QUANTIFYING SEDIMENT LOADS FROM STREAMBANK EROSION AND POTENTIAL LOAD REDUCTIONS FROM STREAMBANK STABILIZATION USING PROCESS-BASED MODELING

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Title of Study: QUANTIFYING SEDIMENT LOADS FROM STREAMBANK EROSION AND POTENTIAL LOAD REDUCTIONS FROM STREAMBANK STABILIZATION USING PROCESS-BASED MODELING

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Abstract: Unstable streambanks contribute a significant sediment load to surface waters in some watersheds. Streambank stabilization techniques are available to increase stability of streambanks or reduce erodibility, thereby reducing sediment loads. Process-based models can be used to evaluate the stability of stream channels and predict sediment yields with and without potential stabilization to determine the effectiveness of stabilization. Two fluvial erosion models are commonly used with in process-based models to simulate the erosion rate of soils: the excess shear stress equation and the Wilson model. Both models include two soil parameters which may be highly variable within a stream system. In order to simulate stabilization practices in process-based models, each practice must be appropriately parameterized. The objectives of this research were to investigate the variability of fluvial erodibility parameters within a watershed and resulting implications for erosion prediction, parameterize stabilization practices for simulation in process-based models, and determine stabilization effectiveness for stream-scale sediment reduction. Jet erosion tests were completed along two streams in both the Illinois River watershed and Fort Cobb Reservoir watershed to determine erodibility parameters. Erodibility parameters were incorporated into a process-based model, CONCEPTS, to simulate bank retreat. Erodibility parameters varied by two to five and one to two orders of magnitude in the Illinois River and Fort Cobb Reservoir watersheds, respectively. Less variation was observed in lateral retreat prediction from CONCEPTS simulations than input erodibility parameters. Two stabilization practices were selected for simulation, riprap and vegetation. Each practice was simulated using two parameters, median particle size, d_{50} and riprap height, h for riprap and added root cohesion, C_r and shear stress adjustment factor, ν for vegetation. An uncertainty analysis showed sediment reduction and retreat predictions were not sensitive to d_{50} or C_r, but were highly sensitive to h and ν. Finally, a framework was developed to evaluate streambank stabilization practices for sediment reduction using process-based models by accounting for public and landowner perception, costs and effectiveness. The methodology was applied using the CONCEPTS model setup for Fivemile Creek in the Fort Cobb Reservoir Watershed. Vegetation with 2:1 bank slopes was the most cost-effective stabilization practice for this stream.

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Variable	Description	Units
τ_c	Critical shear stress	Pa
k_d	Erodibility Coefficient	$cm^3\ N^{-1}\ s^{-1}$
τ	Shear stress	Pa
ε_r	Erosion rate	$cm\ s^{-1}$
b_0	Wilson model parameter	$g\ m^{-1}\ s^{-1}\ N^{-0.5}$
b_1	Wilson model parameter	Pa
c'	Effective cohesion	Pa
ϕ'	Effective internal angle of friction	^{o}
BD	Bulk Density	$g\ cm^{-3}$
d_{50}	median particle size	mm
CV	Coefficient of Variation	-
R^2	Coefficient of Determination	-
v	shear stress adjustment factor	-
C_r	Root Cohesion	kPa
AD	Anderson-Darling Statistic	-
Q_s	Sediment inflow	$kg\ s^{-1}$
Q	Stream flow	cms
a,b	Regression parameters for sediment rating curves	-
h	height of riprap	m
S_r	Relative Sensitivity Coefficient	-
BSS	Briar Skill Score	-
CI	Confidence interval	-
λ	Fraction of stream stabilized	-
Manning's n	Bed and bank roughness	-

CHAPTER 1

INTRODUCTION

1.1 Background

According to the EPA, over half of the water bodies in the US are considered to be impaired, with sediment being ranked sixth on leading causes of impairment (USEPA, 2016). Excess sediment can reduce ecosystem health, threaten drinking water supply, and reduce reservoir capacity (Simon and Klimetz, 2008a). This excess sediment can increase the cost of drinking water treatment and lead to unpleasant odor, taste, or aesthetics and reduce the lifespan of reservoirs (Palmieri et al., 2001). Sediment may also contain excess nutrients, such as phosphorus (Miller et al., 2014), heavy metals, hydrocarbons, and organics that pose could a threat to human health (Lyman et al., 1987).

Sediment sources include upland erosion, channel and gully erosion, and the resuspension of streambed material. The reduction of sediment that reaches reservoirs, streams, and oceans from these sources continues to be the focus of much research. In recent years, the focus on sediment reduction has focused on upland conservation practices, such riparian buffers, conversion of cropland to reduced or no-till, conversion of row crops to pasture, and terracing (Hargrove et al., 2010; Tomer and Locke, 2011) with limited emphasis on in-channel conservation practices (Simon and Klimetz, 2008a; Wilson et al., 2008; Hargrove et al., 2010; Tomer and Locke, 2011). The United States

Department of Agriculture (USDA) developed the Conservation Effects Assessment Program (CEAP)to quantify the effects of conservation practices on sediment reduction in 14 benchmark agricultural watersheds across the country. In these watersheds, upland conservation at the field and catchment scale was shown to be effective at reducing the amount of sediment entering a stream channel (Garbrecht and Starks, 2009) and locally improving water quality (Tomer and Locke, 2011); however, sedimentation problems still existed on the watershed scale.

Upland soil conservation practices have limited impact due to past eroded material being deposited in channels and floodplains, which are susceptible to streambank erosion (Hargrove et al., 2010). Historically, sediment from the pre-conservation era was deposited in floodplains which led to channelization, reduction of flood plain storage capacity, and the acceleration of channel erosion (Yan et al., 2010). This channel erosion contributes higher loading of suspended sediment than from upland sources (Simon and Klimetz, 2008; Wilson et al., 2008; Hargrove et al., 2010; Tomer and Locke, 2011). Wilson et al. (2008) determined 50 to 80% of suspended sediment in CEAP watersheds came from unstable streambanks with the use of radionuclide tracers. When compared to streams in watersheds with stable streambanks, streams in watersheds with unstable streambanks have shown 243% to 7410% higher sediment yields (Simon and Klimetz, 2008a).

Due to the significant contributions of sediment loads to surface waters, it becomes vital to understand the processes of streambank erosion and the factors that influence erosion rates. Streambank erosion is controlled by three main processes: subaerial processes, fluvial erosion of the bed and bank, and mass wasting (Couper and

Maddock, 2001). These three processes are intricately linked and often occur in a cyclical manner. Subaerial processes such as freeze/thaw, and wet and dry cycles can weaken the soil and make the soil particles more susceptible to detachment by fluvial erosion. Fluvial erosion is the detachment of soil particles from the bed or bank by streamflow and is a continuous process. Fluvial erosion can steepen the streambanks by eroding the toe of the bank or by degrading the bed of the stream. This can decrease the stability of the bank, making it more susceptible to mass wasting which occurs when the driving forces exceed the resisting forces to collapse. Mass wasting is an episodic process and can account for a significant portion of streambank sediment loading. Numerous factors contribute to these three processes including land use, climate, soil properties, geomorphology, slope, the presence/absence of vegetation, etc.

Several models are available for predicting streambank erosion at the site, reach, or watershed scale (i.e. BSTEM, CONCEPTS, and SWAT). The Bank Stability and Toe Erosion Model (BSTEM) was developed by scientists at the USDA-ARS National Sedimentation Laboratory, and it can be used predict fluvial erosion and mass wasting processes at one side of a single cross-section. BSTEM does not allow for the adjustment of the bed, which is particularly important in incising channels. Extensive research has utilized BSTEM to evaluate streambank stability and has shown BSTEM to be a useful tool to evaluate site specific bank retreat. However, BSTEM has limited use when determining stream-scale sediment loads (Klavon et al., 2016). The CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) was developed by the USDA-ARS scientists as a follow-up to BSTEM. CONCEPTS models bank stability and fluvial erosion in the same manner as BSTEM, but considers both banks of a cross-section, sediment transport and vertical bed adjustment (Langendoen, 2000; Langendoen and Alsonso, 2008). CONCEPTS links several cross-sections together in a reach to simulate bank erosion and sediment transport processes on the reach scale. Another commonly used model, the Soil and Water Assessment Tool (SWAT) primarily simulates sediment contributions from overland flow, but has recently incorporated streambank erosion processes for watershed scale simulations (Neitsch et al., 2011). However, estimating streambank erosion on such a large scale requires several simplifications. For example, SWAT only allows for one soil layer, and does not simulate mass wasting processes assumes a trapezoidal channel with 2:1 side slopes, which may not accurately represent the channel geometry (Mittelstet et al., 2016).

Process-based models, such as BSTEM and CONCEPTS, typically simulate fluvial erosion using the linear excess shear stress equation (Partheniades, 1965; Hanson 1990a, 1990b). This equation uses two soil erodibility parameters, τ_c and k_d, to predict soil particle detachment. The erodibility parameters can be derived using various techniques, including *in situ* jet erosion tests (JETs) (Hanson, 1990b). Previous research has shown these parameters to be highly variable at the watershed and even site-scale due to variations in soil texture, bulk density, presence of roots, etc. (Daly et al., 2015a,b; Khanal et al, 2016a). However, there is little information on how to account for this variability and the impact of the variability on erosion predictions from process-based models.

CONCEPTS and BSTEM can also be used to evaluate the effectiveness of streambank stabilization and restoration techniques prior to implementation. In recent years, stream restoration and streambank stabilization have become common practices to reduce erosion in channels, often with the goal of correcting anthropogenic disruptions to streams and reduce sediment loads from streambanks (Beechie et al., 2010). Several techniques can be used to stabilize streambanks and reduce erosion, including toe protection, bank armoring, vegetation, and grade control. Previous research has suggested several methods for simulating stabilization in process-based models (Simon et al., 2009; Langendoen, 2011; Daly, 2012; Klavon et al., 2016). However, uncertainty in parameterizing bank stabilization practices still exists.

Billions of dollars have been spent to reduced sediment loads from streambanks through stabilization and restoration projects (Lavendel, 2002; Bernhardt et al., 2005). However, an increase in stream restoration has not reduced the number of degraded miles of streams since the early 1990s (Langendoen, 2011). While these techniques are effective at reducing erosion and sediment loss at the site scale, reach-scale sediment loss may not be reduced. Site scale stabilizations can potentially impact an entire stream reach by cutting off sediment supplies leading to increased scouring and erosion upstream or downstream of the site that has been rehabilitated (Reid and Church, 2015). Little research has been conducted on stream-scale sediment reduction from site-scale stabilization, which is extremely important when the goal of the stabilization is to improve water quality.

1.2 Objectives and Overview

In order to address these gaps, the overall objectives of this research were (1) to quantify streambank erosion processes within a watershed, (2) parameterize streambank stabilization practices for simulation in process-based models, and (3) to determine the effectiveness of stream restoration/stabilization on stream-scale sediment reduction.

First the variability of erodibility parameters derived from jet erosion tests (JETs) was investigated on the watershed scale (Chapter 2). The longitudinal trends in streambank soil erodibility and implications of the watershed variability for lateral bank retreat predictions using the CONCEPTS model were demonstrated. Next, methods for setting up a CONCEPTS simulation for two rapidly migrating streams were demonstrated and two streambank stabilization practices were parameterized for simulation (Chapter 3). An uncertainty analysis in sediment and lateral retreat reduction was conducted. Finally, a modeling framework was developed for prioritizing stabilization practices for reach-scale sediment reduction by integrating process-based modeling results with economic factors (Chapter 4).

CHAPTER 2

WATERSHED VARIABILITY IN STREAMBANK ERODIBILITY AND IMPLICATIONS FOR EROSION PREDICTION

2.1 Abstract

Two fluvial erosion models are commonly used to simulate the erosion rate of cohesive soils: the empirical excess shear stress equation and the non-linear mechanistic Wilson model. Both models include two soil parameters, the critical shear stress (τ_c) and the erodibility coefficient (k_d) for the excess shear stress equation and b_0 and b_1 for the Wilson model. Jet erosion tests (JETs) allow for an in-situ determination of these parameters that may be highly variable within a stream system due to soil heterogeneity. The objectives of this research were to use JET results from two watersheds to (i) investigate variability of fluvial erodibility parameters (τ_c, k_d, b_0, and b_1) obtained from the JETs on the watershed scale, (ii) investigate longitudinal trends in fluvial erodibility parameters obtained from the JET and (iii) to determine the impact of this variability on lateral retreat predicted by a process-based model using both the excess shear stress equation and the Wilson model. JETs were completed at numerous sites along two streams (Barren Fork Creek and the Illinois River) in the Illinois River watershed and along two streams (Fivemile and Willow Creeks) in the Fort Cobb Reservoir watershed. Then, erodibility parameters derived from JETs were incorporated into a process-based model to simulate bank retreat for Barren Fork Creek and Fivemile Creek. Erodibility parameters varied by two to five orders of magnitude in the Illinois River watershed and only one to two orders of magnitude in the Fort Cobb Reservoir watershed. A significant longitudinal trend in erodibility was only observed along the Illinois River. Less variation was observed in lateral retreat prediction from a process-based bank retreat model than input erodibility parameters.

Keywords. *Erodibility parameters, Jet Erosion Test, Variability, Streambank Retreat*

2.2 Introduction

Excess sediment continues to be a major polluter of surface waters in the United States, with streambank erosion being a primary contributor (Wilson et al., 2008; Fox et al., 2016). Streambank erosion is a complex process that involves three primary mechanisms, subaerial processes, fluvial erosion, and mass wasting, and is driven by several soil properties that are spatially variable. Subaerial processes include wetting/drying cycles, freeze/thaw cycles, and other processes that weaken the streambank soil (Couper and Maddock, 2001). Mass wasting, or geotechnical failure occurs when there is an imbalance between the forces resisting erosion and the gravitational forces acting on the streambank. Fluvial erosion is a continual process in which soil particles are detached by the hydraulic forces from streamflow when the applied shear stress exceeds a critical shear stress for the soil. Many streambank erosion models simulate both fluvial erosion and mass wasting processes.

Several particle detachment models are used to predict fluvial erosion for cohesive sediments with the most common being the linear excess shear stress equation (Partheniades, 1965; Hanson 1990a, 1990b):

$$\varepsilon_r = k_d(\tau - \tau_c)^a \tag{2.1}$$

where ε_r is the erosion rate (cm s^{-1}), k_d is the erodibility coefficient (cm^3 N^{-1} s^{-1}), τ is the average hydraulic boundary shear stress (Pa), τ_c is the critical shear stress (Pa), and a is an empirical exponent that is assumed to be one. Once the τ exerted by the water in a stream exceeds the τ_c of the soil, erosion begins at a rate of k_d. The two erodibility parameters, τ_c and k_d, are soil dependent. Models such as the Bank Stability and Toe Erosion Model (BSTEM), Conservational Channel Evolution and Pollutant Transport System (CONCEPTS), and HEC-RAS with BSTEM use the linear excess shear-stress equation to predict fluvial erosion and require τ_c and k_d as input (Langendoen, 2000; Midgley et al., 2012; Klavon et al., 2016). The Soil and Water Assessment Tool (SWAT) either allows the user to input τ_c and k_d, or calculates the parameters based on soil characteristics and empirical relationships (Neitsch et al., 2011).

A nonlinear mechanistic detachment model was developed by Wilson (1993a, 1993b), based on a two-dimensional representation of soil particles to predict fluvial erosion of both soil particles and aggregates:

$$\varepsilon_r = b_0\sqrt{\tau}\left[1 - \exp\left\{-\exp\left(3 - \frac{b_1}{\tau}\right)\right\}\right] \tag{2.2}$$

where b_0 (g m^{-1} s^{-1} N$^{-0.5}$) and b_1 (Pa) are the mechanistically derived parameters of the model. The b_0 is similar to k_d and b_1 is similar to τ_c (Daly et al., 2015a; Khanal et al., 2016a). The Wilson model parameters, b_0 and b_1, must be currently measured and cannot be estimated a priori from soil properties. The benefit of the Wilson model is that it models fluvial erosion as a nonlinear process which may be more representative of actual erosion processes at higher applied τ.

Various techniques can be used to measure the excess shear stress parameters, τ_c and k_d, as well as the Wilson model parameters, b_0 and b_1, such as flume studies, hole erosion tests, and submerged jets. While flume studies and hole erosion tests can be used to measure parameters in laboratory settings, a submerged jet test, known as the Jet Erosion Test (JET), was developed to measure erodibility parameters *in situ* (Hanson, 1990b). The JET impinges a small jet of water into the streambank at a constant pressure to create a scour hole. Scour depth is measured over time to determine a rate of erosion Field JETs rely on the use of a constant head tank or a pressure gauge and water pumped from a nearby stream. Several solver techniques (Blaisdell, scour depth, and iterative solutions) can be used to fit the measured data and iteratively solve for τ_c and k_d based on the measurements from the JET (Hanson and Cook, 1997; Simon et al., 2010; Daly et al., 2013). The Wilson model parameters can also be determined from the JET using the analysis described by Al-Madhhachi et al. (2013).

Physical, geochemical, and biological properties of soil are thought to influence the fluvial erodibility parameters (Grabowski et al., 2011). Soil particle size is an important factor when considering the erodibility of soils. For cohesive soils, the higher amount of clay-sized particles causes higher levels of cohesion and more resistance to erosion. Particle sizes of the stream bed and banks tend to exhibit longitudinal trends, which may contribute to longitudinal trends in soil erodibility. Bed particle size tends to decrease downstream (Church and Kellerhals, 1978; Rice and Church, 1998; Grabowski et al., 2012), as the larger particles settle out more quickly and the finer particles can be transported further downstream.

Streambank soil type can be highly variable throughout a watershed and along the streambanks, but bank material also tends to become finer downstream (Knighton, 1998). This can be attributed to the historical deposition of fine sediments in floodplains, which are often areas of sediment storage within a watershed (Osterkamp et al., 2012). Historically, sediment was deposited in floodplains which led to channelization, reduction of flood plain storage capacity, and the acceleration of channel erosion in downstream reaches (Yan et al., 2010; Hargrove et al., 2010). The downstream fining of particles could also contribute to an increased resistance to erosion downstream. Higher cohesion due to the finer materials downstream had also been observed (Knighton, 1998) and would likely increase the soil resistance to erosion. Konsoer et al. (2016) measured soil particle size, cohesion, and τ_c of streambank soils around two meander bends, each approximately 5 km in length, of the Wabash River in Illinois. Bank materials, cohesion and the τ_c varied between the two river bends and within each bend. Percentage of fines in the soil increased downstream on the first bend and was more uniform in the downstream bend. The authors concluded that the variation in particle size was most likely due to the variability of riparian vegetation and floodplain development due to deposition. However, no significant change in τ_c or k_d was observed along the river.

Wynn et al. (2008) performed JETs at six sites along Stroubles Creek in Virginia and observed four orders of magnitude variation in k_d, but only one order of magnitude variation in τ_c. The same soil was tested in a laboratory setting where it was packed to a consistent bulk density and moisture content. The remolded samples exhibited less variability in erodibility parameters than the field JETs, suggesting that variations in bulk density (BD) and moisture content may also account for some of the variability in the field.

Typically, multiple JETs are performed at a site and an average τ_c and k_d (or b_0 and b_1), are used in predictive modeling. Only a few studies have investigated how parameters vary on the watershed scale (Daly et al., 2015a) and single values of τ_c and k_d are still widely used for an entire watershed. While *in situ* testing with the JET is recommended to determine erodibility parameters (Klavon et al., 2016), running multiple tests at multiple sites within a watershed or stream system becomes time consuming, as it takes at least an hour to run a single JET. The amount of tests needed to adequately characterize the erodibility parameters for each site of interest on an entire stream reach or watershed may be very high and access to certain locations may be limited. Ideally, JETs could be conducted at a few sites and the values extrapolated to other sites within the stream system. However, an understanding of how the parameters vary within the specific stream or at the watershed scale is important to validate such an extrapolation. If a longitudinal trend in erodibility is present, this may allow for the results from the JETs to be extended up and downstream of the test locations.

Therefore, the objectives of this study were to (i) investigate variability of fluvial erodibility parameters for both the excess shear stress and the Wilson model obtained from the JETs on the watershed scale, (ii) investigate longitudinal trends in fluvial erodibility parameters obtained from the JET within two contrasting watersheds and (iii) to determine the impact of this variability on lateral retreat predictions using both the excess shear stress equation and the Wilson model in a process-based bank retreat model.

2.3 Methods and Materials

2.3.1 Description of Watersheds

The Fort Cobb Reservoir watershed (Figure 2.1), which is located in western Oklahoma and the Central Great Plains ecoregion, has been selected for this study. The Fort Cobb Reservoir, which provides public water supply, recreation, and wildlife habitat, is on the Oklahoma 303(d) list for impairment by nutrients, sediments, and siltation (Storm et al., 2003), as well as its four main tributaries. The watershed is predominately agricultural with roads and urban areas accounting for 5% of the watershed and water less than 2% (Becker, 2011). Numerous upland and riparian conservation practices (reduced or no-till cropland, conversion of cropland to pastureland, terracing, riparian buffers, cattle exclusion from streams, etc.) and various structural and water management practices to reduce sediment loading were implemented in the Fort Cobb Reservoir watershed as part of the Conservation Effects Assessment Project, CEAP (Steiner et al., 2008). However, the reservoir still fails to meet water quality standards based on sediment. Using radionuclide tracers, it was determined that 50% of the suspended sediment in Fort Cobb Reservoir originated from unstable tributary streambanks (Wilson et al., 2008). Streambanks in the watershed consist of either single sand or sandy loam layer, while others exhibit layering with sand or sandy loam layers above and below a more cohesive layer with higher clay content.

An additional set of JET data from the Illinois River watershed, located in northeastern Oklahoma (Figure 2.1), was obtained for this study. These data was previously published in Daly et al. (2015a). Approximately 54% of the Illinois River watershed lies in Oklahoma with the remaining portion in Arkansas. This watershed includes Tenkiller Ferry Lake, which provides drinking water to a large portion of the region. Many of the streams and rivers within the watershed have been designated scenic rivers and have created a recreational and tourism industry for the area. Streambanks in the watershed are comprised of a cohesive silty loam top layer above an unconsolidated gravel layer. More details on the watershed are described by Midgley et al. (2012) and Daly et al. (2015a, 2015c).

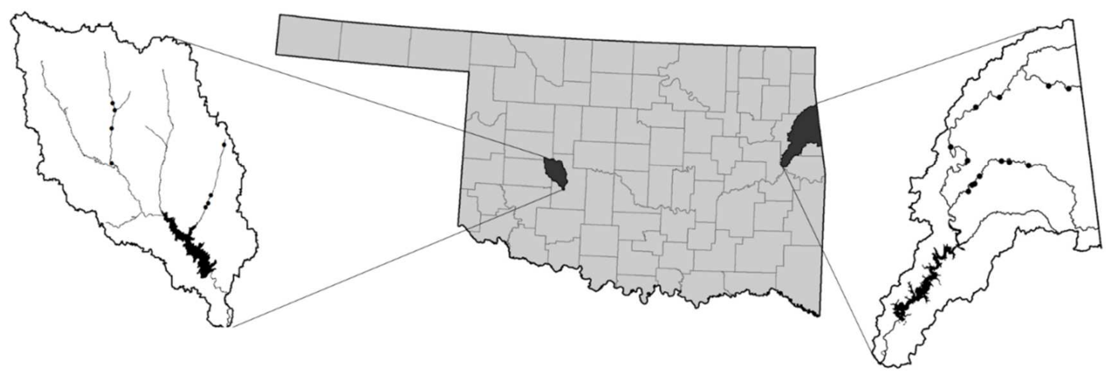

Figure 2.1. Selected field data collection sites along Fivemile and Willow Creeks in the Fort Cobb Reservoir Watershed and the Illinois River and Barren Fork Creek in the Illinois River Watershed.

2.3.1 Jet Erosion Tests

Within the Fort Cobb Reservoir watershed, eight sites have been selected along two of the main tributaries to the reservoir, Fivemile (FM) and Willow (WC) Creeks (Figure 2.1). These tributaries are located on opposite sides of the watershed and the sites were selected to be representative of the entire watershed. JETs were conducted at four sites along a 10.25-km reach of FM and four sites along a 10.1-km reach of WC between March and September 2014 using the "mini"-JET device (Al-Madhhachi et al., 2013). Since the clay layer was not exposed at all sites JET results from the only the sand layer will be used in this study. Within the Illinois River basin, JETs were conducted at seven sites along a 25.5-km reach of Barren Fork Creek (BF) and six sites along a 69.1-km reach of the Illinois River (IR) between October 2011 and April 2012. JETs were only conducted in the silty loam layer. At least two JETs were performed at each site. Additional JETs were performed if time allowed.

The operation of the JETs followed previously described protocols for the "mini"-JET (Al-Madhhachi et al., 2013; Daly et al., 2015a; Khanal et al., 2016a). Heads ranged from 31 cm to 46 cm in the sand layer for FM and WC and 57 cm to 345 cm for BF and IR. At least one 5-cm diameter by 5-cm long cylindrical soil core sample taken from the streambank at each site. The cylindrical soil core sample was used to determine bulk density and moisture content for each site. At least one soil sample was taken at each site was analyzed for particle size using a hydrometer and sieve analysis according to ASTM Standards D421 (ASTM, 2002a) and D422 (ASTM, 2002b).

The scour depth solution, developed by Daly et al. (2013), was used to derive erodibility parameters from recorded Scour depths, time, and constant head setting. This technique minimizes the sum of squared errors (SSE) between measured scour and predicted scour from the excess shear stress equation by using an initial guess and solver routine to determine τ_c and k_d. Wilson model parameters were also derived from observed data using a similar technique as the scour depth approach following Al-Madhhachi et al. (2013).

Statistical analyses were performed using Mini-Tab 17 (Mini-Tab, Inc., State College, PA) and Sigma-Plot 12.5 (Systat Software, Inc., Germany). Average values of erodibility parameters (τ_c, k_d, b_0, b_1) and soil physical properties were determined from the JETs for each of the streams. Additionally, a coefficient of variation (CV) was determined for each parameter. The coefficient of variation is a measure of relative standard deviation and is calculated by taking the ratio of the standard deviation to the mean. This results in a dimensionless parameter which allows for the comparison of variation between parameters with different units and among parameters with large and small values. A regression analysis was conducted in Mini-Tab 17 for the erodibility parameters and soil properties versus distance for FM, WC, BF and IR. Distance was measured in km upstream from the reservoir or the confluence for WC and FM, respectively. Distance was measured in km upstream from the most downstream site on IR and BF. Finally, a Kruskal-Wallis test was performed to determine if a significant difference existed between sites within each stream. The Kruskal-Wallis test is the non-parametric version of an ANOVA and can be used for data sets with small sample sizes, skewed data, or non-normal data (Helsel and Hirsch, 2002). An $\alpha=0.05$ was used for all statistical analyses.

2.3.3 Streambank Erosion Prediction

The erodibility parameters from JETs along FM and BF were input into the CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) to determine the impact of erodibility parameter variability on lateral retreat prediction. CONCEPTS is a one-dimensional, process-based model that simulates sediment transport and streambank erosion processes (fluvial erosion and mass-wasting) at different cross sections along a stream reach, and allows for vertical bed adjustment along the entire reach (Langendoen, 2000; Langendoen and Alsonso, 2008). CONCEPTS requires very detailed information on channel and floodplain geometry, soil properties, soil layering, sediment properties, sediment layering, and channel and floodplain roughness for each cross-section and water and sediment discharge information at the upstream boundary. Streambank soil parameter inputs included the effective cohesion, c', effective internal angle of friction ϕ', and erodibility parameters. Fluvial erosion is typically predicted in CONCEPTS using the linear excess shear stress equation (eq. 1) with τ_c and k_d as input. For this research, the excess shear stress equation was replaced by the Wilson model (eq. 2) in a second set of simulations with b_0 and b_1 as input to the model.

CONCEPTS simulations for BF and FM were used for this study; more details about model implementation can be found in Daly (2012) and Chapter 3, respectively. Simulation periods extended from Oct. 2007 to Oct. 2011, for BF, and from 2008-2013 for FM. For the BF simulations, only the erodibility parameters for the silt layer were adjusted. Wilson model parameters for the gravel layer were determined by Khanal et al. (2016b). For simulations on FM, only the erodibility parameters for the sand layer were adjusted.

The sensitivity of erosion predictions to the site-scale and stream reach-scale variability in JET derived erodibility parameters was investigated. A single cross-section was selected for each stream reach. For BF, the cross section experiencing the highest streambank retreat was selected for the analysis. For FM, the cross-section experiencing the highest lateral retreat was the final cross-section in the model. A sensitivity analysis performed by Daly (2012) noted a higher sensitivity for the most upstream and downstream cross-sections in the model simulation and suggested this may have been attributed to a boundary issue within the model. To avoid the potential higher degree of sensitivity at the downstream cross-section, the cross-section experiencing the second highest lateral retreat was selected for FM. Erodibility parameters derived from each individual JET completed at these cross-sections as well as the mean and median values were used as input. Then, in a similar manner, erodibility parameters derived from each JET performed along the entire stream reach were applied. Observed retreat was determined for each location using aerial imagery obtained from the National Agricultural Imagery Program (NAIP). Images from 2008 and 2013 were used for FM and images from 2008 and 2010 were used for BF. Each image was georeferenced in using ArcMap (v10.0) and streambanks were digitized at the site. Average distances between polylines were used as observed retreat (Purvis and Fox, 2016). For each scenario, observed and predicted lateral retreats at the selected cross-section were compared.

2.4 Results and Discussion

2.4.1 Variability of Linear Excess Shear Stress Parameters

Similar average values of τ_c were observed for FM and WC and similarly for IR and BF (Table 2.1). Higher τ_c and lower k_d were observed within the Illinois River watershed (BF and IR) when compared to the Fort Cobb Reservoir watershed (FM and WC). This suggested the soils within the Illinois River watershed were less erodible. This could be related to the higher clay content in BF and IR soils, predominately silt with a clay content around 20%, while soils from FM and WC consisted of 79 to 97% sand with less than 12% clay (Figure 2.2).

A higher degree of variability in erodibility parameters was observed for Illinois River watershed than the Fort Cobb Reservoir watershed (Figure 2.3). Although FM and

Table 2.1. Summary statistics for parameters measured along Fivemile Creek, Willow Creek, Barren Fork Creek, and Illinois River.

		Critical Shear Stress τ_c (Pa)	Erodibility Coefficient k_d (cm^3 $N^{-1}s^{-1}$)	Wilson Model Parameters b_0 (g $m^{-1}s^{-1}N^{0.5}$)	b_1 (Pa)	% Sand	% Silt	% Clay	Bulk Density BD (g cm^{-3})	Median Particle Size d_{50} (mm)
FM	Mean	0.8	159.3	95.6	7.1	72	19.3	8.7	1.5	0.1
	Median	0.7	120.4	84.3	4.8	75.7	15.7	9.1	1.6	0.1
	Std. dev	0.5	113.6	74.9	6.2	12.8	9.8	4.9	0.2	0.02
	CV	0.64	0.71	0.78	0.88	0.18	0.51	0.56	0.11	0.17
	Count	12	12	11	11	12	12	12	12	12
WC	Mean	0.7	255.7	257.5	3.6	77	15.7	7.3	1.3	0.21
	Median	0.7	203.4	315.1	3.6	79.5	13.1	7.5	1.3	0.11
	Std. dev	0.3	196.9	149.4	1.2	8.3	5.6	2.8	0.2	0.32
	CV	0.45	0.77	0.58	0.34	0.11	0.36	0.39	0.11	1.53
	Count	12	12	12	12	9	9	9	9	9
BF	Mean	3.3	54.6	202	24.8	32.8	50	15	1.2	0.13
	Median	2.2	36.6	98.9	16.7	25.5	54.8	15.7	1.3	0.04
	Std. dev	3.8	78.3	379	28.3	17.4	15.5	3.8	0.1	0.18
	CV	1.13	1.43	1.88	1.14	0.53	0.31	0.25	0.07	1.39
	Count	18	18	18	18	11	11	11	7	11
IR	Mean	3.3	35.7	112.3	23.5	17.2	61.9	17.9	1.2	0.04
	Median	3	20	55.6	20.4	10.7	69.2	19.5	1.3	0.03
	Std. dev	4	51	144.1	21.5	14.8	16.6	3.4	0.04	0.02
	CV	1.21	1.43	1.28	0.92	0.86	0.27	0.19	0.03	0.58
	Count	18	18	18	18	6	6	6	6	6

WC are on opposite sides of the watershed, similar variability was observed between the two creeks. For FM and WC, the τ_c varied by less than one order of magnitude and CVs were 0.64 and 0.45 for FM and WC, respectively. This indicates a lower standard deviation relative to the mean when compared to IR and BF. The highest variability in τ_c (five orders of magnitude) was observed at IR. Three orders of magnitude of variation was observed for k_d along IR and BF, and only two orders of magnitude of variation was observed for FM and WC. The CVs were greater than one for τ_c and k_d along BF and IR. The k_d was more variable for all four streams compared to τ_c based upon CVs. Such results are consistent with the variability in soil textures within the two watersheds (Figure 2.2).

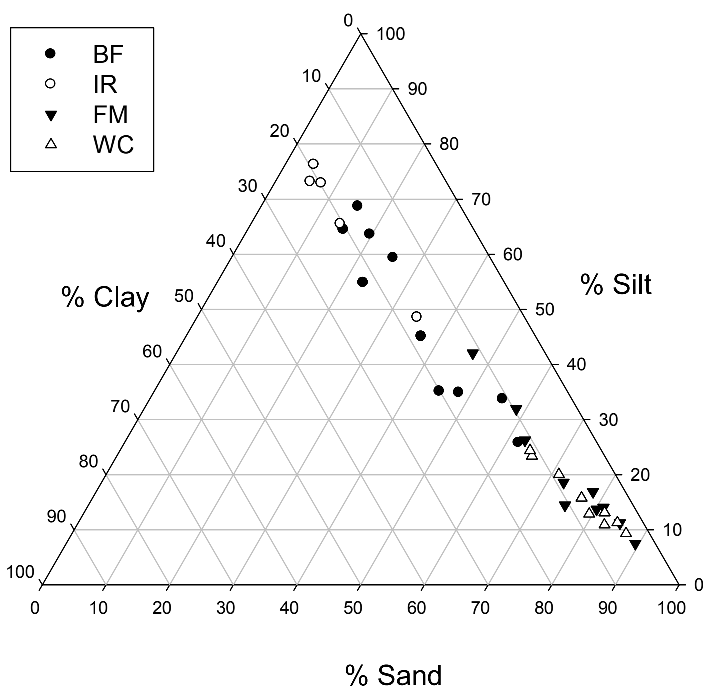

Figure 2.2. Soil texture of streambank soil samples collected at field data collection sites along Barron Fork Creek (BF), Illinois River (IR), Fivemile Creek (FM) and Willow Creek (WC).

As suggested by Hanson and Simon (2001), Wynn and Mostaghimi (2006), Wynn et al. (2008), Daly et al. (2015a) and Daly et al. (2015b), variability observed in erodibility parameters can be attributed to soil heterogeneity and subaerial processes. When compared to these other studies, less variability in erodibility parameters was observed along FM and WC. In addition, soil physical properties, percent sand, silt and clay, d_{50}, and *BD* within the Fort Cobb watershed exhibited less variation than with the other studies. The standard deviations were generally small when compared to the means for all properties for both soil layers, with the exception being d_{50} for WC. A similar degree of watershed-scale variability in erodibility parameters and soil physical properties to that of IR and BF was observed by Thoman and Niezgoda (2008) in the Powder River Basin of Wyoming.

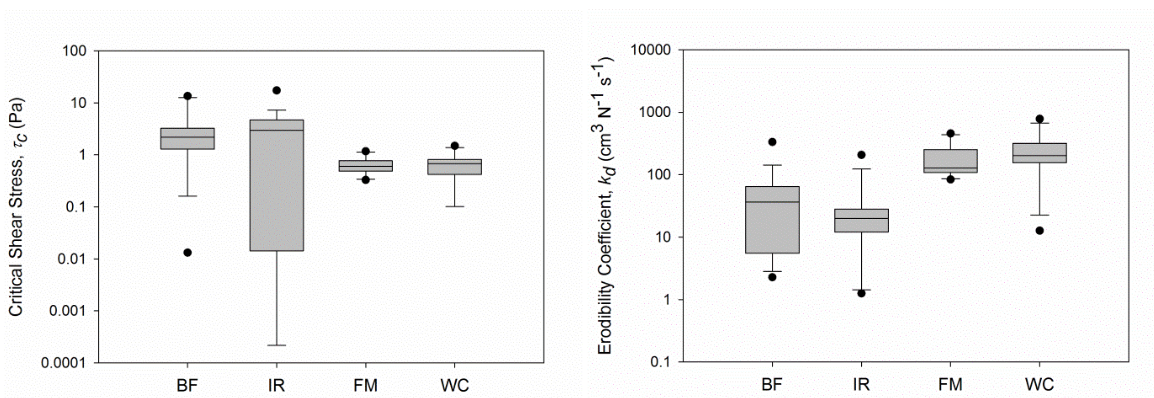

Figure 2.3. Box plots of variation of excess shear stress parameters, τ_c (left) and k_d (right) measured using JETs along Barren Fork Creek (BF), Illinois River (IR), Fivemile Creek (FM) and Willow Creek (WC).

2.4.2 Variability of Wilson Model Parameters

Wilson model parameters, b_0 and b_1, were derived from the JETs using the same methodology proposed by Al-Madhhachi et al. (2013). The b_0 were similar across all four streams, with WC having slightly higher average values (Table 2.1). One to two orders of magnitude variation were observed for b_0 along all four streams, with a slightly higher variation for BF (Figure 2.4). Variability in b_0 (CV=0.58-1.88) was similar to the variability observed in k_d (CV=0.71-1.43) for all four streams, with b_0 being slightly more variable for FM and BF but slightly less so for WC and IR. The b_1 values were lower for FM and WC when compared to BF and IR, which was expected due to the high correlation between b_1 and τ_c and the lower τ_c values observed for FM and WC. Slightly more variation in b_1 was observed than τ_c from FM and BF and much less variation than τ_c for IR. The similar amount of variability observed between excess shear stress and Wilson parameters can be attributed to the similar solver techniques used for the Wilson and scour depth solution used to derive τ_c and k_d (Khanal et al., 2016a).

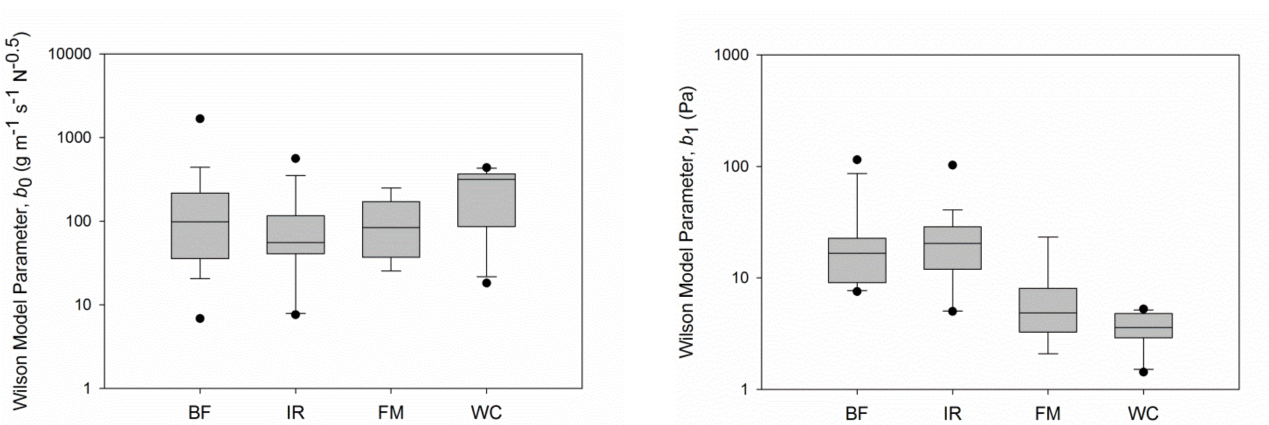

Figure 2.4. Box plots of variation of Wilson Model parameters, b_0 (left) and b_1 (right) measured using JETs along Barren Fork Creek (BF), Illinois River (IR), Fivemile Creek (FM) and Willow Creek (WC).

2.4.3 Longitudinal Trends

No significant longitudinal trends were observed for the erodibility parameters (τ_c, k_d, b_0 or b_1) or soil physical properties for FM, WC, or BF, with the exception of d_{50} along WC (Table 2.2). The lack of longitudinal trends for erodibility parameters along FM, WC, and BF could be attributed to the smaller amount of variability within these streams (Figure 2.5). Mean particle size of bank material decreased in the downstream direction for WC and IR, but not FM or BF. The downstream fining of bank material was expected, as discussed by Knighton (1998) and shown by Konsoer et al. (2016). The lack of a trend for d_{50} along FM may be attributed to the small amount of variability in mean particle size (d_{50} ranged from 0.06 to 0.11 mm) and soil heterogeneity within the stream system.

Table 2.2. Coefficient of determination (R^2) for longitudinal regression for soil parameters versus distance upstream Fivemile Creek (FM), Willow Creek (WC), Barren Fork Creek (BF), and Illinois River (IR). Bold indicates significance at α=0.05.

	BF	IR	FM	WC
Critical Shear Stress, τ_c (Pa)	0.04	**0.30**	0.12	0.03
Erodibility Coefficient, k_d (cm^3 N^{-1} s^{-1})	0.08	**0.32**	0.22	0.22
Bulk Density, *BD* (g cm^{-3})	0.00	0.02	0.09	0.05
Median Particle Size, d_{50} (mm)	0.09	**0.26**	0.04	**0.44**
Sand (%)	0.04	0.00	0.07	0.00
Silt (%)	0.07	0.00	0.06	0.00
Clay (%)	0.04	0.00	0.07	0.01
Wilson Model Parameter, b_0 (g m^{-1} s^{-1} N$^{-0.5}$)	0.04	0.15	0.15	0.06
Wilson Model Parameter, b_1 (Pa)	0.05	**0.29**	0.09	0.01

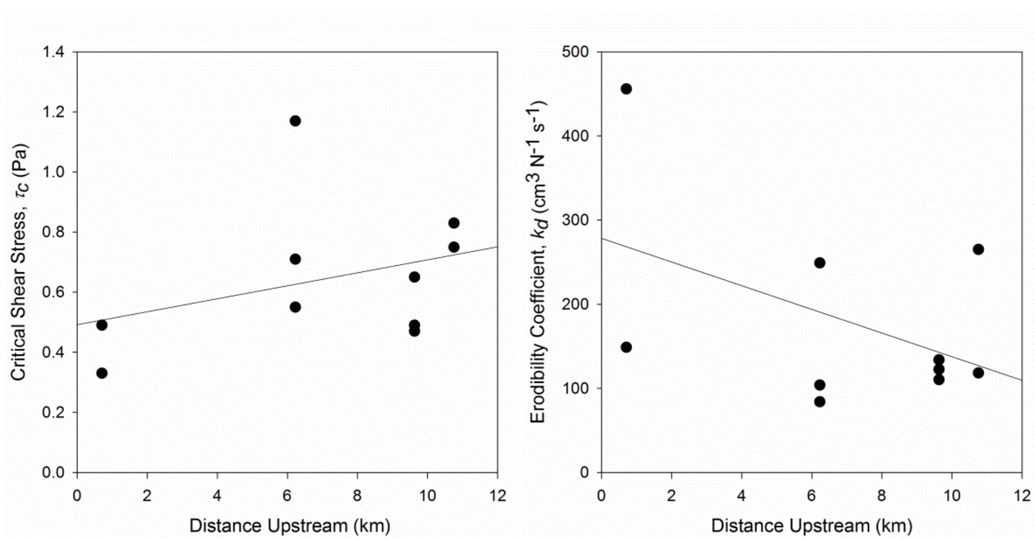

Figure 2.5. Regression for excess shear stress parameters (τ_c and k_d) determined using JETs versus distance upstream for Fivemile Creek.

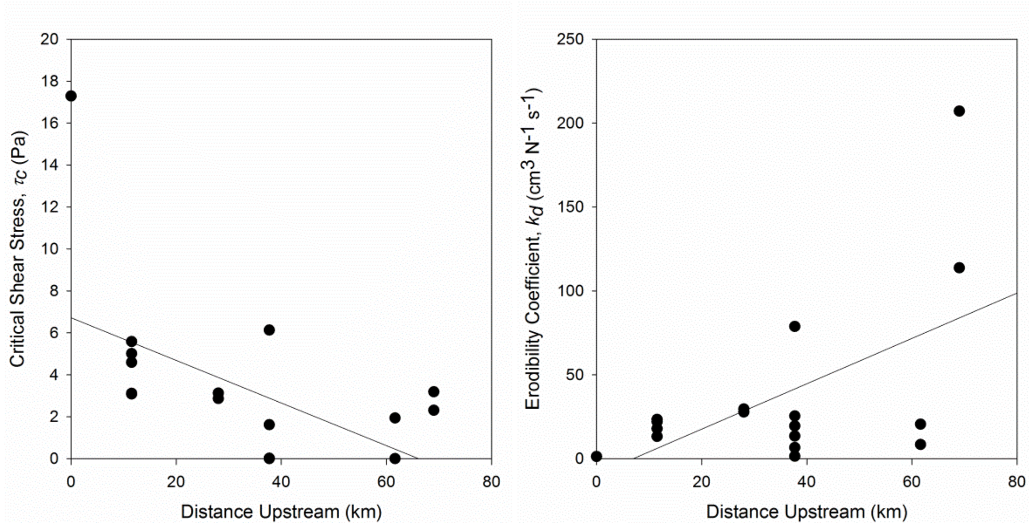

Figure 2.6. Regression for excess shear stress parameters (τ_c and k_d) determined using JETs versus distance upstream for Illinois River.

Three erodibility parameters (τ_c, k_d, and b_1) exhibited weak, but significant longitudinal trends along IR (r^2=0.30 to 0.32). The τ_c decreased and the k_d increased in the upstream direction for IR (Figure 2.6). This may partially due to the downstream fining of soil particle size that was observed along IR. Downstream fining of particles may increase soil cohesion and therefore increase erodibility in the downstream direction (Knighton, 1998; Konsoer et. al, 2016). The significant trends may be attributed to the higher degree of variability within this stream and the larger spatial scale (69.1 km) in which erodibility was measured. Soil measurements were taken along 10.3, 10.1, and 25.5 km reaches of FM, WC, and BF, respectively. A significant longitudinal trend may have been observed if measurements were conducted on longer reaches of these streams.

Since no longitudinal trend was observed, Kruskal-Wallis tests were also used to determine if a significant difference existed between sites. No significant differences were observed between sites for FM or WC for all erodibility parameters (p=0.238 to 0.603). In addition, no significant difference between sites along BF or IR at α=0.05 was observed (p=0.084 to 0.317). Previous studies have also shown no variations between sites along the same stream (Wynn et al., 2008; Konsoer et al., 2016). Ideally, a longitudinal trend could be used to extrapolate JET results to other sites where erodibility was not measured to minimize the number of JETs needed to adequately characterize the erodibility along an entire stream system. While a significant longitudinal trend was not present for either FM or WC, a significant difference between the sites was also not observed. Therefore, it would be expected that the erodibility at locations between sites would be similar to the values measured at one particular site using the JET.

Understanding the degree to which erodibility parameters vary is crucial. In a watershed like Fort Cobb where there was no statistical difference between sites and a small amount of variability. Using average or median τ_c and k_d values obtained from a few locations to estimate the erodibility values at additional sites may provide acceptable results when utilized to model streambank erosion within the stream system. Although a significant difference did not exist between sites along BF or IR, this approach would not be possible due to the high amount of variability in the JET results for these stream systems.

2.4.4 Implications for Lateral Retreat Prediction

Lateral retreat predicted by CONCEPTs based on JET site-scale measurements and JET stream-scale measurements were first compared for both fluvial erosion models (Table 2.3). Consistently, a slightly larger range of lateral retreat was predicted with the stream-scale measurements as compared to the site-scale measurements. This was expected due to the larger range in erodibility parameters obtained from the JETs at the stream-scale. A higher range of lateral retreat was predicted along FM for both models when compared to BF. The CV for input erodibility parameters were consistently smaller than the CV for predicted lateral retreat. For example, τ_c and k_d along FM had a CV of 0.6 and 0.7, respectively, but resulted in a CV of 0.2 for the predicted lateral retreat. The CVs for τ_c and k_d along BF were 1.1 and 1.9, respectively, but resulted in a CV of 0.5 for the predicted lateral retreat. The input variability was diminished due the nonlinear influence between fluvial erodibility and mass wasting processes in the model. However, while the variation in predicted retreat was lower than the corresponding input variables, the large range in predicted retreat highlighted the uncertainty in using a single JET for simulating streambank erosion.

Table 2.3. Summary statistics for predicted lateral retreat (m) from CONCEPTS using JET results along Barren Fork and Fivemile Creeks.

		BF		FM	
		Excess Shear	Wilson Model	Excess Shear	Wilson Model
Site	Mean	12.3	31.1	34.1	37.6
	Std. dev.	6.4	2.6	11.1	7.5
	CV	0.52	0.08	0.32	0.20
	Range	12.6	5.3	22.1	14.1
Stream	Mean	12.1	30.6	40.4	29.1
	Std. dev.	6.0	2.0	9.6	13.4
	CV	0.50	0.06	0.24	0.46
	Range	15.9	6.6	31.6	38.5
Observed retreat		20.0		6.0	

*CV = coefficient of variation

For BF, the excess shear stress equation under predicted lateral retreat when compared to the observed retreat (Figure 2.7), while the Wilson model over predicted lateral retreat. The under prediction of lateral retreat by the excess shear stress equation can be attributed to an increase in applied τ around the outside of the meander located at the BF site. Previous research has shown that the Wilson model predicted lower lateral retreat closer to the observed retreat than the excess shear stress equation when integrated into the Bank Stability and Toe Erosion Model (BSTEM) (Khanal et al., 2016b; Klavon, 2016). This was not the case when the Wilson model was incorporated into CONCEPTS for BF. However, the b_0 and b_1 from Khanal et al. (2016b) used for the gravel layer were estimated based on BSTEM simulations and were not directly measured. These values were also used in the CONCEPTS simulations. Direct measurement of b_0 and b_1 for the gravel layer may predict a lateral closer to the observed retreat.

For FM, both fluvial erosion models over predicted erosion (Figure 2.8). This was expected due to the highly erodible soil and the presence of heavy vegetation, which can significantly decrease the applied τ reaching the detachable soil particles or aggregates (Millar, 2000; Simon and Collison, 2002; Kean and Smith, 2004; Thompson et al., 2004, Klavon et al., 2016). This highlights the need to account for the impact of vegetation or meanders on applied τ during model setup and calibration. For both erosion models along FM and BF, using mean or median results from multiple JETs and adjusting parameters during calibration would likely result in a lateral bank retreat prediction closer to the measured historical retreat.

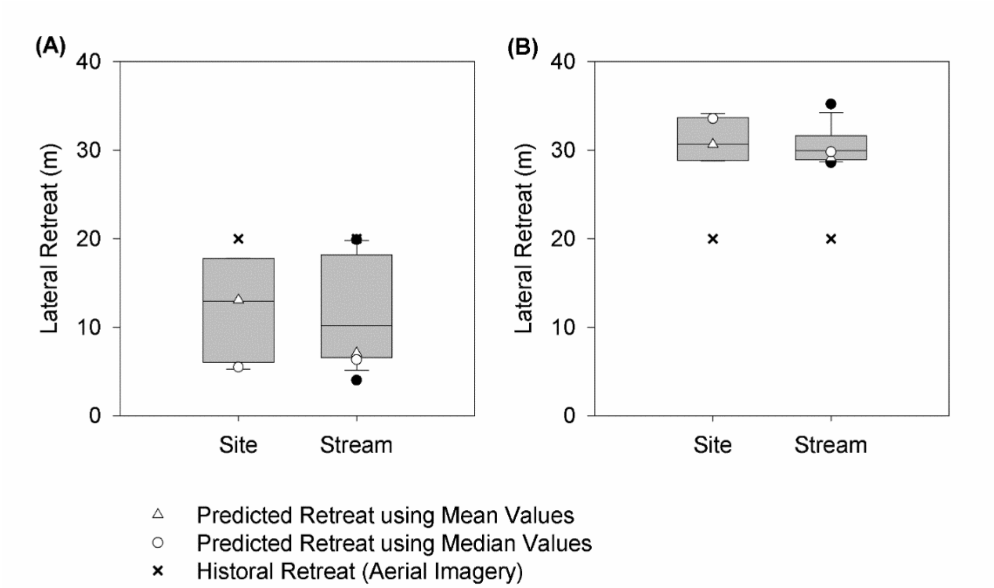

Figure 2.7. Boxplots of variation in predicted lateral retreat at a site on Barren Fork Creek using JET results from the site and entire stream reach for (a) excess shear stress equation and (b) Wilson model.

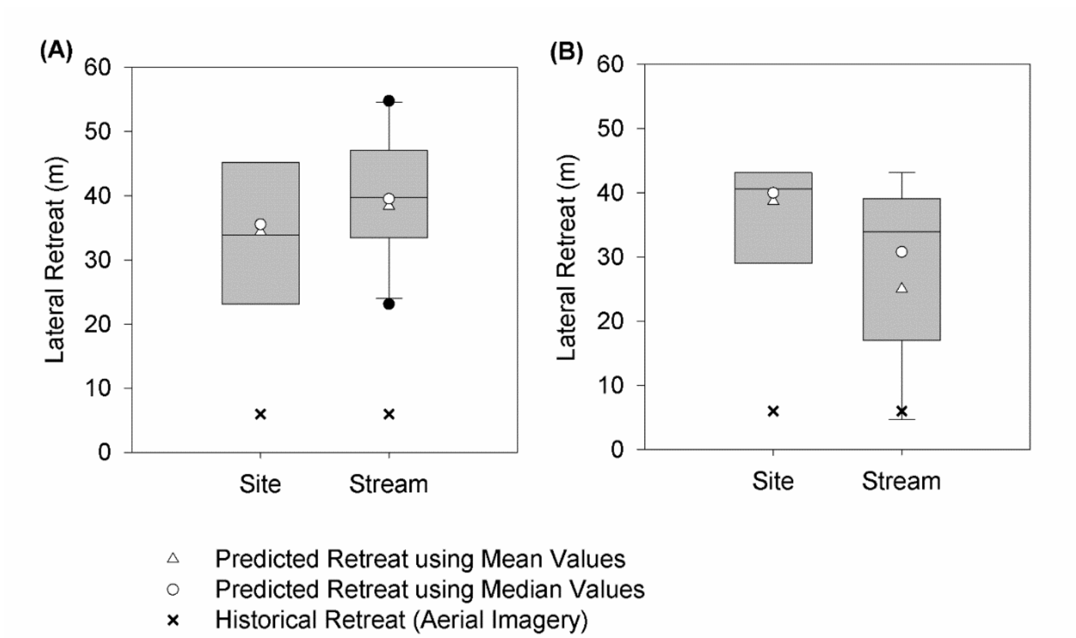

Figure 2.8. Boxplots of variation in predicted lateral retreat at a site on Fivemile Creek using JET results from the site and entire stream reach for (a) excess shear stress equation and (b) Wilson model.

2.4.5 Adjusting Erodibility Parameters During Model Calibration

Applied τ can be impacted by the presence of meanders (increased τ) or vegetation (decreased τ) (Millar, 2000; Simon and Collison, 2002; Kean and Smith, 2004; Thompson et al., 2004; Daly et al. 2015c; Konsoer et al., 2016), which is not taken into account in the one-dimensional calculation of τ (Klavon et al., 2016) in CONCEPTS. Because the model does not allow for the direct adjustment of τ, an v-factor can be used to indirectly adjust τ by adjusting erodibility parameters as discussed in Daly et al. (2015b):

$$\varepsilon_r = k_d(\nu\tau - \tau_c) = (\nu k_d)(\tau - (\frac{\tau_c}{\nu})) \quad (2.3)$$

A similar method can be used to adjust τ in the Wilson model:

$$\varepsilon_r = b_0\sqrt{\nu\tau}\left[1 - exp\left\{-\exp\left(3 - \frac{b_1}{\nu\tau}\right)\right\}\right] = (b_0\sqrt{\nu})\sqrt{\tau}\left[1 - exp\left\{-\exp\left(3 - \frac{(b_1/\nu)}{\tau}\right)\right\}\right] \quad (2.4)$$

Based on model calibrations performed for BF (Daly, 2012) and FM (Chapter 3) by comparing predicted retreat to observed retreat determined from NAIP aerial imagery for the time period simulated, an v = 1.26 was used for the BF site to account for the increase in τ around meanders (sinuosity) and v = 0.27 was used for the FM site to account for the decrease in τ due to heavy vegetative cover. Note that these reported v were based on use of the excess shear stress equation. Combining these calibration factors with mean erodibility parameters measured at the site, the excess shear stress equation resulted in a lateral retreat prediction of 18.7 m and 7.1 m for BF and FM, respectively.

2.5 Conclusions

Site and stream-reach variability in fluvial erodibility parameters may result in uncertainty when modeling particle detachment and fluvial erosion. Fluvial erodibility parameters corresponding to the linear excess shear stress and Wilson models were less variable in watersheds with less cohesive soils. Changes in erodibility parameters in the longitudinal direction or differences between the sites were not observed for the shorter stream reaches; however, longitudinal trends were observed on longer stream reaches. Large degrees of variability may increase the error in using average or single-test values of erodibility parameters for a site, reach, or watershed. When JET results were incorporated into a stream erosion and bank retreat model, less variation was observed in lateral retreat prediction than input erodibility parameters, independently of the type of fluvial detachment model used. Uncalibrated erodibility parameters and simplified applied shear stress estimates failed to match observed lateral retreats. Factors such as vegetation and/or meandering need to be accounted for through model calibration or advanced two- or three-dimensional flow modeling.

CHAPTER 3

UNCERTAINTY AND SENSITIVITY ANALYSIS FOR SIMULATING STREAMBANK STABILIZATION PRACTICES

3.1 Abstract

Streambank erosion can contribute a significant sediment loading to surface waters, lead to loss of land, and threaten infrastructure. Streambank stabilization with riprap or vegetation can be used to reduce erosion and increase stability of streambanks. Several process-based models are available to evaluate stabilization practices prior to implementation. A CONCEPTS model was set-up and calibrated for two rapidly eroding streams in western Oklahoma. In order to simulate stabilization practices in process-based models, each practice must be appropriately parameterized. Typically, such parameterizations involve changing the geotechnical and/or fluvial resistance of the streambank soil layers. Two stabilization practices were selected for evaluation in this research: riprap toe and vegetation with bank grading. Riprap was simulated using two parameters: median particle size and riprap height. Two parameters were identified for simulating vegetation: added root cohesion and shear stress adjustment factor. An uncertainty analysis for sediment reduction and lateral retreat predictions was conducted for each parameter at four sites. Vegetation was simulated for both 2:1 and 3:1 bank slopes. Sediment reduction and lateral retreat predictions were not sensitive to median

particle size or root cohesion, but were highly sensitive to riprap height and the shear stress adjustment factor. Future parameterizations of streambank stabilization practices should focus on these two variables.

KEYWORDS. *streambank erosion, streambank stabilization, process-based models, riprap, vegetation*

3.2 Introduction

Excess sediment is a leading cause of surface water impairment and can reduce water clarity, destroy aquatic habitat, and increase contaminant loads (Lyman et al., 1987; Sekley et al., 2002; Miller et al., 2014; Purvis et al., 2016). In some areas streambank erosion contributes as much as 50 to 80% of sediment loadings (Wilson et al., 2008). In addition, streambank erosion leads to the loss of adjacent land and can threaten infrastructure and nearby structures. Due to the potential negative effects of streambank erosion, stream restoration and streambank stabilization have become common practices to reduce erosion in channels, often with the goal of correcting anthropogenic disruptions to streams and reducing sediment loads from streambanks (Beechie et al., 2010). In recent years, billions of dollars have been spent to reduce sediment loads from streambanks through stabilization and restoration projects (Lavendel, 2002; Bernhardt et al., 2005). Because of the large investment in stabilization and the high amount of streambank material contributing to surface waters, understanding streambank erosion processes and sediment loads is imperative to successful restoration or stabilization practices.

Streambank erosion is controlled by three main processes: subaerial processes, fluvial erosion of the bed and bank, and mass wasting. These three processes are intricately linked and often occur in a cyclical manner (Couper and Maddock, 2001). Subaerial processes such as freeze/thaw, and wet and dry cycles can weaken the soil and make the soil particles more susceptible to detachment by fluvial erosion. Fluvial erosion is the detachment of soil particles from the bed or bank by streamflow. Fluvial erosion can steepen streambanks by eroding the toe of the bank or by degrading the bed of the stream. This can decrease the stability of the bank, making it more susceptible to mass wasting which occurs when the driving forces exceed the resisting forces to collapse. Numerous factors contribute to these three processes including land use, climate, soil properties, geomorphology, slope, the presence/absence of vegetation, etc.

Several models are available for predicting sediment loading from streambank erosion at the site, reach, or watershed scale. The Bank Stability and Toe Erosion Model (BSTEM) was developed by the USDA-ARS National Sedimentation Laboratory in Oxford, MS, and can be used predict fluvial erosion and mass wasting processes at a single site. BSTEM limits the simulation to one side of a cross-section, but does not allow for the adjustment of the bed, which is particularly important in incising channels. BSTEM can be a useful tool to evaluate site specific bank retreat, but has limited use when determining stream-scale sediment loads (Klavon et al., 2016). The CONservational channel evolution and pollutant transport system (CONCEPTS) was developed by the USDA-ARS as a follow-up to BSTEM to consider sediment loads on the reach scale. CONCEPTS models bank stability and fluvial erosion in the same manner as BSTEM, but considers both banks of a cross-section, as well as sediment transport, which allows for vertical bed adjustment (Langendoen, 2000; Langendoen and Alsonso, 2008). CONCEPTS also links several cross-sections together in a reach to simulate bank erosion and sediment transport processes on the reach scale. The Soil and Water Assessment Tool (SWAT) primarily simulates sediment contributions from overland flow, but has recently incorporated streambank erosion processes (Neitsch et al., 2011). However, estimating streambank erosion on such a large scale requires several simplifications. For example, SWAT assumes a trapezoidal channel with 2:1 side slopes, which may not accurately represent the channel geometry, only allows for one soil layer, and does not simulate mass wasting processes (Mittelstet et al., 2016).

Streambank erosion models such as BSTEM and CONCEPTS incorporate the linear excess shear stress equation for fluvial particle detachment (Partheniades, 1965; Hanson 1990a, 1990b):

$$\varepsilon_r = k_d (\tau - \tau_c)^a \tag{3.1}$$

where ε_r is the erosion rate (cm s^{-1}), k_d is the erodibility coefficient (cm^3 N^{-1} s^{-1}), τ is the average hydraulic boundary shear stress (Pa), τ_c is the critical shear stress (Pa), and a is an empirical exponent that is assumed to be one. Geotechnical failures are simulated using a factor of safety approach in which a bank collapse will occur when the driving forces exceed the resisting forces. Resisting forces are dependent on two soil parameters, effective angle of friction, ϕ', and effective cohesion, c'. A more detail description of stability calculations can be found in Simon et al. (2009), Midgley et al. (2012), Daly et al. (2015), and Klavon et al. (2016).

In addition to predicting streambank erosion rates, CONCEPTS was developed in order to evaluate stream channel and stabilization designs (Langendoen and Simon, 2000;

Langendoen, 2011; Daly, 2012). A successful stabilization practice will either increase the forces resisting fluvial erosion and geotechnical failure or reduce the forces acting on the streambank. Common stabilization techniques include placing large rocks, known as riprap, along the bank or bioengineering practices that incorporate the use of vegetation. Traditionally, riprap has been the preferred method of stabilization. In recent years, bioengineering have become more commonly used due to the ecological and economic benefits. Langendoen (2011) described the different types of stabilization practices that can be simulated in CONCEPTS, including grade control, vegetation and riprap. Protection against fluvial erosion can be simulated by adjusting the erodibility parameters of the protected soil layer or setting the τ_c to threshold values for certain bank protection methods. In addition, vegetation can reduce the applied shear stress, τ, experienced by soil particles by 13% to 89% (Thompson et al., 2004). The net effect can be simulated by adjusting the erodibility parameters. Soil cohesion can also be modified to simulate practices that enhance shear strength of soil, such as an increase in cohesion to simulate the effects of roots from vegetation (Pollen and Simon, 2005).

The objectives of this study were to evaluate the sensitivity and uncertainty of a reach-scale streambank erosion and stability model (CONCEPTS) to input parameters used to parametrize streambank stabilization practices. CONCEPTS models were developed for two stream systems in southwestern Oklahoma with rapidly eroding streambanks. Such research provided key guidance on the uncertainty in model predictions relative to uncertainty in important variables for parameterizing stabilization practices.

3.3 Methods and Materials

3.3.1 Watershed Description

The Fort Cobb Reservoir watershed, located in western Oklahoma, was selected for this study. Fort Cobb Reservoir is on the Oklahoma 303(d) list for impairment by nutrients, sediments, and siltation (Storm et al., 2003). The Fort Cobb Reservoir provides public water supply, recreation, and wildlife habitat, and the watershed is predominately agricultural, with roads and urban land use accounting for 5%, and water less than 2% (Becker, 2011). Numerous upland and riparian conservation practices, such as reduced or no-till cropland, conversion of cropland to pastureland, terracing, riparian buffers, and cattle exclusion from streams, and various structural and water management practices to reduce sediment loading were implemented in the Fort Cobb Reservoir watershed as part of Conservation Effects Assessment Program (CEAP) (Steiner et al., 2008). However, the reservoir still fails to meet water quality standards based on sediment. There are four main tributaries to the reservoir, all of which contain unstable streambanks. Using radionuclide tracers, it has been determined that 50% of the suspended sediment in Fort Cobb Reservoir originated from streambanks (Wilson et al., 2008).

Nine sites have been selected along two of the main tributaries to the reservoir, Fivemile Creek (FM) and Willow Creeks (WC), for field data collection (Figure 3.1). These tributaries are located on opposite sides of the watershed and the sites were selected to be representative of the entire watershed. Streambanks in the watershed consist of either a single sand or sandy loam layer, while others exhibit a layering effect of sand or sandy loam layers above and below a more cohesive layer with higher clay content.

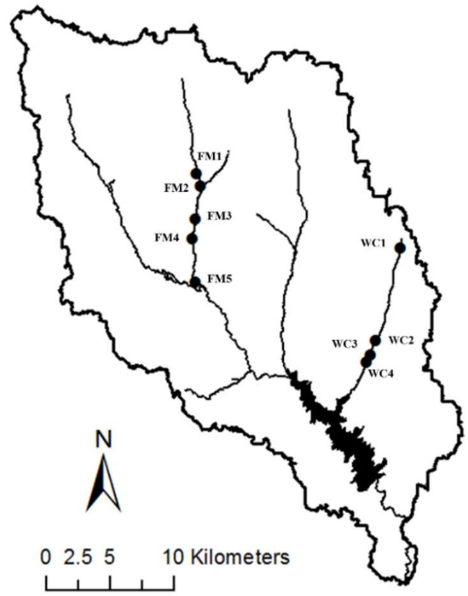

Figure 3.1. Selected field data collection sites along Fivemile Creek (FM) and Willow Creek (WC) in the Fort Cobb Reservoir Watershed.

3.3.2 Field Data Collection

Five sites along Fivemile Creek (FM1-FM5) and four sites along Willow Creek (WC1-WC4) were selected for field data collection. At least one cross-sectional survey was conducted at each site using an automatic level. One site, FM2, was severely impacted by a series of headcuts (Figure 3.2). Seven cross-sectional surveys were conducted at this site. During surveying, detailed information on layering and vegetation were recorded. Soil samples were collected from the thalweg of the channel at each cross-section and were analyzed for soil particle size distribution using the hydrometer and sieve methods: ASTM Standards D421 (ASTM, 2002a) and D422 (ASTM, 2002b). A water level logger (HOBO U20-001-01, Onset, Bourne, MA) was installed at each site to measure absolute pressure. Pressures were converted to water depth using atmospheric pressures determined from the nearby Oklahoma Mesonet site.

Figure 3.2. Site FM2 on Fivemile Creek is severely impacted by a series of headcuts. Multiple cross-sections were surveyed at this site to characterize the sudden changes in channel elevations.

At each site, erodibility parameters were determined using jet erosion tests JETs. At least two JETs were conducted at each site within each visible layer using the "mini"-JET device according to previously reported methods (Al-Madhhachi et al., 2013; Daly et al., 2015; Khanal et al., 2016a). Streambank soil samples were also collected to analyze for bulk density and particle size as described above. Borehole shear tests (BSTs) were conducted to determine geotechnical parameters, ϕ' and c', for each soil layer. However, the texture of the soils and the location of the water table within this watershed resulted in unreliable BST results; therefore, values based on soil texture were selected from list of BSTEM defaults. Soil data from each site is shown in Table 3.1.

Table 3.1. Summary of field data (layering, soil texture, critical shear stress (τ_c), erodibility coefficient (k_d), and bulk density (BD)) for each soil layer at each field data collection site along Fivemile Creek (FM) and Willow Creek (WC). Soil layers where no jet erosion tests (JETs) were completed report the selected representative monitored bank layer. Note that soil layers are listed in order from highest to lowest elevation and bank layers are labeled using the site name - soil layer # format.

Bank Layer	Layer Thickness (m)	Soil Classification	JETs Completed	Average τ_c (Pa)	Average k_d (cm^3 N^{-1} s^{-1})	Average BD (kg m^{-3})
FM1-1	1.1	Loamy Sand	2	0.79	191.73	1.45
FM1-2	0.6	FM2-2	0	FM2-2	FM2-2	FM2-2
FM2-1	1-1.5*	Sandy Loam	3	0.62	366.5	1.52
FM2-2	0.5-0.75*	Sandy Clay Loam	24	11.97	19.71	1.44
FM2-3	1.22*	Sandy Loam	2	1.5	60.28	1.75
FM3-1	5.3	Loamy Sand	3	0.81	145.6	1.54
FM4-1	4.41	Sand	0	FM3-1	FM3-1	FM3-1
FM5-1	2.75	Sandy Loam	2	0.41	302	1.35
FM5-2	1.25	Clay Loam	2	3.65	61.1	1.38
FM5-3	1.22	FM5-1	0	FM5-1	FM5-1	FM5-1
WC1-1	3.35	Sandy Loam	2	0.45	482.25	1.35
WC2-1	3	Loamy Sand	3	0.603	477.8	1.21
WC2-2	1.1	WC3-3	0	WC3-3	WC3-3	WC3-3
WC3-1	2	Sandy Loam	2	0.72	433.62	1.33
WC3-2	1.8	Loamy Sand	3	0.96	135.56	1.46
WC3-3	0.32	Sandy Loam	3	8.6	10.55	1.35
WC4-1	3.45	Sandy Loam	2	0.86	352.15	1.52
WC4-2	1.1	Loam	2	2.63	34.1	1.41

*Multiple Cross-sections at FM2

3.3.3 Determination of Long-Term Erosion Rates

Aerial imagery was used to estimate long-term streambank retreat at each site. National Agricultural Imagery Program (NAIP) images (1m resolution) were obtained for Caddo County for 2008 and 2013. Using ArcMap (v10.0), each image was georeferenced and used to determine bank retreat. Streambanks were digitized at each site for 2008 and 2013, and the average distance between polylines were used as lateral retreat for that site for the time period (Purvis and Fox, 2016). For site FM5, dense vegetation on both images did not allow for analysis; therefore, the retreat was estimated from the nearest visible streambank.

3.3.4 Model Set-Up and Calibration

Field data collected from each site was input into CONCEPTS to develop a simulation for a 10.3-km reach of Fivemile Creek and a 10.1-km reach of Willow Creek. CONCEPTS requires cross-sectional data to include floodplains, as well as channel geometry and cannot handle dips in the cross-sectional geometry. Floodplain geometry was determined from 2009 2-m LiDAR using the 3-D analyst tool in ArcMap (v10.0). Cross-sectional survey data collected at the field sites were merged with floodplain geometries and the cross-section was smoothed (Figure 3.3).

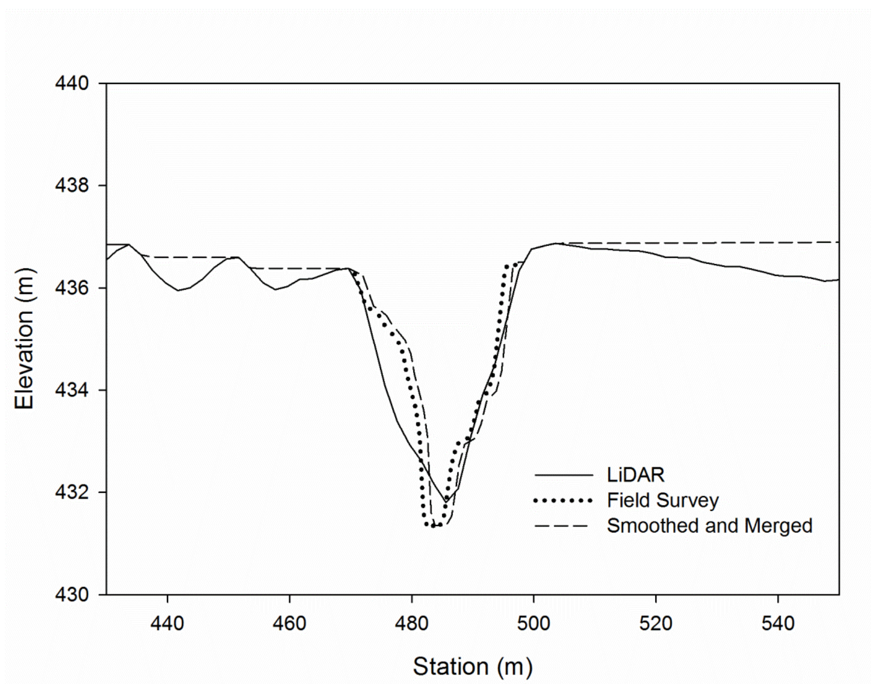

Figure 3.3. Surveyed cross-sections were merged with floodplain geometry from LiDAR data and smoothed to remove dips in elevation for input into CONCEPTS.

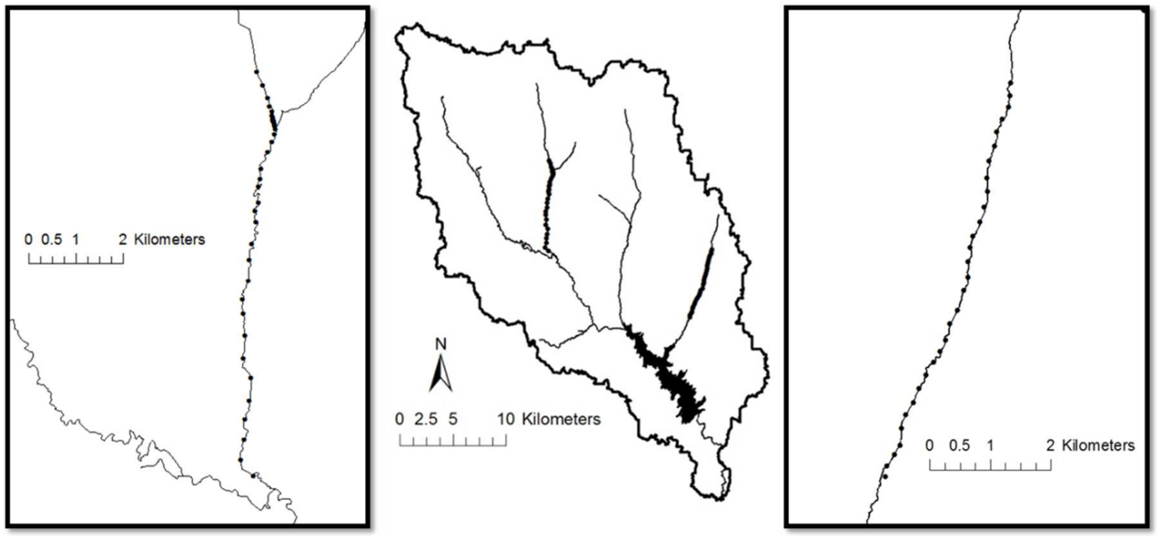

Figure 3.4. Cross-section spacing along Fivemile Creek (Left) and Willow Creek (Right) used in CONCEPTS simulations for each stream.

Due to the large distance between the selected research sites, additional cross-sections (AC) were interpolated from the LiDAR data approximately every 500-m along the channel, for a total of 29 ACs on Fivemile Creek (Figure 3.4) and every 250 m along Willow Creek for a total 34 ACs. LiDAR data have been used in many studies to provide morphological information of stream corridors for hydraulic modelling and streambank erosion estimates where intensive ground surveying was not possible (Bowen and Waltermire, 2002; Thoma et al., 2005; Cavalli et al., 2008). The ACs were more closely spaced around FM2, where several surveyed cross-sections were closely spaced due to the presence of headcuts, to increase the stability of the model. Average soil particle size distributions and bulk densities and default geotechnical parameters were used for the soil and sediment data of each AC. The τ_c values from the JET data were divided by stream and by soil layer to identify the probability distribution using the Individual Distribution Identification function in Mini-tab (v16). The Anderson-Darling (AD) statistic was used to evaluate the distributions. For Fivemile Creek, the τ_c values followed log-normal (AD=0.196 and p=0.848) and Weibull distributions (AD=0.276 and p=>0.25) for the sand and clay layers, respectively. For Willow Creek, the τ_c values followed a log-normal distribution for both the sand (AD=0.190 and p=0.869) and clay (AD=0.258 and p=0.533) layers. Using these distributions, random numbers were generated for τ_c for each AC. A regression equation was used to determine the relationship between τ_c and k_d. This regression was used to determine k_d for each AC.

Because the USGS gauges are downstream of all of the study sites, a daily average stream flow hydrograph for 2008-2013 generated from a calibrated SWAT model for the Fort Cobb Watershed (Moriasi and Starks, 2010; Guzman et al., 2015) was used as flow input. Fluvial erosion is a function of τ and sensitive to peak flows. Therefore, the daily average streamflow hydrograph was converted to an hourly triangular hydrograph using the SCS triangular hydrograph method (SCS, 1972). The converted hydrograph started and ended at base flow that was determined from the daily averaged flow. For flows less than or equal to baseflow, hourly discharge was set to the daily average flow. CONCEPTS requires sediment inflow data (Q_s) for tributaries for each sediment class size in the form of power equations:

$$Q_s = a\, Q^b \tag{3.2}$$

where a and b are regression parameters (Table 3.2). In order to determine the regression parameters of the power equations, data from three USGS gauges (Cobb Creek near Eakly, Lake Creek, and Willow Creek) located in the Fort Cobb Reservoir watershed were combined to develop sediment rating curves for each CONCEPTS particle size. The USGS collected grab samples during various storm events which were analyzed for particle size. Using these data and the streamflow at each gauge, rating curves between sediment discharge, Q_s (kg s^{-1}), and streamflow, Q (cms), were created by fitting a regression equation to the data using SigmaPlot (v12.5, Systat Software, San Jose, CA). Data from all three gauges were used for Fivemile Creek and only data from the Willow creek gauge was used for Willow Creek (Figure 3.5).

Table 3.2. Rating curve coefficients (a and b) for power equation ($Qs = a\ Q^b$, where Qs is sediment discharge (kg s^{-1}) and Q is streamflow (cms)) and coefficients of determination (R^2) determined for each CONCEPTS sediment size class from USGS gauge data for Fivemile Creek and Willow Creek.

Upper Bound Sediment Class Size	Fivemile Creek			Willow Creek		
(mm)	a	b	R^2	a	b	R^2
0.01	0.02	1.05	0.82	0.0413	0.701	0.59
0.025	0.0018	1.19	0.76	0.0011	1.609	0.87
0.065	0.102	1.28	0.91	0.0106	1.491	0.96
0.25	0.0044	1.94	0.92	0.007	2.097	0.93
0.841	0.0003	1.63	0.96	0.0003	1.51	0.95
>0.841	0	1	--	0	1	--

3.3.5 Model Calibration

Water level from the water level loggers and a SWAT generated flow file from June 2014-December 2014 were used to calibrate the roughness of the bed and banks using the hydraulic submodel in CONCEPTS. Fivemile Creek was divided into five sections and roughness for all cross-sections within each section was assumed to be the same. Water depth output from CONCEPTS was compared to the water depth measured by the water level loggers at each site. The roughness of the bed was calibrated during periods of base flow. Bank roughness was calibrated based on peak flows for storm events. CONCEPTS predicted retreat was compared to measured aerial retreat and τ_c and

k_d were adjusted as needed. Streambanks at some sites were heavily vegetated (Figure 3.6). Because vegetation can significantly alter applied shear stress (Thompson et al., 2004), the effect of vegetation had to be taken into account during the calibration period. The model does not allow for the direct adjustment of τ; therefore, an ν-factor was used to modify the applied shear stress (τ) by adjusting τ_c and k_d in the same manner as Daly (2012) and Langendoen and Simon (2008) used to account for the increase in applied shear around a meander bend:

$$\varepsilon_r = k_d(\nu\tau - \tau_c) = \nu k_d\left(\tau - \frac{\tau_c}{\nu}\right) \tag{3.3}$$

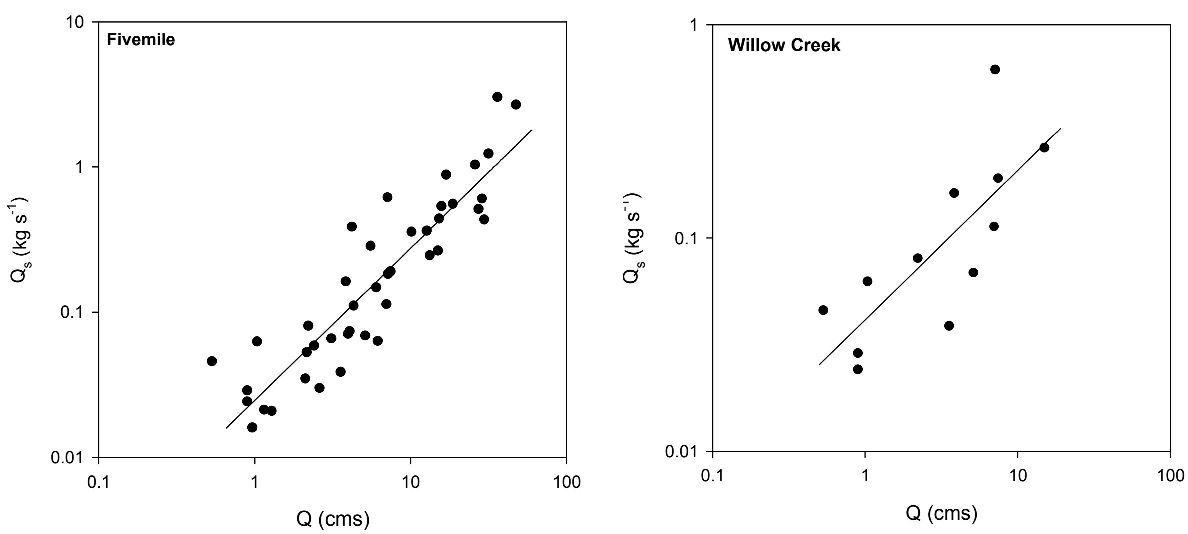

Figure 3.5. Example of sediment rating curves developed from USGS gauge data for Fivemile Creek and Willow Creek used as sediment input for tributaries in CONCEPTS.

Figure 3.6. Streambanks in the Fort Cobb Reservoir Watershed are heavily vegetated. Erodibility parameters were modified to account for this vegetation during the calibration.

3.2.6 Simulating Stabilization Practices

Several stabilization practices were incorporated into the CONCEPTS simulations, including toe protection with riprap, and vegetation and grading of the streambank (2:1 and 3:1 bank slopes). A riprap toe was simulated by modifying the erodibility parameters of the bank toe. The bank toe can be defined as various heights ranging from the depth of water at baseflow (US Army CoE, 2007) to the depth of the bankful or channel forming discharge (NRCS, 2007; Iowa DNR, 2006). For this study, the 2-yr discharge was used for the channel forming discharge (Iowa DNR, 2006). The 2-yr and 100-yr flow for each site was determined by completing a regional flood frequency analysis using data from four USGS gage stations in the watershed and USGS PeakFQ v7.1 (PeakFQ, 2014). The height of the riprap toe (h) was determined by computing the normal depth for the 2-yr discharge determined using Bentley FlowMaster. Riprap size was determined using the median particle size, d_{50}, factor of safety procedure described by Stevens et al. (1976) for the 100-yr discharge. The Shield's

Diagram (Shields, 1936) was used to determine τ_c and the relationship between τ_c and k_d developed by Simon et al. (2011) was used to determine k_d for the riprap. Bank grading was simulated by changing the channel geometry of the cross-sections.

Vegetation impacts streambank erosion in several ways, including reducing hydraulic forces experiences by the soil particles and increasing the cohesion of the bank to reduce bank collapse (Simon et al., 2011). The impact of vegetation on reducing hydraulic force experience by soil particles was simulated by using an ν-factor of 0.15 (Thompson et al., 2004). Added root cohesion (C_r) was determined using the Riproot model that is incorporated into BSTEM (Pollen and Simon, 2005). A bank coverage of 50% grass and 50% trees was assumed to calculate the additional cohesion for the soils.

3.3.7 Sensitivity and Uncertainty Analysis for Stabilization Simulation

Sensitivity and uncertainty analyses were conducted based on the input parameters that were used to characterize stabilization with vegetation (ν and C_r) and riprap (d_{50} and h). Sites FM3, and FM5 on Fivemile Creek and WC3 and WC4 on Willow Creek were used to for this analysis. These cross-sections were selected due to the fact that they both experienced historical retreat and were field data collection sites. First, first a relative sensitivity coefficient, S_r, was calculated for each parameter at each site:

$$S_r = \frac{P}{O}\left(\frac{O_2 - O_1}{P_2 - P_1}\right) \tag{3.4}$$

where P is the baseline parameter and O is the baseline output for either sediment reduction (%) or lateral retreat (m), P_1 and P_2 are input parameters varied by plus and minus 10% of the base line values and O_1 and O_2 are their corresponding outputs (Haan et al., 1995; White and Chaubey, 2005). The larger the magnitude of S_r, the more sensitive the model is to a parameter. However, this method assumes a linear response of output variables and does not account for different degrees of uncertainty associated with each parameter. Therefore, an uncertainty analysis was also conducted. A probability distribution was generated for each of the parameters for each site (Table 3.3). Since the probability distributions for d_{50}, h and ν were not known, simple distributions were assumed. Previously literature has cited a uniform distribution for streambank particle size (Johnson, 1996); therefore, a uniform distribution was used for d_{50} ranging from a lower bound of d_{50} of the streambank soil to an upper bound of d_{50} that was sized using the factor of safety sizing procedure. A uniform distribution was also assumeed for h, with a lower bound of the bottom soil layer and an upper bound of the bank height. A distribution for C_r was determined from the Riproot model output (Pollen and Simon, 2005) and varying percent coverage by trees and grasses. Riproot is a root reinforcement model that estimates the additional root cohesion based on vegetation type, species, and age. The Individual Distribution Identification function in Mini-Tab v. 16 (Mini-Tab, Inc., State College, PA) was used to determine the distribution with the best fit. A Gamma distribution was selected (p=0.19 and AD=0.982). A uniform distribution was assumed for ν, with a minimum value of the lowest calibration ν, and a maximum value of the calibration ν for the site. One hundred random values for d_{50}, ν and C_r were generated according to the distribution for each site. For vegetation, an uncertainty analysis was performed for both 2:1 side slopes and 3:1 side slopes, with the exception of WC3 where the original cross-section geometry had higher than 2:1 side

Table 3.3. Input distributions for uncertainty analysis of sediment reduction and lateral retreat following stabilization with vegetation and riprap toe. Vegetation was simulated using a shear stress adjustment factor (ν) and added root cohesion (C_r). Riprap was simulated using riprap median particle size (d_{50}) and height of riprap placement on the bank (h).

Stabilization Practice	Parameter	Distribution	Uncertainty Analysis Inputs* FM3		FM5		WC3		WC4	
Vegetation	ν	Uniform	a=0.01	b=0.27	a=0.01	b=0.18	a=0.01	b=1.8	a=0.01	b=0.70
	C_r	Gamma	k=0.596	c=2.043	k=0.596	c=2.043	k=0.596	c=2.043	k=0.596	c=2.043
Riprap Toe	d_{50}	Uniform	a=0.12	b=99	a=0.11	b=171	a=0.09	b=184	a=0.09	b=184
	h	Uniform	a=0.0	b=3.0	a=0.0	b=4.0	a=0.0	b=3.8	a=0.0	b=3.3

* a=minimum value; b maximum value; k = shape factor; and c = scale factor

slopes. Confidence intervals (80, 90, and 95%) for percent reduction and lateral retreat for each parameter at each site were determined.

3.4 Results and Discussion

3.4.1 Calibration Results

The CONCEPTS predicted retreat was compared to historical retreat from aerial imagery (Figure 3.7). A Brier Skill Score (BSS) was used to evaluate the calibration based on lateral bank retreat (Abderrezzak et al., 2016). A BSS equal to 0.60 was determined for Fivemile Creek, which suggested a "good" model fit, and 0.85 for Willow Creek, which suggested an "excellent" model fit. Adjustment factors (ν) ranging from 0.01 to 0.6 were used to calibrate the model and adjust for vegetation along Fivemile Creek and ν ranging from 0.2 to 1.8 for Willow Creek (Table 3.4). The site with the heaviest vegetation (FM1) resulted in smallest ν (Table 3.4). The streambanks at this site were entirely covered by thick grass. Vegetation cover at other sites was a mix of grasses and trees.

Calibration along Willow Creek required adjustment factors of greater than one at number of cross-sections. This could be attributed to the SWAT flow data that were converted from daily data to hourly data and therefore the peaks of the storm events may be under predicted. In addition, Willow Creek is more sinuous and ν greater than one may have been needed to account for the increase in τ on the outside of meanders. Previous research has used ν-values ranging from 1.0 to 3.7 to account for the increase in applied shear around meanders (Langendoen and Simon, 2008; Daly et al., 2015). The sinuosity of WC3 required an increase in τ and resulted in an ν of 1.8.

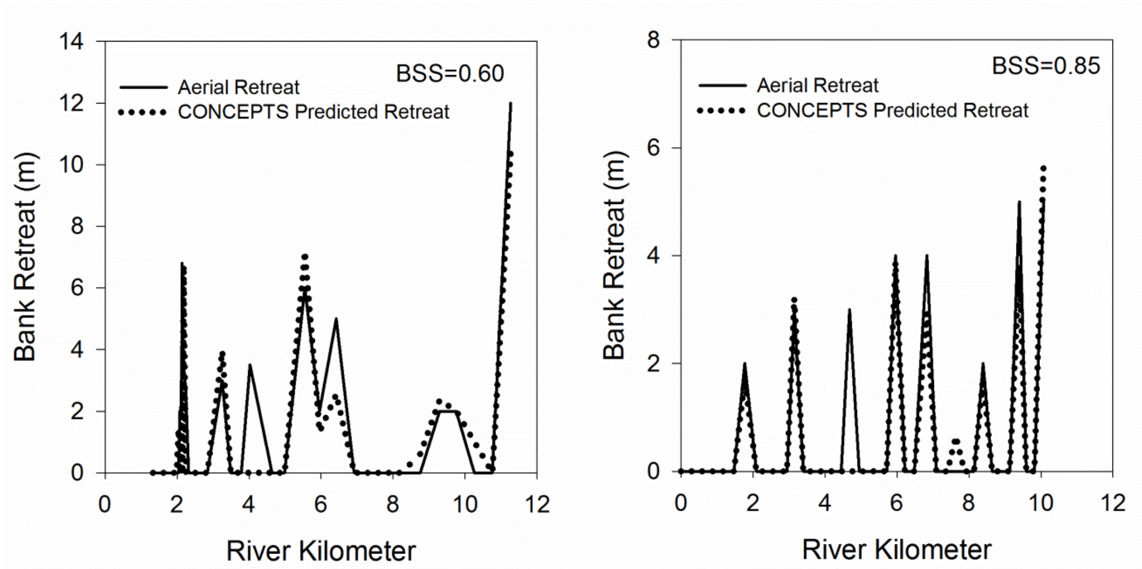

Figure 3.7. Calibration results for Fivemile Creek (left) and Willow Creek (right). CONCEPTS predicted retreat was compared to the historical retreat obtained from aerial imagery. Note: BSS=Briar Skill Score.

Table 3.4. Calibration parameters adjustments for applied shear stress due to vegetation (ν) and bed and bank roughness (Manning's *n*) for CONCEPTS simulations developed for Fivemile Creek and Willow Creek.

	Cross-section	ν	Roughness (Mannings' *n*)	
			Bed	**Bank**
Fivemile Creek	FM1	0.01	0.04	0.06
	FM2	0.1-0.5*	0.03	0.05
	FM3	0.27	0.077	0.115
	FM4	0.6	0.077	0.12
	FM5	0.2	0.075	0.12
	LiDAR Cross-Sections	0.01-2	Varied**	Varied**
Willow Creek	WC1	0.2	0.05	0.1
	WC2	1	0.05	0.07
	WC3	1.8	0.06	0.12
	WC4	0.7	0.06	0.05
	LiDAR Cross-Sections	0.35-1.8	Varied**	Varied**

*Multiple Cross-sections at FM2

**Roughness for LiDAR Cross-sections was assumed to be equal to the roughness of the closest surveyed cross-section

3.4.2 Effectiveness of Streambank Stabilization Practices

CONCEPTS provides several outputs, including sediment yield at each site, lateral retreat, and cross-sectional geometry changes to allow for the evaluation of stabilization practices. All stabilization practices reduced lateral retreat and sediment yield to the stream. Vegetation and grading was more effective at reducing sediment yield and lateral retreat than RRT for three of the four sites. For vegetation, all sites resulted in higher sediment reduction and lower retreats when 3:1 side slopes were used compared to 2:1 side slopes. This is likely due to the increase in geotechnical stability. For WC3 and WC4, all stabilization practices completely reduced lateral retreat and VEG31 completely reduced lateral retreat for FM3. While lateral retreat was zero in these scenarios, there was still some sediment yield due to toe erosion (vegetation) or erosion above the height of RRT (Figure 3.8). While bank stabilization measures were shown to be effective at reducing lateral retreat for the study period, when the sediment supply from the banks is cut off, the stream begins to incise (Figure 3.8). Grade control will likely need to be included in stabilization for long term stability in these two streams. Sediment loads from stabilization scenarios were compared to site scale sediment yield from the calibrated model to determine a percent reduction using typical values used to parameterize stabilization (Figure 3.9).

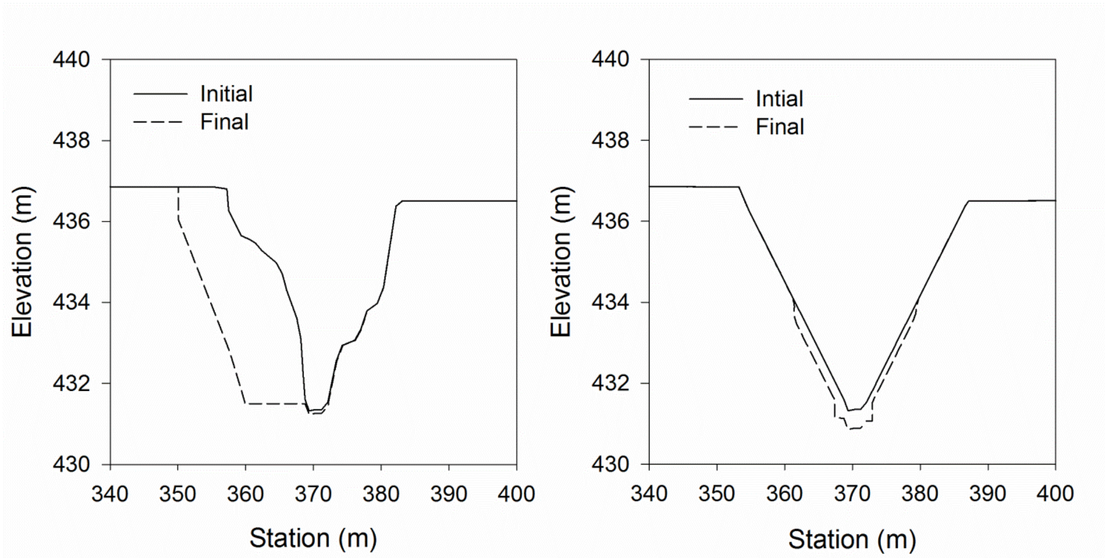

Figure 3.8. Example cross-section from Site FM3 with no stabilization (left) and vegetation with 3:1 side slopes (right).

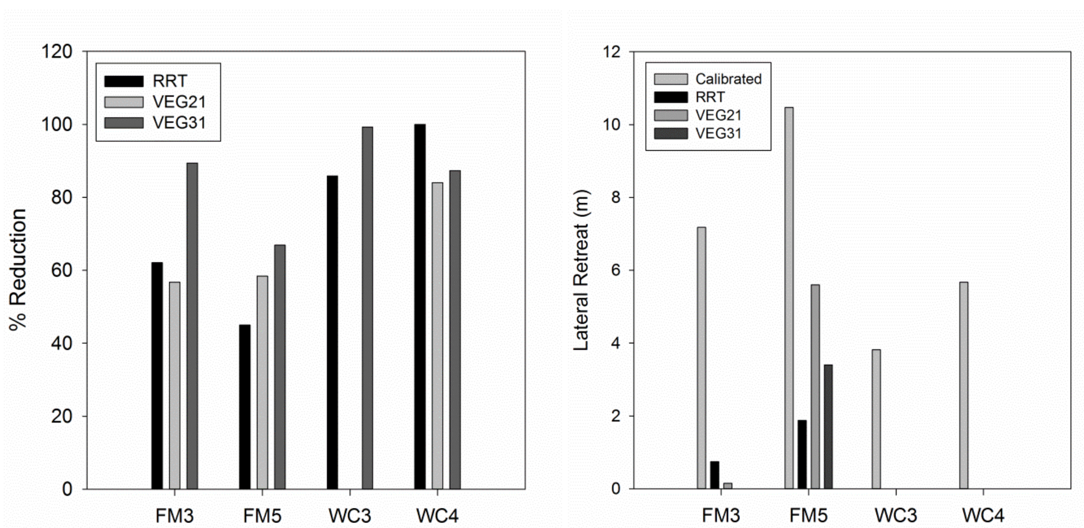

Figure 3.9. Site-scale sediment reduction and lateral retreat from stabilization, including riprap toe (RRT) and vegetation with 2:1 side slopes (VEG21) and 3:1 side slopes (VEG31). Note VEG21 scenario was not completed for site WC3.

3.4.3 Sensitivity Analysis

The sensitivity analysis results (Table 3.5) showed model predictions were not sensitive to C_r or d_{50} for the range of values tested. S_r could not be calculated for bank retreat for some parameters due to no lateral retreat for the baseline output. Predicted sediment reduction at all sites, except for WC3, were sensitive to ν. Negative S_r indicates a decrease in sediment reduction with an increase in ν. Sediment reduction at FM5 showed a greater sensitivity to ν than the other sites. This site required a calibration ν of closer to the ν selected for simulating vegetation than the other sites, which may account for the higher sensitivity. For RRT, sediment reduction at all sites except WC4 were only sensitive to h and not d_{50}. WC4 was not sensitive to either RRT parameter. While the sensitivity analysis demonstrated model predictions were not sensitive to C_r or d_{50} in the range of values tested (+/- 10% of baseline value), a larger range of these input values could be expected, therefore the uncertainty analysis was conducted on all four stabilization parameters.

Table 3.5. Relative sensitivity coefficients (S_r) determined for each parameter used to simulate stabilization with vegetation (ν and C_r) and riprap toe (d_{50} and h).

		FM3		FM5		WC3		WC4	
Stabilization Parameter	Bank Slopes	% Sediment Reduction	Lateral Retreat (m)	% Sediment Reduction	Lateral Retreat (m)	% Sediment Reduction	Lateral Retreat (m)	% Sediment Reduction	Lateral Retreat (m)
Shear stress adjustment factor, ν	2:1	-0.47	5.34	-1.49	3.76	-	-	-0.53	**
	3:1	-0.36	**[a]	-0.72	4.57	0.00	**	-0.63	**
Root Cohesion, C_r	2:1	0.00	0.00	0.00	0.00	-	-	0.00	**
	3:1	0.00	**	0.00	0.00	0.00	**	0.00	**
Riprap Median particle size, d_{50}	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**
Riprap height, h	-	2.21	-0.11	2.82	-1.41	1.71	-0.27	0.00	**

[a] ** - not calculated due to no lateral retreat in the baseline scenario.

3.4.4 Uncertainty Analysis

Summary statistics and confidence intervals from the 100 model simulations for each parameter at each site for sediment reduction and lateral retreat are shown in Tables 3.6 and 3.7, respectively. Sediment yield predictions were the most sensitive to ν and h and resulted in wider CI intervals when compared to C_r and d_{50}. Sediment yield reduction was only sensitive to d_{50} as it approached the d_{50} of the site (Figure 3.10). Sediment reduction reached an asymptotic value as riprap size increased. For each site, 94-99% of the simulations resulted in same sediment reduction (Figure 3.11). Only FM3 had variation in the lateral retreat for the RRT simulations. For WC3 and WC4, all d_{50} simulations resulted in no lateral retreat, while all d_{50} simulations for FM4 resulted in a lateral retreat of 1.9 m. For RRT, sediment reduction and lateral retreat were more sensitive to h compared to d_{50} (Figure 3.11). Sediment reductions at WC3 and WC4 increased linearly as h increased and then leveled off at 100 percent reduction at values of h greater than 2 m (Figure 3.12). This was not the case for FM3 and FM5, for which sediment reduction continued to increase as h increased. The large range in predicted sediment reduction and lateral retreat for this parameter highlights the need to focus more on h rather than d_{50} to evaluate the effectiveness of RRT bank protection using process-based models.

Table 3.6. Confidence intervals (CI) for CONCEPTS predicted sediment reduction (%) from simulating stabilization with vegetation and riprap toe. Vegetation parameters included a shear stress adjustment factor (ν) and added root cohesion (C_r). Riprap parameters included riprap median particle size (d_{50}) and height of riprap placement on the bank (h).

FM3									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	57.8	64.8	46.9	69.8	28.7	69.8	25.0	69.8
	3:1	89.8	92.3	77.5	100.0	72.5	100.0	69.8	100.0
C_r	2:1	58.6	58.3	58.0	58.4	56.8	58.6	56.8	58.6
	3:1	89.5	89.5	89.4	89.4	89.4	89.4	89.4	89.4
d_{50}		61.8	62.1	62.1	62.1	62.1	62.1	62.0	62.3
h	-	58.9	65.1	58.1	65.1	34.4	66.7	20.0	66.7

FM5									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	82.3	94.8	57.9	100.0	46.4	100.0	45.0	100.0
	3:1	90.3	100.0	73.5	100.0	64.8	100.0	59.4	100.0
C_r	2:1	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4
	3:1	68.5	66.9	66.9	73.6	66.9	73.6	66.9	73.6
d_{50}	-	44.2	44.5	44.5	44.5	44.5	44.5	44.5	44.5
h	-	67.8	72.8	34.2	98.3	33.8	99.4	33.8	100.0

WC3									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	-	-	-	-	-	-	-	-
	3:1	68.4	77.4	37.2	100.0	9.4	100.0	5.4	100.0
C_r	2:1	-	-	-	-	-	-	-	-
	3:1	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3
d_{50}	-	84.5	89.9	89.9	89.9	89.9	89.9	89.9	89.9
h	-	85.1	100.0	61.6	100.0	36.43	100	11.71	100.0

WC4									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	42.8	24.2	3.4	99.5	1.4	100.0	0.7	100.0
	3:1	73.5	62.4	60.9	96.0	60.8	99.1	60.7	100.0
C_r	2:1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1
	3:1	87.3	87.3	87.3	87.3	87.3	87.3	87.3	87.3
d_{50}	-	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
h	-	93.5	100.0	61.6	100.0	36.4	100.0	11.7	100.0

Table 3.7. Confidence intervals (CI) for CONCEPTS predicted lateral retreat from simulating stabilization with vegetation and riprap toe. Vegetation parameters included a shear stress adjustment factor (ν) and added root cohesion (C_r). Riprap parameters included riprap median particle size (d_{50}) and height of riprap placement on the bank (h).

Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
FM3									
ν	2:1	1.3	0.4	0.4	1.5	0.3	4.2	0.2	5.6
	3:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_r	2:1	0.3	0.2	0.2	0.2	0.2	1.4	0.1	1.5
	3:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
d_{50}	-	0.7	0.7	0.7	0.7	0.7	0.7	0.5	0.7
h	-	1.6	0.8	0.5	1.9	0.5	5.9	0.4	7.7
FM5									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	2.1	0.0	0.0	5.4	0.0	7.4	0.0	8.2
	3:1	0.6	0.0	0.0	0.7	0.0	3.5	0.0	4.7
C_r	2:1	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
	3:1	2.2	2.8	0.6	2.8	0.6	2.8	0.6	2.8
d_{50}	-	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
h	-	6.6	6.7	0.7	11.9	0.1	12.1	0	12.1
WC3									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	-	-	-	-	-	-	-	-
	3:1	0.4	0.0	0.0	0.0	0.0	2.0	0.0	2.7
C_r	2:1	-	-	-	-	-	-	-	-
	3:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
d_{50}	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
h	-	0.7	0.0	0.0	1.8	0.0	3.2	0.0	4.3
WC4									
Stabilization Parameter	Bank Slopes	Mean	Median	80% CI		90% CI		95% CI	
ν	2:1	3.0	3.9	0.0	5.4	0.0	5.7	0.0	5.9
	3:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_r	2:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3:1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
d_{50}	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
h	-	0.2	0.0	0.0	0.0	0.0	0.2	0.0	2.5

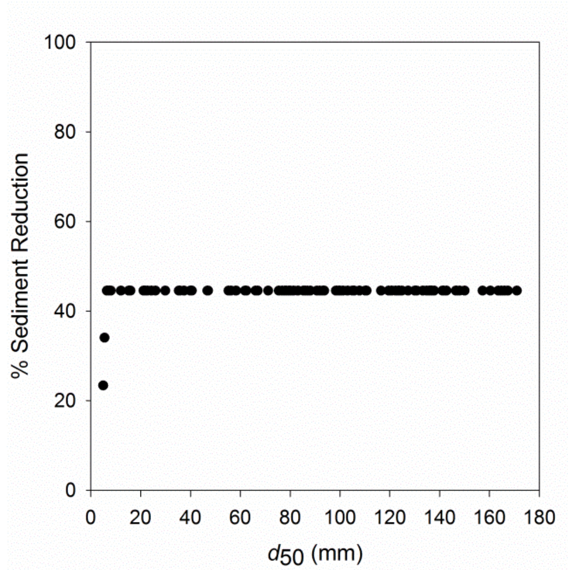

Figure 3.10. CONCEPTS predicted sediment reduction versus riprap median particle size for site WC4.

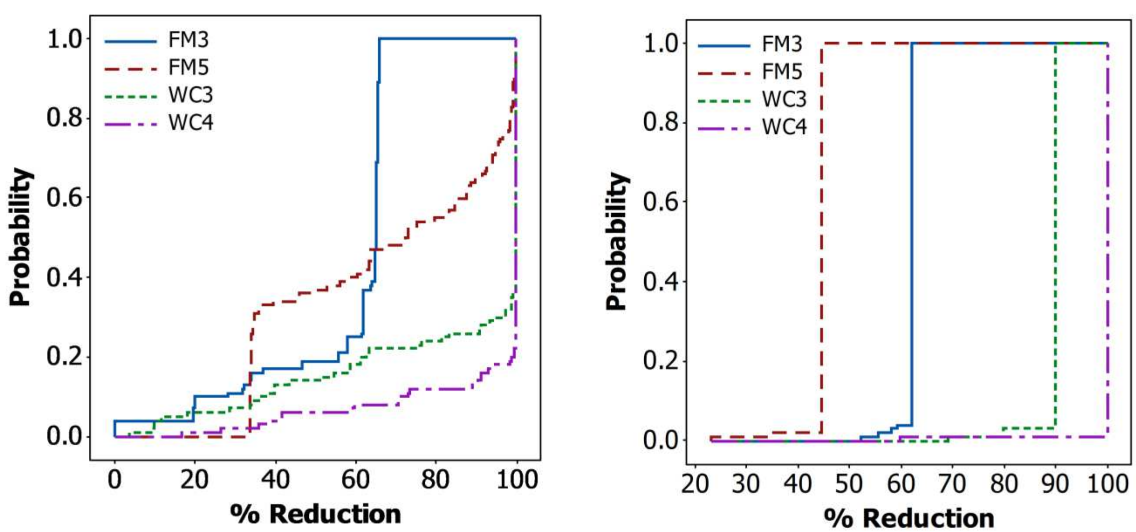

Figure 3.11. Empirical cumulative probability distribution for predicted percent sediment reduction for riprap toe parameters: d_{50} (left) and h (right) for all sites determined from uncertainty analysis.

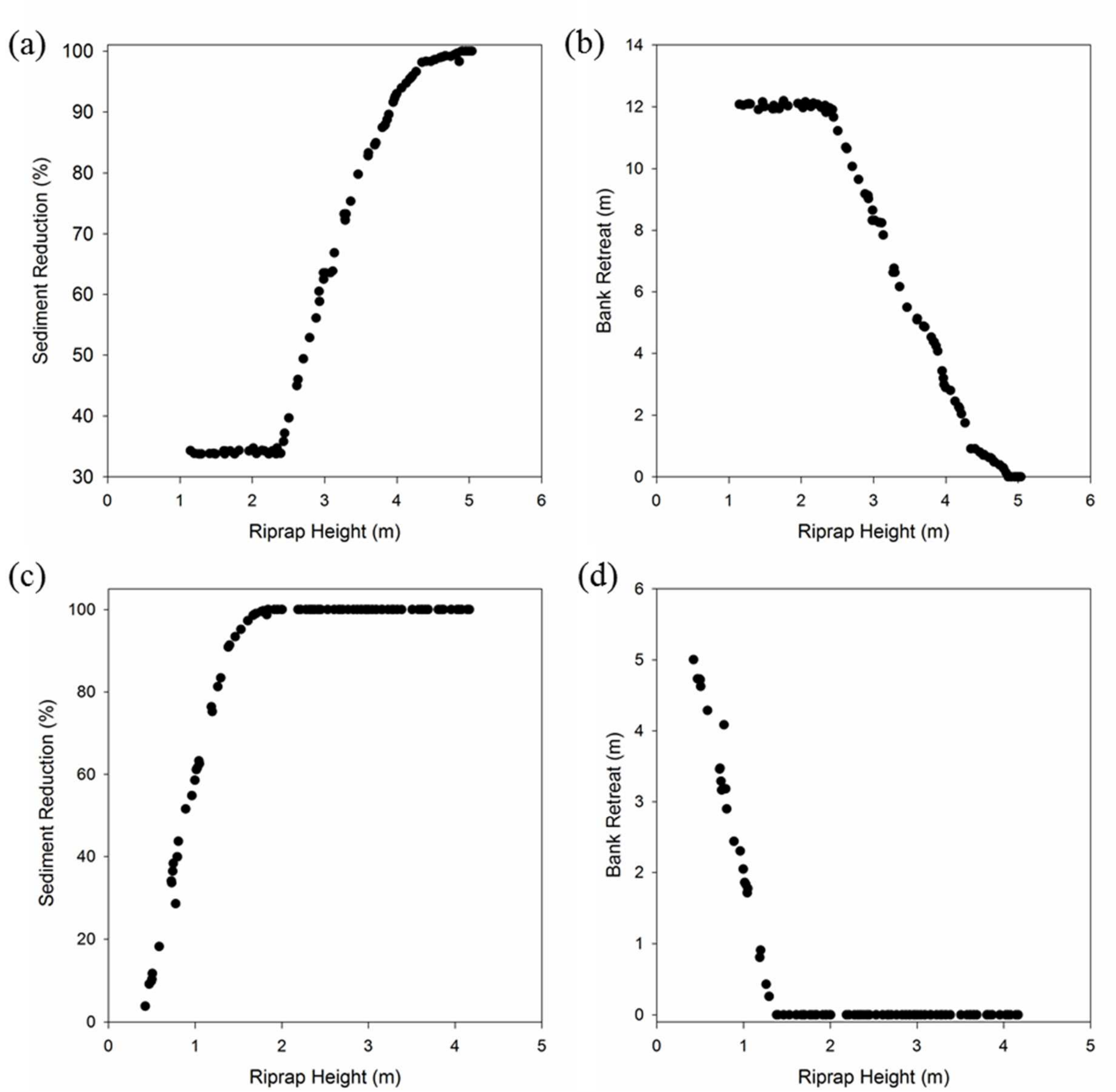

Figure 3.12. Riprap height (*h*) versus CONCEPTS predicted sediment reduction and bank retreat for FM5 (a,b) and WC3 (c,d).

Vegetation was simulated using two parameters: ν and C_r. Sediment reduction and lateral retreat were more sensitive to ν than either C_r or d_{50}. WC3 and WC4 resulted in the highest range of sediment reduction for ν with a 95% CI interval of 5.4 to 100% and 0.7 to 100%, respectively. A wider range of ν was used for these sites when compared to the FM sites due to the higher calibration ν for these two sites. For FM3, FM5 and WC4 changes in geometry to a 3:1 side slopes led to a much higher sediment reduction and lateral retreat. As ν approached the calibration ν of the site for VEG21 scenario at FM3, sediment reduction approached zero (Figure 3.14) while sediment reduction was still 69% for the VEG31 scenarios. Note that the original geometry of this cross-section had side slopes close to 2:1. For sites FM5 and WC4 changing geometry to 3:1 side slopes while using the calibration ν accounted for 58% and 61% sediment reduction, respectively. This is likely due to the increase in geotechnical stability due to decreasing the bank slopes. Previous research has shown that geotechnical failures may account for 80 to 85% of sediment from bank erosion (Simon et al., 2011) and practices that can increase geotechnical stability, such as bank geometry changes can significantly reduce bank erosion. Site FM5 resulted in the highest number of scenarios that resulted in 100% sediment reduction, with 43% and 52% of simulations for VEG21 and VEG31, respectively (Figure 3.14). For VEG31 scenario, 100% of simulations predicted 0 m of lateral retreat for WC4 and FM3 and nearly 80% of simulations for FM5 and WC3 (Figure 3.15). In these simulations, toe erosion may still be occurring (Figure 3.8). For VEG21 scenarios, 55% of simulations and 32% of simulations for FM5 and WC4, respectively, predicted no lateral retreat.

These results highlight the importance of accounting for the impacts of vegetation on hydraulic erosion. However, more research is needed to understand the potential values of ν to increase certainty in model prediction. Previous research by Thompson et al. (2004) found vegetation to reduce applied τ by 13 to 89% (ν of 0.13 to 0.89) based on idealized vegetation in a controlled flume study. Another study by Klavon (2016) determined ν to range between 0.01 to 0.20. In addition, the ν-factor can be used to account for both vegetation and sinuosity (Daly et al., 2015; Klavon et al., 2016). In locations where both are impacting τ, it may be more difficult to simulate the effects of vegetation, as with sites WC3 and WC4 in this study.

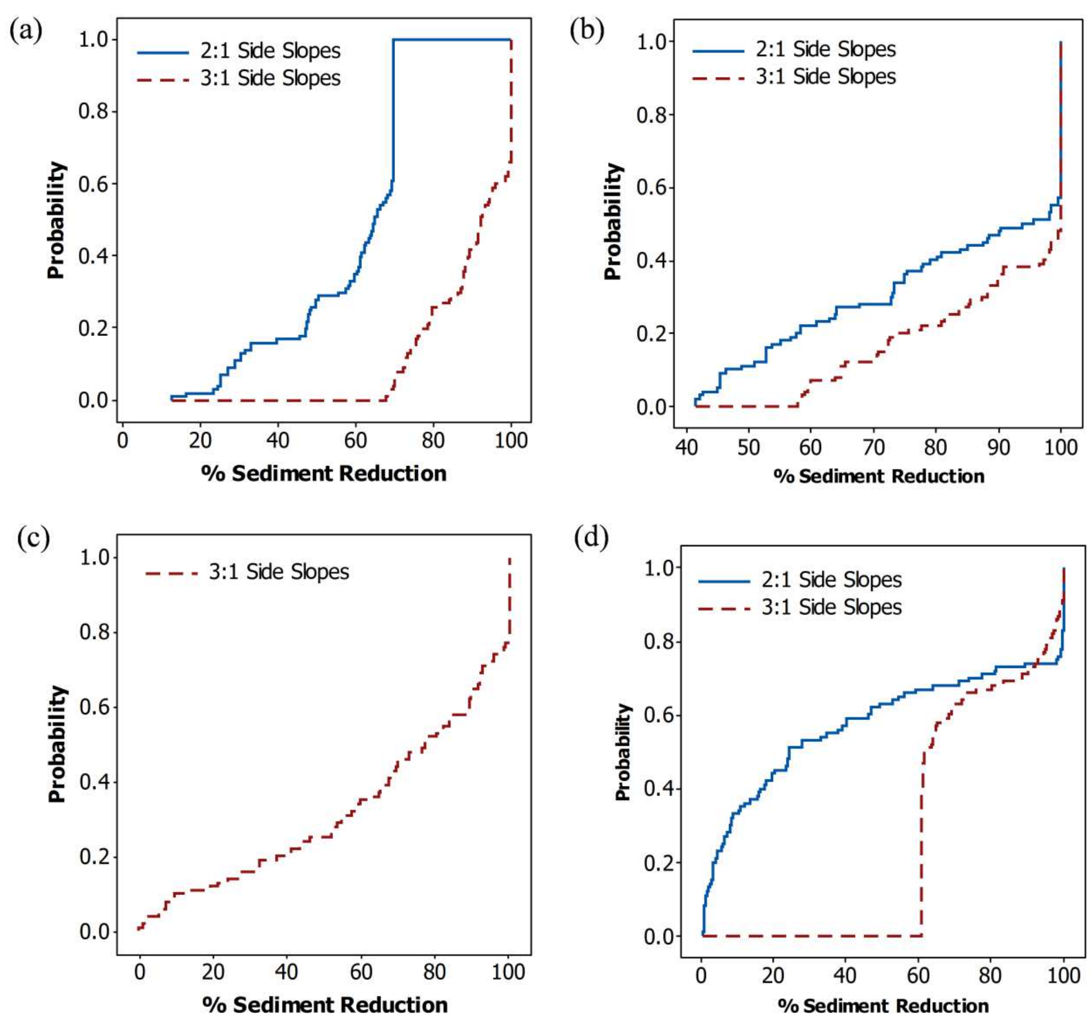

Figure 3.13. Empirical cumulative probability density functions determined from uncertainty analysis for sediment reduction based on vegetation shear stress adjustment factor, ν, for (a) FM3, (b) FM5, (c) WC3, and (d) WC4.

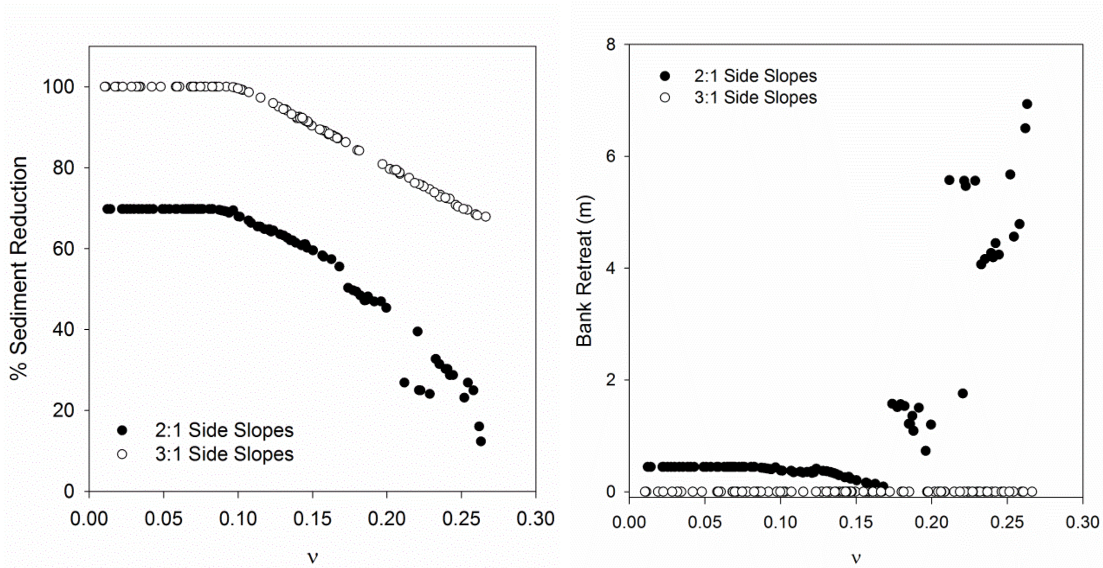

Figure 3.14. Sediment reduction (left) and lateral retreat (right) versus vegetation shear stress adjustment factor, ν, for FM3.

While model predictions were very sensitive to ν, they were not sensitive to the addition of C_r for either of the WC sites or for VEG21 at FM5 or VEG31 at FM3. Previous studies have reported model simulations to not be sensitive the added C_r for highly unstable and rapidly retreating streambanks (Daly et al. 2015). For FM5, a C_r greater than 2 kPa resulted in an increase in percent reduction from 67 to 74% (Figure 3.16-3.17) and a decrease in lateral retreat from 2.8 to 0.6 m for the VEG31 stabilization scenario. A C_r equal to 2 kPa corresponded to a 85%/15% grass/tree coverage three years after planting or 50/50 coverage after four years. A similar trend was observed for VEG21 at site FM3. For C_r greater than 4.5 kPa lateral retreat decreased from 1.4 to 0.2 m. However, a C_r of 4.5 kPa corresponded to 90% grass coverage five years after planting.

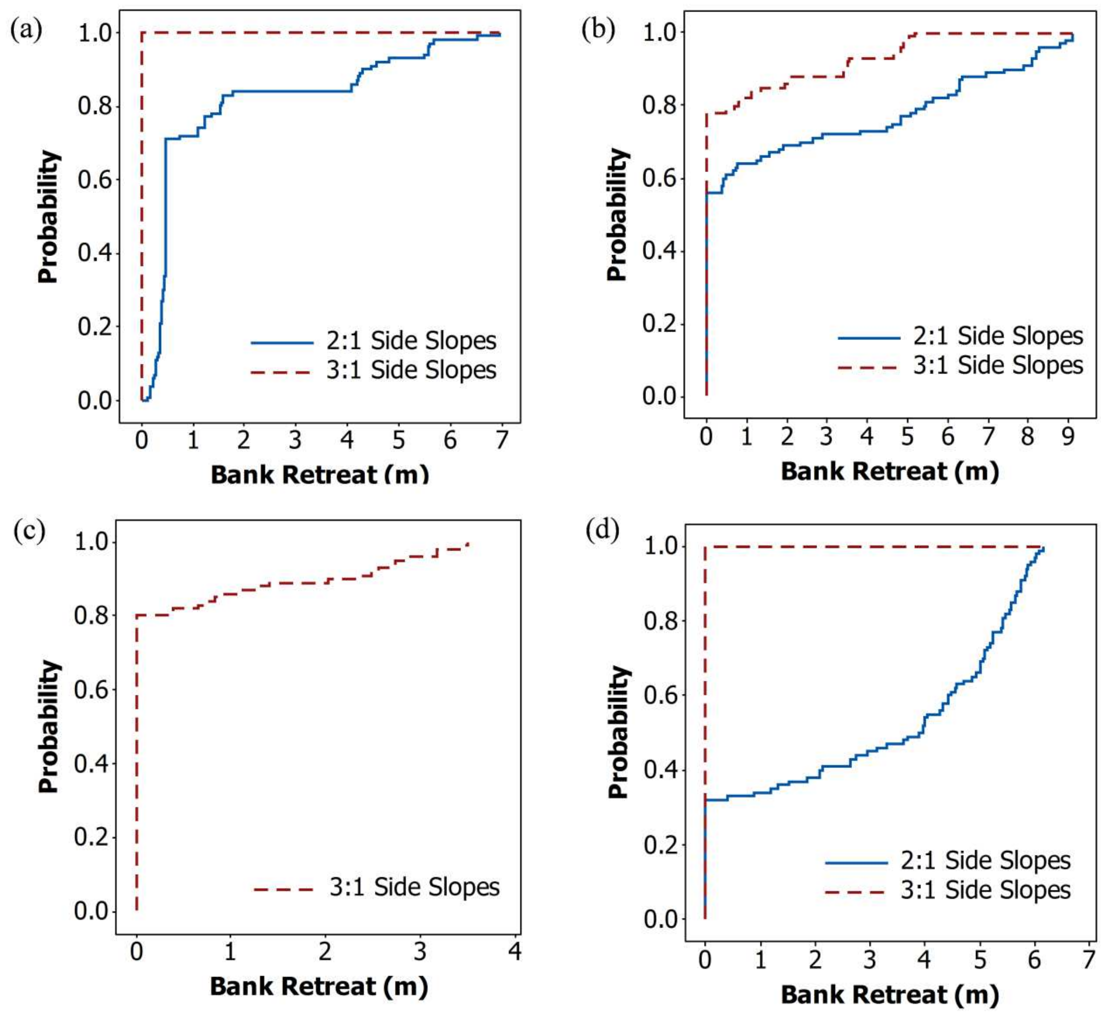

Figure 3.15. Empirical cumulative probability density functions for bank retreat (m) determined from uncertainty analysis of the shear stress adjustment factor, ν, used to simulate stabilization with vegetation for sites (a) FM3, (b) FM5, (c) WC3, and (d) WC4.

Although predicted sediment reduction and lateral retreat due to stabilization with vegetation was not as sensitive to C_r as compared to ν, both parameters should be considered when simulating vegetation, as model simulations may be sensitive to C_r at higher values of C_r. Previous research has shown both the mechanical and hydraulic effects of vegetation are important to bank stability (Simon and Collison, 2002).

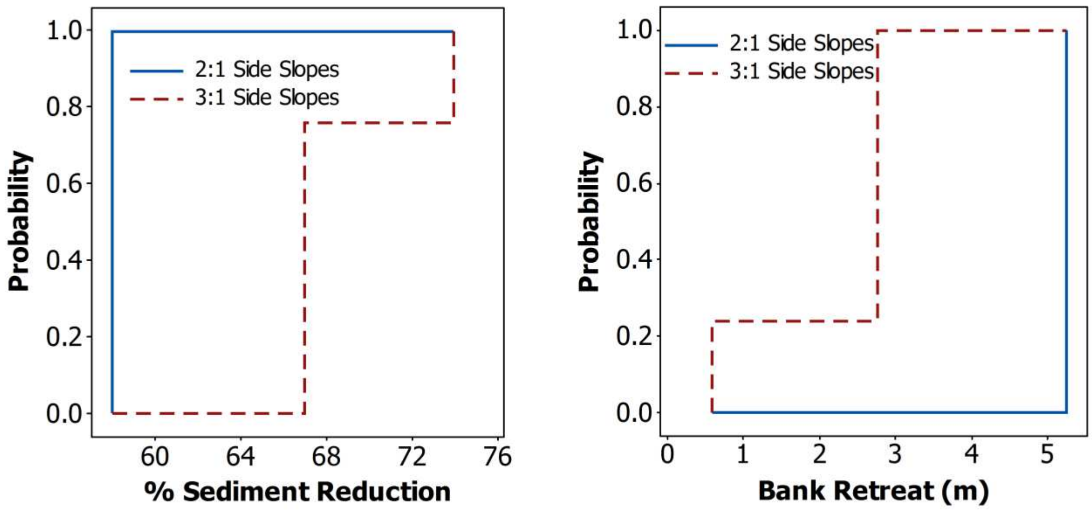

Figure 3.16. Empirical cumulative probability density functions from uncertainty analysis of root cohesion, C_r, for bank retreat and sediment reduction at site FM5.

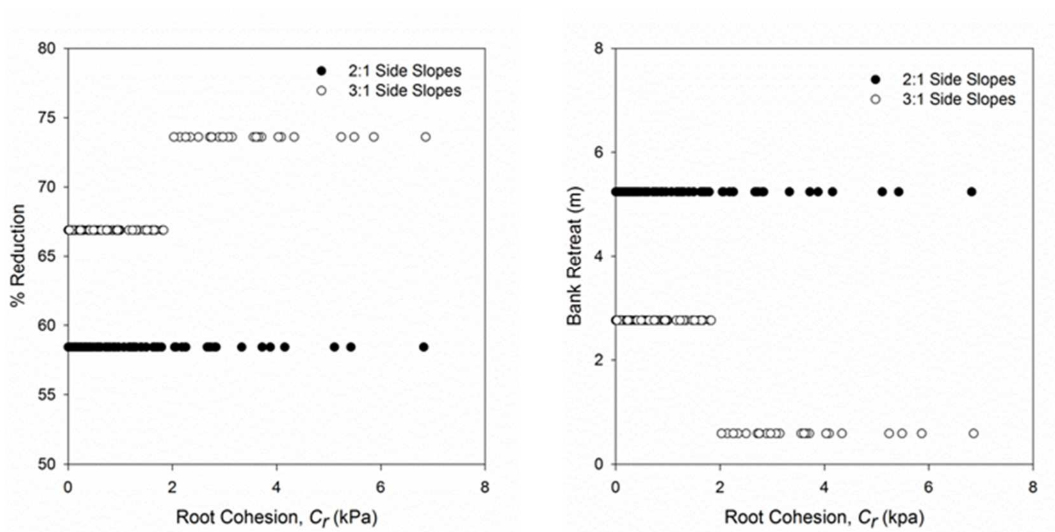

Figure 3.17. Predicted sediment reduction and bank retreat versus added root cohesion, C_r, at site FM5.

3.5 Conclusion

Streambank stabilization using riprap toe and vegetation with bank grading can be very effective at reducing sediment loads and lateral retreat from unstable and rapidly eroding streambanks. Process-based models offer a way to evaluate practices prior to implementation, but must be properly parameterized for incorporation into the model. Riprap toe can be simulated using two parameters, median particle size and height. When incorporated into CONCEPTS, sediment lateral retreat predictions were more sensitive to riprap height rather than the median particle size. Vegetation can reduce streambank erosion in two ways, by adding cohesion to increase stability and reducing applied shear stress experience by the streambank soil. These two processes were parameterized using shear stress adjustment and added root cohesion. An uncertainty analysis showed model simulations were not sensitive to added root cohesion, but were highly sensitive to the shear stress adjustment factor, suggesting that the impact of vegetation on applied shear has a greater impact on reducing sediment yields from streambank erosion for these stream systems. However, more research is needed to more accurately quantify this process to accurately simulate the impact of vegetation in process-based models across a gradient of stream systems.

CHAPTER 4

A MODELING FRAMEWORK FOR EVALUATING STREAMBANK STABILIZATION PRACTICES FOR REACH-SCALE SEDIMENT REDUCTION

4.1 Abstract

Unstable streambanks contribute a significant sediment load to surface waters in some watersheds. Several streambank stabilization techniques are available to increase stability of streambanks or reduce erodibility, thereby reducing sediment loads. Process-based models can be used to evaluate the stability of a stream channel and predict sediment yields with and without potential stabilization scenarios to determine the effect of stabilization prior to implementation. However, a lack of guidelines exist on how to utilize these tools to evaluate streambank stabilization measures; instead, many restoration or stabilization projects rely on empirical approaches that fail to consider the impact of the implementation on the stream system from a functional approach. The objective of this study was to develop a framework to evaluate streambank stabilization practices for sediment reduction using process-based hydraulic and sediment transport models and that account for public and landowner perception, costs and effectiveness. This methodology results in a set of sediment reduction graphs to determine the length of stabilization needed to reach a desired sediment reduction and a second set of graphs to determine the cost. The methodology was applied to Fivemile Creek, located in western

Oklahoma. A CONCEPTS simulation was developed for a 10.25-km reach and several streambank stabilization techniques, including grade control, riprap toe, and vegetation, were simulated. Using the framework, vegetation with 2:1 bank slopes was determined to be the most cost-effective stabilization practice for this stream system. However, the addition of grade control was also recommended due to the incising nature of the stream.

Keywords: Framework; Process-based models; Sediment; Streambank erosion; Streambank stabilization; Conservation effects assessment project (CEAP).

4.2 Introduction

Excess sediment from upland sources, channel and gully erosion, and the resuspension of bed material is a major polluter of surface waters across the United States with streambank erosion from unstable channels contributing as much as 50% to 90% (Wilson et al., 2008; Fox et al., 2016). Stream restoration or stabilization can reduce sediment contributions from the streambanks and these practices have become more common in recent years with the goal of correcting anthropogenic disruptions to streams (Beechie et al., 2010). However, an increase in stream restoration has not reduced the number of degraded miles of streams since the early 1990s (Langendoen, 2011). Restoration typically involves extensive channel modification and integrates channel stabilization to lock the channel in place. Florsheim et al. (2008) highlighted several shortcomings of current streambank erosion management strategies, including failure to understand erosion processes, failure to consider bank erosion on the appropriate scale, and failure to understand secondary effects of bank infrastructure.

Current channel modification strategies place an emphasis on channel form rather than channel erosion processes (Kondolf, 1996) and often fail to address the cause of degradation (Beechie et al., 2010). Typically, a “cookbook” approach that relies on channel classification rather than erosion process is applied to stream restoration and stabilization projects (Kondolf, 1996; Lave, 2009). This method often relies on creating a certain channel form that is considered “good”, but this channel form may not be suitable for the amount of sediment or the valley slope and will eventually fail (Beechie et al., 2010). Understanding erosion processes, such as fluvial erosion of the bed and bank and mass wasting, are vital to a successful restoration or stabilization project (Shields et al., 2003). For example, river stabilization often only addresses fluvial erosion and will fail where mass wasting is a dominant process (Florsheim et al., 2008). Streams adjust to changes within the watershed by the processes of erosion until a dynamic equilibrium is reached. Channel modification projects that do not allow for a balance of sediment supply and transport capacity often fail (Shields et al., 2008) and lead to either aggradation or degradation of the channel.

Stabilization practices often address erosion at the site scale, focusing on local scour and deposition, not considering sediment transport outside of the project site and system wide instability (Kondolf, 1996; Shields et al., 2008). A basin-wide analysis or the potential for geomorphic processes to impact the project site rarely occurs (Miller and Kochel, 2010). The limited focus of stabilization on the site and ignoring the location within the watershed is a common reason for project failure (Palmer and Allan, 2006; Langendoen, 2011). The consideration of upstream condition is vital as sediment and water discharge are influenced by land use and affect channel response up and downstream (Morris, 1995; Palmer and Allan, 2006).

Stabilization using bank infrastructure also has morphological impacts throughout a reach. Channel bank infrastructure alters the geomorphic process and can lead to more erosion locally and at great distances up and downstream of the stabilized site (Florsheim et al., 2008; Reid and Church, 2015). Engineered structures may be ineffective over the long term (Florsheim et al., 2008). The use of riprap or other hard structures increases flood velocities, disrupts lateral sediment exchanges (Florsheim et al., 2008), alters flow conditions (Kondolf, 1996) and influences local and downstream sediment transport (Reid and Church, 2015). Bank stabilization reduces sediment supply downstream, but the transport capacity remains the same leading to scour of the bed and banks downstream, thereby displacing the original problem (Kondolf, 1996; Watson et al., 2002; Piegay et al., 2005; Reid and Church, 2015). If a stream can no longer adjust laterally, due to stabilization such as riprap (Reid and Church, 2015), the channel will begin to adjust downward, leading to incision. The increase in erosion downstream may require additional bank stabilization to compensate and could ultimately harden an entire reach (Florsheim et al., 2008; Miller and Kochel, 2010; Reid and Church, 2015). Additionally, bank protection or stabilization can lead to knickpoint migration upstream causing further instability (Gregory, 2006).

While the effect of stabilization on sediment transport and downstream bank erosion is apparent, literature discussing actual sediment reduction to be expected from streambank stabilization is limited. Many bank stabilization projects do not consider the downstream impacts or include a long term monitoring plan; therefore, the amount of sediment reduction on the reach or watershed scale is not known. Stabilization or restoration projects often utilize an empirical "cookbook" approach rather than utilizing process-based models that are available to determine the effect of restoration on sediment reduction prior to implementation. In addition, the lack of guidelines for the evaluation of stabilization or restoration practices through the use of process-based models limit the use of these tools. Further research is needed to quantify the amount of sediment reduction from bank stabilization on the reach-scale and prioritize stabilization practices prior to implementation. Therefore, the objectives of this research were to develop a framework for prioritizing streambank stabilization practices for sediment reduction, to evaluate the potential sediment load reduction from those practices, and to determine the cost associated with a desired amount of sediment reduction. This framework was applied using a tributary to the Fort Cobb Reservoir, Fivemile Creek, as a case study.

4.3 Methods and Materials

4.3.1 Process-Based Framework

A graphical representation of the proposed methodology for evaluating streambank stabilization is shown in Figure 4.1. Several factors contribute to a successful restoration plan and are integrated into this process including public and landowner perception, costs, and, most importantly, effectiveness. This methodology results in the development of a set of sediment reduction graphs, one for each stabilization practice, to determine the length of stream that needs to be stabilized to achieve a desired sediment reduction and a second set of graphs to determine the cost of stabilization based upon length of stream stabilized.

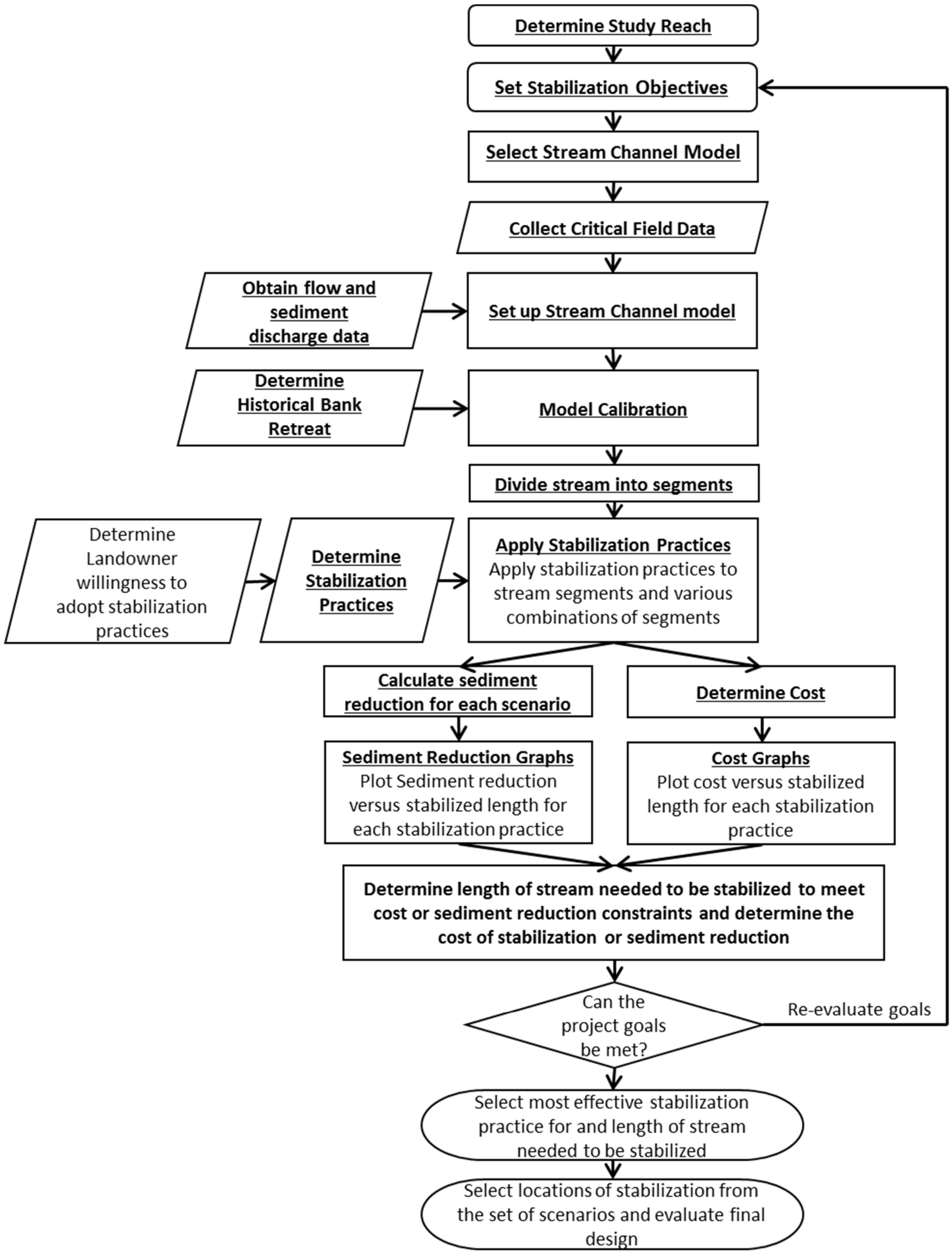

Figure 4.1. Flowchart describing methodology for utilizing reach-scale process-based models to evaluate streambank stabilization measures for sediment reduction.

4.3.2 Determine Study Reach

The study reach should include an entire stream system if possible, or at least highly unstable sites within the stream system and areas immediately up and downstream of the unstable areas, to evaluate potential negative geomorphic effects (Reid and Church, 2015). Study reach lengths will vary depending on scale of erosion problems and size of the channel. A rapid geomorphic assessment (RGA) (Simon and Klimentz, 2008b) or historic aerial photos can be used to aid in the selection of the study reach.

4.3.3 Set Stabilization Objectives

Once the study reach is determined, specific and measurable project parameters should be set (e.g., a desired sediment reduction or cost constraint). Ultimately, both cost and sediment reduction will be considered, but one or the other may be a driving factor for the project. For example, if a certain amount of money is available for stabilization, the objective could be to determine the most effective stabilization practice for that investment. Alternatively, a certain amount of sediment reduction may be required to be in compliance with water quality standards; thus, the objective may be to find the least expensive solution to achieve the sediment reduction goal.

4.3.4 Select Stream Channel Model

An appropriate stream channel model should incorporate sediment transport and bed adjustment, fluvial erosion and mass wasting processes of the streambank, and should be able to simulate these processes on a reach-scale. Incorporation of a reach-scale model allows for the consideration of any potential negative effects of stream stabilization upstream and downstream of the site of interest. A number of one-, two-, or three-dimensional numerical models for hydraulics and sediment transport are available. While one-dimensional models cannot simulate complex flows around in-stream structures or localized changes in morphology as accurately as a two- or three-dimensional models, they are more computationally efficient and can accurately evaluate long-term channel stability following stabilization (Langendoen, 2011). Two examples of one-dimensional reach-scale bank erosion and stability models are the CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) and HEC-RAS with the Bank Stability and Toe Erosion Model (BSTEM). Once a model has been selected, the input for the specific model can be determined. In addition, the user should determine the cross-sectional spacing needed to give the desired resolution of the model.

Streambank erosion models typically incorporate the linear excess shear stress equation for fluvial detachment (Partheniades, 1965; Hanson 1990a, 1990b):

$$\varepsilon_r = k_d(\tau - \tau_c)^a \tag{4.1}$$

where ε_r is the erosion rate (cm s^{-1}), k_d is the erodibility coefficient (cm^3 N^{-1} s^{-1}), τ is the average hydraulic boundary shear stress (Pa), τ_c is the critical shear stress (Pa), and a is an empirical exponent that is assumed to be one. Calculations of bank stability take the form of a factor of safety approach that balances the resisting to driving forces for bank collapse. A more detail description of stability calculations can be found Simon et al. (2009), Midgley et al. (2012), Daly et al. (2015), and Klavon et al. (2016).

4.3.5 Collect Critical Data for Model Setup

Critical input data may vary slightly depending on the numerical model selected, but should include cross-sectional geometries and soil properties for each cross-section. Channel cross-sections can be determined using field survey data. However, it may not be time efficient to survey enough cross-sections to give the desired resolution of the model. In this case, critical areas can be surveyed and additional cross-sections can be determined from digital elevation data (e.g., DEMs or LiDAR). LiDAR data have been used in many studies to provide morphological data of stream corridors for hydraulic modelling and streambank erosion estimates where intensive ground surveying was not possible (Bowen and Waltermire, 2002; Thoma et al., 2005; Cavalli et al., 2008; Gichamo et al., 2012). However, the accuracy of these data will depend on the channel size and may not be suitable for lower order headwater streams under dense canopy (James et al., 2007).

Critical soil properties will include soil resistance to geotechnical failure (c' and ϕ') and resistance to fluvial erosion (typically in the form of τ_c and k_d). Several methods are available to determine the soil resistance to geotechnical failure in the form of effective shear strength parameters (c' and ϕ') including direct shear tests, triaxial tests and borehole shear tests. Erodibility parameters (τ_c and k_d) can also be determined in a number of ways, including laboratory tests (flumes and hole erosion tests) and *in situ* tests, such as jet erosion tests (JETs) (Hanson, 1990a, 1990b). Site specific soils properties should be determined when possible. Typically, multiple tests are conducted at each location and average values are used for that particular site. A more detailed description and comparison of the methods available to estimate these soil properties can be found in Klavon et al. (2016). Other soil properties that may be required include soil particle size for bed and bank layers, bulk density, and particle density. In addition, detailed information on soil layering and the associated soil properties with each layer should be determined to account for bank heterogeneity (Suarto et al., 2014).

Discharge and sediment inflow data for a desired time period are also needed for the model setup. Long-term flow data from a gauging station is ideal for the inflow hydrograph. The USGS has gauging stations at 8,000 locations across the United States (USGS, 2016). Most USGS gauging stations also monitor sediment concentrations which can be utilized for sediment inflow data. However, a gauging station may not be available for all project locations or the gauging station may be located downstream of the study reach. In this case, flow and sediment discharge estimates can be obtained from a watershed model, such as SWAT (Moradkhani et al., 2010; Jähnig et al., 2012; Giacomoni et al., 2014) or AnnAGNPS (Simon et al., 2002; Schwartz and Drum, 2010).

Finally, information on historical bank retreat for the same time period of the flow data is needed. Previously collected survey data or erosion pin measurements at the study sites can be used. However, this information is not typically available, therefore most streambank erosion studies calculate bank retreat from historical aerial imagery (Klavon et al., 2016).

4.3.6 Model Calibration

Upon incorporation of the critical data for each cross-section, model calibration is conducted. Applied τ, which is used for fluvial detachment predictions, is a function of water depth. Therefore, calibration of the open channel hydraulics is important for accurate model estimation. This can be done by adjusting channel roughness (typically Manning's n). Initial estimates of Manning's n can be obtained using the median particle size, d_{50}, or from Chow (1959). Several metrics are available for evaluation of the hydraulic calculations (Moriasi et al., 2007). Data from stream gauges can be used for calibration of Manning's n or a water level logger can be installed in the stream and used for roughness adjustments.

After calibration of the hydraulics, erodibility parameters can be adjusted for accurate prediction of historical retreat at each cross-section. Several studies suggest calibration based on k_d alone and others suggest adjusting both erodibility parameters. Vegetation and channel meandering can impact applied τ and can be accounted for in one dimensional models using a lumped ν -factor as discussed in Daly et al. (2015). In addition, c' can be adjusted to account for the presence of roots in the streambank.

The calibrated model is then used to determine locations which are contributing the highest sediment yield and to help understand the dominant erosion processes occurring within the study reach. A baseline sediment yield is also determined.

4.3.7 Select Potential Stabilization Practices

A successful stream stabilization practice will either reduce the forces acting on a bank or increase the forces resisting erosion (Simon et al., 2011). Several common stabilization practices include toe protection with riprap or large woody debris, grade control of the bed, vegetative planting, and bank grading. Insights into the dominant erosion processes obtained during the model calibration can be used to determine appropriate stabilization practices for the stream system. For example, if the stream is incising, practices involving grade control may be necessary. If the dominant erosion process is fluvial erosion of the bank toe, practices involving toe protection should be considered, while steep unstable banks may require bank grading to reduce geotechnical failures.

In addition to considering the dominant erosion processes, the willingness of landowners to adopt specific practices and the public's perception of various stabilization practices needs to be considered. A survey of landowners should occur to determine the most appealing practices and what factors will influence their willingness to adopt the practices. For example, aesthetics, costs, available cost sharing programs, maintenance requirements, absentee landowners, and understanding the benefits all may influence the likelihood of a landowner to adopt a practice (Tong et al., 2017). The amount of land necessary for a specific erosion control practice may also be an important factor. Establishment of riparian zones in agricultural areas may take land out of production and sloping banks may result in a significant loss of land depending on the height of the banks.

Taking into account the dominant erosion processes and the willingness of landowners to adopt certain practices, a list of potential stabilization practices can be determined. Once the practices are selected, methods for simulating the practices in the numerical model must be determined. Extensive literature exists on how to incorporate stabilization practices in process-based models or how various stabilization materials modify soil properties (Simon et al., 2009; Langendoen, 2011; Klavon et al., 2016).

4.3.8 Simulate Stabilization via the Calibrated Model

For each stabilization practice, a set of scenarios in which stabilization is applied to varying stream lengths and locations should be generated. To limit the number of model simulations, the stream can be divided into segments based on landowner, changes in land use, roads or other metrics. Because location of stabilization will also impact sediment yield reduction, various combinations of stream segments, including upstream and downstream locations, should be stabilized. Lengths of stream stabilized should range from zero kilometers to the entire reach.

The sediment yield from each scenario can then be compared to the baseline prediction from the calibrated model to calculate a percent reduction. Percent reduction can then be plotted against the length of stream stabilized for each stabilization practice. The cost for each scenario can be determined and plotted against the stabilization length. This process will result in a set of sediment reduction graphs and a corresponding set of cost graphs.

4.3.9 Decision Making

The length of stabilization, associated sediment reduction, and cost to meet the project objectives can be determined using the two sets of graphs. There will likely be a set of potential solutions that will meet the goals. The willingness of landowners to adopt specific practices can be taken into account during this step to determine the best practice to implement in the area. Conversely, if the project goals cannot be met, the objectives can be re-evaluated.

Once the length and stabilization practices have been determined, locations of the stabilization can also be determined from the set of scenarios for that stabilization practice. Any potential negative effects can then be evaluated (i.e., increase in erosion downstream) as well as the bank retreat at specific locations.

4.4 Case Study: Fivemile Creek

The framework developed for prioritizing streambank stabilization for sediment reduction was applied to Fivemile Creek, a tributary to the Fort Cobb Reservoir in western Oklahoma. Fort Cobb Reservoir provides public water supply, recreation, and wildlife habitat and is listed on the Oklahoma 303(d) list for impairment by nutrients, siltation, and sediment (Storm et al., 2003). The watershed is located in the Central Great Plains eco-region and is predominately agricultural, with only 5% of the watershed classified as urban land use and less than 2% water (Starks et al., 2014). As part of the USDA's Conservation Effects Assessment Program (CEAP), numerous upland and riparian conservation, and structural and water management practices were implemented to reduce sediment loading to the reservoir (Steiner et al., 2008). The reservoir still fails to meet water quality standards based on sediment, and it was estimated that 50% of the suspended sediment in the reservoir originated from streambanks (Wilson et al., 2008). Streambanks in the watershed consist of either single sand or sandy loam layer, while others exhibit a layering effect of sand or sandy loam layers above and below a more cohesive layer with higher clay content.

4.4.1 Set Stabilization Objectives

Although determining a cost or sediment reduction constraint is likely a necessary step in a real-world application, the objective for the case study was to determine the most cost-effective practice for Fivemile Creek. A series of stabilization scenarios, described below, are tacitly assumed to be the stabilization practices needed to achieve our (unstated) sediment reduction goals.

4.4.2 Determine Study Reach

An RGA of the Fort Cobb Reservoir watershed was completed in 2006 and identified the entire length of Fivemile Creek to be in stages IV and V of the channel evolution model (Simon and Klimetz, 2008a; Moriasi et al., 2014). Stage IV (degradation and widening) and Stage V (aggradation and widening) are the two most unstable stages of channel evolution. A 10.25-km reach was selected for this study.

4.4.3 Select Stream Channel Model

CONCEPTS (Langendoen, 2000) was selected as the stream channel model for simulations on Fivemile Creek. CONCEPTS simulates one-dimensional hydraulics, fluvial erosion and mass wasting processes, and graded sediment transport. Cross-sectional geometry, fluvial erodibility parameters, soil geotechnical parameters, bank soil and bed sediment particle size distributions, soil and sediment layer, and sediment and flow data are required to set up a CONCEPTS simulation.

4.4.4 Collect Critical Data for Model Setup

Five sites along Fivemile Creek (FM1-FM5) were selected for field data collection (Figure 4.2). At least one cross-sectional survey was conducted at each site using an automatic level. One site, FM2, was severely impacted by a series of headcuts. Seven cross-sectional surveys were conducted at this site. During surveying, detailed information on layering and vegetation were recorded. Soil samples were collected from the thalweg of the channel at each cross-section and were analyzed for soil particle size distribution using hydrometer and sieves: ASTM Standards D421 (ASTM, 2002a) and D422 (ASTM, 2002b). A Hobo water level logger (Onset, Bourne, MA) was installed at each site to measure absolute pressure. Pressures were converted to water depth using

HOBOware software and atmospheric pressures determined from the nearby Oklahoma Mesonet site (http://www.mesonet.org).

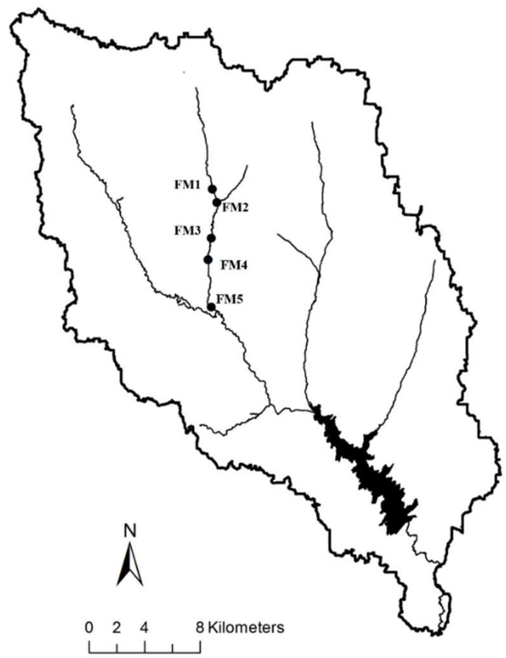

Figure 4.2. Selected field data collection sites (FM1-FM5) along Fivemile Creek in the Fort Cobb Reservoir watershed.

At each site, erodibility parameters were determined using the “mini”-JET device. At least two JETs were conducted at each site within each visible layer (Table 4.1). Streambank soil samples were also collected to analyze for bulk density and particle size as described above. Borehole shear tests (BSTs) (Handy and Fox, 1967) were conducted to determine geotechnical parameters, φ' and c', for each soil layer. However, the texture of the soils and the location of the water table within this watershed resulted in unreliable BST results; therefore, values based on soil texture were selected from a list of defaults incorporated into BSTEM, a commonly used site-scale streambank stability model (Simon et al., 2011).

Table 4.1. Field data for each soil layer at each site along Fivemile Creek (FM). Soil layers where no jet erosion tests (JETs) were completed report the selected representative monitored bank layer. Note that soil layers are listed in order from highest to lowest elevation and bank layers are labeled using the site name - soil layer # format.

Bank Layer	Layer Thickness (m)	Soil Type	JETs Completed	Average τ_c (Pa)	Average k_d ($cm^3\ N^{-1}\ s^{-1}$)	Average Bulk Density ($kg\ m^{-3}$)
FM1-1	1.1	Loamy Sand	2	0.8	191.7	1.5
FM1-2	0.6	Sandy Clay Loam	0	FM2-2	FM2-2	FM2-2
FM2-1	1-1.5[a]	Sandy Loam	2	0.6	366.5	1.5
FM2-2	0.5-0.8[a]	Sandy Clay Loam	24	11.9	19.7	1.4
FM2-3	0.4-1.2[a]	Sandy Loam	0	1.5	60.3	1.8
FM3-1	5.3	Loamy Sand	3	0.8	145.6	1.5
FM4-1	4.4	Sand	0	FM3-1	FM3-1	FM3-1
FM5-1	2.8	Sandy Loam	2	0.4	302	1.4
FM5-2	1.3	Clay Loam	2	3.7	61.1	1.4
FM5-3	1.2	Sandy Loam	0	FM5-1	FM5-1	FM5-1

[a]Multiple Cross-sections at FM2

4.4.5 Determination of Long-Term Erosion Rates

Aerial imagery was used to estimate long-term streambank retreat at each site. National Agricultural Imagery Program (NAIP) images (1 m resolution) were obtained for Caddo County for 2008 and 2013. Using ArcMap (v10.0), each image was georeferenced and used to determine bank retreat. Streambanks were digitized at each site for 2008 and 2013, and the average distance between polylines were used as lateral retreat for that site (Purvis and Fox, 2016). For site FM5, dense vegetation on both images did not allow for analysis; therefore, the retreat was estimated from the nearest visible streambank.

4.4.6 Model Set-up and Calibration

Because of the large distance between the selected research sites, additional cross-sections (AC) were interpolated from the LiDAR data at approximately every 500-m along the channel for a total of 29 ACs on Fivemile Creek (Figure 4.3). The ACs were more closely spaced around FM2, where several surveyed cross-sections were closely spaced due to the presence of headcuts, to increase the stability of the model. Average soil particle size distributions, bulk densities and default geotechnical parameters were used for the soil and sediment data of each AC. The τ_c values from the JET data were grouped by soil layer to identify the probability distribution using the Individual Distribution Identification function in Minitab (v16, Minitab, Inc., State College, PA). The Anderson-Darling (*AD*) statistic was used to evaluate the distributions. The τ_c values followed log-normal ($AD = 0.196$, $p = 0.848$) and Weibull distributions ($AD = 0.276$, p => 0.25) for the sand and clay layers, respectively. Using these distributions, random numbers were generated for τ_c for each AC. A regression equation was used to determine the relationship between τ_c and k_d. This regression was used to determine k_d for each AC. For field data collection sites, site specific soil data was used. Average τ_c and k_d from the JETs conducted at each site were used as input.

A USGS stream gauge was not available for Fivemile Creek. Therefore, a daily average stream flow hydrograph for 2008-2013 generated from a calibrated SWAT model for the Fort Cobb Watershed (Moriasi and Starks, 2010; Guzman et al., 2015) was used as flow input. Fluvial erosion is a function of applied τ and is sensitive to peak flows (*Q*). Therefore, the daily average streamflow hydrograph was converted to an hourly triangular hydrograph using the SCS triangular hydrograph method (SCS, 1972). The

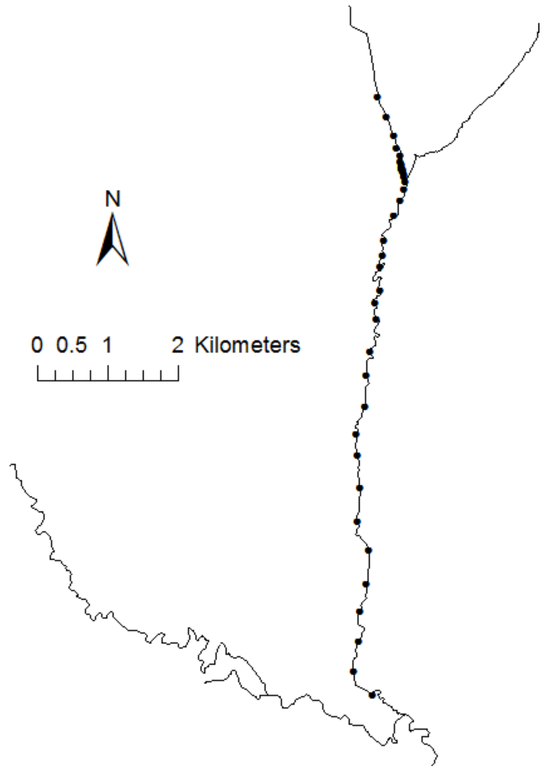

Figure 4.3. Location of surveyed and LIDAR cross-sections along Fivemile Creek incorporated into CONCEPTS.

converted hydrograph started and ended at base flow that was determined from the daily averaged flow. For flows less than or equal to baseflow, hourly discharge was set to the daily average flow. One tributary was incorporated into the model. CONCEPTS requires sediment inflow data (Q_s) for tributaries for each sediment class size in the form of power equations:

$$Q_s = a\,Q^b \tag{4.2}$$

where *a* and *b* are regression parameters (Table 4.2).

In order to determine the regression parameters of the power equations, data from three USGS gauges (Cobb Creek near Eakly, Lake Creek, and Willow Creek) located in the Fort Cobb Reservoir watershed were combined to develop sediment rating curves for each CONCEPTS particle size. The USGS collected grab samples during various storm

Table 4.2. Rating curve coefficients (a and b) for power equation ($Qs = a\ Q^b$, where Qs is sediment discharge (kg s^{-1}) and Q is streamflow (cms)) and coefficients of determination (R^2) determined for each CONCEPTS sediment size class from three USGS gauges used as sediment inflow for tributary to Fivemile Creek.

Upper Bound Sediment Class Size	Regression Parameters		
(mm)	a	b	R^2
0.01	0.02	1.05	0.82
0.025	0.0018	1.19	0.76
0.065	0.102	1.28	0.91
0.25	0.0044	1.94	0.92
0.841	0.0003	1.63	0.96
>0.841	0	1	--

events which were analyzed for particle size. Using these data and the streamflow at each gauge, rating curves between sediment discharge, Q_s (kg s^{-1}), and streamflow, Q (cms), were created by fitting a regression equation to the data using SigmaPlot (v12.5, Systat Software, San Jose, CA).

Water levels from the HOBO loggers and a SWAT generated flow file were used to calibrate the roughness of the bed and banks using the hydraulic submodel in CONCEPTS. Fivemile Creek was divided into five sections based on proximity to surveyed cross-sections and roughness for all cross-sections within each section was assumed to be the same. Water depth output from CONCEPTS was compared to the water depth measured by the water level loggers at each site. The roughness of the bed was calibrated during periods of base flow. Bank roughness was calibrated based on peak flows for storm events (Table 4.3).

Table 4.3. Calibration parameters adjustments for applied shear stress due to vegetation (ν) and bed and bank roughness (Manning's *n*) for each CONCEPTS cross-section along Fivemile Creek.

Cross-section	ν-factor	Roughness (Mannings' *n*)	
		Bed	Bank
FM1	0.01	0.04	0.06
FM2	0.1-0.5*	0.03	0.05
FM3	0.27	0.077	0.115
FM4	0.6	0.077	0.12
FM5	0.2	0.075	0.12
LiDAR cross-sections	0.01-2	Varied**	Varied**

*Multiple Cross-sections at FM2

**Roughness for LiDAR Cross-sections was assumed to be equal to the roughness of the closest surveyed cross-section

CONCEPTS predicted retreat was compared to measured aerial retreat and τ_c and k_d for each cross-section were adjusted as needed (Figure 4.4). A Brier Skill Score (BSS) was used to evaluate the calibration based on lateral bank retreat (Abderrezzak et al., 2016). A BSS equal to 0.60 was determined, which suggested a "Good" model fit. Streambanks at some sites were heavily vegetated. Because vegetation can significantly alter τ (Thompson et al., 2004), the effect of vegetation was taken into account during the calibration period. The model did not allow for the direct adjustment of τ, therefore an ν-factor was used to modify τ by adjusting τ_c and k_d in the same manner that Daly et al. (2015) used to account for the increase in τ around a meander bend:

$$\varepsilon_r = k_d(\upsilon\tau - \tau_c) = \upsilon k_d(\tau - \frac{\tau_c}{\upsilon}) \tag{4.3}$$

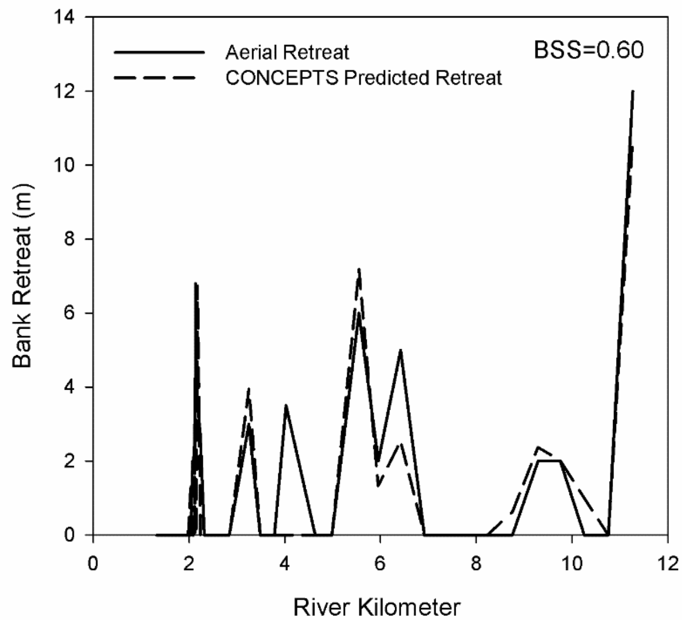

Figure 4.4. Calibration results for Fivemile Creek. Comparison of CONCEPTS predicted retreat and historical lateral retreat determined from aerial imagery.

4.4.7 Select Potential Stabilization Practices

Several factors were considered when selecting stabilization practices to be simulated, including stream incision, the amount of land required for stabilization practice, and cost. Three stabilization practices were selected for analysis: grade control (GC), riprap toe (RRT), and vegetation and bank grading with both 2:1 (VEG21) and 3:1 bank slopes (VEG31). Four scenarios of single practices (GC, RRT, VEG21 and VEG31) and seven combinations of the practices (RRT+GC, VEG21+GC, VEG21+RRT, VEG21+RRT+GC, VEG31+GC, VEG31+RRT, VEG31+RRT+GC) were simulated.

4.4.8 Apply Stabilization Practices to Calibrated Model

A riprap toe was simulated by modifying the erodibility parameters of the bank toe. Riprap size was determined using the d_{50} factor of safety procedure described by

Stevens et al. (1976). The Shield's Diagram (Shields, 1936) was used to determine τ_c and the relationship between τ_c and k_d developed by Simon et al. (2011) was used to determine k_d for the riprap. Bank grading was simulated by changing the channel geometry of the cross-sections. Vegetation was simulated by using an ν-factor of 0.15 (Thompson et al., 2004). Root cohesion (C_r) was determined using the Riproot model that is incorporated into BSTEM (Pollen and Simon, 2005). A bank coverage of 50% grass and 50% trees was assumed to calculate the additional cohesion for the soils. Grade control was simulated by setting the bedrock elevation equal to the thalweg elevation (Langendoen, 2011).

Fivemile Creek was divided into five sections based upon land ownership to limit the number of combinations of sites. For each of the 11 stabilization scenarios, the stabilization practice was first applied to a single cross-section. Eight simulations of single cross-sections were simulated. Next, stabilization was applied to a single land owner and then combinations of two, three, and four landowners. Finally, a scenario with the entire stream stabilized was considered. A total of 38 model simulations were performed for each of the stabilization scenarios.

4.4.9 Cost Calculations

Costs for each practice were calculated using RSMeans (2016) Facilities and Construction Cost (A. Stoecker, personal communication) and based on costs reported for use in 2016. A spreadsheet tool was developed to aid in cost estimation (Appendix C). Excavation costs were based on volumes of soil to be removed and an average costs per cubic yard for a 0.38 m^3 excavator as reported by RSMEANS (2016). Volume of soil excavated for each model cross-section was determined based on site-specific dimensions for bank height, bank slope, desired bank slope, and length of bank stabilized. Riprap costs are for random broken stone 45 kg average in place. Cost of riprap toe was calculated based on volume of riprap stone required for each site. This volume was determined based on height of riprap to be placed on the bank, length of stream segment, and size of trench excavated at the toe. Vegetation costs included 900 N tensile strength geotextile fabric, bare root willow seedlings with a density of 10 per m^2, and fescue seeding using a tractor spreader. Dimensions of bank height, slope, and length of stream section for each site were used to calculate surface area required for plantings. Grade control cost were estimated based on cross-vanes spaced approximately five to seven channel widths. Dimensions for channel width, cross vane angle, and cross vane width for each cross-section were used to determine volume of rock needed for cross vane construction and the cost associated with this volume of rock. In addition, an excavation volume to key the cross-vane into the bank was determined. Finally, a 5% engineering and surveying expense was included in each cost estimate.

4.5 Results and Discussion

4.5.1 Sediment Reduction and Stabilization Costs

The sediment yield from each scenario was compared to the baseline sediment yield from the calibrated model to calculate sediment reduction. A regression between sediment reduction and fraction of the stream stabilized, λ, was calculated using SigmaPlot (v12.5, Systat Software, San Jose, CA) for each of the stabilization scenarios. Higher R^2 values (0.91-0.93) were observed for scenarios involving vegetation (VEG21, VEG21 +RRT, etc.) than the scenarios incorporating RRT and GC alone (R^2=0.49-0.68). A sediment reduction and the cost for each model simulation were determined to develop a pair of graphs for each of the 11 stabilization practices. Examples are provided in Figures 4.5 to 4.7. Values of λ less than 0.05 corresponds with a single cross-section stabilized in the model and represents less than 500 m of streambank stabilized. For all practices evaluated this resulted in a small amount of sediment reduction when considering the entire reach. A range of λ from 0.1 to 0.3 represents the entire length of stream for a single landowner, while λ between 0.3 to 0.5 represents two landowners, 0.5 to 0.7 represents three landowners, and 0.7 to 0.9 represents four landowners. The λ=1 is the scenario where stabilization is applied to the entire length of stream.

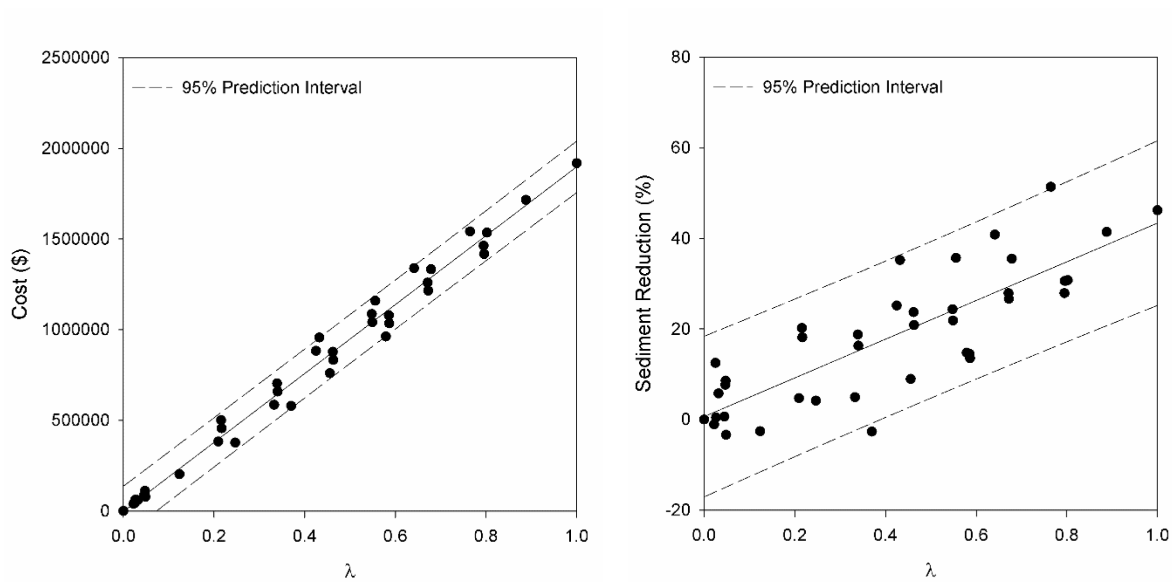

Figure 4.5. Sediment reduction and cost versus fraction of the stream stabilized (λ) for Riprap Toe (RRT).

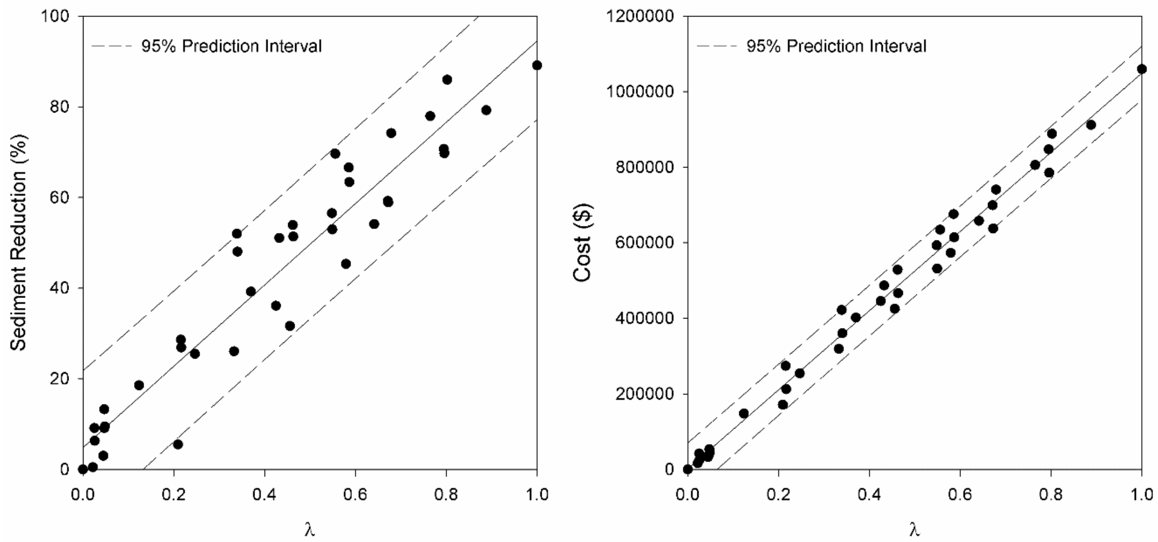

Figure 4.6. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetated banks graded to a 2:1 side slope with grade control of the bed (VEG21+GC).

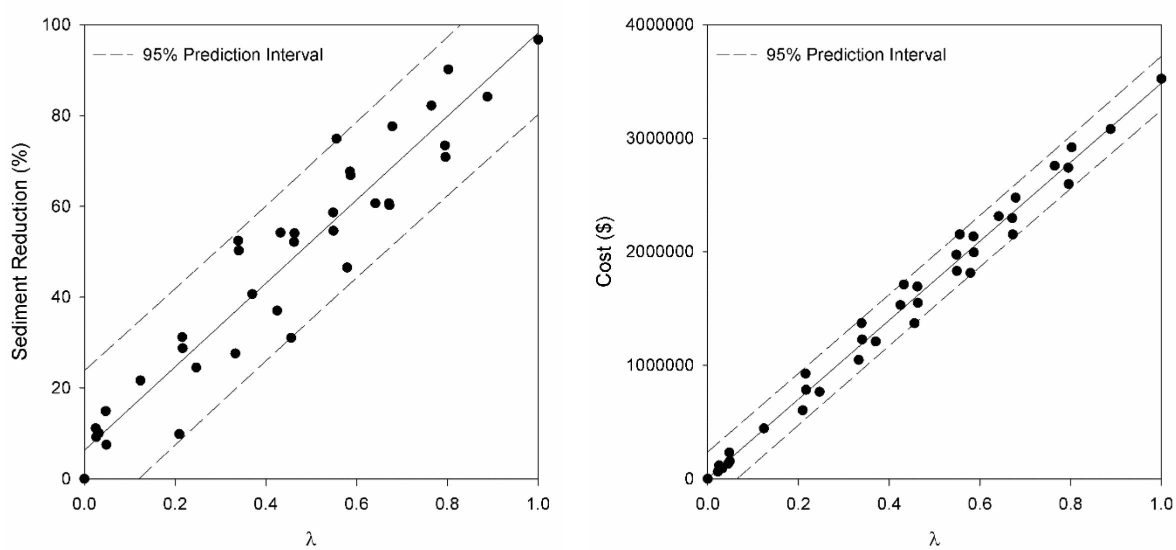

Figure 4.7. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetated banks graded to a 3:1 side slope, with riprap toe and grade control of the bed (VEG31+RRT+GC).

4.5.2 Evaluation of Stabilization Practices

After regression equations were developed for the stabilization practices, the effectiveness of each practice was compared (Figure 4.8). The GC alone scenario resulted in an increase in sediment as it was applied to increasing lengths of the stream. If bank protection was not incorporated with grade control, the stream began to adjust laterally and an increase in bank erosion was predicted. Practices that incorporated vegetation as a means of bank stabilization resulted in a higher amount of sediment reduction when compared to RRT only, RRT+GC and GC only scenarios, indicating vegetation needed to be incorporated. The VEG31+RRT+GC scenario resulted in the highest amount of sediment reduction for all lengths of stream stabilized. In addition, bank protection alone does not prevent channel incision and resulted in lower sediment reduction when compared to the same practice with the addition of grade control (i.e., a higher sediment reduction was observed with the VEG21+GC scenario when compared to the VEG21 or RRT+GC scenarios when compared to the RRT scenario). As previous research has shown, both bed and bank protection should be incorporated for optimal sediment reduction (Shields et al., 1995).

The sets of graphs can also be used to determine the amount of sediment reduction to be expected based upon an amount invested between different stabilization practices. For example, if $800,000 was available to invest in a streambank stabilization project along Fivemile Creek, a λ of 0.48 is expected for the RRT scenario which would result in approximately 20% reduction in sediment load (Figure 4.5). Conversely, if the stabilization practice VEG21+GC was selected, 75% of the stream could be stabilized for a predicted sediment load reduction of 70% (Figure 4.6). The VEG31+RRT+GC scenario resulted in a λ equal to 0.25 and a predicted sediment load reduction of 28% (Figure 4.7). For the VEG21 only scenario, a sediment reduction of 75% was expected. Therefore, for an investment of $800,000, the VEG21 scenario would result in the highest sediment reduction for Fivemile Creek. However, as previously stated, GC may be needed for long term stability.

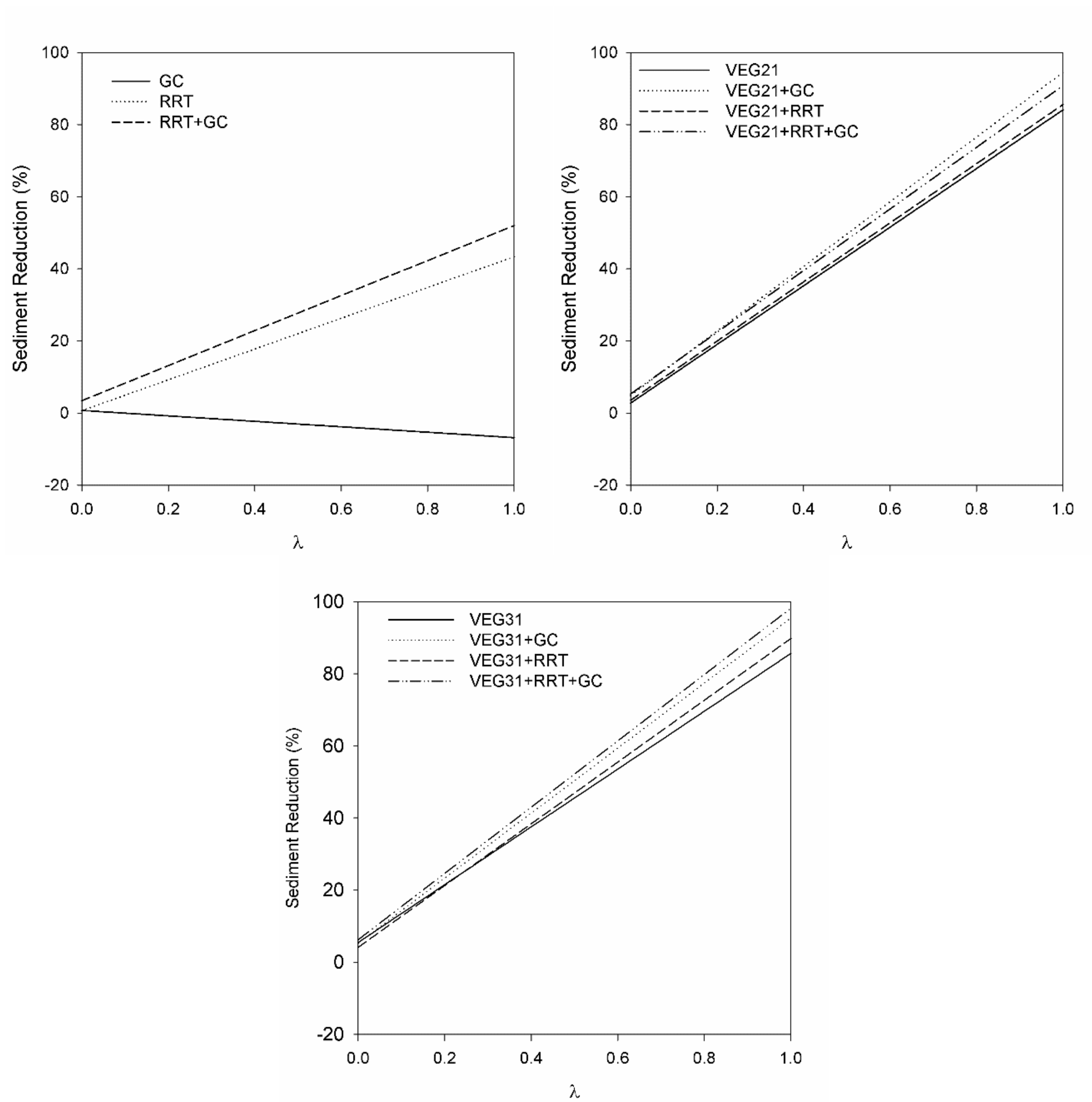

Figure 4.8. Sediment reduction versus fraction of stream stabilized (λ) for Grade Control (GC), Riprap Toe (RRT), and vegetation with 2:1 (VEG21) or 3:1 (VEG31) bank slopes.

4.5.3 Cost of Streambank Stabilization

Cost of streambank stabilization projects are highly variable depending on type of stabilization, materials used, amount of earthwork needed, channel dimensions, etc. Reported costs from stabilization practices across the U.S. range from $39 to $880 per linear meter of bank stabilized (Bair, 2000; OKFWS, 2007; KWO, 2013; Herrington et al., 2015) and $131-$880 for projects in Oklahoma. Costs estimates for streambank stabilization along Fivemile Creek were with in this range. The least costly practice, VEG21, averaged $84 per linear meter and the most costly practice, VEG31+RRT+GC, averaging $327 per linear meter.

While incorporating multiple practices in stabilization resulted in higher sediment reduction, the cost was also much higher. Cost effectiveness was determined for each scenario and an average cost effectiveness ($/tonne and $ per percent reduction) was calculated for each practice (Table 4.4). The GC scenario resulted in an increase in sediment yield and therefore the cost effectiveness was not calculated. Although, the VEG31+RRT+GC scenario was the most effective in terms of sediment reduction it ranked seventh in terms of cost effectiveness, indicating that the most physically effective practice is not necessarily the most cost effective practice for a streambank erosion control. The VEG21 scenario was the most cost effective stabilization practice, with the VEG21+GC scenario a close second. If a longer time period was considered, a higher degree of incision may be observed which could have ultimately caused an increase occurrence of bank failure and higher sediment loads if grade control was not included. Although slightly less cost effective, the VEG21+GC scenario would be recommended for Fivemile Creek for long term stability due to the highly incised nature of this stream system.

Cost of streambank erosion practices is often quite high and a major factor for stakeholders when determining which practices to adopt. Several conservation programs funded by federal and state governments are available to assist with the cost of erosion control including the Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), and Environmental Quality Incentives Program (EQIP) (Tong et al., 2017). With a finite amount of resources for these programs, it becomes vital to understand which practices are the most cost effective for a particular stream system to achieve optimal sediment reduction.

Table 4.4. Cost Effectiveness of streambank erosion control for Fivemile Creek.

	Average Cost Effectiveness	
Stabilization Scenario [a]	**$/tonne reduction**	**$/%reduction**
GC	----	----
RRT	11.2 ± 10.9	45,900 ± 36,600
RRT+GC	11.1 ± 8.7	42,000 ± 32,900
VEG21	2.6 ± 0.7	9,900 ± 2,500
VEG21+GC	2.9 ± 1.5	10,800 ± 5,800
VEG21+RRT	7.9 ± 2.5	47,200 ± 9,400
VEG21+RRT+GC	7.6 ± 3.7	29,000 ± 13,900
VEG31	3.7 ± 1.1	14,000 ± 4,200
VEG31+GC	3.7 ± 1.1	14,600 ± 6,200
VEG31+RRT	8.6 ± 2.3	33,400 ± 9,800
VEG31+RRT+GC	8.0 ± 2.8	30,500 ± 10,400

[a] GC: Grade Control; RRT: Riprap Toe; VEG21: Vegetation with 2:1 bank slopes; VEG31: Vegetation with 3:1 bank slopes

4.6 Conclusion

Streambank stabilization practices can be very costly; therefore, it is important to understand the possible benefits prior to implementation and to evaluate potential alternatives. Process-based models are useful tools to evaluate potential streambank stabilization practices, and a number of validated reach-scale sediment transport and bank erosion/stability models are available. The framework presented in this paper provides an example of how to use these tools to determine the most effective practice for a particular stream system based on both sediment reduction and cost analyses. Choosing practices without regard to cost would result in greater costs per tonne at the expense of other projects or more miles of river stabilized. This methodology was applied to Fivemile Creek to evaluate various stabilization scenarios to determine the most cost effective stabilization practice. It was determined that vegetation with 2:1 bank slopes and grade control would be the best choice for this stream system.

CHAPTER V

SUMMARY OF CONCLUSIONS

5.1 Conclusions

Streambank erosion contributes a significant amount of sediment loading to surface waters. Process-based models offer a way to quantify sediment loads and predict lateral bank retreat, as well as understand streambank erosion processes occurring within a stream system. In addition, process-based models allow for the evaluation of streambank stabilization practices. This research utilized the process-based model CONCEPTS to quantify bank erosion on the reach and watershed scale and evaluate bank stabilization practices. The overall objectives of this research were to (1) quantify streambank erosion processes within a watershed, (2) parameterize streambank stabilization practices for simulation in process-based models, and (3) determine the effectiveness of stream restoration/stabilization on stream-scale sediment reduction. The major conclusions from this research were as follows:

1. The excess shear stress parameters, τ_c and k_d varied by less than one order of magnitude for Fort Cobb Reservoir watershed, which is less variation than has previously been observed in other watersheds including the Illinois River

watershed. This may be due to the higher clay content and larger variation in grain size distributions within the Illinois River watershed.

2. A similar degree of variability in the Wilson model parameters (b_1 and b_0) was observed in both watersheds.
3. Significant longitudinal trends in soil erodibility or soil physical properties were not observed along shorter stream reaches (less than 26 km). A weak but significant trend was observed for soil erodibility and median particles size on the longer stream reach of the Illinois River.
4. Lateral retreat predictions were less variable than the input erodibility parameters as additional processes being simulated in the model dampens the input variability. Both the excess shear stress equation and Wilson model over predicted bank retreat when heavy vegetation was present (Fivemile Creek) and under predicted bank retreat around a meander (Barren Fork).
5. Fluvial erodibility parameters need to be adjusted when used in process-based models to account for the presence of vegetation or meander bends. This can be done indirectly by using an ν factor to adjust the applied shear stress. The ν value of less than one was used to account for presence of vegetation and greater than one for increase in applied shear stress around a meander. CONCEPTS simulations were calibrated using an ν factor ranging from 0.01 to 1.8 to account for vegetation and meandering. The sites with the heaviest vegetation resulted in the smallest ν.
6. Streambank stabilization using riprap toe or vegetation and grading can be effective at reducing lateral bank retreat and sediment yields from bank erosion.

Site-scale sediment yield predictions were reduced by 40 to 100%. While bank stabilization was effective at reducing bank erosion, grade control is likely necessary for long term channel stability in an incising channel.

7. Riprap toe can be parameterized using median particle size (d_{50}) and height of riprap (h). An uncertainty analysis showed sediment yield and lateral retreat prediction are more sensitive to h rather than d_{50}. Sediment reduction predictions were only sensitive to d_{50} of riprap as d_{50} approached d_{50} of the site and increased as h increased.
8. Bank stabilization with vegetation can be parameterized using a shear stress adjustment factor (ν) and added root cohesion (C_r). Sediment yield and lateral retreat predictions were more sensitive to ν rather the C_r. More research is needed to quantify the impact of vegetation on applied shear stress for accurate simulation in process-based modelling.
9. Grading the banks to a 3:1 side slope to increase geotechnical stability can significantly reduce sediment loads and lateral bank retreat and accounted for 58 to 69% of sediment reduction.
10. A methodology was presented that demonstrates how process-based models can be utilized to evaluate streambank stabilization practices to determine the most cost effective practice for a stream reach. These guidelines can be applied using any reach-scale sediment transport and bank erosion model.
11. Site scale stabilization is not enough to significantly reduce sediment loads generated by bank erosion. If water quality improvement is a primary goal of stabilization, longer reaches need to be stabilized for reach-scale reduction.

12. Incorporating multiple stabilization practices (i.e. vegetation with riprap toe and grade control) were more effective at reducing sediment yield, but were also more expensive. Therefore, a cost effectiveness analysis needs to be completed to determine which practice is the best investment. Vegetation with 2:1 bank slopes was the most cost effective practice for Fivemile Creek, however the addition of grade control was recommended for long term stability.

5.2 Directions for Future Research

Most of the previous research on streambank erosion has focused on the use of the linear excess shear stress equation for fluvial erosion. A few recent studies have demonstrated ability of the nonlinear Wilson model more accurately predict fluvial erosion and have incorporated into BSTEM. Future research is needed to further evaluate the Wilson model and methods for calibration of the Wilson model parameters in order for it to be more widely used. In addition, methods for parameterizing stabilization practices by modifying the Wilson model parameters need to be investigated.

Studies to validate the methods for simulating stabilization, both riprap toe and vegetation and grading, discussed in this research need to be conducted. This research presents methods for simulating the reduction in applied shear stress from presence for vegetation using a ν factor. However, further investigation into the magnitude of ν for different vegetation types and coverage is needed to more accurately quantify the impact of vegetation on reducing fluvial erosion. In addition, more information is needed on how to account for the shear stress is altered when both meandering and vegetation is present.

Finally, methods for cost-effective optimization of bank stabilization should be investigated. The cost effectiveness analysis presented in this paper focused on a single practice used for the entire stream reach. A cost-effective optimization would allow for the consideration of multiple practices placed at different locations along the stream reach for optimal sediment reduction. These advances would allow for more accurate simulation of streambank erosion and stabilization and making more informed watershed management decisions.

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APPENDICES

Appendix A: Soil and sediment model input data

Appendix B: Surveyed cross-sections and ground based photographs for each data collection site

Appendix C: Cost estimation spreadsheet

Appendix D: Cost and sediment reduction graphs resulting from methodology described in Chapter 4

APPENDIX A

SOIL AND SEDIMENT MODEL INPUT DATA

Table A1. Soil physical properties measured for each soil layer at each data collection site along Fivemile Creek (FM) and Willow Creek (WC).

Site	Layer	Layer Depth (m)	Description	Porosity	Bulk density (kg/m3)	ν	# of JETs Completed	Critical shear stress (Pa)	Erodibility (m/s Pa)	Cohesion (Pa)	Root Cohesion (Pa)	Friction angle	Suction angle
FM1	1	0.0-1.1	Sand	0.45	1445	0.01	2	0.79	1.91E-04	400	9600	32.3	15
	2	1.1-2.0	FM2-2	0.46	1440	0.01	0	11.27	1.91E-05	8200	0	26.4	15
FM2	1	0.0-1.0	Sand	0.43	1510	0.1-0.5	3	0.62	1.22E-04	400	9600	32.3	15
	2	1.0-1.75	Clay	0.46	1440	0.1-0.5	24	11.27	1.91E-05	8200	0	26.4	15
	3	1.75-3.1	Sand	0.34	1750	0.1-0.5	2	1.5	6.03E-05	400	0	32.3	15
FM3	1	0.0-5.4	Sand	0.42	1540	0.27	3	0.81	1.46E-04	400	4000	32.3	15
FM4	1	0.0-4.6	FM3-1	0.42	1540	0.6	0	0.81	1.46E-04	400	200	32.3	15
FM5	1	0.0-2.8	Sand	0.47	1410	0.2	2	0.41	3.02E-04	400	9600	32.3	15
	2	2.8-4.1	Clay	0.48	1370	0.2	2	3.65	3.06E-05	8200	0	26.4	15
	3	4.1-5.2	FM5-1	0.47	1410	0.2	0	0.41	3.02E-04	400	0	32.3	15
WC1	1	0.0-3.5	Sand	0.49	1350	0.2	2	0.45	4.82E-04	400	800	32.3	15
WC2	1	0.0-3.0	Sand	0.54	1210	1	3	0.6	4.77E-04	400	800	32.3	15
	2	3.0-4.4	WC3-3	0.49	1350	1	0	8.6	1.06E-05	8200	0	26.4	15
WC3	1	0.0-2.0	Sand	0.50	1330	1.8	2	0.72	2.16E-04	400	1000	32.3	15
	2	2.0-3.8	Sand	0.45	1460	1.8	3	0.83	1.07E-04	400	1000	32.3	15
	3	3.8-4.1	Clay	0.49	1350	1.8	3	8.6	1.06E-05	8200	0	26.4	15
WC4	1	0.0-3.3	Sand	0.43	1520	0.71	2	0.43	3.52E-04	400	1000	32.3	15
	2	3.3-4.5	Clay	0.47	1410	0.71	3	2.63	3.41E-05	8200	1000	26.4	15

Table A2. Particle size distributions for bed sediment samples collected at data collection sites along Fivemile Creek (FM) and Willow Creek (WC).

		% Finer																
Site	XSEC #	Total Clay	Very Fine Silt	Fine Silt	Medium Silt	Coarse Silt	Very Coarse Silt	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand	Very Fine Gravel	Fine Gravel	Medium gravel	Coarse Gravel	Very Coarse Gravel	Small Cobble
FM1		4.4	4.5	5.1	6.2	7.3	8.8	63.5	99.0	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
FM2	1	9.5	11.4	13.1	16.8	27.0	39.1	73.4	97.8	99.0	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0
	2	16.5	21.3	28.3	38.7	56.5	64.4	86.8	98.7	99.5	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	3	18.4	29.1	34.4	42.2	46.4	55.6	88.6	97.4	98.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	4	12.0	13.2	14.3	16.8	25.3	36.2	74.6	93.6	95.0	97.0	98.9	100.0	100.0	100.0	100.0	100.0	100.0
	5	6.2	6.9	7.9	8.7	12.9	23.9	69.1	97.8	99.3	99.8	99.9	100.0	100.0	100.0	100.0	100.0	100.0
	6	17.5	20.4	24.8	30.3	41.4	54.7	83.3	97.5	98.7	99.3	99.7	99.9	100.0	100.0	100.0	100.0	100.0
	7	19.0	22.9	26.7	32.4	42.3	51.9	81.1	96.5	98.1	99.1	99.7	99.8	100.0	100.0	100.0	100.0	100.0
FM3		1.7	2.3	2.8	2.8	3.7	6.5	45.3	83.0	98.3	99.7	99.8	99.9	100.0	100.0	100.0	100.0	100.0
FM4		4.5	4.7	5.6	7.0	8.5	10.6	18.5	29.2	81.9	94.9	98.0	99.4	100.0	100.0	100.0	100.0	100.0
FM5		3.9	4.7	6.2	7.8	9.8	11.1	26.8	55.0	95.4	97.7	98.2	98.9	100.0	100.0	100.0	100.0	100.0
WC1		5.8	7.0	8.4	9.6	12.2	15.6	60.4	96.0	98.5	99.6	99.7	99.8	100.0	100.0	100.0	100.0	100.0
WC2		5.6	5.8	6.8	7.4	9.6	13.4	37.7	46.0	88.8	98.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WC3		1.9	2.4	3.1	3.7	4.9	5.1	17.4	42.6	61.7	78.4	81.7	86.1	87.3	95.1	100.0	100.0	100.0
WC4		1.7	1.7	2.2	2.8	3.4	4.7	17.3	42.2	61.1	72.3	77.6	82.4	87.8	95.8	100.0	100.0	100.0

Table A3. Particle size distributions for streambank soil samples collected at data collection sites along Fivemile Creek (FM) and Willow Creek (WC).

		% Finer																
Site	Layer	Total Clay	Very Fine Silt	Fine Silt	Medium Silt	Coarse Silt	Very Coarse Silt	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand	Very Fine Gravel	Fine Gravel	Medium gravel	Coarse Gravel	Very Coarse Gravel	Small Cobble
FM1	1	10.1	11.5	12.7	13.8	19.7	30.1	70.2	98.1	99.5	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
FM2	1	10.1	11.5	12.7	13.8	19.7	30.1	70.2	98.1	99.5	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	2	20.0	22.5	24.8	28.0	35.1	42.8	70.3	95.9	99.1	99.7	99.9	100.0	100.0	100.0	100.0	100.0	100.0
	3	12.8	20.7	22.5	25.6	25.9	33.9	76.0	98.3	99.7	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
FM3	1	2.7	6.0	6.3	7.7	9.5	22.0	69.7	97.9	99.1	99.8	99.9	100.0	100.0	100.0	100.0	100.0	100.0
FM4	1	6.3	8.0	8.8	10.1	13.6	23.7	69.3	97.9	99.3	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
FM5	1	6.0	6.6	7.4	8.7	11.7	19.0	67.9	97.6	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	2	28.3	35.6	38.7	45.4	56.5	62.2	87.1	98.0	99.2	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WC1	1	8.1	8.7	9.9	11.6	15.0	24.8	69.4	97.2	98.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WC2	1	4.7	4.7	6.1	7.8	11.5	15.2	66.4	99.3	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WC3	1	7.5	8.8	9.4	11.1	16.0	23.2	74.2	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	2	5.2	6.0	7.3	8.3	12.4	18.2	70.6	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	3	13.8	16.1	18.0	20.7	29.3	38.5	76.4	99.3	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WC4	1	11.4	12.6	13.6	16.7	24.0	34.8	78.0	99.0	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	2	16.3	18.1	20.8	25.8	36.0	47.7	81.8	99.0	99.6	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0

APPENDIX B

SURVYED CROSS-SECTIONS AND GROUND BASED PHOTOGRAPHS

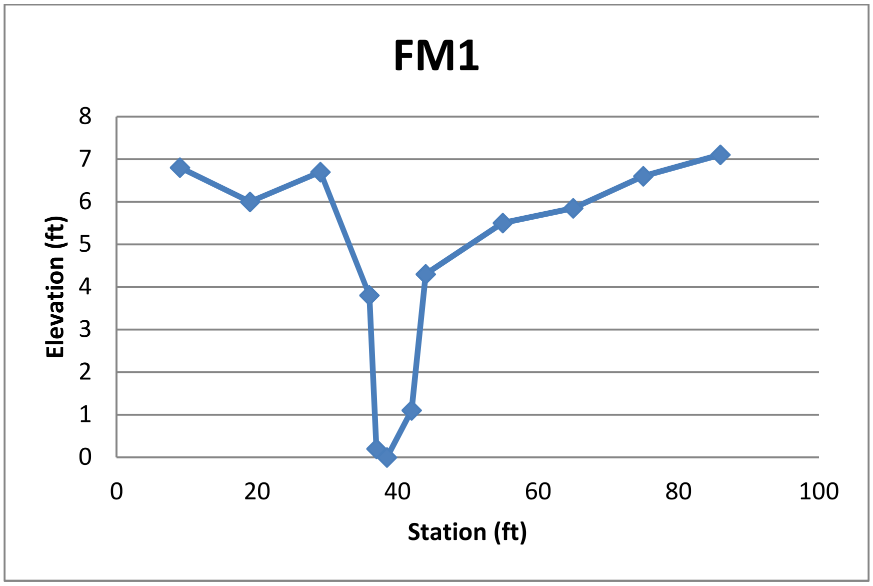


Figure B1. Cross-sectional survey and ground based photograph for site FM1.

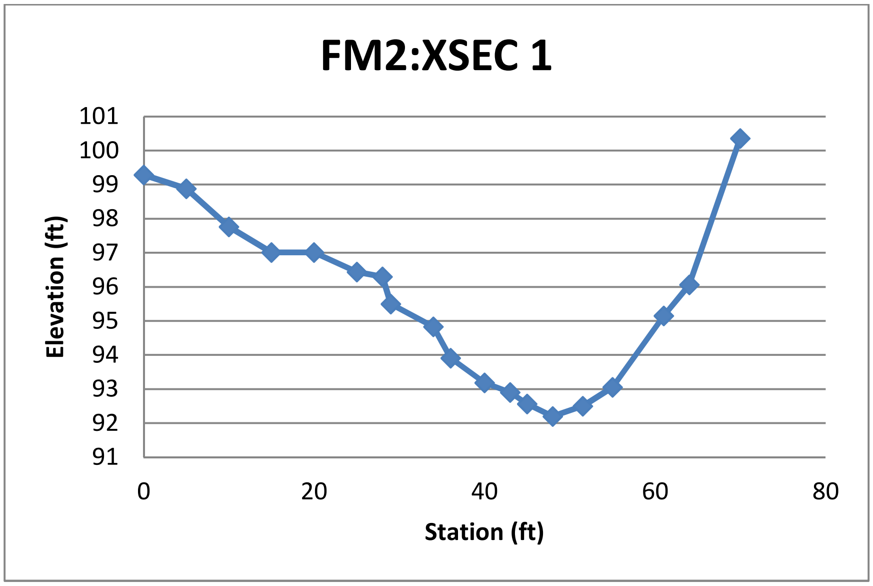


Figure B2. Cross-sectional survey and ground based photograph for site FM2 XSEC1.

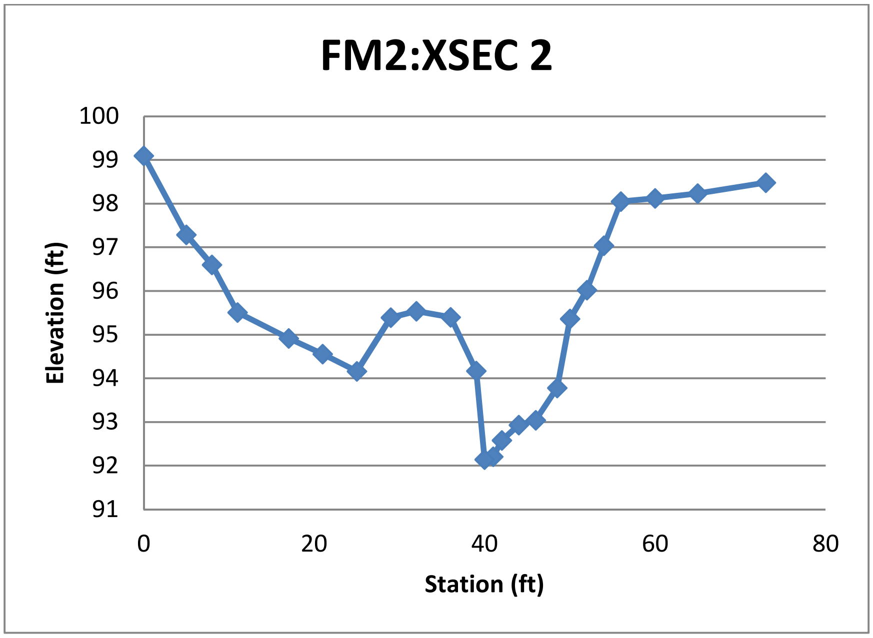


Figure B3. Cross-sectional survey and ground based photograph for site FM2 XSEC2.

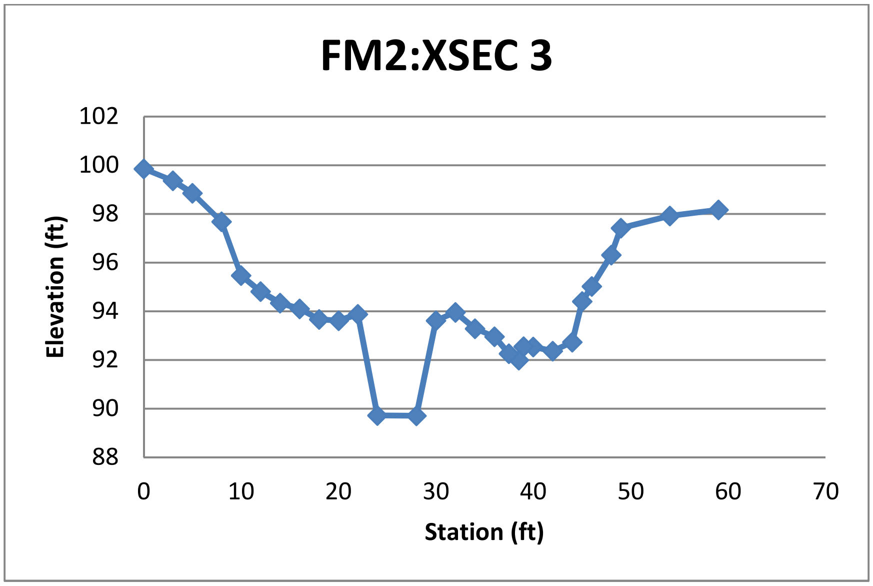


Figure B4. Cross-sectional survey and ground based photograph for site FM2 XSEC3.

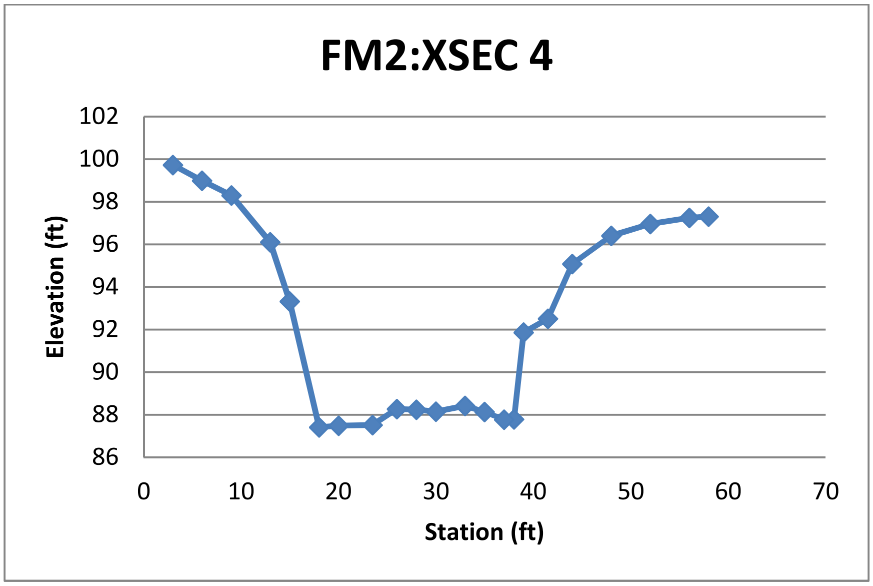


Figure B5. Cross-sectional survey and ground based photograph for site FM2 XSEC4.

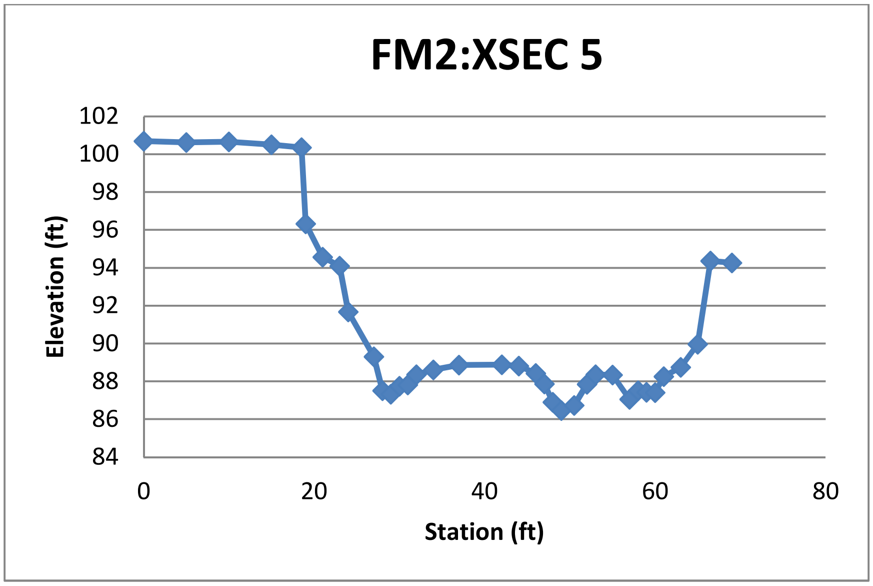


Figure B6. Cross-sectional survey and ground based photograph for site FM2 XSEC5.

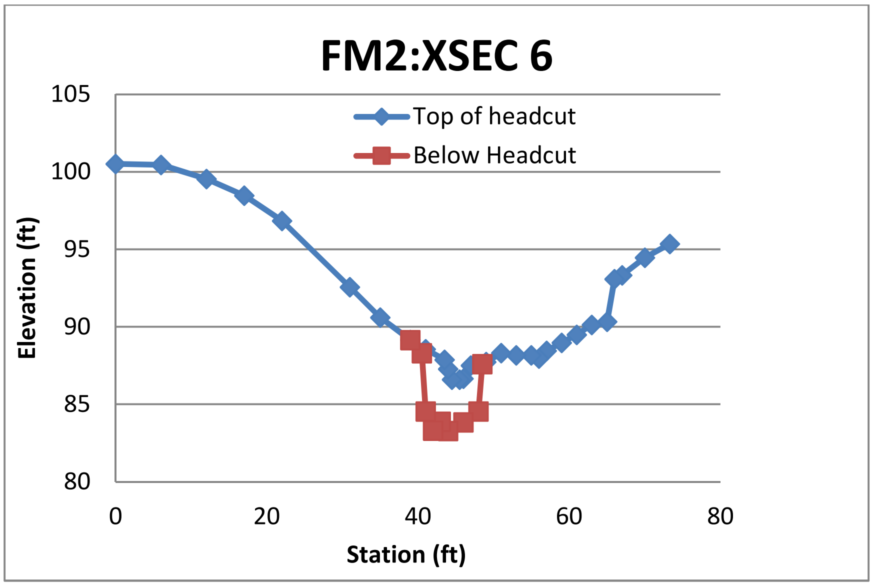


Figure B7. Cross-sectional survey and ground based photograph for site FM2 XSEC6.

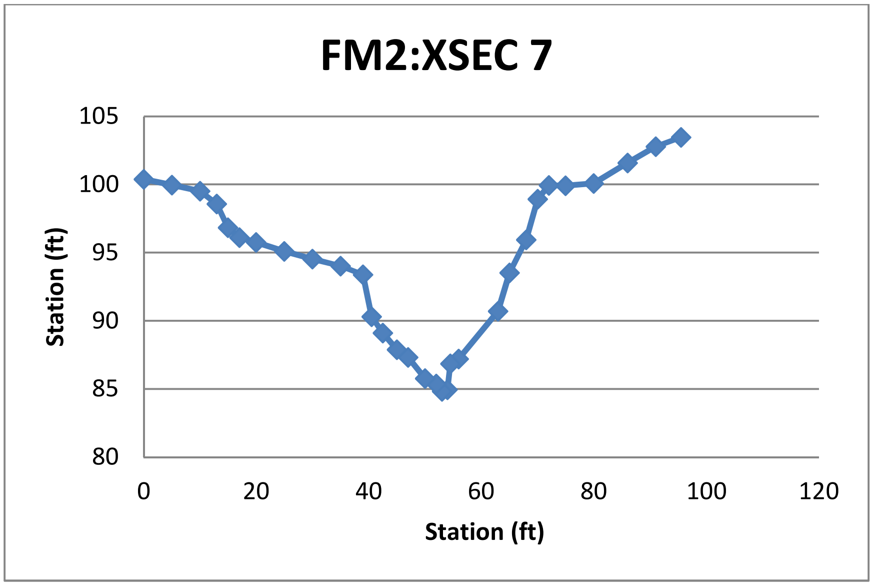


Figure B8. Cross-sectional survey and ground based photograph for site FM2 XSEC7.

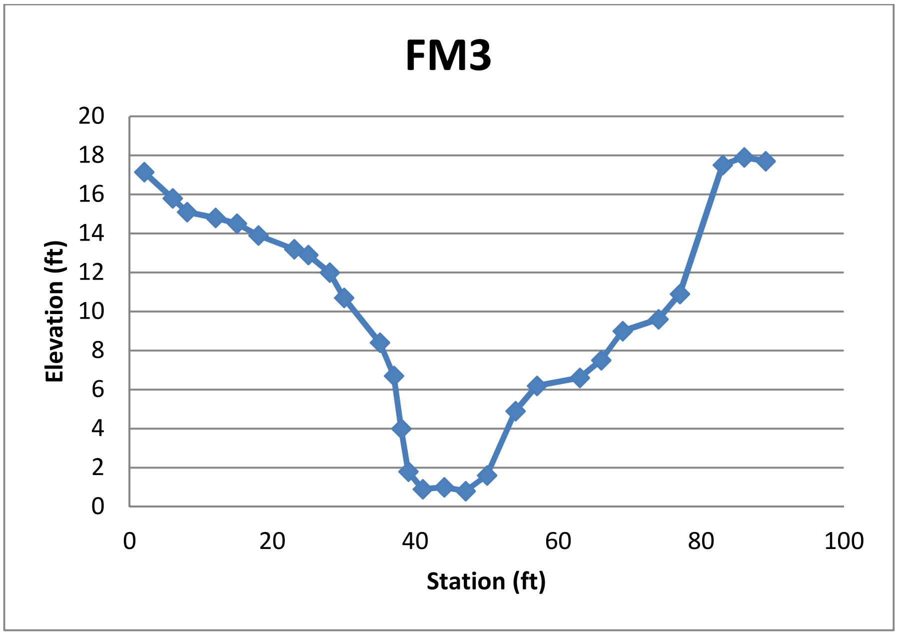


Figure B9. Cross-sectional survey and ground based photograph for site FM3.

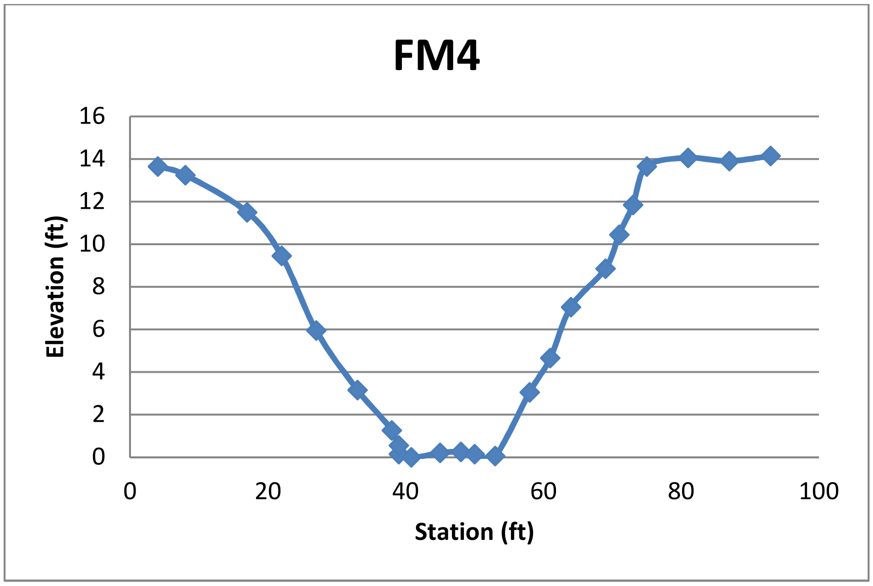


Figure B10. Cross-sectional survey and ground based photograph for site FM4.

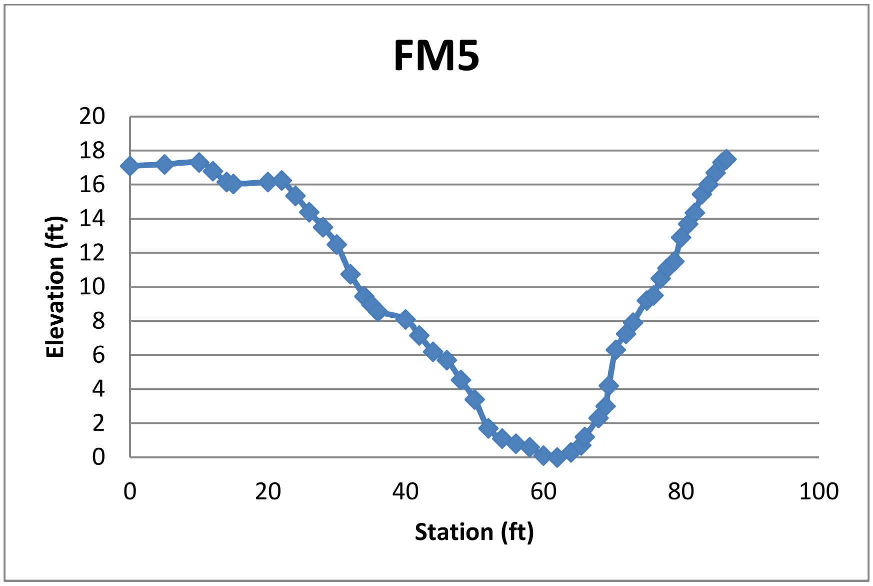


Figure B11. Cross-sectional survey and ground based photograph for site FM5.

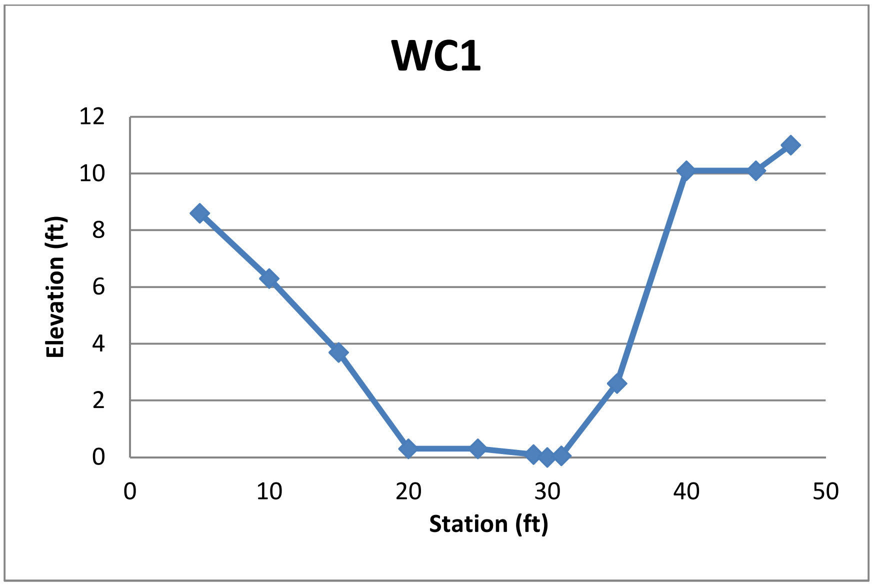


Figure B12. Cross-sectional survey and ground based photograph for site WC1.

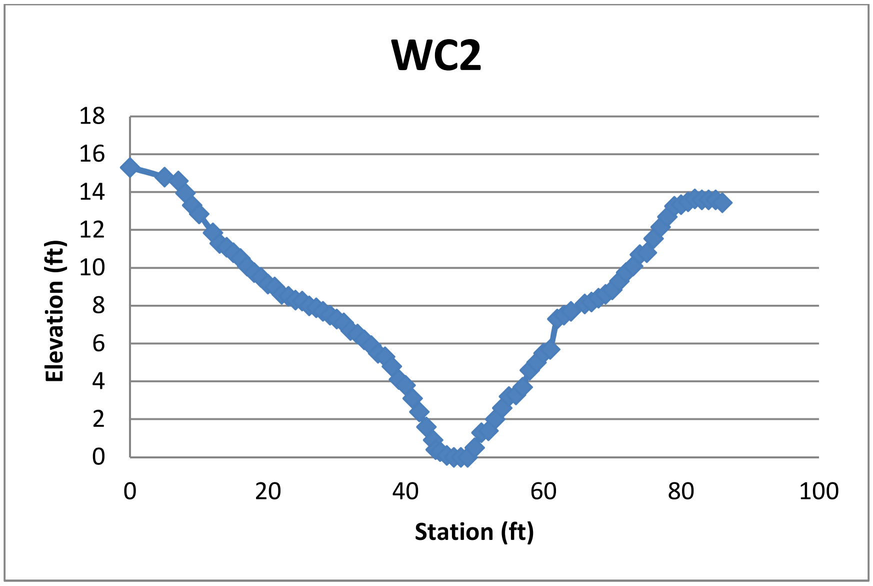


Figure B13. Cross-sectional survey and ground based photograph for site WC2.

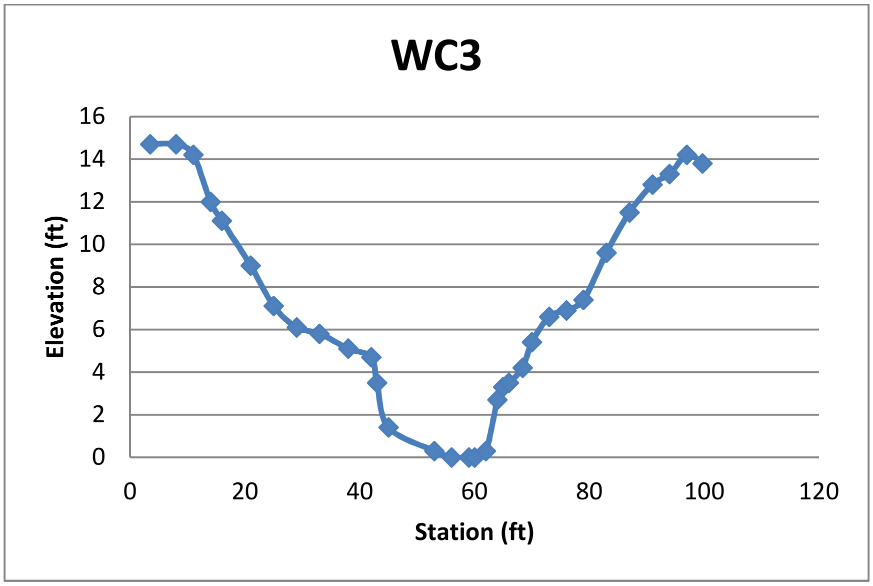


Figure B14. Cross-sectional survey and ground based photograph for site WC3.

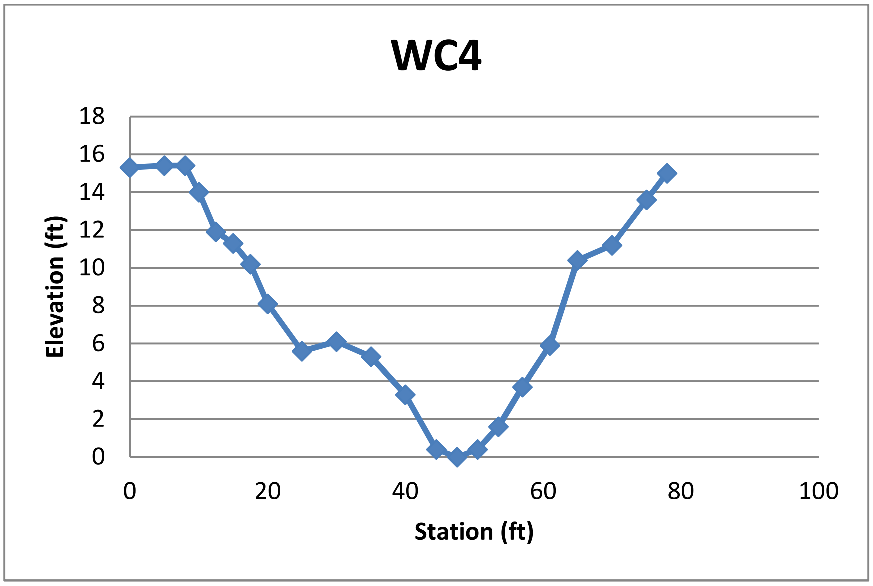


Figure B15. Cross-sectional survey and ground based photograph for site WC4.

APPENDIX C

COST ESTIMATION SPREADSHEET

Current Bank Slope	0.5	%	**Bank Excavation and Vegetation**	
Desired Bank Slope	0.3	%	**ENTER YOUR DATA IN YELLOW CELLS**	
Bank Height (ft)	14	ft		
Length of Bank (ft)	839	ft		
Number of Trees/sqft	1	number	Choose Excavation Equipment	
			loam,SandyClay, 1/2 Cyd excavator $4.55209759253915/bcy, 216 tons/	
Cubic Feet to be Removed	76357.9076	cuft		
Cubic Yards to be Removed	2828.1	cuyd	Choose Geotextile Type	2
			Geotextile Fabric,Woven, 200 lb. tensile strength	
Cost of Excavation/ cubic yard	$ 4.55			
Total Cost of Excavation	$12,873.64			1
Geotextile Soil Stabilaztion Total cost	$ 486.92		Select Height of Trees	
Square Feet of Vegetation Required	11452	sqft	Willow, Local Cut, Bare root seedlings, 3"-5" Height	
Cost of each Tree	$ 0.76			
Cost of Trees per square foot	$ 0.76			1
Cost of Fescue per square foot	$ 0.04		Select Fescue Planting Method	
			Fescue 5.5#/M.S.F., tall, Hydro or air seeding, with mulch and fertilzei	
Cost of Vegetation	$ 9,230.59			
				3
Total Construction Cost for Vegetated Bank	$22,591.15			
Surveying and Engineering Costs	$ 1,129.56			
Total Cost	$23,720.71			

Figure C1. Screenshot of cost estimation spreadsheet used to calculate cost of stabilization with vegetation and grading.

1	CROSS VANES						
2							
3	B3 Width of Stream or Channel		30.00	ft	Select Desired Angle of Cross Vane		
4	B4 Depth top bank - depth channel		6.46	ft	30 Degrees	6	
5	Bank Slope v/h		1			ENTER YOUR DATA IN YELLOW CELLS	
6	B6 '1/3 width left side		10.00	ft			
7	B7 1/3 center section		10.00	ft			
8	B8 1/3 width right side		10.00	ft			
9	B9 Width of Vane		5.00	ft			
10	B10 Thickness of Vane		4.00	ft			
11	Depth of Vane		4.00	ft	Choose Excavation Equipment		
12	B12 Key into Bank						
13	Depth of Key		5.00	ft	loam,SandyClay, 10' to 14' deep, 3/4 Cyd excavator w/ trench box $6.49357076537509/bcy,		
14	B14 Width of Key		5.00	ft			
15	Length of Key		10.06	ft			15
16	Excavation Bottom of Channel						
17	Total Length of Vane		50.00	ft	Select Type of Rip-Rap		
18	Volume Removed cuyd		37.04	cuy	Rip-Rap and Rock Lining, Random, broken stone, 300 lb. average,Material $ 27, In Place $30.3116048894308 / to		
19	Excavation for Key in bank						
20	Volume removed cuyd		18.63	cuyd	27	tons	6
21	Total Qt Excavated cuyd		55.67	cuyd			
22	Excavation Cost $/bcy	$	6.49				
23	Total Excavation Cost	$	601.99				
24	Material Cost						
25	Rip Rap cuyd		40.74	cuyd			
26	Rip Rap tons (2ton/cuyd)		81.48				
27	Cost unit (tons) RipRap	$	2.33				
28	Cost of Rip Rap	$	189.85				
29							
30	Total Construction Cost of Cross Vane	$	791.84				
31							
32	Surveying and Engineering Costs	$	39.59				
33							

Labels refer to cells in Column B

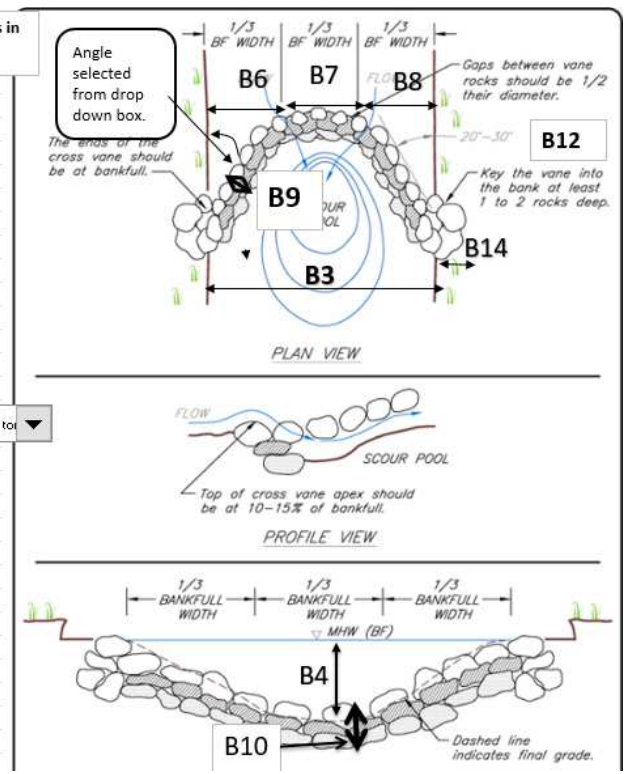
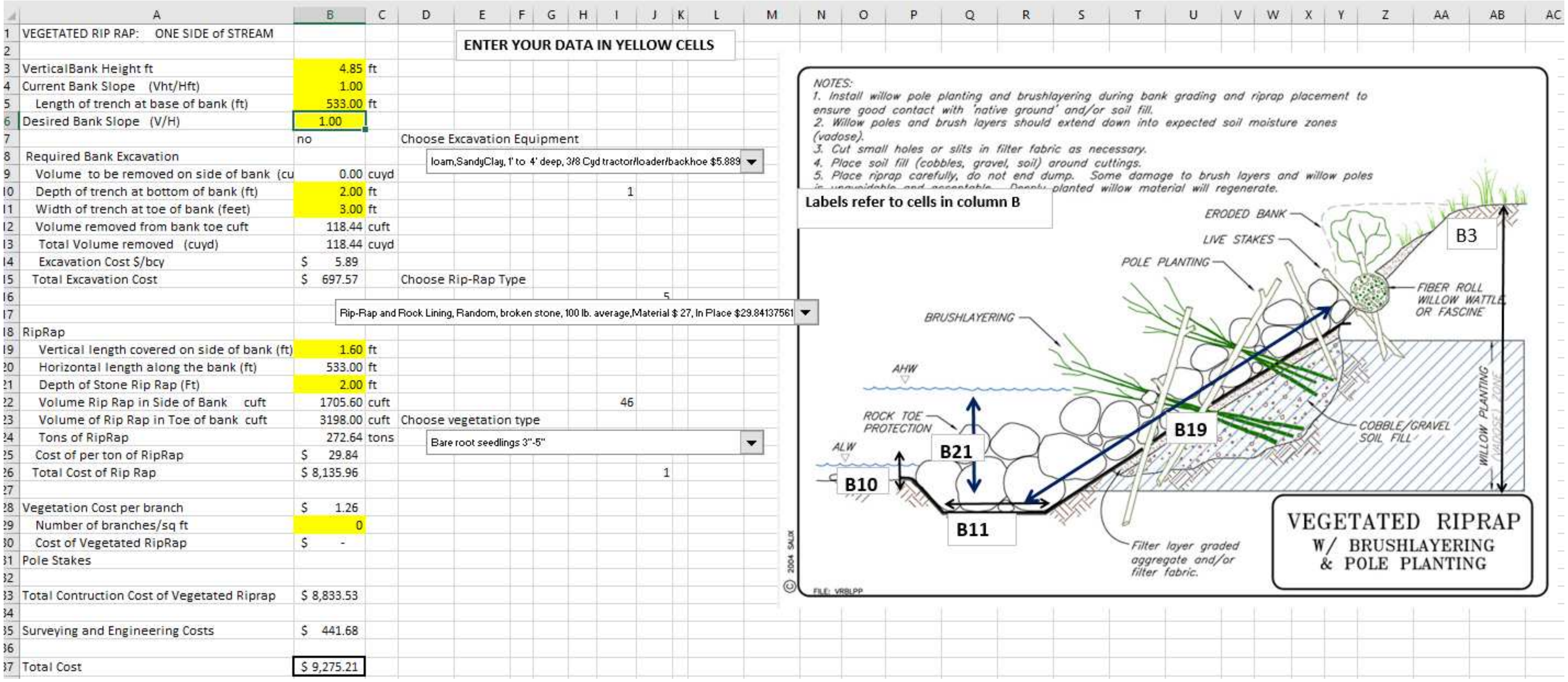


Figure C2. Screenshot of cost estimation spreadsheet used to calculate cost of grade control with cross vane.



	A	B	C
1	VEGETATED RIP RAP: ONE SIDE of STREAM		
2			
3	VerticalBank Height ft	4.85	ft
4	Current Bank Slope (Vht/Hft)	1.00	
5	Length of trench at base of bank (ft)	533.00	ft
6	Desired Bank Slope (V/H)	1.00	
7		no	
8	Required Bank Excavation		
9	Volume to be removed on side of bank (cu	0.00	cuyd
10	Depth of trench at bottom of bank (ft)	2.00	ft
11	Width of trench at toe of bank (feet)	3.00	ft
12	Volume removed from bank toe cuft	118.44	cuft
13	Total Volume removed (cuyd)	118.44	cuyd
14	Excavation Cost $/bcy	$ 5.89	
15	Total Excavation Cost	$ 697.57	
16			
17			
18	RipRap		
19	Vertical length covered on side of bank (ft)	1.60	ft
20	Horizontal length along the bank (ft)	533.00	ft
21	Depth of Stone Rip Rap (Ft)	2.00	ft
22	Volume Rip Rap in Side of Bank cuft	1705.60	cuft
23	Volume of Rip Rap in Toe of bank cuft	3198.00	cuft
24	Tons of RipRap	272.64	tons
25	Cost of per ton of RipRap	$ 29.84	
26	Total Cost of Rip Rap	$ 8,135.96	
27			
28	Vegetation Cost per branch	$ 1.26	
29	Number of branches/sq ft	0	
30	Cost of Vegetated RipRap	$ -	
31	Pole Stakes		
32			
33	Total Contruction Cost of Vegetated Riprap	$ 8,833.53	
34			
35	Surveying and Engineering Costs	$ 441.68	
36			
37	Total Cost	$ 9,275.21	

Figure C3. Screenshot of cost estimation spreadsheet used to calculate cost of bank stabilization with riprap toe.

APPENDIX D

COST AND SEDIMENT REDUCTION GRAPHS FROM METHODOLOGY DESCRIBED IN CHAPTER 4

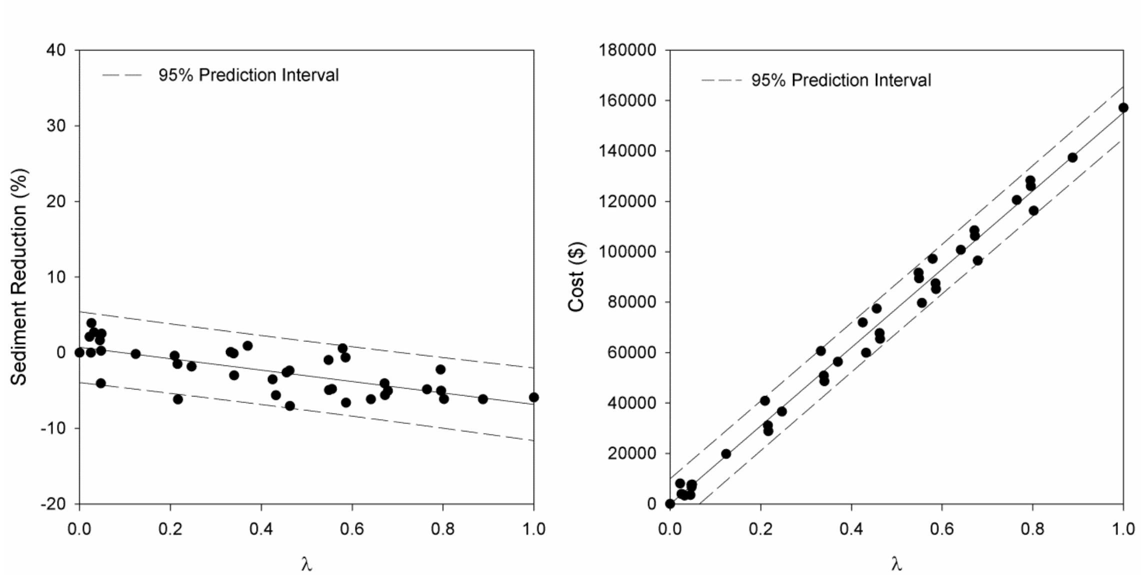


Figure D1. Sediment reduction and cost versus fraction of the stream stabilized (λ) for grade control (GC).

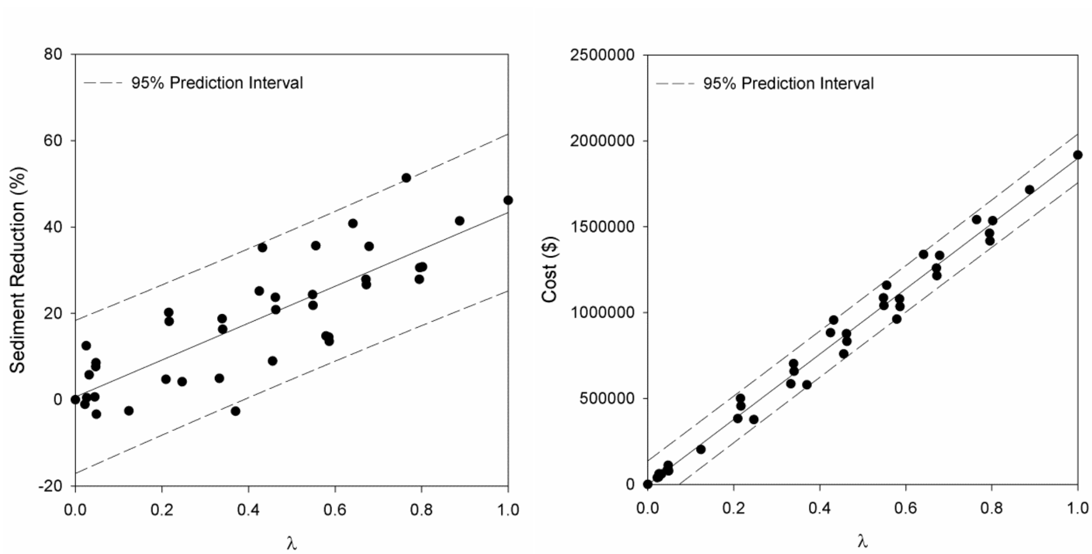


Figure D2. Sediment reduction and cost versus fraction of the stream stabilized (λ) for Riprap Toe (RRT).

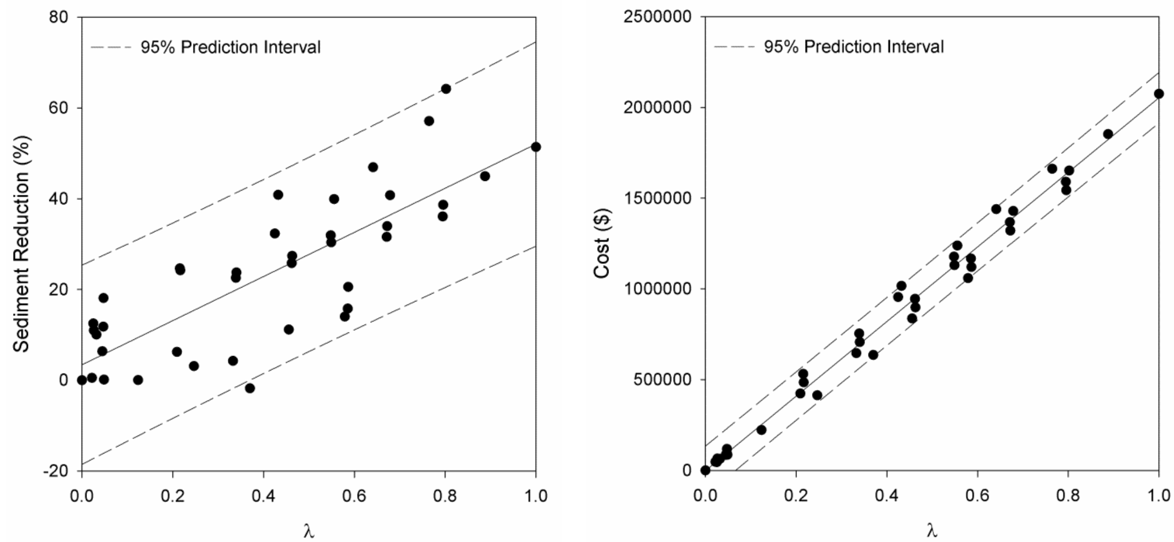


Figure D3. Sediment reduction and cost versus fraction of the stream stabilized (λ) for riprap toe with grade control (RRT+GC).

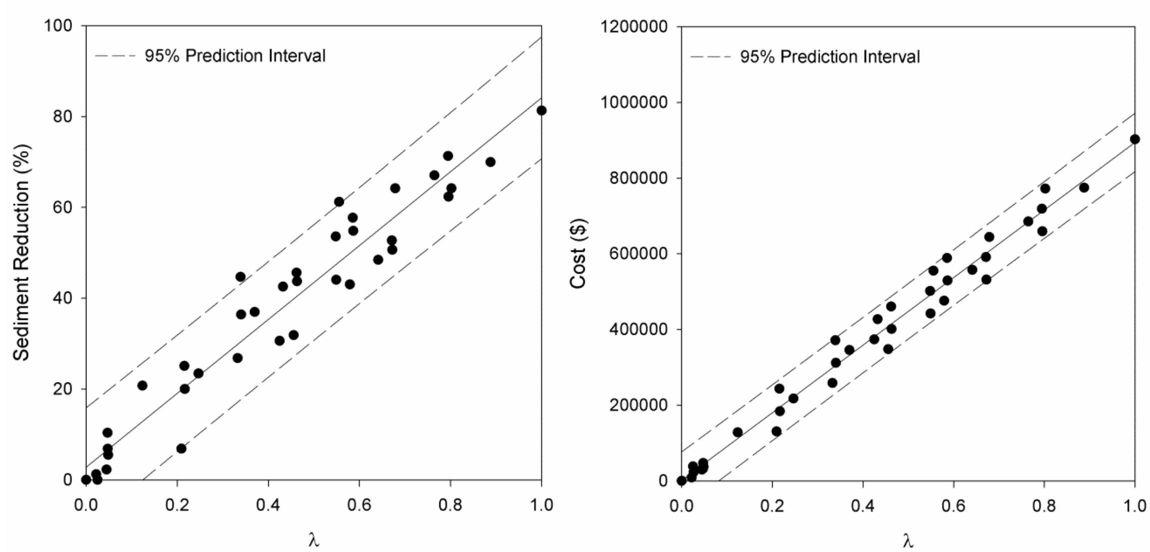


Figure D4. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetation with 2:1 banks slopes (VEG21).

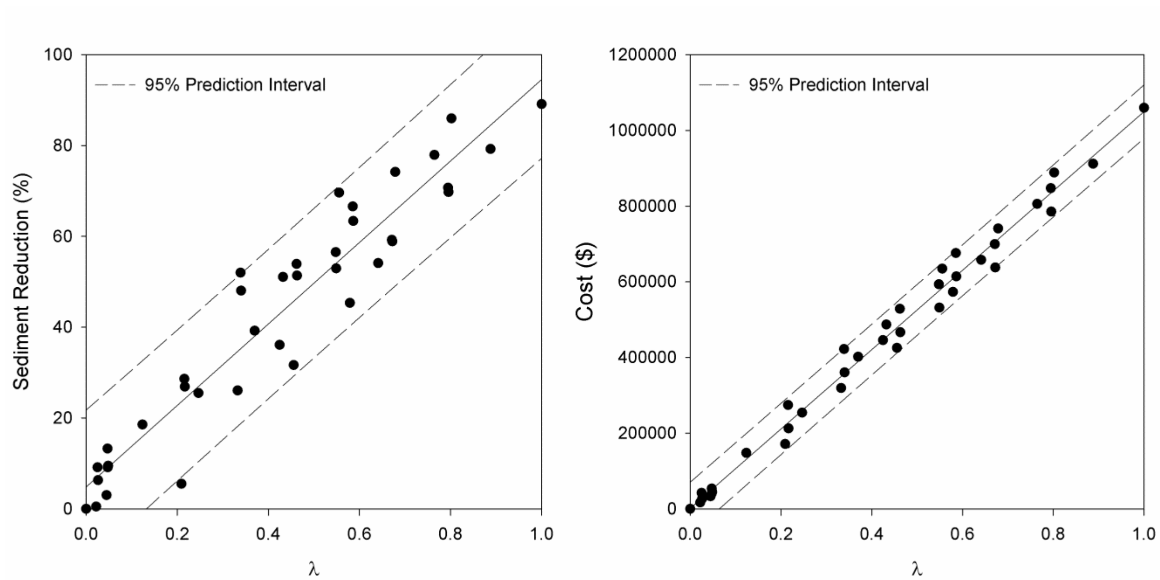


Figure D5. Sediment reduction and cost versus fraction of the stream stabilized (*λ*) for vegetation with 2:1 banks slopes and grade control (VEG21+GC).

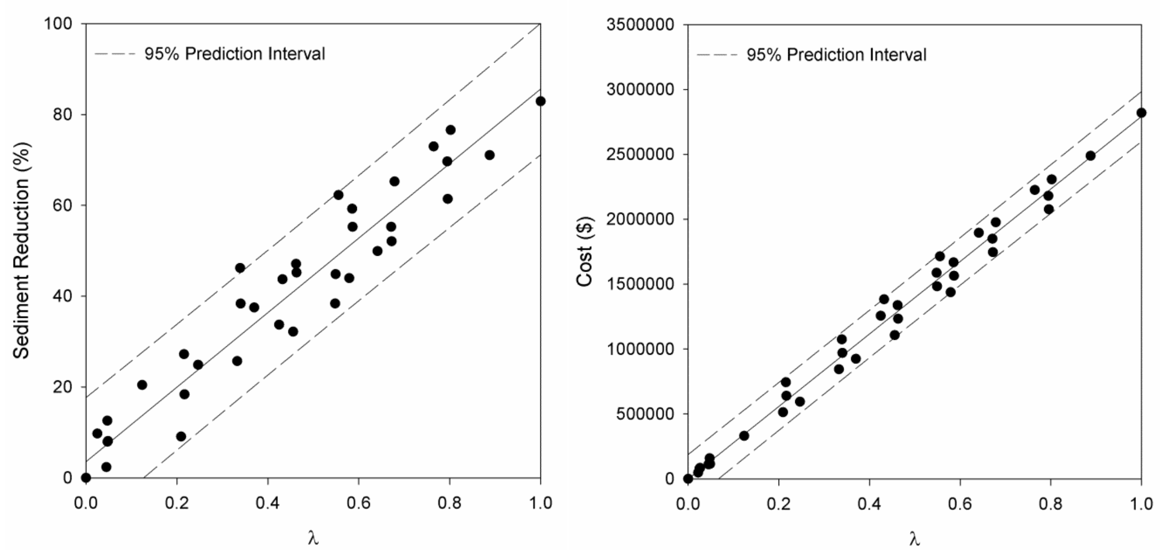


Figure D6. Sediment reduction and cost versus fraction of the stream stabilized (*λ*) for vegetation with 2:1 banks slopes with riprap toe (VEG21+RRT).

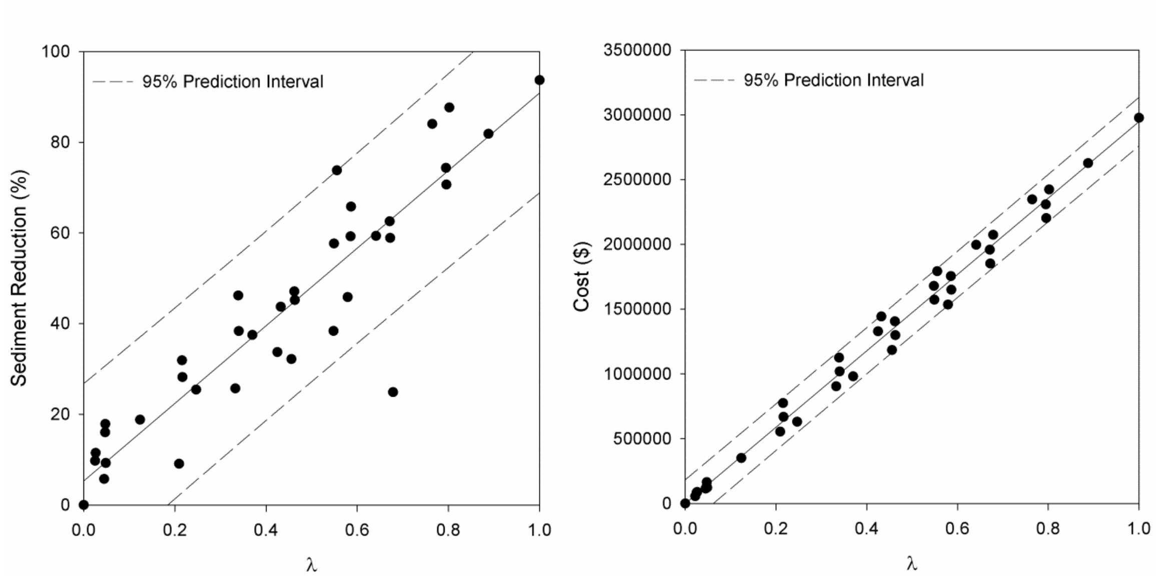


Figure D7. Sediment reduction and cost versus fraction of the stream stabilized (*λ*) for vegetation with 2:1 banks slopes, riprap toe and grade control (VEG21+RRT+GC).

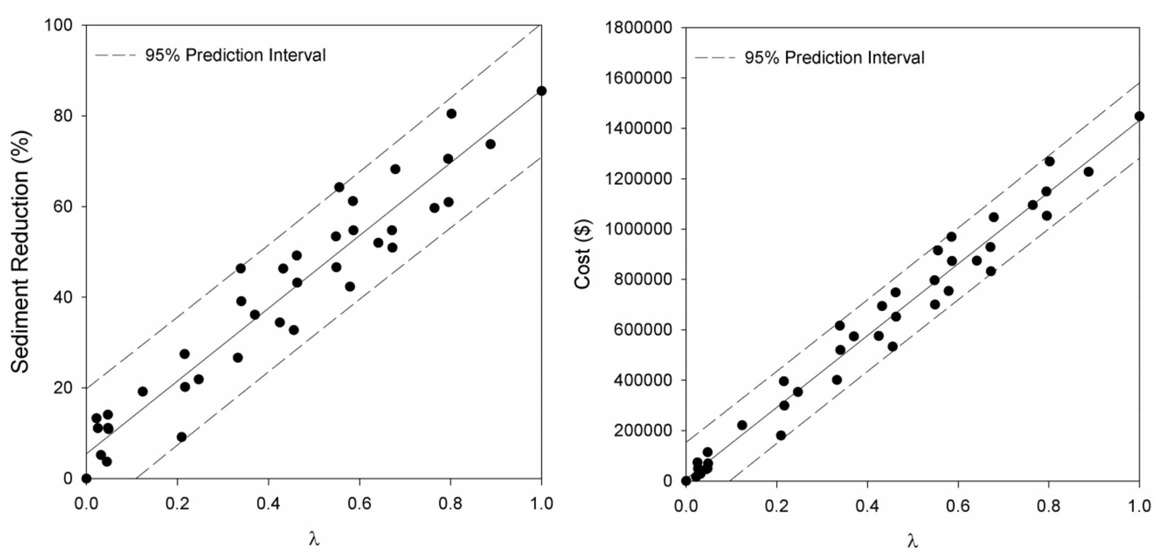


Figure D8. Sediment reduction and cost versus fraction of the stream stabilized (*λ*) for vegetation with 3:1 banks slopes (VEG31).

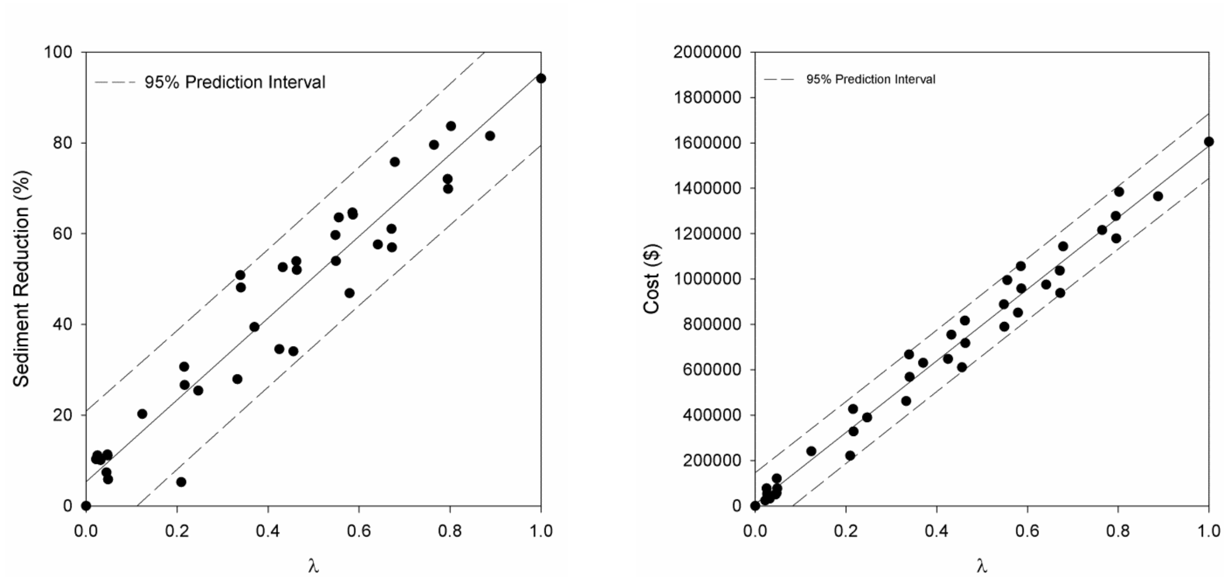


Figure D9. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetation with 3:1 banks slopes and grade control (VEG31+GC).

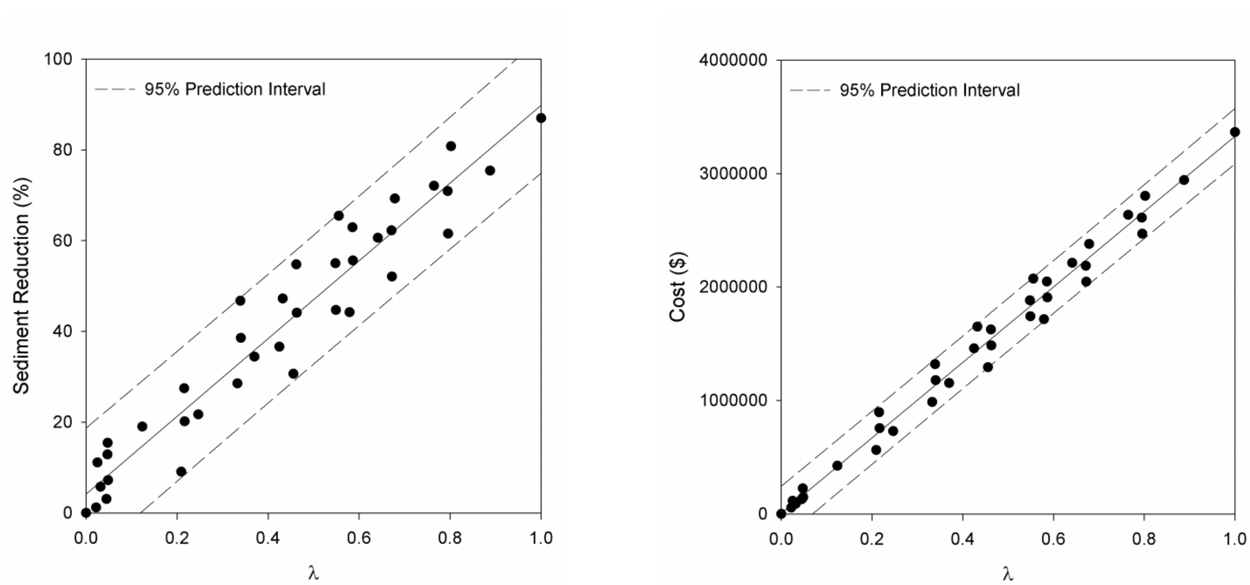


Figure D10. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetation with 2:1 banks slopes with riprap toe (VEG21+RRT).

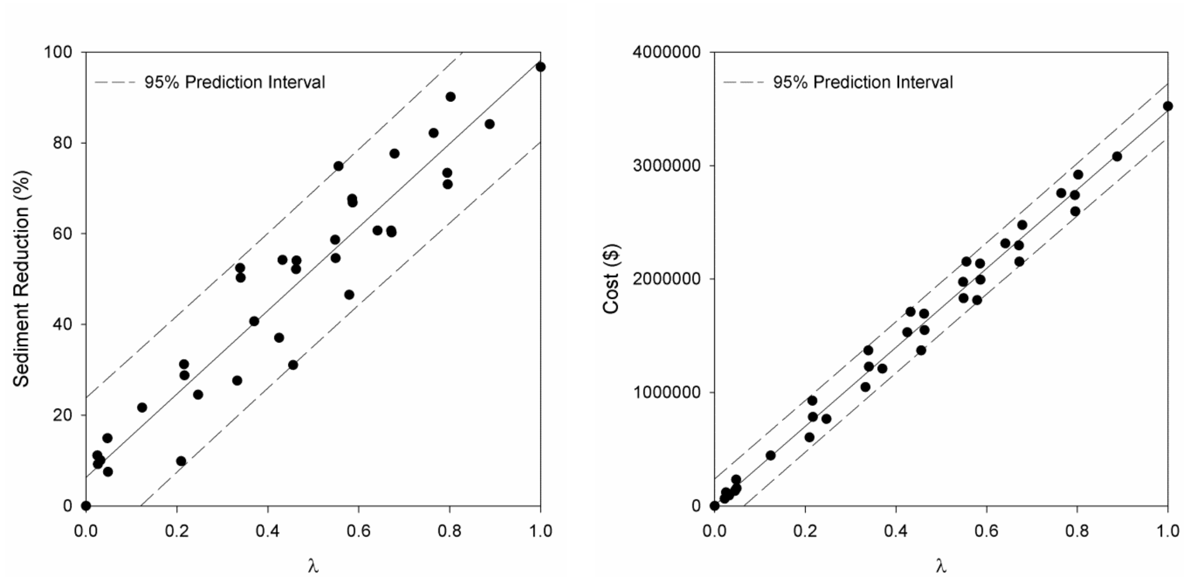


Figure D11. Sediment reduction and cost versus fraction of the stream stabilized (λ) for vegetation with 3:1 banks slopes, riprap toe and grade control (VEG31+RRT+GC).

VITA

Holly Kristina Enlow

Candidate for the Degree of

Doctor of Philosophy

Thesis: QUANTIFYING SEDIMENT LOADS FROM STREAMBANK EROSION AND POTENTIAL LOAD REDUCTIONS FROM STREAMBANK STABILIZATION USING PROCESS-BASED MODELING

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2010-2012: Undergraduate Research Assistant, University of Kentucky

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American Society of Civil Engineers
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