparian buffers, and to locate the confluence of tributaries and drainage-ways for mapping. Sleepy Creek was mapped with data points established using Geographic Information System (GIS) and Global Positioning System (GPS) coordinates. A total of 308 points of reference were collected along 33.1 miles of the main stem. Maps were produced employing these data points on digital USFS 1:24,000 topographic base maps, along with satellite image layers (mrSIDS). A database of information about each location was developed, with nine maps covering the main stem of the stream, linked with over 1,000 digital photographs.

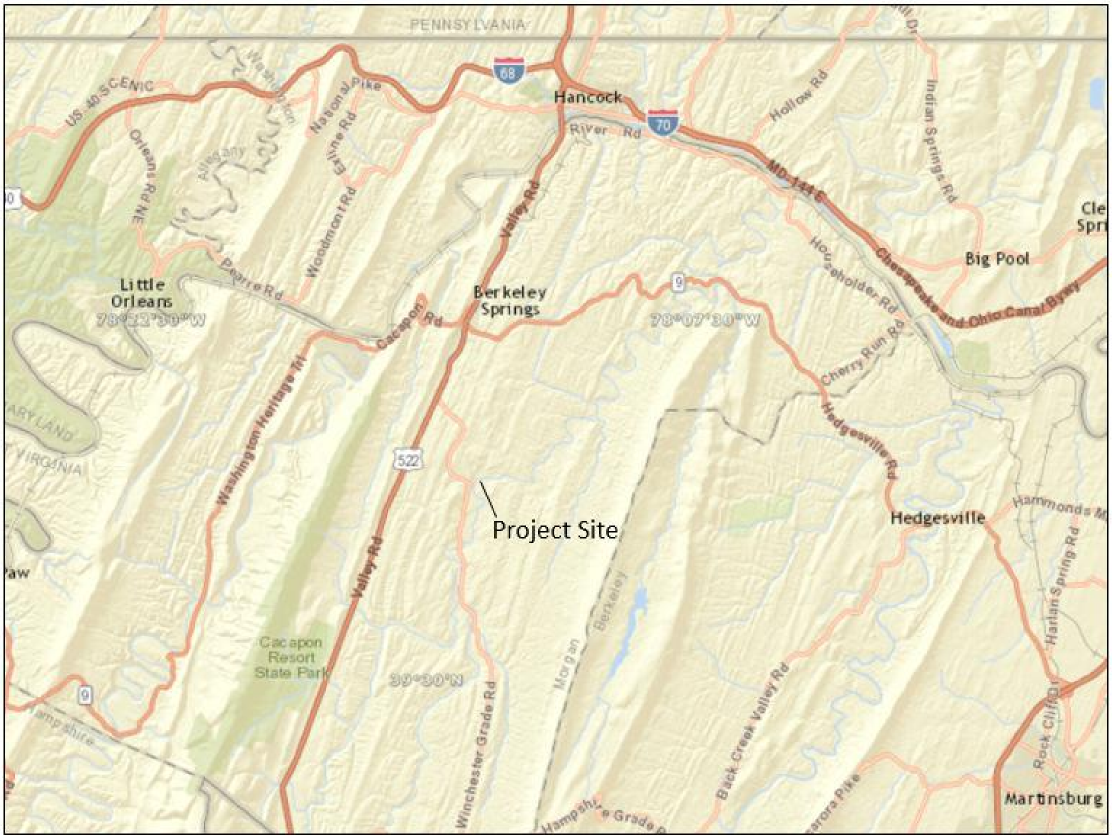
**Figure 1. Subwatersheds of the Sleepy Creek Watershed**
Source: *Sleepy Creek Watershed Assessment 2006*



## PROJECT PURPOSE

The purpose of this project is to restore a highly eroding stream bank along approximately 800 feet of Sleepy Creek downstream of the bridge at Spriggs Road, south of Berkeley Springs, West Virginia (see **Figure 2**). The project is an on-going effort by the Sleepy Creek Watershed Association to improve water quality in the creek. The site of this proposed streambank stabilization is one of many identified by the Association for future work. The streambank is located on an outer meander bend of the creek. The eroded bank is migrating westward, impacting the forested riparian zone.

**Figure 2. Vicinity Map**



## GEOMORPHIC ASSESSMENT

### BANKFULL HYDRAULIC GEOMETRY AND BANKFULL DISCHARGE

On February 24th, 2017, the Partnerships for Ecological Restoration team conducted a topographic survey on the banks of and within Sleepy Creek at the study area. A longitudinal survey in the thalweg of the creek was generated from the topographic survey data. On April 29 and 30, 2017, Partnerships for Ecological Restoration performed four measured cross sections across Sleepy Creek downstream of the Spriggs Road Bridge. The cross sections were conducted with a surveyor's level and stadia rod. The purpose of the cross sections was to assess existing conditions of the stream channel and determine bankfull discharge (flow) and channel characteristics. Stakes were driven into the ground at each cross section that can be recovered for future reference. The cross sections were also used to assess changes in shear stress and bankfull flow elevations resulting from proposed bank stabilization treatments.

The cross sections were entered into the Ohio Department of Natural Resources' *The Reference Reach Spreadsheet Version 4.3*. This spreadsheet is highly used by stream restoration professionals to evaluate the stream's dimension, pattern, and profile. It can be used to enter and organize data for a single channel reach. It includes worksheets for channel cross section dimension, meander form, longitudinal shape profile, and channel material. Data derived in the spreadsheet can be reduced to dimensionless ratios allowing comparison within and between channels.

Under stable conditions, bankfull field indicators can be used to estimate the bankfull stage. These indicators generally include:

- The height of depositional features such as point bars
- A change in vegetation, especially the lower limit of perennial species
- Slope or topographic breaks along the bank
- Undercuts in the bank
- Stain lines or the lower extent of lichens on boulders

Reliable bankfull field indicators exist along the right bank of Sleepy Creek within the study area. For the most part the bankfull stage corresponds to the top of bank or to a shelf near the top of the bank. The report *Development and Analysis of Regional Curves for Streams in the Non-Urban Valley and Ridge Physiographic Province, Maryland, Virginia, and West Virginia*, was used to calibrate and validate the bankfull stage at the project site.

The regional curves report cited above contains regression equations that are used to calculate bankfull discharge and bankfull channel characteristics. Bankfull stage and discharge are the bases for natural channel design. Bankfull cross sectional area, bankfull width, and mean bankfull depth are calculated as a function of drainage area. Following are the equations for these variables:

$A = 12.595\ DA^{0.7221}$
$W = 12.445\ DA^{0.4363}$
$D = 1.001\ DA^{0.2881}$
$Q = 43.249\ DA^{0.7938}$

The watershed of Sleepy Creek at the confluence with the Potomac River is 145 square miles. Approximately 75 square miles of the watershed lies downstream of the project site, and therefore the drainage area at the project site is approximately 70 square miles. Entering 70 square miles into the regression equations yields the following:

Cross sectional area = 270.7 square feet
Width = 79.4 feet
Depth = 3.4 feet
Discharge = 1260 cubic feet per second (CFS)

The four cross sections and their bankfull hydraulic geometry are included in Appendix B. The bankfull stream widths for the four cross sections are 79.7, 73.9, 62.8, and 72.1, respectively, and the mean bankfull depths are 3.5, 3.6, 4.0, and 3.7, respectively. These widths and depths correspond well to the calculated regional curve widths and depths. As can be seen on the dimension graphs in the appendix, the bankfull stage that yields the discharge approximated by the regional curves lies at or near the top of the right bank.

The bankfull velocity, discharge, and hydraulic geometry, as well as shear stress and stream power, are tabulated below the graphs in Appendix B.

### MANNING'S COEFFICIENT

Manning's roughness coefficient is one of the variables used in Manning's Equation for calculating bankfull velocity and discharge. The other variables are hydraulic radius (cross sectional area divided by the wetted perimeter) and water surface slope. The slope of the bankfull regression equation was used for this geomorphic analysis. Manning's roughness coefficient was calculated from two pebble counts collected on April 29th, 2017. A roughness coefficient of .030 was used for Cross Section 1 and .031 was used for Cross Sections 2, 3, and 4.

### ROSGEN STREAM CLASSIFICATION

From the cross section data, the ODNR reference reach spreadsheet calculates the width to depth ratio, entrenchment ratio, and channel slope, which are needed to classify the creek. The height of the flood-prone area is defined as two times the maximum bankfull depth. The creek classifies as the C3 stream type. C3 streams are cobble bed streams characterized as moderately meandering, riffle-pool, with a well-developed floodplain. They have gentle channel gradients of less than 2%, and display a high width/depth ratio. The riffle/pool sequence of the C3 stream type is on average at 5-7 bankfull channel widths.

### BANK HEIGHT RATIO AND VERTICAL STABILITY

The bank height ratio (BHR) is the ratio of the height of the low bank to the maximum bankfull depth. It is a measure of the degree of vertical incision, or down-cutting. The low bank is the right bank (looking downstream) within the study area. BHRs greater than 1.3 are considered vertically unstable and BHRs greater than 1.5 are considered highly unstable (Rosgen 2002). The BHRs for the four cross sections are 1.0, 1.1, 1.0, and 1.1. This is significant in that Sleepy Creek is not incised and the right bank is vertically stable. Only the left bank within the study area is vertically unstable. Another measure of vertical stability is the ratio of the bank height to the bankfull height on the bank. This ratio is used in the BANCS assessment discussed below. For eight locations along the left bank the bank height/bankfull height ratio was rated very high for two sites and extreme for six sites.

## STREAMBANK EROSION

The rate of streambank erosion can be predicted by a methodology developed by Rosgen entitled Bank Assessment for Non-point Source Consequences of Sediment (BANCS). In the Chesapeake Bay Program's *Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects*, approved in 2013, the expert panel adopted the BANCS methodology for estimating streambank erosion rates. From their literature review the panel and case studies, the panel also established default values for nitrogen and phosphorus loads from soils eroded from stream banks. Studies have shown that when the BANCS method is properly applied it can be an excellent predictor of the streambank erosion rate. An estimate of the pre-project erosion rate is made by performing Bank Erosion Hazard Indicator (BEHI) and near bank stress (NBS) assessments for the stream bank within the restoration reach. BEHI and NBS scores are then used to estimate annual lateral erosion rates from a regional bank erosion curve.

The pre-project lateral erosion rate is then multiplied by the length and height of the study reach bank to estimate the volume of sediment eroding from the bank per year. This volume is then multiplied by the bulk density of the bank soil to estimate the annual sediment loading rate in tons/year.

To estimate nutrient loading rates, the sediment loading rates are multiplied by the median total phosphorus and total nitrogen concentrations found in stream sediments. These nutrient loading rates are 1.05 pounds of phosphorus per ton of sediment and 2.25 pounds of nitrogen per ton of sediment. The expert panel concluded that qualified stream restoration projects reduce these loads by 50%.

A BANCS assessment was conducted for the Sleepy Creek study reach. Eight BEHIs were conducted, all on the left bank (facing downstream). BEHIs measure the bank height relative to the bankfull height, the depth of the root zone in the bank, the average root density, the bank angle, and bank protection at the toe of the bank. Adjustments are then made for bank materials and stratification of unstable layers in relation to the bankfull stage. Near bank stress was given a moderate rating for the BANCS analysis. Although the ratio of the radius of curvature to bankfull width (WARSSS Method 2 for estimating near bank stress) suggests a low near bank stress, the ratio of the near bank maximum depth to mean depth (Method 5) suggests a low to moderate near bank stress rating. There are several locations along the stream study reach where the stream flow is directed into the left bank, and under bankfull conditions exerts moderate to high shear stresses on the bank. Therefore, a near bank stress rating of moderate was used for this analysis. Data sheets for the BEHI in Appendix A. BEHI results varied from High to Extreme potential for streambank erosion.

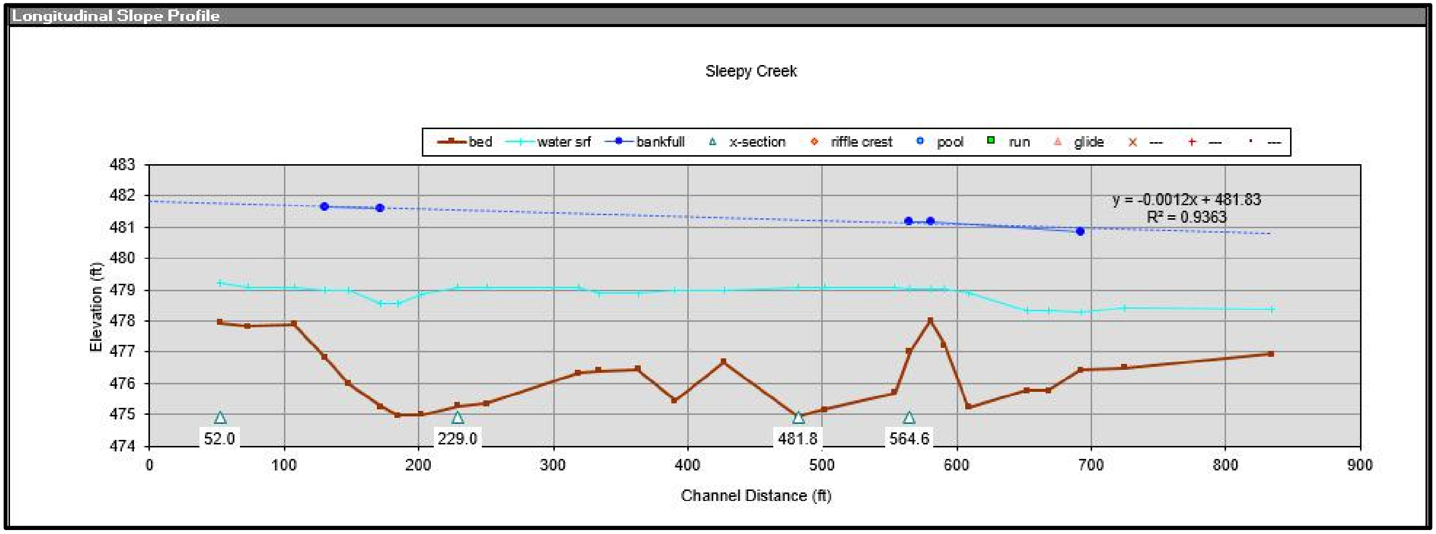
From the BANCS assessment, the total sediment erosion rate for 612 feet of Sleepy Creek's left bank was estimated at 163 tons per year, while phosphorus load was estimated at 171 pounds per year and nitrogen at 372 pounds per year. The expert panel also concluded that streambank stabilization projects can conservatively reduce sediment loads by 50%. Accordingly, the streambank stabilization project at Sleepy Creek may reduce annual sediment by approximately 81.5 tons/year, nitrogen by 186 pounds per year, and phosphorus by 85.5 pounds per year. However, if only 400 feet of streambank protection is provided where the erosion condition of the bank is the worst along the study reach, the sediment, nitrogen, and phosphorus may be reduced by 54 tons, 124 pounds, and 57 pounds, respectively.

## SEDIMENT TRANSPORT

The Bedload Assessment for Gravel-Bed Streams, developed by the U.S. Forest Service in 2009, contains six bedload transport equations developed specifically for gravel-bed streams. Transport capacities are calculated on the basis of field measurements of channel cross section geometry, reach-average slope, and bed material grain size. Two of the equations require a surface grain size distribution from the pebble count data, and the others require a grain size distribution from a sub-pavement or point bar wet sieve analysis. The two that require surface samples are the Parker (1990) and Wilcock and Crowe (2003). The cross section distances and elevations from the geomorphic survey were entered into the model for Cross Section 2, and the data from the pebble count for Cross Section 2 and average water surface slope were also entered into the model.

The Parker and Wilcock and Crowe models indicate that minimal sediment is transported at the project site under bankfull conditions. This can be explained by the fact that the hydraulic slope of the creek is minimal at the project site (0.12%), and the large particle size of the stream bed (D50 of 72mm - small cobble, and D84 of 150mm – large cobble) relative to the average boundary shear stress. The low slope of the channel is caused by a natural rock grade control accumulation at Station 5+80 along the study each. Upstream of this structure the low flow water surface slope is nearly zero, except for a riffle that starts at Station 1+07 along the reach. Figure 3 below depicts the profile of the stream bed, the profile of the water surface, and the profile of the bankfull slope that was measured on February 24, 2017.

**Figure 3. Sleepy Creek Profile**



## SHEAR STRESS RATIO

The shear stress ratio is used as an indicator of sediment competence at various discharge stages within the stream channel. The shear stress ratio is the ratio of the average boundary shear stress to the critical shear stress required to initiate the movement of channel bed material. It is defined by the equation:

$$\tau e = \tau o \,/\, \tau c,$$

Where τe is the shear stress ratio, τo is the average boundary shear stress, and τc is the critical shear stress. The average boundary shear stress is defined by:

$$\tau o = YRS$$

Where Y is the specific weight of water (62.4 pounds per cubic feet), R is the hydraulic radius (nearly identical to depth for streams having a W/d ratio greater than 12), and S is the channel slope.

The critical shear stress is calculated as follows:

$\tau c = \theta(Ys - Y)D$, where θ is Shields parameter, Ys is the specific weight of sediment and Y is the specific weight of water. Shields parameter is a function of particle size and the density of particle arrangement. The pebble count D50 particle size for Cross Section 2 of 72mm, or 0.236 feet was used for the analysis.

Selecting the appropriate value for Shields parameter is critical to this analysis. The paper *Stability Thresholds for Stream Restoration Materials*, by Craig Fischenich, May 2001 was used for selecting Shields parameter. On page 3 of the paper is a listing of Shields parameters that are based on stream bed particle size. For small cobble, which the D50 particle sizes of 72mm is considered, the Shields parameter listed is 0.052, and Shields parameter 0.052 was used to calculate critical shear stress, $\tau c = \theta(Ys - Y)D$,

Where Ys = 165.4 $\text{lb/ft}^3$ and Y = 62.4 $\text{lb/ft}^3$**.** Therefore, the critical shear stress required to move the 72 mm particle is 1.26 $\text{lb/ft}^2$. The critical shear stress required to initiate movement of the D84 of 150mm at Cross

Section 2 is 2.6 lb/ft². The average boundary shear stress for Cross Section 2 is 0.26 lb/ft². The shear stress ratio for the 72mm particle is therefore 0.21, and for the 150mm particle the shear stress ratio is 0.1.

A shear stress ratio of greater than one suggests that the stream is competent to transport sediment in the stream bed. For this Sleepy Creek reach upstream of the natural rock grade control structure the shear stress ratio is much less than one, suggesting that little sediment is being transported at the bankfull stage. This corroborates the findings of the sediment transport modeling.

A modified Cross Section 2 was created in the ODNR spreadsheet that mimics a design scenario of constructing a boulder revetment or riprap revetment extending 9 feet out from the toe of the bank. The 9-foot extension out from the bank allows adequate room for installing soil lifts behind the structure. In this case the average boundary shear stress remains essentially unchanged.

## DESIGN ALTERNATIVES

The main focus for this project is streambank stabilization. Severe erosion is occurring on the outside meander bend within the study area (the left bank facing downstream). The right bank, however, is much lower in height and is stable with several gravel and cobble point bars. Typically, the left bank varies in height from 6 to 8 feet, with a bank angle varying from 75 to 90 degrees, with a tree root overhang and undercut bank, and a narrow wooded riparian buffer containing 18 trees with a DBH of 12 inches or greater. The riparian buffer borders an agricultural field that the owner leases to a farmer.

One alternative to stabilize the eroding bank would be to provide protection of the toe of the left bank with a boulder revetment or riprap revetment and grading the bank back at a 3:1 slope. This would involve removing most of the wooded riparian buffer and replanting the graded slope with trees and shrubs. It would also involve some grading into the agricultural field which the owner opposes. However, over time this alternative would provide the greatest stability to the eroding bank.

Another alternative would be to provide protection of the toe of the left bank with a boulder and/or riprap revetment and installing vegetated soil lifts on a steep slope up to the tree root overhang. This alternative would protect the existing wooded buffer and would not encroach into the agricultural field. The soil lifts would be vegetated with deciduous shrubs native to the area and would stabilize the eroding bank. Soil lift technology is an accepted practice for erosion protection but may carry some risk of adjustment or failure should the natural fiber matting degrade before the roots of the plants stabilize the soil in the lifts. From an ecological perspective the soil lifts approach with toe protection is preferred because the wooded riparian buffer can be maintained and exposed tree roots that overhang and extend into the creek that provide shade and cover for fish can also be maintained.

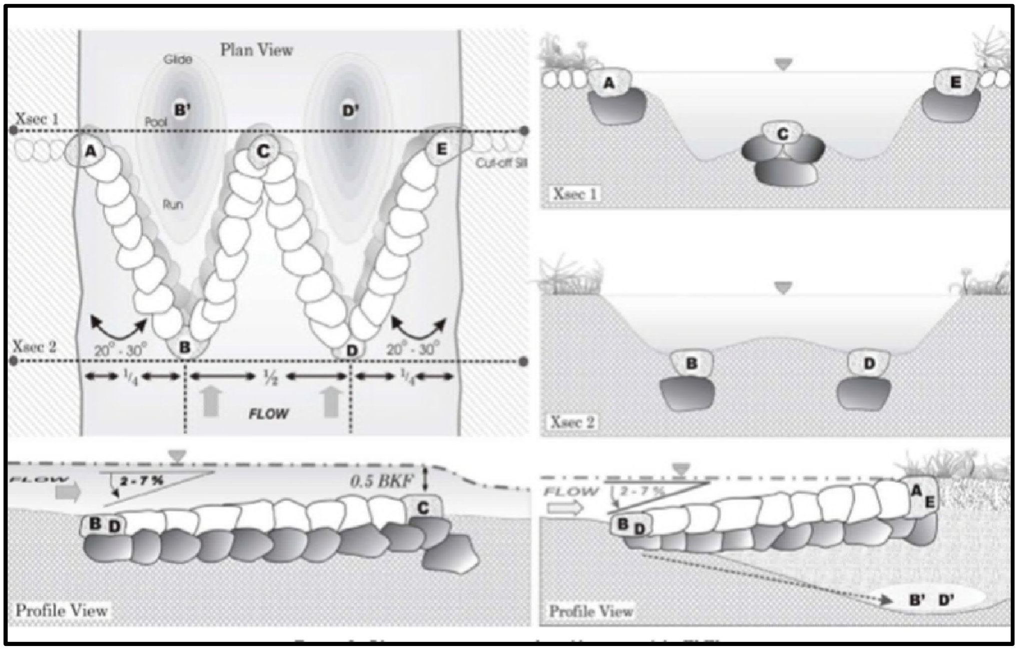
Alternatives that minimize encroachment of structures and grading into the creek would minimize the increase in stream flow elevations. A 9-foot extension into the creek for installation of boulder and/or riprap revetments increase bankfull water surface elevations (approximately the 1.5-year recurrence interval) by about 0.5 feet. This additional increase in flow elevation would be contained within the slope adjacent to the top of the right bank. Flows from larger storms, however, would be spread over the floodplain on the east side of the creek resulting in minimal or no increase in flood elevations. In addition, the natural rock grade control structure at the downstream end of the site could be lowered by 0.5 feet if necessary to compensate for the increase in water surface elevation for the more frequent storms. Lowering the elevation of the natural grade control would also increase the water surface slope through the reach and may improve sediment transport.

Four J-hook vanes are recommended for the site. J-hook vanes are used to deflect near-bank erosional forces away from unstable streambanks and into the center of the channel, and improve or create aquatic habitat through the formation of scour pools. The structure is identical to a straight rock vane with the addition of several gapped rocks placed in the middle third of the channel in a parabolic arc. The additional “J-rocks” create a scour pool with moderate to high fish habitat value. The four J-hook vanes would be placed in areas where the water depths are the least.

Grade control at the downstream end of the site is recommended to maintain stream bed elevations and prevent any down-cutting from occurring in the future. Given the 75-foot width of the stream, a W-Weir (“W” as looking in the downstream direction) is recommended for grade control. The objectives of W-Weir are to provide grade control on larger rivers (greater than 40 feet wide), enhance fish habitat, provide recreational boating variability in the stream, stabilize stream banks, and divert shear stresses away from the near bank region. The W-Weir will be designed in accordance with Rosgen’s *The Cross-Vane, W-Weir, and J-Hook Vane Structures…Their Description, Design, and Application for Stream Stabilization and River Restoration* (2006).

Below is an illustration of the W-Weir from Rosgen’s 2006 paper.

**Figure 4. W-Weir Plan, Cross Section, and Profile**



## ROCK SIZES FOR CONSTRUCTION

As discussed above, rock toe protection is proposed at the base of either the existing bank for the bank grading option or out from the bank for the soil lift option. Sizing of the rock used for construction is an important consideration towards reducing failure risk.

Fischenich (2001) provides data on critical shear stress levels required to entrain sediment particles. For the Sleepy Creek study area the average boundary shear stress is 0.25 pounds per square foot. For sinuous channels the maximum shear stress is a function of the ratio of the radius of curvature to channel width, and for Sleepy Creek with a radius of curvature of 368 feet, the maximum shear stress is 0.3 lb/ft$^2$. Fischenich recommends applying a factor of 1.1 to 1.2 to account for instantaneous maximums. After applying a factor of 1.2, the maximum critical shear stress is 0.36 lb/ft$^2$. Based on Fischenich's data, a shear stress of 0.36 lb/ft$^2$ will entrain coarse to very coarse gravel, but not cobbles and boulders.

For the riprap toe revetment, a graded mixture of rock ranging from 6 inches (medium cobble) to 36 inches (medium boulder) should withstand maximum shear stresses that are encountered in the Sleepy Creek channel. For the boulder revetment, boulders with an intermediate axis ranging from 2 to 3 feet should also withstand maximum shear stresses encountered in the channel.

For the J-hook vanes and the W-Weir, Rosgen has developed an empirical equation for sizing rock that is used in the construction of in-stream structures. Based on this equation rock with an intermediate axis of 2.4 feet should withstand maximum shear stresses in the channel. A technical specification requiring rock with a minimum 2 to 3-foot intermediate axis is recommended.

## SUMMARY

The left bank within the study reach is undergoing severe streambank erosion. Loss of sediment, nitrogen, and phosphorus from the creek banks are estimated at 81.5 tons, 186 pounds, and 85.5 pounds, respectively, per year. The existing water surface slope through the reach is minimal and bed particles are large, thereby limiting sediment transport.

The recommended method for restoring the eroding creek banks is the installation of boulder and riprap toe revetments extending 9 to 10 feet out from the left bank and installing soil lifts to stabilize the bank above the toe revetments. This method would minimize tree clearing and prevent encroachment into the adjacent agricultural field. This method would also protect the tree root overhangs that extend over and into the creek that provide shade and cover for fish. In-stream structures including one W-Weir for grade control and four J-Hook Vanes that direct flows toward the center of the stream channel away from the eroding bank are recommended.

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# APPENDIX A – BANCS DATA SHEETS

# TOTAL BANK EROSION CALCULATION

## Adapted from Worksheet 5-10 in WARSSS

| | | |
|---|---|---|
| Stream: Sleepy Creek | Total Bank Length: 612 feet | Stream Type: C3 |
| Observers: Hogan, Piskor | Date: April 29-30, 2017 | Graph Used: USFWS |

| **Station (ft.)** | **BEHI (adjective)** | **Near Bank Stress (adjective)** | **Erosion Rate (ft/yr)** | **Length of Bank (ft)** | **Bank Height (ft)** | **Erosion Subtotal (ft$^3$/yr)** |
|---|---|---|---|---|---|---|
| 14-40 Left Bank | High | Moderate | 0.15 | 26 | 6.4 | 25 |
| 40-130 Left Bank | Very High | Moderate | 0.8 | 90 | 7.7 | 554 |
| 130-233 Left Bank | Very High | Moderate | 0.8 | 103 | 6.8 | 560 |
| 233-333 Left Bank | High | Moderate | 0.15 | 100 | 9 | 135 |
| 333-407 Left Bank | Very High | Moderate | 0.8 | 74 | 8.2 | 485 |
| 407-455 Left Bank | High | Moderate | 0.15 | 48 | 7.8 | 56 |
| 455-546 Left Bank | Extreme | Moderate | 2.5 | 91 | 8 | 1,820 |
| 546-626 Left Bank | High | Moderate | 0.15 | 80 | 7.8 | 94 |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Note: NBS of Moderate was chosen because of high maximum pool depth to mean depth ratio and high radius of curvature width to bankfull width ratio. | | | | | **Total Erosion (ft$^3$/yr)** | 3,730 |
| | | | | | | |
| | | | | | **Total Erosion (yd$^3$/yr)** | 138 |
| | | | | | | |
| Bulk density of loam = 87.4 lb/ft$^3$ per nrcs | | | | | **Total Erosion (tons/yr)** | **163** |
| | | | | | | |
| Nitrogen Loading: 2.28 pounds N/ton of sediment | | | | | **Total N Loading (pounds)** | **372** |
| Phosphorus Loading: 1.05 pounds P/ton of sediment | | | | | **Total P Loading (pounds)** | **171** |
| | | | | | | |

*Worksheet 20. BEHI variable worksheet*

Stream: Sleepy Creek

Cross Section: Sta. 0+14

Date: 4/29/17

Observers: TH, UP

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 6.4 A | Bankfull Height (ft) 2.5 B | A/B = 2.6 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 4.2 D | Study Bank Height (ft) 6.4 A | D/A = 0.7 E |

**Weighted Root Density (G)**

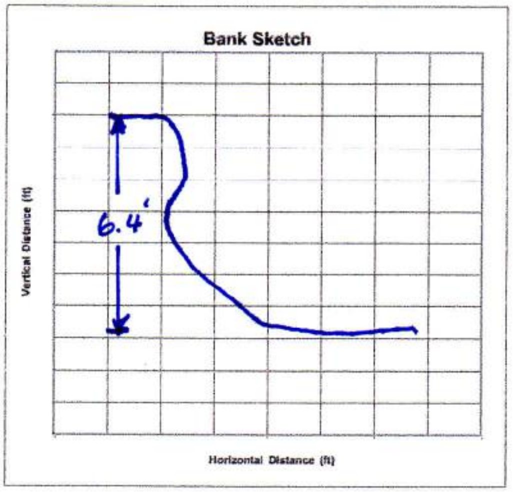
| | |
|---|---|
| Root Density (%) 30 F | F*E = 21 G |

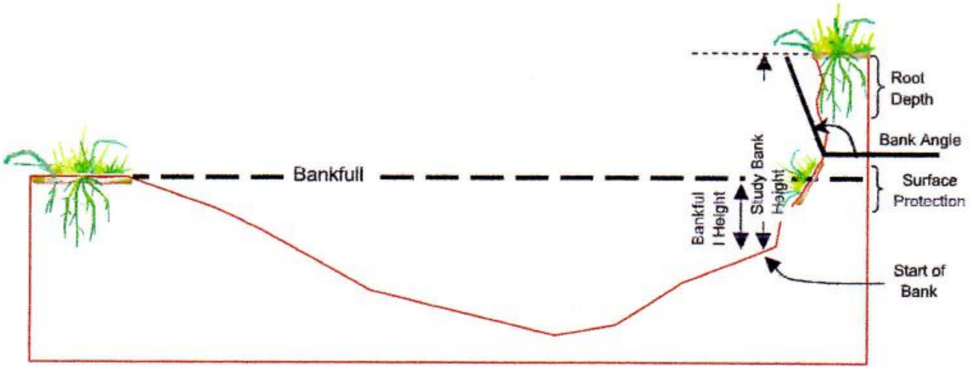
**Bank Angle (H)**

Bank Angle (Degrees) 85 H

**Surface Protection (I)**

Surface Protection % 0 I





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek Reach Sta 0+14 Date 4/29/17 Crew TH, VP

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Bank Height (ft):<br>Bankfull Height (ft): | | **Bank Height/ Bankfull Ht** | **Root Depth/ Bank Height** | **Root Density %** | **Bank Angle (Degrees)** | **Surface Protection%** |
| **Bank Erosion Potential** | **VERY LOW** | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | **Choice** | V: I: | V: ~~0.7~~ I: | V: I: | V: I: | V: I: |
| | **LOW** | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | **Choice** | V: I: | V: 0.7 I: 3.3 | V: I: | V: I: | V: I: |
| | **MODERATE** | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | **HIGH** | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | **Choice** | V: I: | V: I: | V: 21 I: 6.9 | V: 85 I: 7.3 | V: I: |
| | **VERY HIGH** | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | **Choice** | V: 2.6 I: 8.7 | V: I: | V: I: | V: I: | V: I: |
| | **EXTREME** | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: 0 I: 10 |

V = value, I = index

**SUB-TOTAL** (Sum one index from each column) 36.2

**Bank Material Description:**

**Bank Materials**

**Bedrock** (Bedrock banks have very low bank erosion potential)

**Boulders** (Banks composed of boulders have low bank erosion potential)

**Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)

**Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)

**Sand** (Add 10 points)

**Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| **VERY LOW** | **LOW** | **MODERATE** | **HIGH** | **VERY HIGH** | **EXTREME** |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 36.2

**BEHI RATING** High

*Worksheet 20. BEHI variable worksheet*

|  |  |  |  |
|---|---|---|---|
| Stream: Sleepy Creek | Cross Section: Sta. 0+40 | Date: 4/30/17 | Observers: TH, VP |

**Bank Height/Max Depth Bankfull (C)**

|  |  |  |
|---|---|---|
| Study Bank Height (ft) 7.7 A | Bankfull Height (ft) 2.5 B | A/B = 3.1 C |

**Root Depth/Bank Height (E)**

|  |  |  |
|---|---|---|
| Root Depth (ft) 3.0 D | Study Bank Height (ft) 7.7 A | D/A = 0.4 E |

**Weighted Root Density (G)**

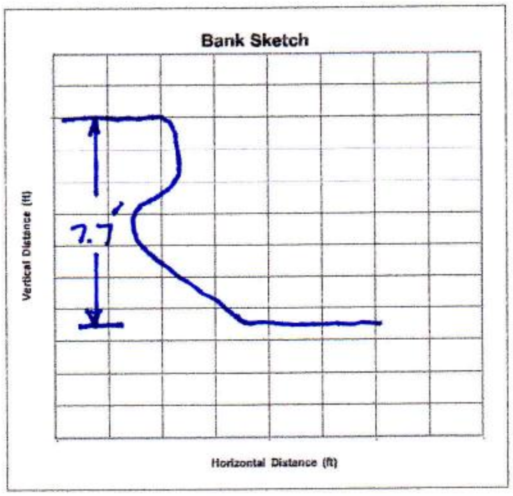
|  |  |
|---|---|
| Root Density (%) 30 F | F*E = 12 G |

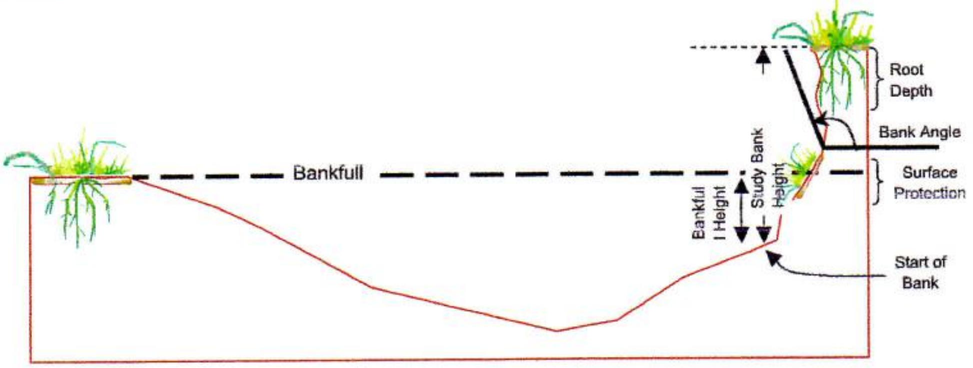
**Bank Angle (H)**

Bank Angle (Degrees) 85 H

**Surface Protection (I)**

Surface Protection % 0 I





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

**Bank Erosion Hazard Rating Guide**

Stream Sleepy Creek Reach Sta. 0+40 Date 4/30/17 Crew TH, UP

| | Bank Height (ft):<br>Bankfull Height (ft): | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| Bank Erosion Potential | VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: I: |
| | LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: I: |
| | MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | Choice | V: I: | V: 0.4 I: 4.7 | V: I: | V: I: | V: I: |
| | HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | Choice | V: I: | V: I: | V: I: | V: 85 I: 7.7 | V: I: |
| | VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | Choice | V: I: | V: I: | V: 12 I: 8.7 | V: I: | V: I: |
| | EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | Choice | V: 3.1 I: 10 | V: I: | V: I: | V: I: | V: 0 I: 10 |
| | V = value, I = index | | | | **SUB-TOTAL** (Sum one index from each column) | | 41.1 |

**Bank Material Description:**

**Bank Materials**

**Bedrock** (Bedrock banks have very low bank erosion potential)
**Boulders** (Banks composed of boulders have low bank erosion potential)
**Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)
**Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)
**Sand** (Add 10 points)
**Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 41.1

**BEHI RATING** Very High

*Worksheet 20. BEHI variable worksheet*

| | | | |
|---|---|---|---|
| Stream: Sleepy Creek | Cross Section: Sta. 1+30 | Date: 4/30/17 | Observers: TH, VP |

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 6.8 A | Bankfull Height (ft) 2.5 B | A/B = 2.7 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 1.8 D | Study Bank Height (ft) 6.8 A | D/A = 0.3 E |

**Weighted Root Density (G)**

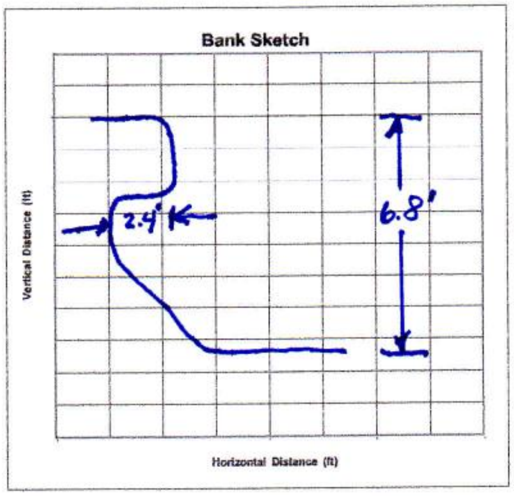
| | |
|---|---|
| Root Density (%) 20 F | F*E = 6 G |

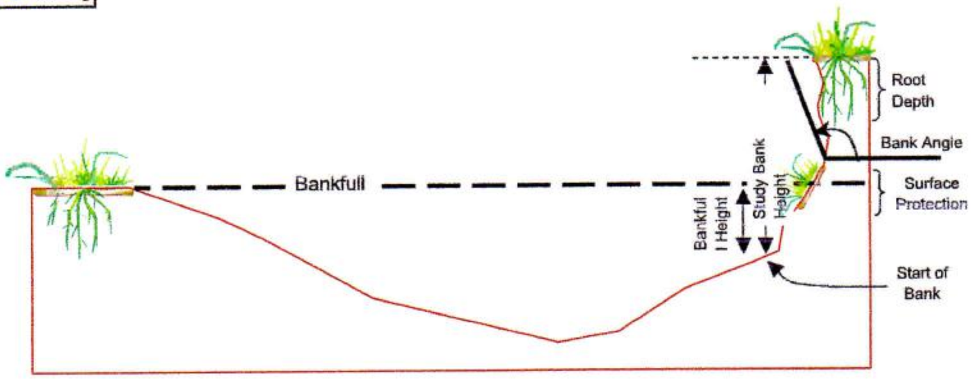
**Bank Angle (H)**

Bank Angle (Degrees) 85 H

**Surface Protection (I)**

Surface Protection % 0 I





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

**Bank Erosion Hazard Rating Guide**

Stream Sleepy Creek Reach Sta. 1+30 Date 4/30/17 Crew TH, VP

| Bank Erosion Potential | Bank Height (ft):<br>Bankfull Height (ft): | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| | VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | **Choice** | V: I: | V: 0.3 I: 5.9 | V: I: | V: I: | V: I: |
| | HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: 85 I: 7.3 | V: I: |
| | VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | **Choice** | V: 2.7 I: 8.9 | V: I: | V: 6 I: 8.8 | V: I: | V: I: |
| | EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: 0 I: 10 |
| | V = value, I = index | | | | **SUB-TOTAL** (Sum one index from each column) | | 40.9 |

**Bank Material Description:**

**Bank Materials**

**Bedrock** (Bedrock banks have very low bank erosion potential)

**Boulders** (Banks composed of boulders have low bank erosion potential)

**Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)

**Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)

**Sand** (Add 10 points)

**Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 40.9

**BEHI RATING** Very High

*Worksheet 20. BEHI variable worksheet*

Stream: Sleepy Creek | Cross Section: Sta. 2+33 | Date: 4/29/17 | Observers: TH, VP

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 9.0 A | Bankfull Height (ft) 3.0 B | A/B = 3.0 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 8.0 D | Study Bank Height (ft) 9.0 A | D/A = 0.9 E |

**Weighted Root Density (G)**

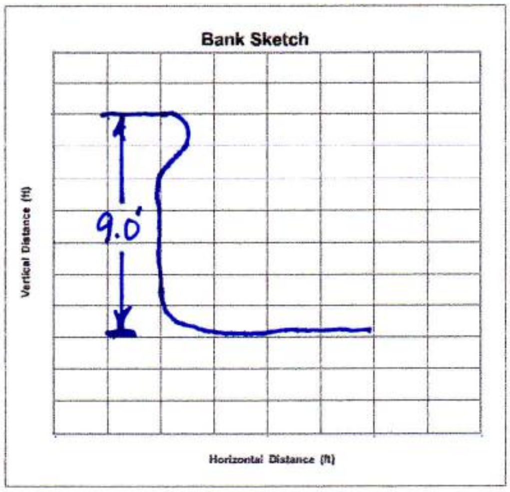
| | |
|---|---|
| Root Density (%) 70 F | F*E = 63 G |

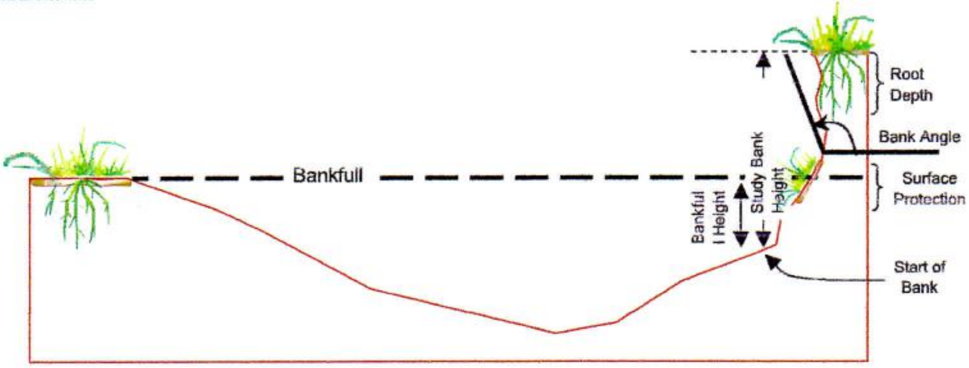
**Bank Angle (H)**

Bank Angle (Degrees) 90 H

**Surface Protection (I)**

Surface Protection % 20 I





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek  Reach Sta. 2+33  Date 4/29/17  Crew TH, VP

| | Bank Height (ft):<br>Bankfull Height (ft): | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| Bank Erosion Potential | VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | **Choice** | V: I: | V: 0.9 I: 2.0 | V: 63 I: 3.0 | V: I: | V: I: |
| | MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: 90 I: 7.9 | V: 20 I: 7.0 |
| | VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | **Choice** | V: 3.0 I: 10 | V: I: | V: I: | V: I: | V: I: |
| | V = value, I = index | | | **SUB-TOTAL** (Sum one index from each column) | | | 29.9 |

**Bank Material Description:**

**Bank Materials**

**Bedrock** (Bedrock banks have very low bank erosion potential)

**Boulders** (Banks composed of boulders have low bank erosion potential)

**Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)

**Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)

**Sand** (Add 10 points)

**Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach  Outside of Bend

**GRAND TOTAL** 29.9

**BEHI RATING** High

*Worksheet 20. BEHI variable worksheet*

| | | | |
|---|---|---|---|
| Stream: Sleepy Creek | Cross Section: Sta. 3+30 | Date: 4/30/17 | Observers: TH, VP |

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 8.2 A | Bankfull Height (ft) 2.5 B | A/B = 3.3 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 1.0 D | Study Bank Height (ft) 8.2 A | D/A = 0.12 E |

**Weighted Root Density (G)**

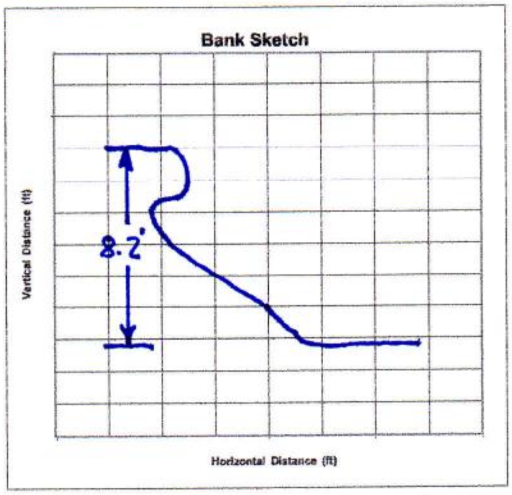
| | |
|---|---|
| Root Density (%) 20 F | F*E = 2.4 G |

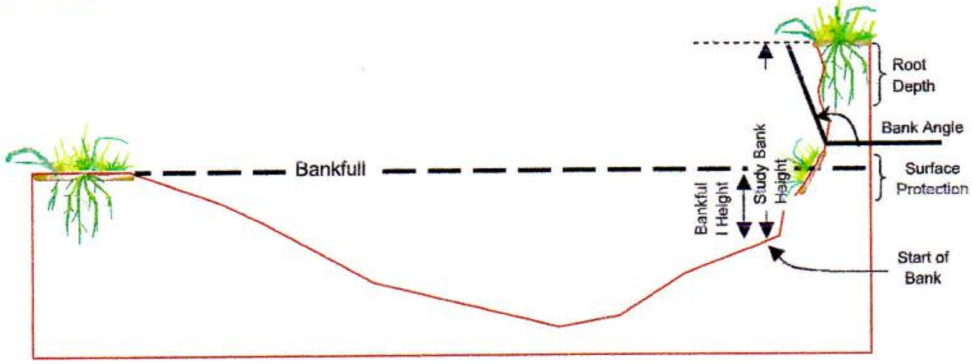
**Bank Angle (H)**

| |
|---|
| Bank Angle (Degrees) 60 H |

**Surface Protection (I)**

| |
|---|
| Surface Protection % 0 I |





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek Reach Sta. 3+30 Date 4/30/17 Crew TH, UP

| | | Bank Height (ft):<br>Bankfull Height (ft): | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| **Bank Erosion Potential** | **VERY LOW** | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | **LOW** | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: 60 I: 3.9 | V: I: |
| | **MODERATE** | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | **HIGH** | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | **VERY HIGH** | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | **Choice** | V: I: | V: .12 I: 8.7 | V: I: | V: I: | V: I: |
| | **EXTREME** | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | **Choice** | V: 3.3 I: 10 | V: I: | V: 2.4 I: 10 | V: I: | V: 0 I: 10 |
| | V = value, I = index | | | | **SUB-TOTAL** (Sum one index from each column) | | 42.6 |

**Bank Material Description:**

**Bank Materials**

- **Bedrock** (Bedrock banks have very low bank erosion potential)
- **Boulders** (Banks composed of boulders have low bank erosion potential)
- **Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)
- **Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 42.6

**BEHI RATING** Very High

*Worksheet 20. BEHI variable worksheet*

Stream: Sleepy Creek | Cross Section: Sta. 4+07 | Date: 4/30/17 | Observers: TH, VP

**Bank Height/Max Depth Bankfull (C)**

Study Bank Height (ft) 7.8 A | Bankfull Height (ft) 2.5 B | A/B = 3.1 C

**Root Depth/Bank Height (E)**

Root Depth (ft) 2.2 D | Study Bank Height (ft) 7.8 A | D/A = 0.3 E

**Weighted Root Density (G)**

Root Density (%) 70 F | F*E = 21 G

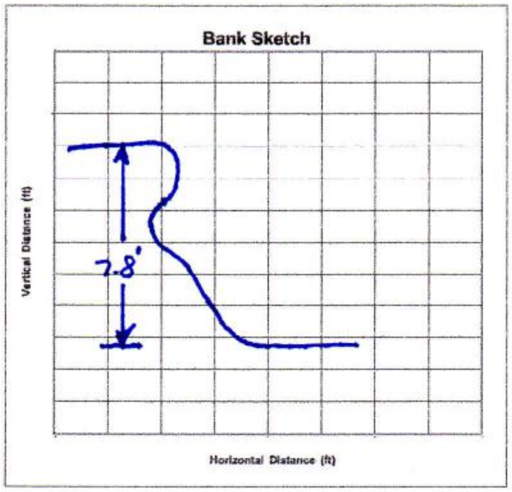
**Bank Angle (H)**

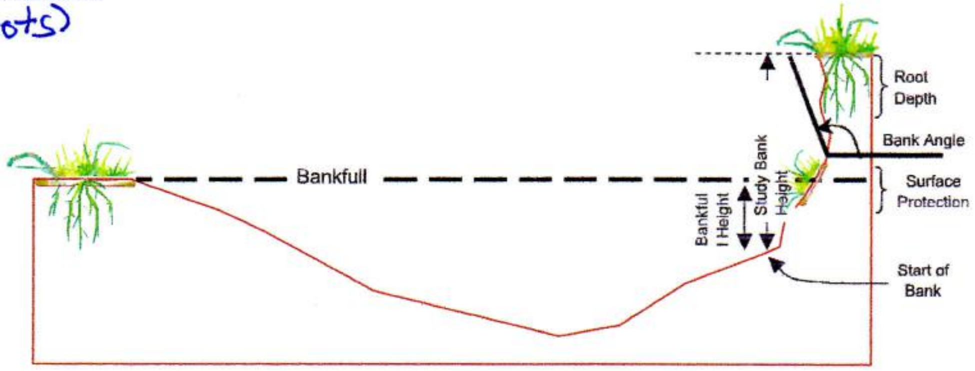
Bank Angle (Degrees) 80 H

**Surface Protection (I)**

Surface Protection % 5 I

(few roots)





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek Reach Sta. 4.07 Date 4/30/17 Crew TH, JP

**Bank Erosion Potential**

| Bank Height (ft):<br>Bankfull Height (ft): | | **Bank Height/ Bankfull Ht** | **Root Depth/ Bank Height** | **Root Density %** | **Bank Angle (Degrees)** | **Surface Protection%** |
|---|---|---|---|---|---|---|
| **VERY LOW** | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| **LOW** | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| **MODERATE** | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | **Choice** | V: I: | V: 0.3 I: 5.9 | V: I: | V: 80 I: 5.9 | V: I: |
| **HIGH** | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | **Choice** | V: I: | V: I: | V: 21 I: 7.1 | V: I: | V: I: |
| **VERY HIGH** | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| **EXTREME** | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | Index | 10 | 10 | 10 | 10 | 10 |
| | **Choice** | V: 3.1 I: 10 | V: I: | V: I: | V: I: | V: 5 I: 10 |
| V = value, I = index | | | | **SUB-TOTAL** (Sum one index from each column) | | 38.9 |

**Bank Material Description:**

**Bank Materials**

**Bedrock** (Bedrock banks have very low bank erosion potential)

**Boulders** (Banks composed of boulders have low bank erosion potential)

**Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)

**Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)

**Sand** (Add 10 points)

**Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| **VERY LOW** | **LOW** | **MODERATE** | **HIGH** | **VERY HIGH** | **EXTREME** |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 38.9

**BEHI RATING** High

*Worksheet 20. BEHI variable worksheet*

Stream: Sleepy Creek

Cross Section: Sta. 4+55

Date: 4/30/17

Observers: TH, VP

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 8.0 A | Bankfull Height (ft) 2.5 B | A/B = 3.2 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 1.0 D | Study Bank Height (ft) 8.0 A | D/A = 0.13 E |

**Weighted Root Density (G)**

| | |
|---|---|
| Root Density (%) 50 F | F*E = 6.5 G |

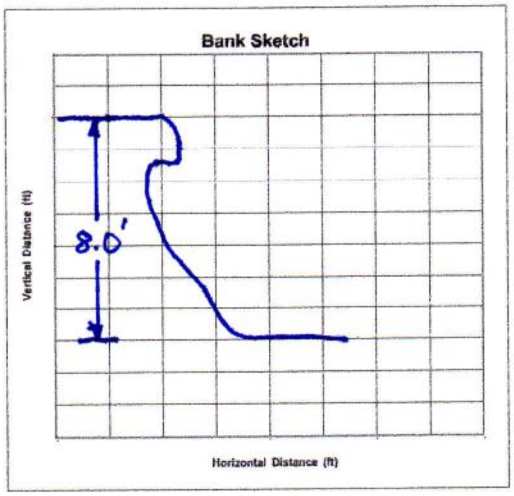
**Bank Angle (H)**

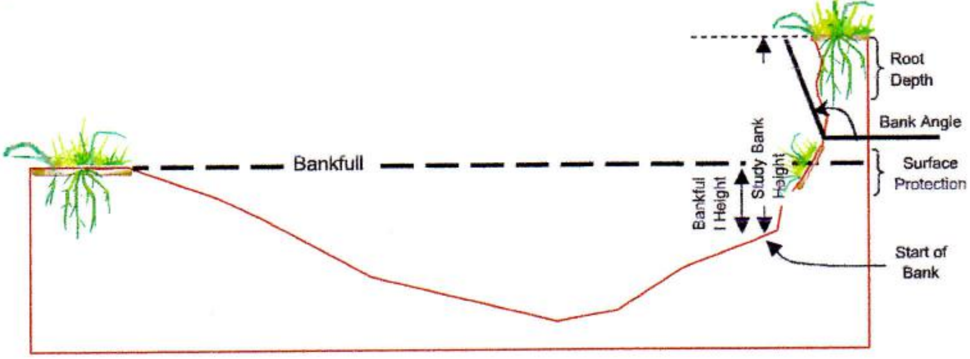
Bank Angle (Degrees) 85 H

stratification - clay lens

**Surface Protection (I)**

Surface Protection % 0 I





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek Reach Sta 4+55 Date 4/30/17 Crew TH, VP

| | | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| | Bank Height (ft):<br>Bankfull Height (ft): | | | | | | |
| Bank Erosion Potential | VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: I: | V: I: |
| | HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | **Choice** | V: I: | V: I: | V: I: | V: 85 I: 7.3 | V: I: |
| | VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | **Choice** | V: I: | V: .13 I: 9.0 | V: 6.5 I: 8.7 | V: I: | V: I: |
| | EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | **Choice** | V: 3.2 I: 10 | V: I: | V: I: | V: I: | V: 0 I: 10 |
| | V = value, I = index | | | | **SUB-TOTAL** (Sum one index from each column) | | 45.0 |

**Bank Material Description:**

**Bank Materials**

- **Bedrock** (Bedrock banks have very low bank erosion potential)
- **Boulders** (Banks composed of boulders have low bank erosion potential)
- **Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)
- **Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 10

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

Straight Reach Outside of Bend

**GRAND TOTAL** 55.0

**BEHI RATING** Extreme

*Worksheet 20. BEHI variable worksheet*

Stream: Sleepy Creek | Cross Section: Sta 5+46 | Date: 4/30/17 | Observers: TH, VP

**Bank Height/Max Depth Bankfull (C)**

| | | |
|---|---|---|
| Study Bank Height (ft) 7.8 A | Bankfull Height (ft) 1.7 B | A/B = 4.6 C |

**Root Depth/Bank Height (E)**

| | | |
|---|---|---|
| Root Depth (ft) 2.6 D | Study Bank Height (ft) 7.8 A | D/A = 0.33 E |

**Weighted Root Density (G)**

| | |
|---|---|
| Root Density (%) 5 F | F*E = 1.7 G |

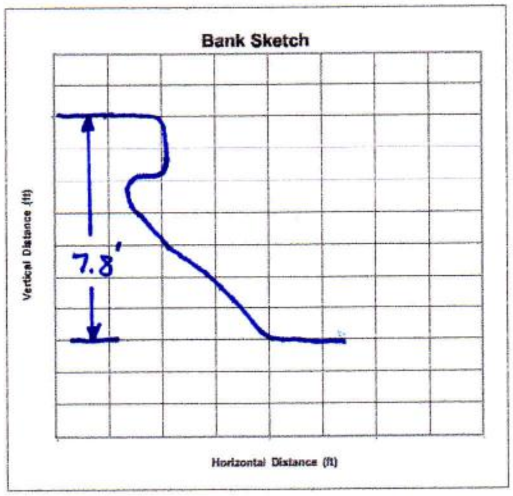
**Bank Angle (H)**

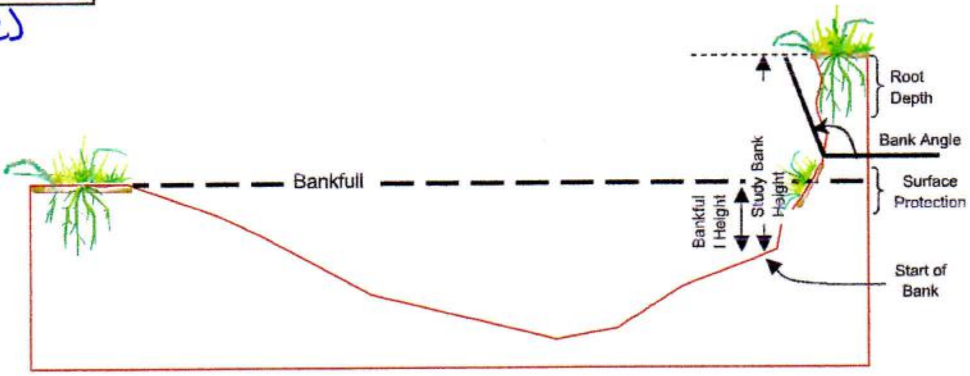
Bank Angle (Degrees) 75 H

**Surface Protection (I)**

Surface Protection % 25 I

(cobble)





*Worksheet 21. Summary of bank erosion hazard index (BEHI)*

## Bank Erosion Hazard Rating Guide

Stream Sleepy Creek Reach Sta 5+46 Date 4/30/17 Crew TH, VP

| Bank Erosion Potential | Bank Height (ft):<br>Bankfull Height (ft): | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% |
|---|---|---|---|---|---|---|---|
| | VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 |
| | | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: I: |
| | LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 |
| | | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: I: |
| | MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 |
| | | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 |
| | | Choice | V: I: | V: .33 I: 5.9 | V: I: | V: 75 I: 5.0 | V: I: |
| | HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 |
| | | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: 25 I: 6.2 |
| | VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 |
| | | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 |
| | | Choice | V: I: | V: I: | V: I: | V: I: | V: I: |
| | EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 |
| | | Index | 10 | 10 | 10 | 10 | 10 |
| | | Choice | V: 4.6 I: 10 | V: I: | V: 1.7 I: 10 | V: I: | V: I: |
| | V = value, I = index | | | | SUB-TOTAL (Sum one index from each column) | | 37.1 |

**Bank Material Description:**

**Bank Materials**

- **Bedrock** (Bedrock banks have very low bank erosion potential)
- **Boulders** (Banks composed of boulders have low bank erosion potential)
- **Cobble** (Subtract 10 points. If sand/gravel matrix greater than 50% of bank material, then do not adjust)
- **Gravel** (Add 5-10 points depending percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt Clay** (+ 0: no adjustment)

**BANK MATERIAL ADJUSTMENT** 0

**Stratification Comments:**

**Stratification**

Add 5-10 points depending on position of unstable layers in relation to bankfull stage

**STRATIFICATION ADJUSTMENT** 0

| VERY LOW | LOW | MODERATE | HIGH | VERY HIGH | EXTREME |
|---|---|---|---|---|---|
| 5-9.5 | 10-19.5 | 20-29.5 | 30-39.5 | 40-45 | 46-50 |

**Bank location description (circle one)**

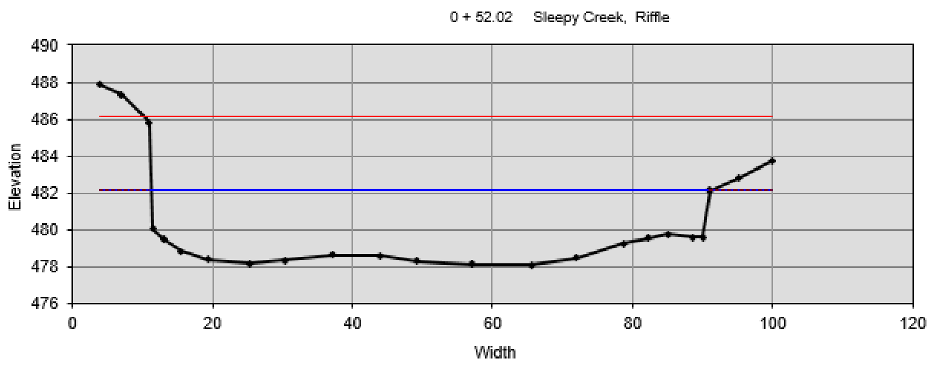
Straight Reach Outside of Bend

**GRAND TOTAL** 37.1

**BEHI RATING** High

# APPENDIX B – CROSS SECTIONS

## Cross Section 1



| Bankfull Dimensions | |
|---|---|
| 275.3 | x-section area (ft.sq.) |
| 79.7 | width (ft) |
| 3.5 | mean depth (ft) |
| 4.0 | max depth (ft) |
| 83.6 | wetted parimeter (ft) |
| 3.3 | hyd radi (ft) |
| 23.1 | width-depth ratio |

| Flood Dimensions | |
|---|---|
| --- | W flood prone area (ft) |
| --- | entrenchment ratio |
| 4.0 | low bank height (ft) |
| 1.0 | low bank height ratio |

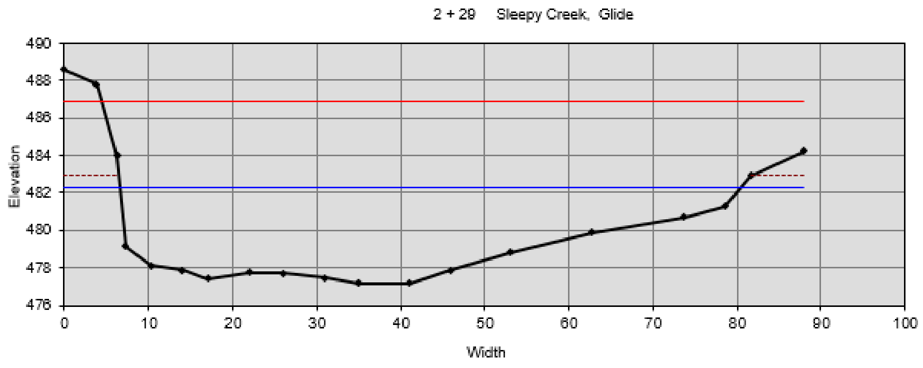
| Materials | |
|---|---|
| 56 | D50 Channel (mm) |
| 110 | D84 Channel (mm) |
| 12 | threshold grain size (mm): |

| Bankfull Flow | |
|---|---|
| 3.8 | velocity (ft/s) |
| 1047.9 | discharge rate (cfs) |
| 0.37 | Froude number |

| Flow Resistance | |
|---|---|
| 0.030 | Manning's roughness |
| 0.07 | D'Arcy-Weisbach fric. |
| 8.6 | resistance factor u/u* |
| 9.6 | relative roughness |

| Forces & Power | |
|---|---|
| 0.12 | channel slope (%) |
| 0.25 | shear stress (lb/sq.ft.) |
| 0.36 | shear velocity (ft/s) |
| 0.98 | unit strm power (lb/ft/s) |

## Cross Section 2



| Bankfull Dimensions | |
|---|---|
| 268.1 | x-section area (ft.sq.) |
| 73.9 | width (ft) |
| 3.6 | mean depth (ft) |
| 5.1 | max depth (ft) |
| 77.2 | wetted parimeter (ft) |
| 3.5 | hyd radi (ft) |
| 20.3 | width-depth ratio |

| Flood Dimensions | |
|---|---|
| --- | W flood prone area (ft) |
| --- | entrenchment ratio |
| 5.8 | low bank height (ft) |
| 1.1 | low bank height ratio |

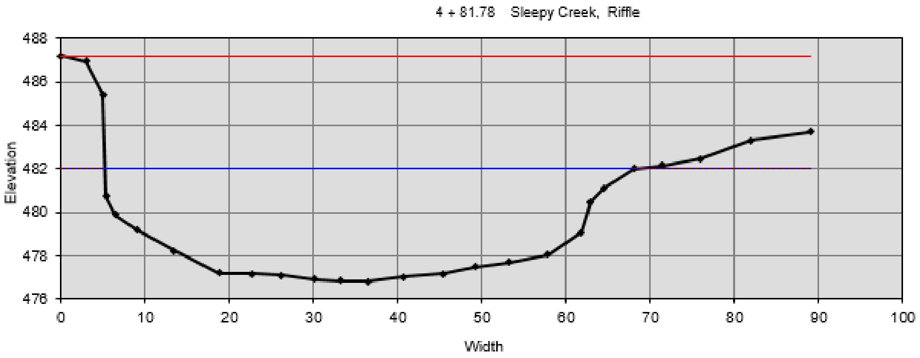
| Materials | |
|---|---|
| 56 | D50 Channel (mm) |
| 110 | D84 Channel (mm) |
| 13 | threshold grain size (mm): |

| Bankfull Flow | |
|---|---|
| 3.8 | velocity (ft/s) |
| 1023.5 | discharge rate (cfs) |
| 0.36 | Froude number |

| Flow Resistance | |
|---|---|
| 0.031 | Manning's roughness |
| 0.07 | D'Arcy-Weisbach fric. |
| 8.8 | resistance factor u/u* |
| 10.1 | relative roughness |

| Forces & Power | |
|---|---|
| 0.12 | channel slope (%) |
| 0.26 | shear stress (lb/sq.ft.) |
| 0.37 | shear velocity (ft/s) |
| 1.04 | unit strm power (lb/ft/s) |

## Cross Section 3



| Bankfull Dimensions | |
|---|---|
| 252.1 | x-section area (ft.sq.) |
| 62.8 | width (ft) |
| 4.0 | mean depth (ft) |
| 5.2 | max depth (ft) |
| 65.6 | wetted parimeter (ft) |
| 3.8 | hyd radi (ft) |
| 15.6 | width-depth ratio |

| Flood Dimensions | |
|---|---|
| --- | W flood prone area (ft) |
| --- | entrenchment ratio |
| 5.2 | low bank height (ft) |
| 1.0 | low bank height ratio |

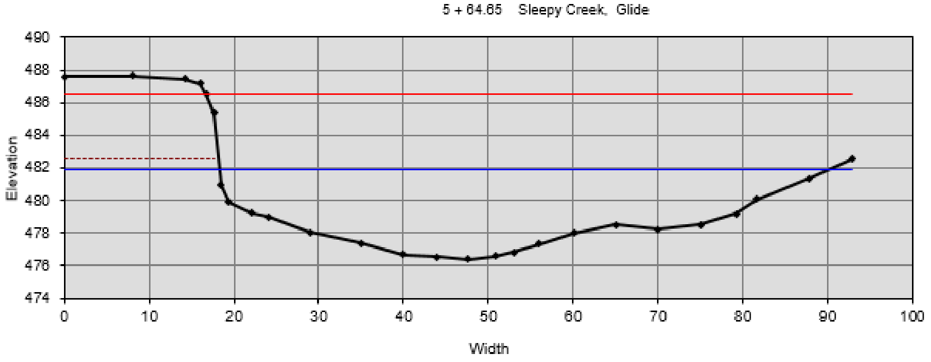
| Materials | |
|---|---|
| 56 | D50 Channel (mm) |
| 110 | D84 Channel (mm) |
| 14 | threshold grain size (mm): |

| Bankfull Flow | |
|---|---|
| 4.1 | velocity (ft/s) |
| 1028.4 | discharge rate (cfs) |
| 0.37 | Froude number |

| Flow Resistance | |
|---|---|
| 0.031 | Manning's roughness |
| 0.07 | D'Arcy-Weisbach fric. |
| 9.0 | resistance factor u/u* |
| 11.1 | relative roughness |

| Forces & Power | |
|---|---|
| 0.12 | channel slope (%) |
| 0.29 | shear stress (lb/sq.ft.) |
| 0.39 | shear velocity (ft/s) |
| 1.23 | unit strm power (lb/ft/s) |

## Cross Section 4



| Bankfull Dimensions | |
|---|---|
| 263.9 | x-section area (ft.sq.) |
| 72.1 | width (ft) |
| 3.7 | mean depth (ft) |
| 5.6 | max depth (ft) |
| 74.2 | wetted parimeter (ft) |
| 3.6 | hyd radi (ft) |
| 19.7 | width-depth ratio |

| Flood Dimensions | |
|---|---|
| --- | W flood prone area (ft) |
| --- | entrenchment ratio |
| 6.1 | low bank height (ft) |
| 1.1 | low bank height ratio |

| Materials | |
|---|---|
| 56 | D50 Channel (mm) |
| 110 | D84 Channel (mm) |
| 13 | threshold grain size (mm): |

| Bankfull Flow | |
|---|---|
| 3.9 | velocity (ft/s) |
| 1022.7 | discharge rate (cfs) |
| 0.36 | Froude number |

| Flow Resistance | |
|---|---|
| 0.031 | Manning's roughness |
| 0.07 | D'Arcy-Weisbach fric. |
| 8.9 | resistance factor u/u* |
| 10.1 | relative roughness |

| Forces & Power | |
|---|---|
| 0.12 | channel slope (%) |
| 0.27 | shear stress (lb/sq.ft.) |
| 0.37 | shear velocity (ft/s) |
| 1.06 | unit strm power (lb/ft/s) |

# APPENDIX C – PHOTOS

February 2017 photo showing woody debris from eroding left bank

February 2017 photo showing stable right bank and cobble and gravel point bar

February 2017 photo showing eroding left bank

February 2017 photo showing undermined trees on left bank

May 2017 photo sowing eroding left bank
at one of the deep pools

May 2017 photo showing the natural rock
grade control near the downstream
end of the project reach

May 2017 photo looking upstream at the natural rock grade control

May 2017 photo looking downstream in the area of the proposed W-Weir