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The Relationships of Streambank Angles and Shapes to Streambank Erosion Rates in the Little River Watershed, TN

William Ryan Foster
University of Tennessee - Knoxville, wfoster@utk.edu

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To the Graduate Council:

I am submitting herewith a thesis written by William Ryan Foster entitled "The Relationships of Streambank Angles and Shapes to Streambank Erosion Rates in the Little River Watershed, TN." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Carol P. Harden, Major Professor

We have read this thesis and recommend its acceptance:

Liem Tran, Henri Grissino-Mayer

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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The Relationships of Streambank Angles and Shapes to Streambank Erosion Rates in the Little River Watershed, TN

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

William Ryan Foster
August 2010

Dedication

To my parents, R.D. and Donna Foster, for instilling in me an ethical code that will always guide me through life.

Acknowledgements

I would like to thank my advisor, Dr. Carol Harden, for sharing a bit of her wisdom over the last few years and for leading many enjoyable trips into the Little River watershed. I also thank my committee members, Dr. Liem Tran and Dr. John Schwartz for additional guidance. I thank Christopher Morris for his help in the field and Tim Green for making the maps of the Little River Watershed. Lastly, I want to extend my gratitude to Monica Rother for her tremendous support and her warm smile. Thank you.

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Abstract

Sediment is a leading cause of water quality impairment throughout the United States. In the Little River watershed in eastern Tennessee, several tributaries have been classified as impaired due primarily to sedimentation. Researchers at The University of Tennessee, in collaboration with a group of local and state organizations, began monitoring Little River tributaries to better understand their sources of pollution. To investigate the rates and processes of streambank erosion, erosion-pin monitoring sites were established on 32 banks in the watershed. This thesis complements the erosion-pin monitoring efforts by determining morphological bank characteristics and examining the relationships of streambank angles and shapes to observed erosion rates. The specific objectives of this study were to: (1) characterize streambank angles, (2) describe the relationships between streambank angles and bank erosion rates, (3) characterize bank shape, and (4) determine if bank shapes at erosion-pin monitoring sites are representative of their immediate stream reaches.

Streambank angles were measured at erosion pins. Bank angles averaged approximately 55° and varied significantly between tributaries and individual monitoring sites. Bank angle measurements were compared to erosion-pin exposure using correlation analysis. Data were then sorted into subgroups by pin position, soil texture, and bank shape, and further analyses were conducted. Results indicated streambank erosion was significantly, positively associated with bank angle for angles $\geq 30°$. Significant, positive relationships were also found low on banks, where soil texture was clay, and where banks were classified as undercut.

Bank profiles were documented to classify the bank shapes of erosion-pin monitoring sites and assess how well the banks at those sites represented the immediate reach. In the Little River watershed, bank profile shapes vary, but nearly three-fourths of all documented bank profiles were steeply sloping or undercut. The majority of monitoring sites (78%) were representative of the immediate stream reach with regard to bank shape. However, other factors, including surrounding land use and soil type, may differ within the immediate reach. Thus, data extrapolation from erosion pins to the reach scale should be done cautiously and take into consideration variability of individual site characteristics.

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Chapter One

1. Introduction

1.1 Background and Justification

Sediment is a leading cause of water quality impairment in Tennessee (USEPA 2005a; TDEC 2006), as well as throughout the United States (Oschwald 1972; USEPA 1990). Excessive instream sediment is detrimental to the diversity and abundance of aquatic organisms (Burkhead *et al.* 1997; Freeman and Schorr 2004). Additional concerns include the filling of reservoirs (Clark *et al.* 1985; Crowder 1987; Denton *et al.* 2000; Juracek 2006), increased costs of water treatment (Forster *et al.* 1987; Holmes 1988; Dearmont *et al*. 1998), and the transport of bacteria, pesticides and other contaminants (Pimentel *et al.* 1980; Stone *et al.* 1995). The U.S. Clean Water Act requires states to improve watershed conditions where impaired streams flow, but these efforts require a better understanding of sediment sources and processes.

The University of Tennessee (UT), in cooperation with the Blount County Soil Conservation District, the Tennessee Valley Authority (TVA), and the Tennessee Department of Environment and Conservation (TDEC), is currently monitoring the Little River watershed as part of a U.S. Environmental Protection Agency Targeted Watershed Initiative. The Initiative's goal is to improve water quality in the Little River and its tributaries. Monitoring activities include the following: total suspended solids in storm-flow (TVA), particle size (UT-Harden), discharge (UT-Harden), aquatic habitat assessment (TDEC and UT-Harden), pathogens (UT-Layton), water quality (UT-Harden and Layton), and streambank erosion rates (UT-Harden).

This thesis complements the Targeted Watershed Initiative by evaluating the relationship of certain physical streambank characteristics to the amount of soil loss measured from erosion pins placed on banks of Little River tributaries. The primary goals of this research are to characterize bank angles and shapes, and to investigate the relationship of these physical characteristics to streambank erosion. While previous studies in other locations have measured erosion by using pins inserted into streambanks (Wolman 1959; Hooke 1979; Stott 1997; Couper and Maddock 2001), few or no studies examine the relationships between bank angle at erosion pins, bank shape, and erosion rates.

1.2 Erosion and Sediment

Sediment is delivered to streams by way of erosion. Erosion is the removal of particles from the landscape by agents such as wind, water and ice (Pidwirny 2006). Particles are detached, entrained and transported by these agents until they settle out and are deposited on a surface (Gordon *et al.* 2004; Pidwirny 2006). Sediment is considered a form of non-point source pollution (Karr and Schlosser 1977), meaning that its source is not easily identifiable. Erosion can occur on uplands, or streambanks themselves may erode as channels widen or move laterally across a watershed. Although sediment is a natural part of stream systems, increased amounts of fine inorganic particles found in flowing water or deposited on the streambed can be detrimental to aquatic life (Waters 1995).

1.2.1 Streambank Erosion

The size, geometry and structure of streambanks, along with the properties of the bank material, the hydraulics of flow in the channel, and climatic conditions, all play a role in determining the erodibility of streambanks (Thorne and Tovey 1981). Streambank erosion occurs by a combination of three processes: subaerial processes, fluvial entrainment, and mass wasting (Lawler 1995). Subaerial processes, such as wet-dry or freeze-thaw cycling at or near the bank surface, weaken streambank soils. This weakening may force bank materials from the bank, or act as a preparatory process making them more vulnerable to fluvial entrainment (Thorne and Tovey 1981). Fluvial entrainment is the direct removal of soil from the bank face by flowing water and is dependent on the properties of streambank materials and of the eroding fluid (Grissinger 1982). Mass wasting, or bank failure, occurs when the weight of the bank exceeds the shear strength of the bank materials. Downward moving gravitational forces and the resistant forces of friction and cohesion are the controlling factors of mass failure. Failures occur when bank heights are increased due to scouring of the bank toe, or when undercutting increases bank angles (ASCE 2008).

Bank erosion is highly variable over spatial and temporal scales and is largely dependent on the cohesiveness of bank materials (Thorne 1981). *In-situ* measurements of bank retreat are necessary for detailed erosion data analysis. Bank erosion influences channel width, and thus fluvial system adjustments, and can also contribute large amounts of sediment to the stream load (Thorne 1981). The natural occurrence of streambank erosion is commonplace, however anthropogenic activities, such as land-use change, serve to enhance its rate and distribution (Waters 1995).

1.3 Land Use and Sediment

Euro-Americans have altered the landscape to meet the needs of a growing industrialized culture. Agriculture, forestry, mining, and urban development have substantially increased the amount of sediment entering our nation's streams (Wilson 1902; Waters 1995; Walling 1999; Wang *et al.* 2002). For example, U.S. Secretary of Agriculture James Wilson, reported in the early 20th century that unrestrained clearing of vegetation on mountainous terrain by loggers was leading to extensive sedimentation in southern Appalachian streams (Wilson 1902). Meade (1969) later estimated that by the 1960s sedimentation rates of Atlantic slope rivers were four to five times higher than rates before Euro-American settlement.

The relationship between land-use changes and increased sediment has also been recognized in the Little River watershed. Several UT theses observed how land use has affected water quality (Sutherland 2004; Hart 2006; Burley 2008). Sutherland (2004) examined the relationship between nonpoint source pollution (including sediments and nutrients) and aquatic diversity in two subwatersheds of the Little River. She concluded, in part, that poor streambank conditions and poor benthic habitats were correlated, which implies that land use can, to some extent, be responsible for impaired water quality. Hart (2006) reported that drainage areas that consisted of a forested land cover had lower concentrations of total suspended solids (TSS) than drainage areas classified as either agricultural or urban. Hart found that the situation was worsening, as TSS concentrations in the Little River watershed almost doubled between 2000 and 2004. Burley (2008) explored the relationship between land cover and water quality and found that degraded water quality occurred where land cover is most anthropogenically influenced. This relationship was especially strong in the urbanized subwatershed of Pistol Creek. Together these complementary theses indicate that land use can be a predictor of water quality throughout the Little River watershed.

1.4 Consequences of Excessive Sediment

1.4.1 Imperiled Aquatic Organisms

Increased bank erosion and excessive stream-borne sediment may degrade habitat for aquatic organisms (Burkhead *et al.* 1997; Freeman and Schorr 2004). When the amount of instream sediment exceeds the amount that can be moved through the system, stream bottom substrates become covered, or embedded. Interstitial spaces are then filled and habitat is decreased (Waters 1995). This process impacts benthic macroinvertebrates, as the coarser particles that provide their habitat are covered by finer particles (Burkhead *et al.* 1997). Kaller and Hartman (2004) examined the relationship between fine sediment accumulation and the diversity of three benthic macroinvertebrate species. Although these processes are not fully understood, they found that, in seven Appalachian streams, the diversity of these species decreased during drought when fine sediments exceeded 0.8-0.9% of substrate accumulations.

In addition to reducing the amount of suitable space in which aquatic organisms live, streambank erosion can limit food availability. Benthic macroinvertebrates feed on litter from riparian vegetation, and as the amount of vegetation decreases, food shortages can occur (Barbour *et al.* 1999). Benthic macroinvertebrates also feed on periphyton, which are sessile organisms such as algae and small crustaceans that live attached to surfaces projecting from the bottom of a freshwater aquatic environment. Bank erosion, resulting in excessive sediments to the stream channel, reduces the abundance of periphyton by covering them in a layer of fine sediment (Barbour *et al.* 1999). These changes may affect higher trophic levels by limiting the amount of prey available to fish (Allan 1995; Waters 1995; Burkhead *et al.* 1997).

1.4.2 Costs of Soil Erosion

Soil erosion from fluvial processes has been estimated to cost over $7 billion per year in the United States (Pimentel *et al.* 1995). When all sources of sediment are considered, costs may exceed $16 billion (Osterkamp *et al.* 1998). There are several reasons why sediment can be costly, including associated water treatment costs (Forster *et al.* 1987; Holmes 1988; Dearmont *et al.* 1998). Eroded particles can act as a conveyor of sediment-sorbed contaminants such as nutrients from agricultural fertilizers, pesticides, and heavy metals, which must later be removed through water treatment processes (Pimentel *et al.* 1980; Knezovich and Harrison 1987). Dearmont *et al.* (1998) found that, in Texan cities, high sediment loads caused raw surface water to require substantially more chemical treatment than uncontaminated water. Sediment may also reduce reservoir storage capacity (Clark *et al.* 1985; Crowder 1987; Denton *et al.* 2000; Juracek 2006; TDEC 2006). As reservoirs become filled with fine sediment, water depth decreases, and dredging may be required to restore functionality. Similarly, sediment may fill waterways and reduce the ability to transport goods via commercial navigation (Clark *et al.* 1985; TDEC 2006). Another cost associated with soil erosion is the reduction of land used for agricultural purposes. Specifically, streambank erosion may cause channel widening and thereby encroach on surrounding agricultural land (Hooke 1979).

1.5 Research Objectives

I conducted this thesis research to build upon the existing knowledge base of streambank erosion in the Little River watershed. To do this I investigated bank angles and shapes on five tributaries throughout the watershed. This research tested the hypotheses that erosion pins should display higher rates of erosion when located on steeper-angled bank segments, and that certain bank shapes (*e.g.* undercut) are more associated with higher erosion rates than other shapes (*e.g.* gently sloping). This research also related certain channel factors such as bank shape, soil texture, and height on the bank to erosion rates. In addition, I compared the characteristics of erosion-pin monitoring sites to those of a broader stream area to determine if monitoring sites are representative, thus evaluating if erosion-pin data can be extrapolated. This research is important because of its potential to inform management decisions regarding land use, sediment sources, and stream channel rehabilitation. Specific objectives and related questions are as follows:

1. Characterize bank angles.

    Q. What are the average bank angles at the monitoring sites?

    Q. Do bank angles vary by height on the bank (pin position)?

    Q. Do bank angles vary by stream and/or by site?

2. Characterize the relationship between bank angles and pin exposure.

Q. Does a greater bank angle correlate with greater pin exposure?

Q. Is this relationship affected by pin position, soil texture, and/or bank shape?

3. Characterize bank shape.

Q. What bank shapes are found in the study reaches?

4. Determine if bank shapes at monitoring sites are representative of the immediate stream reach.

Q. How do bank shapes at erosion-pin monitoring sites compare to bank shapes in the immediate stream reach?

1.6 Organization of Thesis

This thesis is divided into five chapters. The first chapter justifies my research and places it in the larger context of the Little River Targeted Watershed Initiative. It also gives an overview of the relevant literature and presents the primary research questions and objectives. Chapter Two describes the study area and gives detailed descriptions of the included tributaries. The field and statistical methods are explained in Chapter Three, while the fourth chapter presents the results of the study. Finally, in Chapter Five, I discuss the results, present major conclusions, and suggest possible directions for future research.

Chapter Two

2. Study Area

2.1 General Setting

The Little River watershed (HUC 06010201) drains 98,000 ha of East Tennessee in Blount, Knox, and Sevier Counties (Figure 2.1). Most of the basin is in Blount County (70,200 ha), and it includes the cities of Townsend, Maryville and Alcoa. The Little River originates in Great Smoky Mountains National Park (GSMNP) on the north slope of Clingmans Dome, the highest point in Tennessee and the third highest peak in eastern North America. It then flows 96 km northwestward through both agricultural and urban areas until it reaches Fort Loudoun Reservoir, an impoundment of the Tennessee River. The Little River is a perennial stream that supports several federally and state protected species (USEPA 2005b), is used for recreational purposes, and supplies drinking water to over 100,000 residents. The Tennessee Department of Environment and Conservation (TDEC) designates the portion of the Little River in GSMNP as a Blue Ridge ecoregion reference site, and uses it as a benchmark for assessing stream health in that region (TDEC 2006).

2.2 Physiography, Geology, and Vegetation

The Little River watershed is located in an area of wide-ranging environmental resources. The watershed extends across two Level III ecoregions: the Blue Ridge (ecoregion 66) and the Ridge and Valley (ecoregion 67). Elevations in the watershed

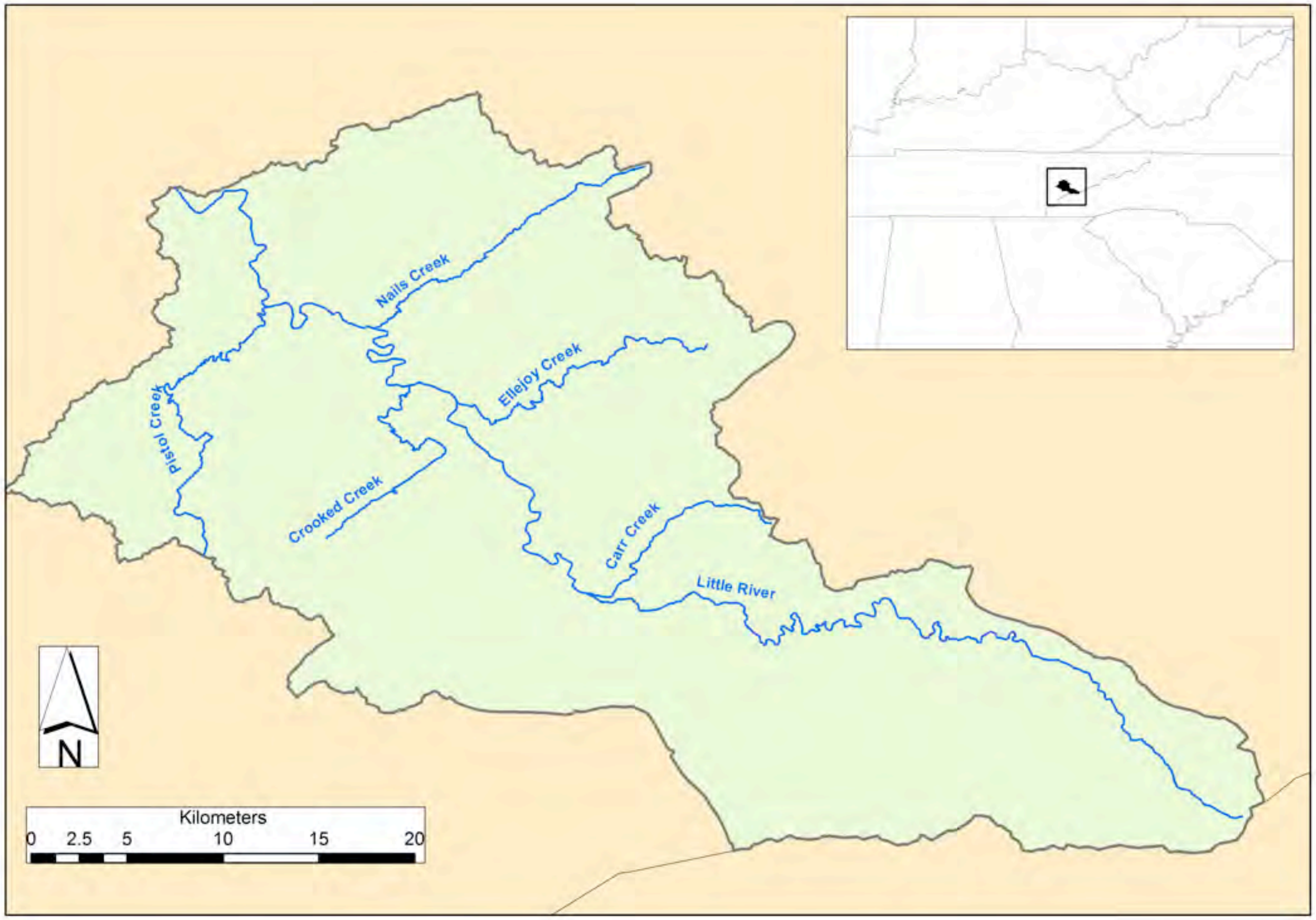

Figure 2.1 The Little River watershed.

range from approximately 250 m above sea level at the Little River's mouth to over 2000 m at its headwaters near Clingmans Dome.

The Blue Ridge Mountains are one of the most biologically diverse ecosystems in the eastern United States (TDEC 2000) and the most floristically diverse in Tennessee (Griffith *et al.* 1997). As part of the Appalachian Mountain range, these mountains are among the oldest in the world. The Appalachian range was created by the tectonic collision of the landmasses now known as Africa and North America during the formation of the supercontinent Pangaea approximately 300 million years ago (Abramson and Haskell 2006). This intense geologic event caused folding and faulting of once horizontal sedimentary rocks, which formed the dramatic relief we see today.

The Ridge and Valley ecoregion is relatively low in elevation and is situated between the Blue Ridge Mountains and the Cumberland Plateau. This region is characterized by alternating ridges and valleys that run in a southwest-northeast direction. Due to extreme folding and faulting, the ridges and valleys vary in width, height, and geologic composition. The geology includes limestone, dolomite, shale, siltstone, sandstone, chert, mudstone, and marble. The karst topography commonly found in this region is a product of soluble limestone and dolomite, which weathers to create the area's many sinkholes and caves. The Ridge and Valley ecoregion has high aquatic habitat diversity despite the impoundments on the Tennessee River and its major tributaries (Griffith *et al.* 1997).

Within the two Level III ecoregions found in the Little River watershed there are eight Level IV subecoregions (Figure 2.2). The Southern Sedimentary Ridges (66e), the Limestone Valleys and Coves (66f), the Southern Metasedimentary Mountains (66g), and

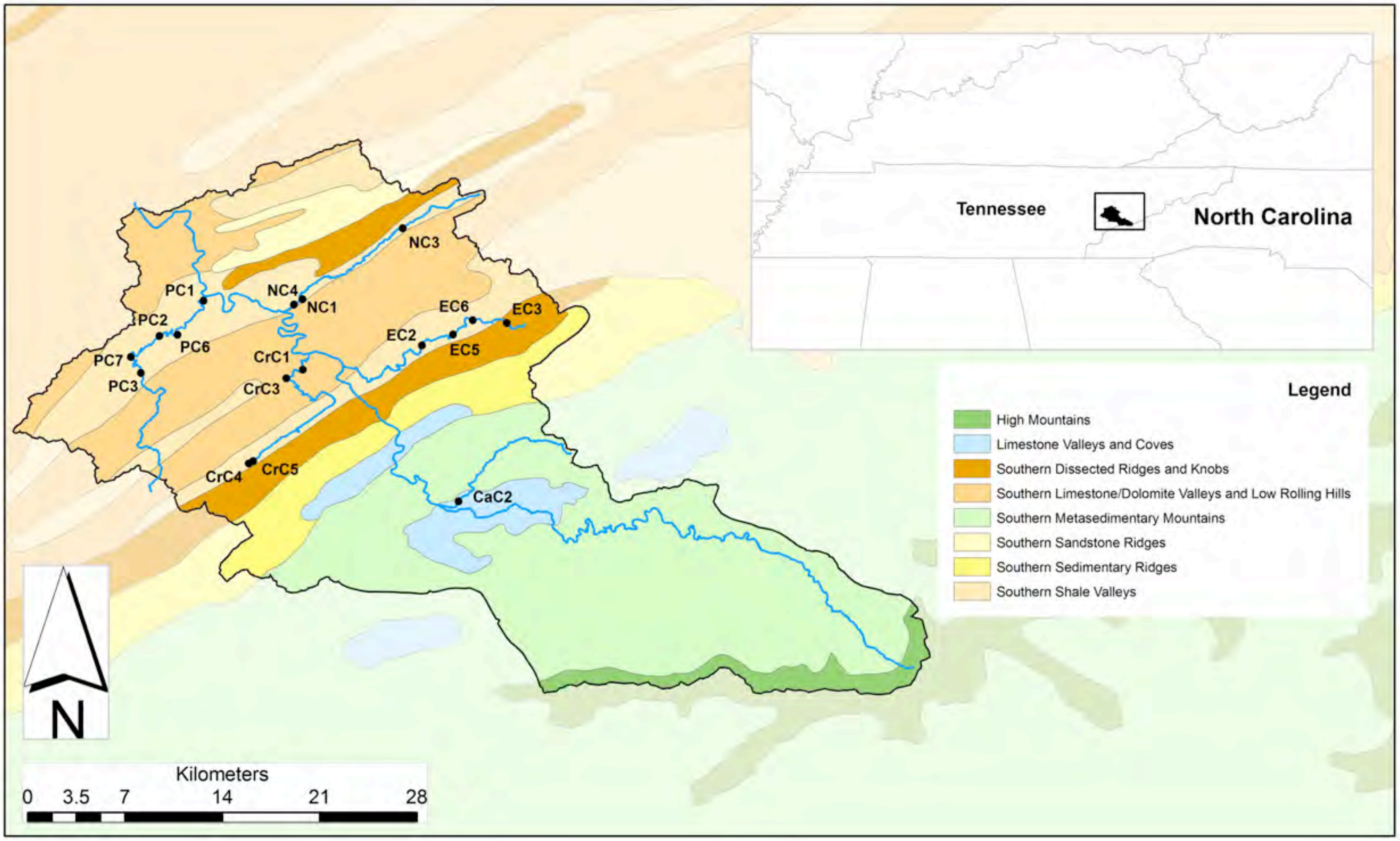

Figure 2.2 Level IV Ecoregions in the Little River watershed.

the High Mountains (66i) all belong to the Blue Ridge ecoregion. The Ridge and Valley ecoregion consists of the Southern Limestone/Dolomite Valleys and Low Rolling Hills (67f), the Southern Shale Valleys (67g), the Southern Sandstone Ridges (67h), and the Southern Dissected Ridges and Knobs (67i) subecoregions.

The Southern Sedimentary Ridges (66e) include some of the foothills of the Blue Ridge Mountains with steep slopes as high as 1,300 m. The geology is composed mostly of Cambrian-age sedimentary rocks, although some lower elevation streams cut through limestone. Common vegetation is mostly mixed oak and oak-pine forests. The Limestone Valleys and Coves (66f) are lowland areas of the Blue Ridge. In areas such as Cades Cove in GSMNP, geologic windows have formed, as older rocks, which were forced up and over younger rocks, erode away. The Southern Metasedimentary Mountains (66g) and the High Mountains (66i) are located along the eastern border of Tennessee and include the highest peaks of the Smoky Mountains. The geology of these ecoregions is composed primarily of Precambrian-age metamorphic and sedimentary materials. Appalachian oak and northern hardwood forests of the area include a variety of oaks (*Quercus*) and pines (*Pinus*) as well as hemlocks (*Tsuga*), yellow poplars (*Liriodendron*), birch (*Betula*) and beech (*Fagus*). Above 1,600 m, in ecoregion 66i, Evergreen red spruce (*Picea rubens)* and Fraser fir (*Abies fraseri)* forests are common. Acid rain and invasive pests such as the balsalm woolly adelgid (*Adelges piceae*) have adversely affected these high elevation spruce-fir forest ecosystems (Griffith *et al*. 1997).

The Southern Limestone/Dolomite Valleys and Low Rolling Hills (67f) are composed primarily of limestone and cherty dolomite. The nearly parallel rolling hills and valleys are characteristic landforms. Common forest types are white oak (*Quercus* *alba*), bottomland oak (*Quercus spp*.), and riparian forests consisting of sycamore (*Platanus occidentalis*), ash (*Fraxinus*), and elm (*Ulmus*) (Griffith *et al.* 1997). Cedar barrens dominated by native perennial grasses with scattered red cedar trees (*Juniperus virginiana*) are also found in this ecoregion. The Southern Shale Valleys (67g) are composed of lowlands, rolling hills and valleys, and slopes. Cambrian-age shales containing narrow bands of limestone underlie this area. The Southern Sandstone Ridges (67h) not only contains the sandstone ridges, but also include some areas of shale and siltstone. Due to highly acidic soils, pine forests are dominant on these steep, smooth ridges. The Southern Dissected Ridges and Knobs ecoregion (67i) contains broken ridges, unlike the smooth sandstone ridges of ecoregion 67h. Geologic materials include calcareous shale, limestone, siltstone, sandstone, and conglomerate. Oak-pine forests are common at higher elevations, whereas mixed mesophytic forests are found on the lower portions.

2.3 Soils

In the Little River watershed, soils consist of deep, well-drained Inceptisols. These soils are developed from residuum parent material and are found in cool to very warm, humid and sub-humid regions (USDA 1959). There are five USDA soil groups represented at the five tributaries included in this study. They are the Ramsey-Rock Outcrop-Barbourville group (silty loam), the Cumberland-Etowah-Talbott group (sandy loam), the Decatur-Dewey-Emory group (sandy loam), the Dandridge-Linside-Sequoia group (silt loam), and the Litz-Sequoia-Fullerton group (silt loam-silty clay) (NRCS 2007).

Morris (2008) found that the majority (59%) of streambank materials at Little River bank erosion monitoring sites were composed of clay rich, moderately fine and fine-textured soils (Appendix A). These findings differed from the available National Resource Conservation Service (NRCS) soil survey maps. In general, streambanks usually consist of coarser materials, while finer particles are deposited on the floodplain (Gordon *et al.* 2004). Morris suggests that one possible explanation for the discrepancy could be channelization, or the physical relocation of stream channels by humans. He explains that another cause might be increased influxes of fine sediment due to widespread deforestation. Finally, this discrepancy could be due to a difference in soil sampling methods. Morris sampled from points on streambanks, whereas NRCS soil survey maps were based on a combination of aerial photos and spatially distributed soil samples. This variation should be noted by anyone studying streambanks in the Little River watershed, as *in situ* samples may be a better indicator of soil type than the more often used NRCS soil survey maps.

2.4 Climate

The Southeastern United States is characterized by a Köppen *Cfa* climate (Pidwirny 2006). The region is affected by both dry continental air from the northwest, and by moist air originating in the Gulf of Mexico. An orographic effect is responsible for higher levels of precipitation in the Smoky Mountains than in the adjacent lowlands;

mean annual precipitation for the Little River watershed is 1,470 mm in GSMNP and 1,245 mm outside of the National Park (TVA 2003). Precipitation occurs relatively steadily throughout the year. Snowfall is most common at higher elevations such as in GSMNP. Temperature in the watershed is highly seasonal, with lowest temperatures occurring December through February, and highest temperatures occurring June through August. At lower elevations, annual maximum and minimum temperatures from 1966 to 2007 averaged 20.6 °C and 7.6 °C, respectively (SERCC 2009).

2.5 Land Use

Prior to Euro-American settlement, the Tsalagi, or Cherokee inhabited the Southern Appalachians, including East Tennessee. There were several Cherokee villages in the Upper Tennessee River Valley. One of these villages, named Elajay, was located near the confluence of Ellejoy Creek and the Little River until the mid-1800s (Williams 1948). Throughout the Southern Appalachian region, aboriginal peoples, including the Cherokee, are known to have used fire (Harmon 1982; Abrams 1992; Delcourt and Delcourt 1997). They burned to enhance crop production, to clear land for agriculture, to increase accessibility, and also to facilitate hunting practices (Goodwin 1977).

During the period of Euro-American settlement in the mid-1800s, humans continued to use fire and also began logging to clear land for farming (Harmon 1982). The impacts made by these subsistence-farming settlers were small compared to the large-scale logging that shaped the landscape in the early 20th century. In 1901, a group of men headed by Colonel W.B. Townsend bought over 40,000 ha along the Little River.

Soon after, the Little River Lumber Company was founded. It would become among the largest commercial logging operations in the Southern Appalachians. From 1901-1939, Townsend's lumber company built over 240 km of railroad. Two branches of the railroad extended into present-day GSMNP, with numerous spurs going further. Townsend eventually sold much of the land that became GSMNP to the state of Tennessee in 1925. However, the contract gave the lumber company the right to log for another 15 years. The Little River Lumber Company officially closed its mill in 1938, but not before sawing 560 million board feet (1.3 million cubic meters) of timber (Little River Railroad and Lumber Co. Museum 2010).

Today, various human activities place pressure on the Little River watershed. In 2003, TVA conducted an Integrated Pollutant Source Identification study and found land use in the watershed to be 60% forested (25% in GSMNP), 25% agricultural (cropland, livestock farms, and pasture), 10% residential, 4% commercial/industrial and 3% water and wetlands (TVA 2003). Inside GSMNP, the Little River is designated as an Outstanding National Resource Water, which restricts regulated degradation of the stream (TDEC 2006). Outside of the National Park, however, human land-use practices have led to extreme habitat alteration. Blount County has experienced increased development and urbanization, and is one of the fastest growing regions in Tennessee. With an expected 30% increase in population by the year 2030 (Ezzell *et al.* 2005), this trend will probably continue throughout the Little River watershed for many years to come.

2.6 Descriptions of Study Sites

The streambank erosion monitoring sites are located in five subwatersheds of the Little River. In all, 17 monitoring sites were established on 13 streams (Table 2.1). These subwatersheds drain a total of approximately 34,000 ha, ranging from 1,652 ha to 10,080 ha each. In June of 2007, baseflow water widths ranged from 1.13 m to 12.80 m. Average discharge during this time ranged from 0.009 cms to just above 0.81 cms. Average bank height throughout the studied stream reaches is 1.25 m, ranging from approximately 0.8 m to just above 2.0 m (Harden *et al.* 2009). The erosion-pin monitoring sites are located in four Level IV ecoregions.

2.6.1 Carr Creek

Carr Creek flows in a northeasterly direction close to GSMNP. Covering only 1,652 ha in rural Blount County, Carr Creek drains the smallest area of the studied subwatersheds. The only monitoring site is located in this watershed (CaC2) is in the Limestone Valleys and Coves ecoregion (66f). There is a bridge crossing approximately 10 m upstream and the streambanks at this site are approximately 1.1 m high. Soils of the streambanks are composed of moderately fine to moderately coarse-textured soils (Morris 2008). Land use is forested on the left bank and pasture on the right bank. Riparian buffer vegetation is thickest on the left bank and consists of native hardwoods intermixed with non-native Chinese privet (*Ligustrum sinense*).

Table 2.1 Locations and characteristics of erosion-pin monitoring sites. Modified from Harden *et al.* (2009).

				Baseflow[a]	
Site	**Tributary**	**Latitude**	**Longitude**	**Width**	**Discharge**
		Degrees N	Degrees W	m	cms
CaC2	Carr Creek	35.6864	-83.7772	1.92	0.023
CrC1	Crooked Creek	35.7714	–83.8781	9.14	0.230
CrC3	Flag Branch	35.7659	–83.8887	4.88	0.010
CrC4	North Fork Crooked Creek	35.7103	–83.9131	3.05	0.045
CrC5	South Fork Crooked Creek	35.7103	–83.9128	3.96	0.030
EC2	Ellejoy Creek	35.7873	–83.8011	4.75	0.048
EC3	Ellejoy Creek	35.8017	–83.7459	1.68	0.009
EC5	Millstone Branch	35.7898	–83.7733	3.41	0.009
EC6	Pitner Creek	35.8115	–83.7683	8.84[b]	0.013[b]
NC1	Nails Creek	35.8135	–83.8838	4.72	0.168
NC3	Nails Creek	35.8626	–83.8132	1.13	0.023
NC4	Wildwood Creek	35.8123	–83.8828	2.26	0.016
PC1	Pistol Creek	35.8159	–83.9418	12.80	0.812
PC2	Pistol Creek	35.7931	–83.9706	6.40	0.832
PC3	Pistol Creek	35.7693	–83.9828	13.75	0.286
PC6	Springfield Branch	35.7859	–83.9567	2.59	0.065
PC7	Culton Creek	35.7796	–83.9897	11.61	0.144

[a] Data from June 2007, except for EC6

[b] July 07 data

2.6.2 Crooked Creek

Crooked Creek joins the Little River from the southeast and its watershed is 8,274 ha, cutting through Level IV ecoregions 67f and 67g. The four study sites are located in Crooked Creek proper (CrC1), Flag Branch (CrC2), North Fork Crooked Creek (CrC4), and South Fork Crooked Creek (CrC5). Land use around the four sites is predominately pasture. Riparian buffer vegetation is sparse (TVA 2003). Bridges divert the flow directly upstream from two of the four sites (CrC1 and CrC3). Streambank heights of the monitored reaches are typically around 1.2 m, although CrC1 is 1.7 m. Bank materials at the monitoring sites are generally moderately fine-textured with the exception of CrC5, where they range from fine to coarse-textured (Morris 2008).

2.6.3 Ellejoy Creek

Ellejoy Creek's watershed is 9,885 ha and land use surrounding the study sites is mostly pasture with some forests. Four erosion-pin monitoring sites are located in this watershed. Two sites are on the main stem (EC2 and EC3), one site is on Millstone Branch (EC5), and another site is on Pitner Creek (EC6). Study site EC3 is located in ecoregion 67i, while the other study sites are in ecoregion 67g. The watershed contains approximately 50 beef cattle sites adjacent to the stream (TVA 2003). Riparian vegetation is sparse with a few hardwoods and some cool-season grasses present. Both EC2 and EC3 have a bridge directly upstream. The studied streambanks of Ellejoy Creek are normally 1.2 m high. However, at the EC5, bank height is near 2.0 m. Streambank materials consist of moderately fine-textured soils, though some coarse-textured soils were found at EC3 (Morris 2008).

2.6.4 Nails Creek

Nails Creek has a watershed of 4,628 ha. Study sites are located on Nails Creek (NC1 and NC3) and Wildwood Creek (NC4). All three study sites in the subwatershed are located in the Southern Shale Valleys ecoregion (67g). Agriculture is the predominant land use in the watershed. As at other sites, riparian buffer vegetation is sparse, although NC4, right bank, is forested. NC1 has a bridge 25 m upstream and at NC4 a concrete wall disrupts the helical flow 10 m upstream. Approximately 20% of the streambanks in Nails Creek watershed were found to be actively eroding (TVA 2003). Streambank materials are moderately fine-textured, but some coarse-textured soils are present at NC4 (Morris 2008).

2.6.5 Pistol Creek

Pistol Creek flows through the metropolitan areas of Maryville and Alcoa. On the main stem of Pistol Creek there are three study sites (PC1, PC2, and PC3). Two other sites are located on Springfield Branch (PC6) and Culton Creek (PC7). All study sites, like those in Nails Creek, are in the Southern Shale Valleys ecoregion (67g). Over half of the 10,000 ha in the watershed are classified as urban. Impervious surfaces such as pavement cover approximately 23% of the watershed. Land uses adjacent to study sites are more variable (TVA 2003). There are bridges located directly upstream from both

PC3 and PC7. Riparian vegetation is thin with a few hardwoods and abundant Chinese privet. Streambanks are composed of fine to moderately fine-textured soils (Morris 2008).

Chapter Three

3. Methods

3.1 Site Selection

In 2005, the Little River in East Tennessee was one of 12 streams in the United States to be awarded a Targeted Watershed Grant by the U.S. Environmental Protection Agency. The goal of these grants is to “encourage successful community-based approaches and management techniques to protect and restore the nation's watersheds” (USEPA 2009). Beginning in 2006, a group of organizations, led by the Blount County Soil Conservation District and Tennessee Valley Authority (TVA), established 28 sites on eight Little River tributaries to monitor stream flow and water quality. Of those 28 sites, 17 were chosen for a study of streambank erosion.

The 17 streambank erosion monitoring sites are located in the subwatersheds of five Little River tributaries and are the focus of my research. The Tennessee Department of Environment and Conservation denoted these five tributaries as impaired due to high levels of siltation/sedimentation (TDEC 2006). In selecting individual monitoring sites on each tributary, accessibility was a key factor. The studied streams are wadable and monitored banks are located in close proximity to roads. In most cases, the studied banks were chosen to be representative of banks on the tributaries and streambank erosion appeared typical for the watershed (Harden *et al.* 2009). However, five banks (EC5-left bank, NC1-right bank, CaC2-right bank, CrC5-right bank, and PC2-right bank) were included due to visibly high levels of erosion. At two of these sites (NC1 and EC5), only one bank was monitored. Thus, erosion pins were installed and monitored on 32 stream banks.

3.2 Erosion Pins

3.2.1 Erosion-Pin Installation

Dr. Carol Harden and students from the UT Geography Department, including myself, installed a total of 123 erosion pins between December 18, 2006 and February 14, 2007. The pins were made from 3.2 mm diameter steel rods cut to a length of 25 cm. One end of each erosion pin was painted white to enhance its visibility in the field for relocation purposes. Following research methods used by TVA and the United States Forest Service (Harrelson *et al.* 1994), erosion pins were inserted perpendicular to the slope of each bank with 2 cm of each pin exposed for reference. Four pins were aligned vertically, with one at the top of the bank (#1), one pin midway between the top of the bank and the normal water line (#2), one at the water line (#3), and another pin approximately 15 cm below the normal water line (#4) (Figure 3.1). For this study, the normal water line was established based on field observations of typical water levels, vegetation or lack thereof, and bank morphology. At five sites, erosion pin #4 was not installed due to rocks or an unstable substrate. Where roots or other obstructions existed, the pins were offset slightly. Pin placements were documented photographically and by measurements of their distance from landmarks.

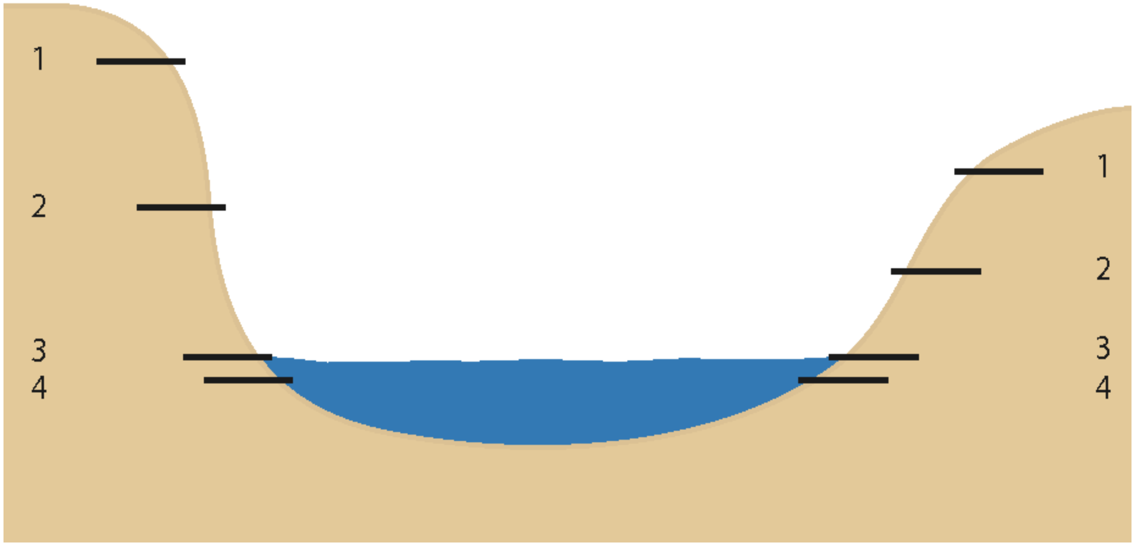

Figure 3.1 Positioning of erosion pins on left and right banks. From Harden *et al*. (2009).

3.2.2 Erosion-Pin Measurements

Between June 2007 and December 2008 we measured erosion pin exposure on six occasions. The first measurements took place in June and then December of 2007. Due to observations of high rates of streambank erosion, the schedule was changed from biannual to quarterly, with subsequent measurements taking place in March, June, October, and December of 2008. Erosion-pin measurements were reported to the nearest millimeter using a ruler at the point of greatest exposure. Initially, only one individual took measurements, but beginning in March of 2008, we added an additional quality control step. Separate measurements taken by two individuals were compared to minimize personal error. When measurements varied by more than 2 mm, pin exposure was remeasured until a consensus was reached.

In some cases, a pin measurement could not be taken and a substitution was required. Numerical values were assigned to pins that were known to be buried or missing due to erosion. In this thesis, pins that were missing are assigned a value of 20 cm and buried pins are assigned a value of -5 cm. For consistency, these assigned values assume that pins exposed by 20 cm would be eroded away, and that pins known to buried were covered by at least -5 cm. Erosion pins that were considered lost were excluded from analysis because we did not have knowledge regarding the cause of their disappearance.

3.3 Bank Angles

3.3.1 Bank Angle Measurements

In March of 2008, I measured streambank angles at each erosion pin using an Abney Level. More specifically, the level was used to record the vertical slope of a 10 cm bank segment centered on each pin. Angle was recorded to the nearest degree. Several bank segments centered on #4 pins were not measured because they were submerged below the water or were absent. However, low water levels due to drought conditions allowed the assessment of many of these bank segment angles. Also, because an Abney Level is designed to measure angles between 0 and 90°, obtuse angles could not be measured and as a result were reported as 95°. While numerous other studies have measured slope angle of an entire bank, to my knowledge, this technique of measuring bank angles at individual erosion pins has not been previously used.

3.3.2 Bank Angle Data Analyses

To characterize bank angles, I calculated descriptive statistics for the entire study area, for each pin, and for each tributary. The statistics I calculated included mean, median, standard deviation, minimum and maximum values, range, and upper and lower quartiles. To test whether bank angle (measured over a 10 cm segment centered on each erosion pin) is associated with two-year cumulative erosion rates, I ran several statistical analyses. I first ran two Kolmogorov-Smirnov (KS) tests to determine the normality of the bank angle and erosion-pin exposure data. The results showed that bank angle data were normally distributed but that the erosion pin data were not. Any time erosion pin exposure data were used in further analyses, I used nonparametric tests, but if bank angle data were used exclusively, parametric tests were implemented. All analyses were conducted using SPSS 17 software.

I used correlation analysis to assess the relationship between bank angle and pin exposure. Because pin exposure data were not normal, I used a nonparametric test based upon Spearman's rank correlation coefficient (r_s). The following relationships were tested:

- All bank angles to pin exposure.
- Bank angles ≥ 30° to pin exposure.
- Bank angles ≤ 90° to pin exposure.
- Bank angles sorted by pin number (bank position) to pin exposure.
- Bank angles sorted by bank shape to pin exposure.
- Bank angles sorted by soil texture to pin exposure.

To determine how bank angles varied spatially across the study area, I ran additional tests on the bank angle data. Specifically, I wanted to determine whether the relationship between bank angle and pin exposure was different between tributaries and/or monitoring sites. These tests were conducted through analysis of variance (ANOVA), a parametric test that compares the means of three or more groups.

3.4 Bank Shapes

3.4.1 Bank Profile Measurements

I documented bank profiles to classify the bank shapes of erosion-pin monitoring sites and to assess how well the banks at those sites represent a broader area. To document bank profiles, I measured the distance from a vertical stadia rod in the stream to the bank using a Trimble Spectra Precision Laser HD50 range finder. I installed a bubble level on the stadia rod for horizontal accuracy. All measurements were taken with the stadia rod at the same location in the stream, sliding the laser up the leveled stadia rod in 10 cm increments (Figure 3.2). Distances were measured three times to the nearest millimeter. The median measurement was used to graph the profiles. I collected bank profile data every 5 m of a 20 m reach, including the erosion-pin monitoring site, for a total of five profiles per bank. Profiles were documented once at each site.

3.4.2 Bank Shape Classification

Profile measurement data were entered into Microsoft Excel and graphically depicted. Streambank profiles were then classified into one of four bank shape categories: gradually sloping, moderately sloping, steeply sloping, or undercut (Table 3.1). These classes are similar to the types of streambank shapes used by the Environmental Protection Agency for the assessment of streambank and channel characteristics (USEPA 2010) (Figure 3.3). Undercut shapes were determined by a visual assessment of the bank profile graphs. If any portion of a bank appeared to be > 90°, it was classified as undercut. For profiles that were not undercut, I delineated between gently, moderately,

Figure 3.2 Profiling technique with laser point visible on bank of Nails Creek. Photo by Monica Rother.

and steeply sloping. Using the profile graphs, I calculated the arctan of the entire profile slope and then converted radians to degrees. Gently sloping banks were defined as having whole-bank slope angles of 0-29°, moderately sloping banks had angles of 30-49° and steeply sloping banks had angles of 50-90°.

3.4.3 Bank Shape Analyses

I compared bank profile shapes (undercut, steeply sloping, moderately sloping, gently sloping) of erosion-pin monitoring sites to those up and down stream to determine if the monitoring sites were representative of the stream reach in terms of bank shape. If the profile shape of the monitoring site matched at least two of the other four bank shapes in the 20 m reach, the monitoring site was considered representative. For example, if the monitoring site was classified as undercut, and two or more of the profiles in the stream reach were also undercut, the monitoring site was considered representative. However, if the erosion-pin monitoring site profile shape was undercut and only one other profile in the 20 m reach was undercut, the monitoring site was deemed not representative of the reach.

Table 3.1 Description of bank shape classes.

Bank shape class	Description
Gently sloping	Bank slope is 0-29°
Moderately sloping	Bank slope is 30-49°
Steeply sloping	Bank slope is 50-90°
Undercut	Portion of bank is > 90°

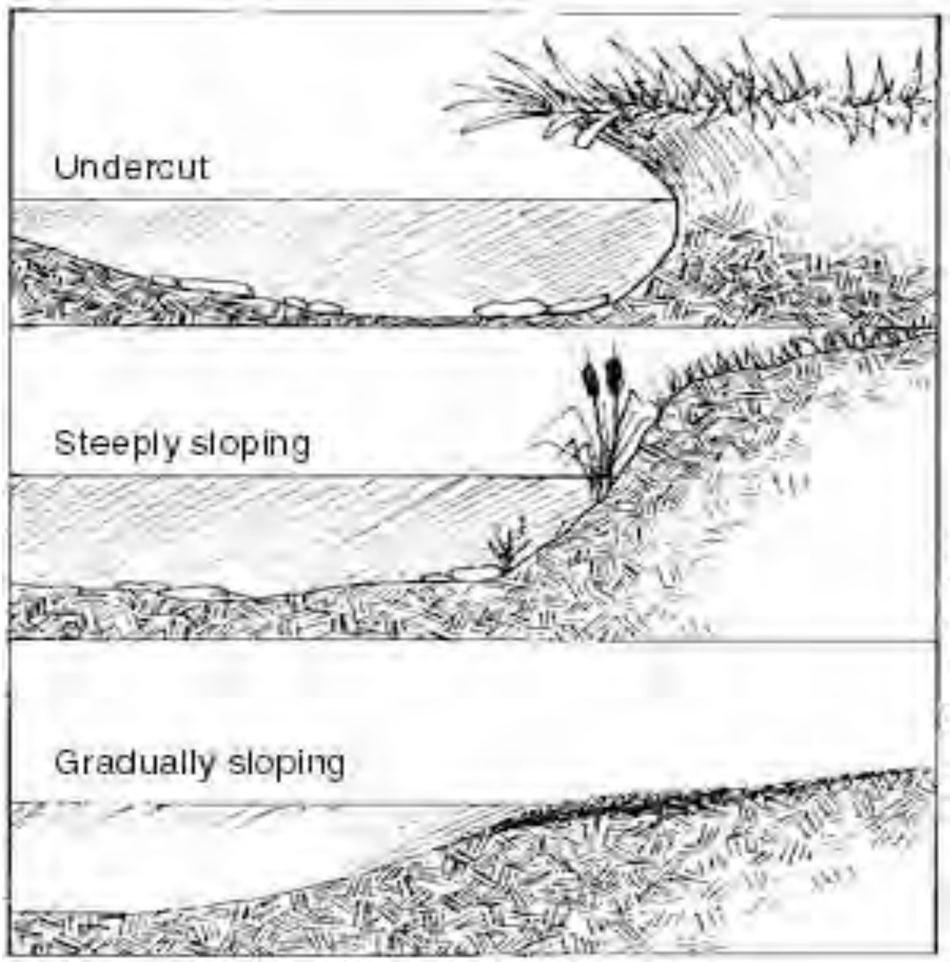

Figure 3.3 Types of streambank shapes (USEPA 2010).

Chapter Four

4. Results

4.1 Erosion-Pin Data

Erosion-pin exposure was measured in June and December of 2007, and in March, June, October, and December of 2008. These six visits to each monitoring site over the course of two years yielded over 700 individual pin measurements. The erosion-pin exposure measurements were prepared, analyzed, and published in 2009 by Harden *et al.* (Appendix B). The data represent cumulative change in pin exposure over a two-year period. Although nearly 20% of measurable pins showed gains rather than losses of sediment, median erosion-pin exposure after two years was 3 cm. This level of exposure can be interpreted as 1 cm loss because original pin exposure was set at 2 cm. Mean erosion-pin exposure, 4.2 cm, was higher than the median pin exposure. In general, exposure at pin #4 was notably greater than at pin positions that were higher on the streambanks. Although losses were greatest at pin #4, two-thirds of pins with losses of 3 cm or more were located above the water line and these pins generally recorded erosion even during drought conditions.

4.2 Bank Angles

4.2.1 General Characteristics

I measured 113 angles on 32 streambanks using an Abney Level in March of 2008 (Appendix C). Angles at 10 erosion pins (approximately 8% of all pins) were not measured because the pins were either absent or submerged. The mean angle of all measurements was 55.2° and the median was 50.0°. The data were not tightly clustered around the mean, as the average standard deviation was 25.5°. Angles ranged between a minimum of 10° and a maximum of 95°, the latter being assigned as a close estimate for angles > 90°.

Descriptive statistics indicated that angles varied by pin position (height on bank). The mean angle ranged approximately 50 to 60° between pins, with average angles greatest at pin #3. The median angle ranged approximately 30 to 58°, with angles again greatest at pin #3. At all four pin positions, a maximum angle of 95° was recorded, and the minimum angle ranged 10 to 20°. I found that angles were most variable at pin #4, which was located below the ordinary water line. This variability is reflected by the high standard deviation, widely spaced lower and upper quartiles, and large range (Table 4.1, Figure 4.1).

I examined the descriptive statistics of bank angle by tributary, and observed that bank angles varied by location (Figure 4.2, Table 4.2). Mean angle ranged from 44.9 to 70.0°; bank angles are highest at monitoring sites in the subwatersheds of Carr Creek and Ellejoy Creek. To determine whether these differences in mean angle were statistically significant, I used ANOVA to test whether bank angles differed between the five tributaries. I then further broke down the data and tested for differences between the 17 monitoring sites. In both cases, ANOVA results were significant at the $P < 0.05$ level, indicating that the means were not equal (Table 4.3, Table 4.4).

4.2.2 Relationship Between Bank Angle and Pin Exposure

Correlation analyses revealed many significant relationships between bank angle and pin exposure (Table 4.5). Spearman's rank correlation coefficient (r_s) between all pin exposure values and corresponding bank angle data was 0.289, where $P < 0.01$ and $n = 113$ (Figure 4.3). When angles < 30° were excluded, r_s increased slightly and was 0.351, where $P < 0.01$ and $n = 95$ (Figure 4.4). When angles > 90° were excluded, r_s was 0.237, where $P < 0.05$ and $n = 92$ (Figure 4.5). When bank angles were sorted by pin position, correlations were significant only for pin #3 ($r_s = 0.362$, $P < 0.05$, $n = 32$) and pin #4 ($r_s = 0.497$, $P < 0.05$, $n = 17$) (Figure 4.6, Figure 4.7). In the case of soil texture, the correlation between angles and pin exposure was significant where soil texture was clay ($r_s = 0.517$, $P < 0.05$, $n = 17$) (Figure 4.8). Finally, when angles were sorted by bank shape, the relationship between bank angle and pin exposure on banks classified as undercut was significant ($r_s = 0.431$, $P < 0.05$, $n = 30$) (Figure 4.9). All other tested relationships were not significant.

4.3 Bank Shapes

I plotted five profiles for each of the 32 monitored streambanks, for a total of 160 profiles. I then classified streambank profiles into one of four bank shape categories: gradually sloping, moderately sloping, steeply sloping, or undercut (Appendix D, Appendix E). Of the 160 profiles, approximately 28% were undercut ($n = 45$) and approximately 44% were steep ($n = 70$). When I compared the bank shapes of erosion-pin monitoring sites to those up and down stream, I determined that streambank shape at 25 of the 32 monitoring sites was representative of the broader stream reach (Table 4.6).

Thus approximately 78% of monitoring sites were determined to be representative of the reach.

Table 4.1 Descriptive statistics of bank angles in degrees for each pin position.

Pin	*n*-size	Mean	Median	SD	Min.	Max.	Range
1	32	50.4	46.0	22.1	20	95	75
2	32	58.1	55.0	22.3	19	95	76
3	32	59.6	57.5	24.6	14	95	81
4	19	47.1	30.0	36.1	10	95	85
All Sites	113	55.2	50.0	25.5	10	95	85

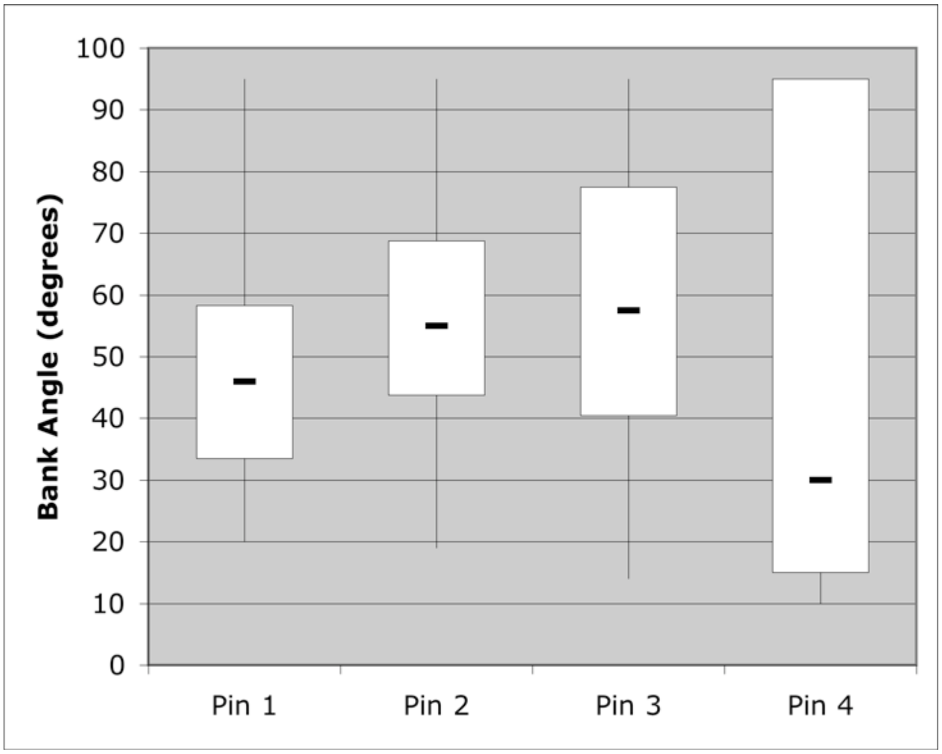

Figure 4.1 Variability of bank angle by pin position. The maximum, upper quartile, median, lower quartile, and minimum values are displayed for each pin.

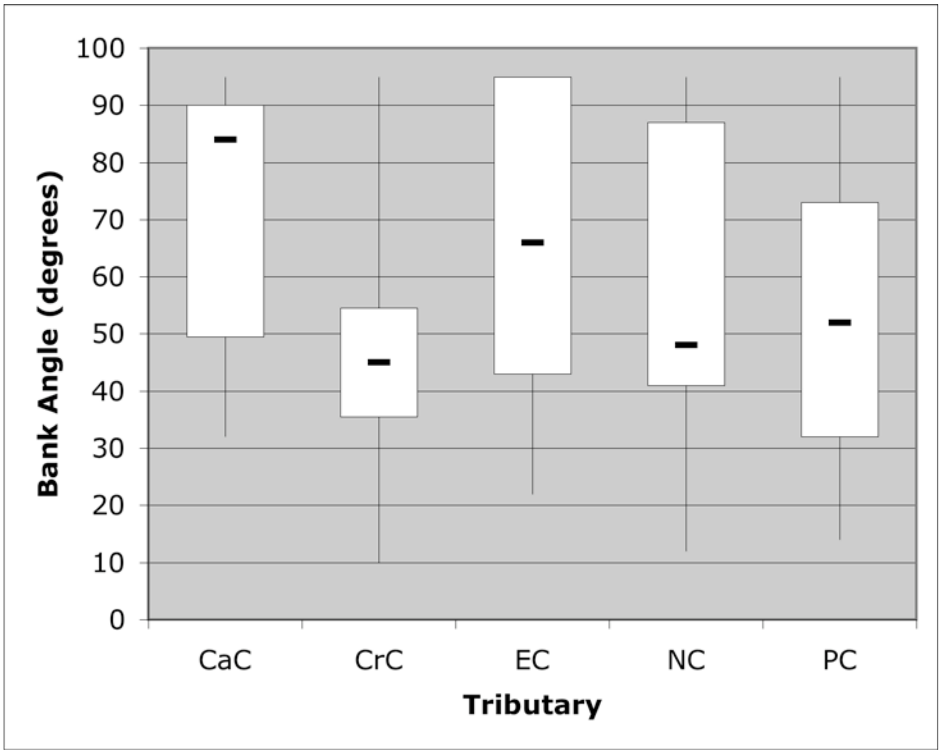

Figure 4.2 Variability of bank angle by tributary. The maximum, upper quartile, median, lower quartile, and minimum values are displayed for each tributary.

Table 4.2 Descriptive statistics of bank angles in degrees of all five tributaries.

Tributary	*n*-size	Mean	Median	SD	Min.	Max.	Range
CaC	7	70.0	84.0	25.9	32	95	63
CrC	28	44.9	45.0	17.5	10	95	85
EC	24	65.5	64.5	25.6	22	95	73
NC	17	55.2	48.0	28.5	12	95	83
PC	37	53.6	52.0	26.6	14	95	81
All Sites	113	55.2	50.0	25.5	10	95	85

Table 4.3 Results from ANOVA test on bank angles by tributary.

	Sum of Squares	Degrees of Freedom	Mean Square	F	*P*
Between Groups	7152.778	4	1788.195	2.932	.024
Within Groups	65862.939	108	609.842		
Total	73015.717	112			

Table 4.4 Results from ANOVA test of bank angles by monitoring site.

	Sum of Squares	Degrees of Freedom	Mean Square	F	*P*
Between Groups	18560.163	16	1160.010	2.045	.017
Within Groups	54455.554	96	567.245		
Total	73015.717	112			

Table 4.5 Results of Correlation Analyses. Only statistically significant correlations are included.

Test	r_s	*P*-value	n-size
Angles to pin exposure	0.289**	0.002	113
Angles ≥30° to pin exposure	0.351**	0.000	95
Angles ≤ 90° to pin exposure	0.237*	0.023	92
Angles to pin exposure (pin 3 only)	0.362*	0.042	32
Angles to pin exposure (pin 4 only)	0.497*	0.042	17
Angles to pin exposure (undercut only)	0.431*	0.018	30
Angles to pin exposure (clay only)	0.517*	0.034	17

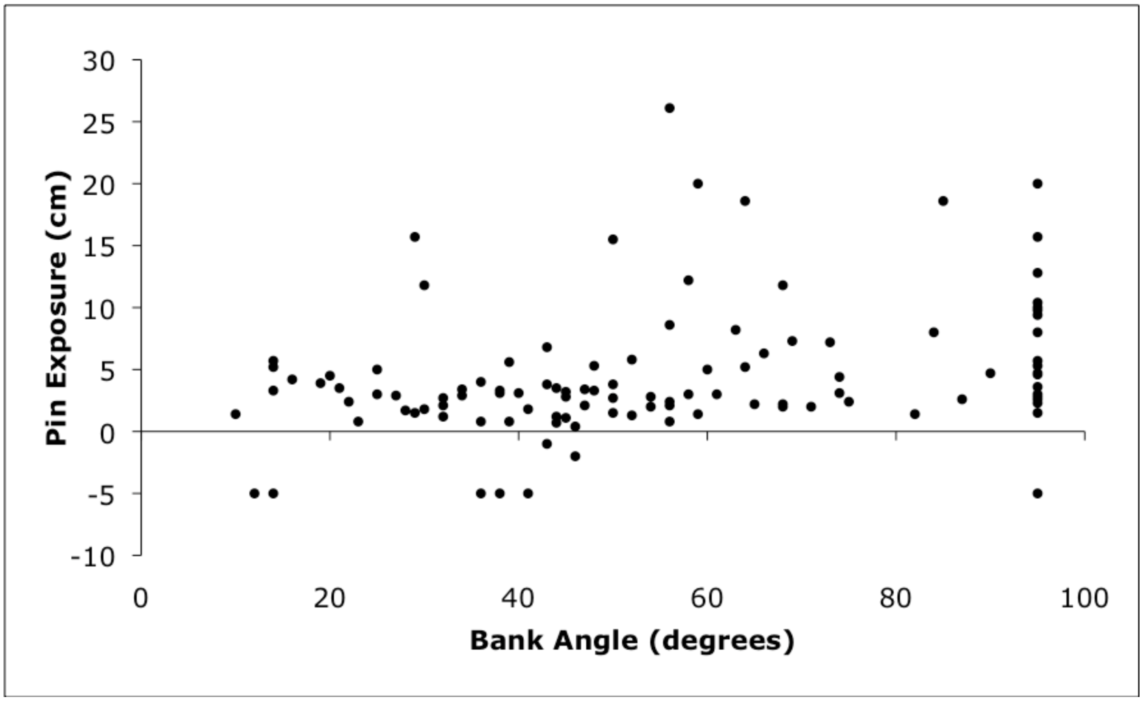

Figure 4.3 Relationship between bank angle and pin exposure.

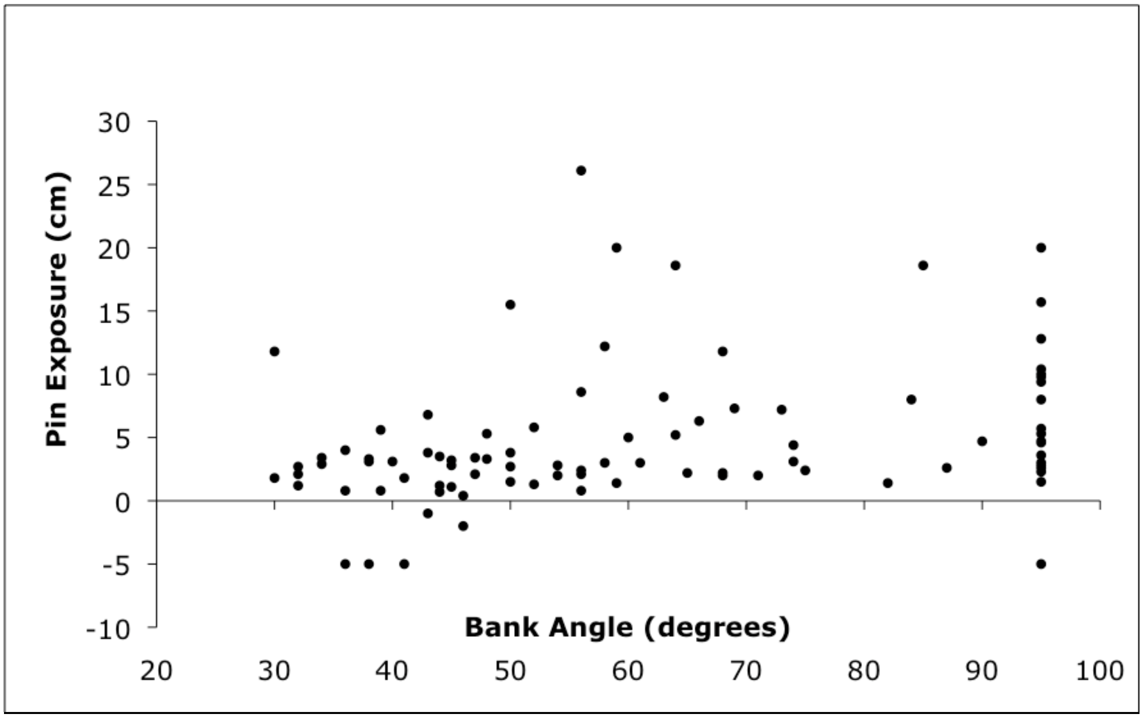

Figure 4.4 Relationship between bank angles ≥ 30° and pin exposure.

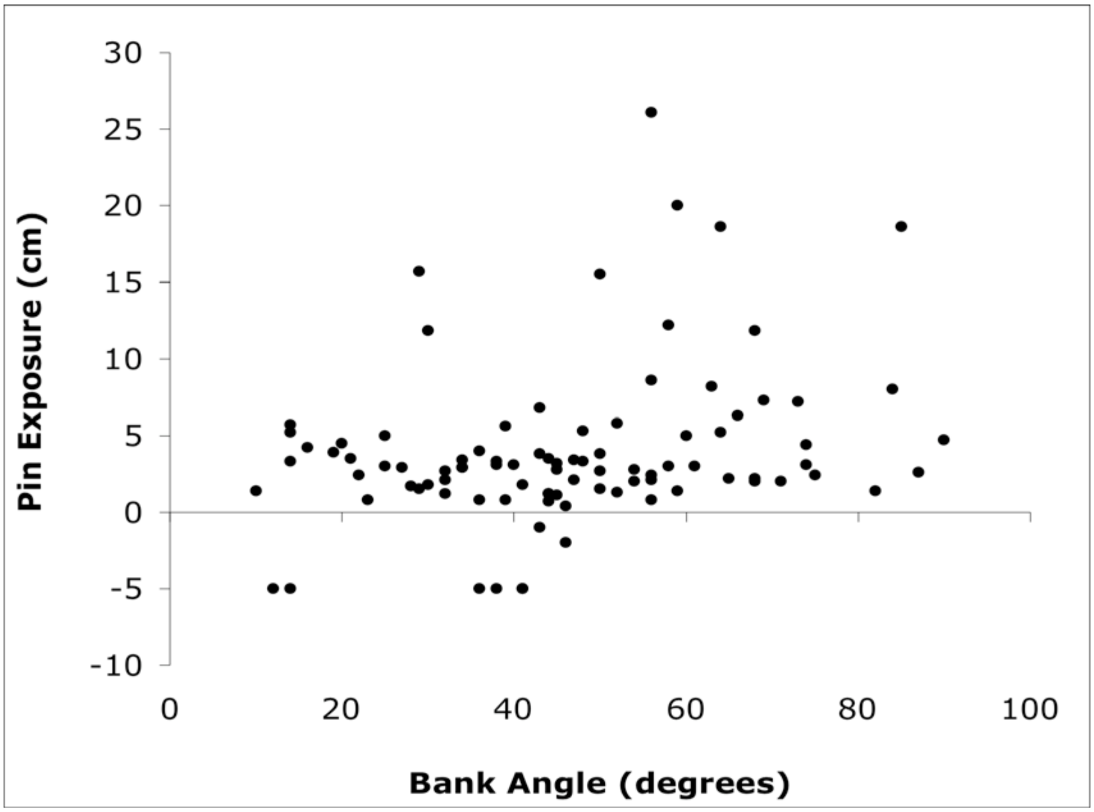

Figure 4.5 Relationship between bank angles ≤ 90° and pin exposure.

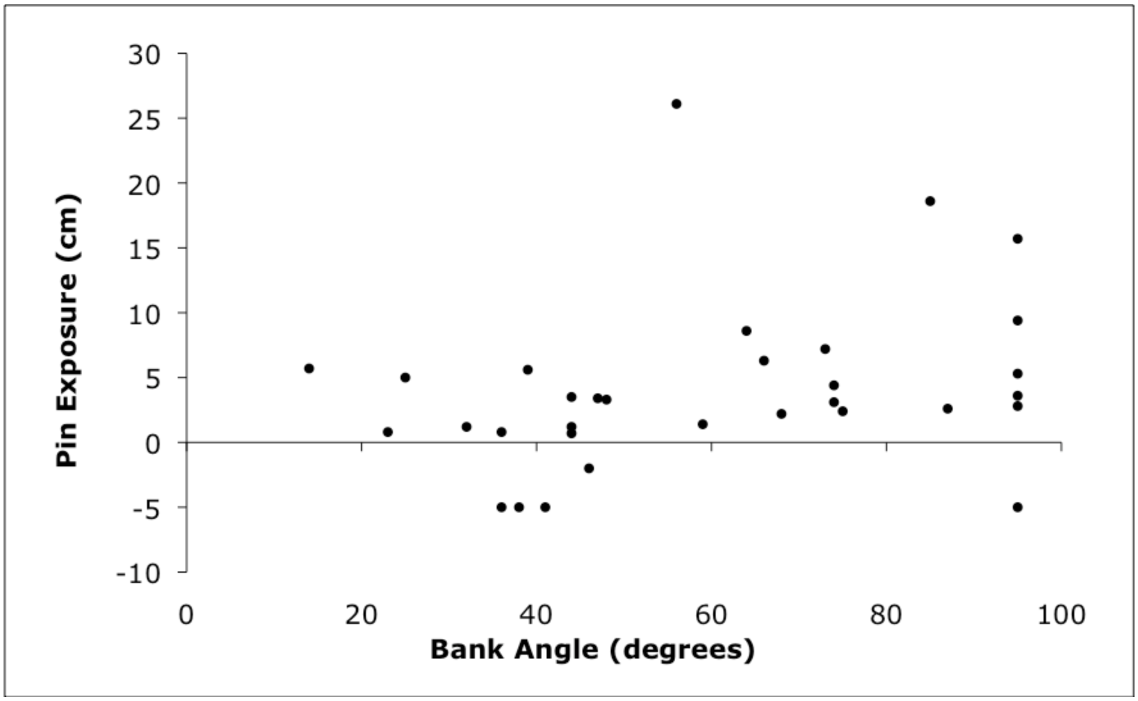

Figure 4.6 Relationship between bank angle and pin exposure for #3 pins.

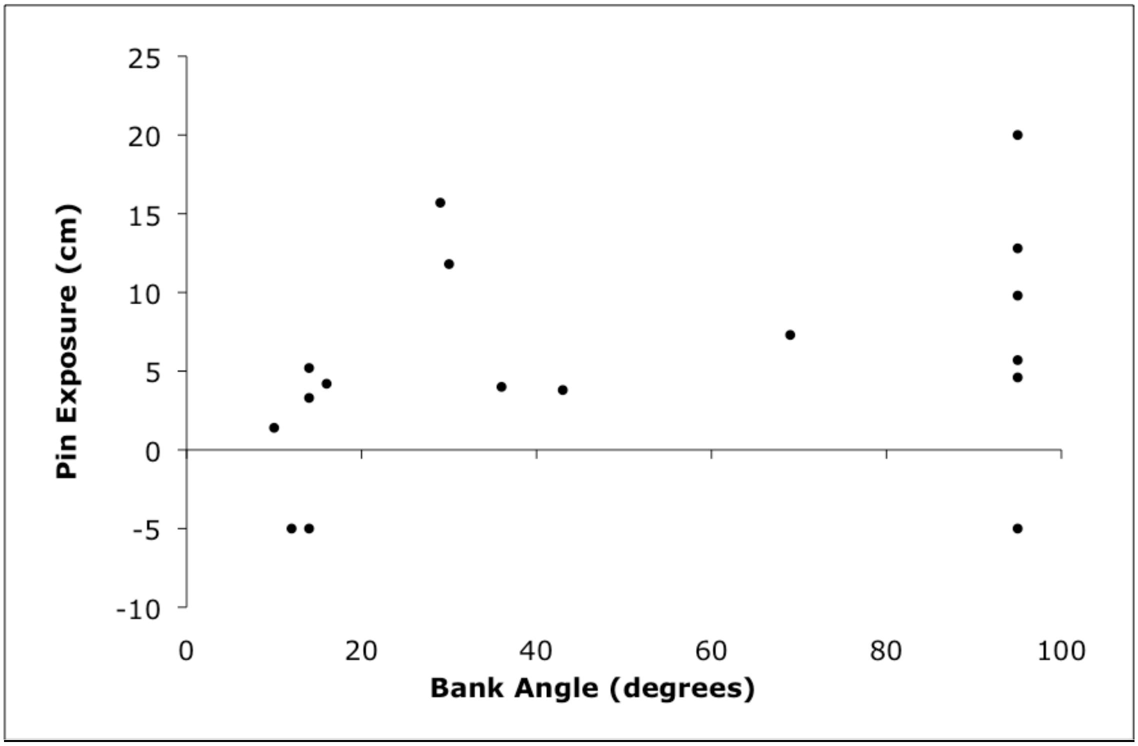

Figure 4.7 Relationship between bank angle and pin exposure for #4 pins.

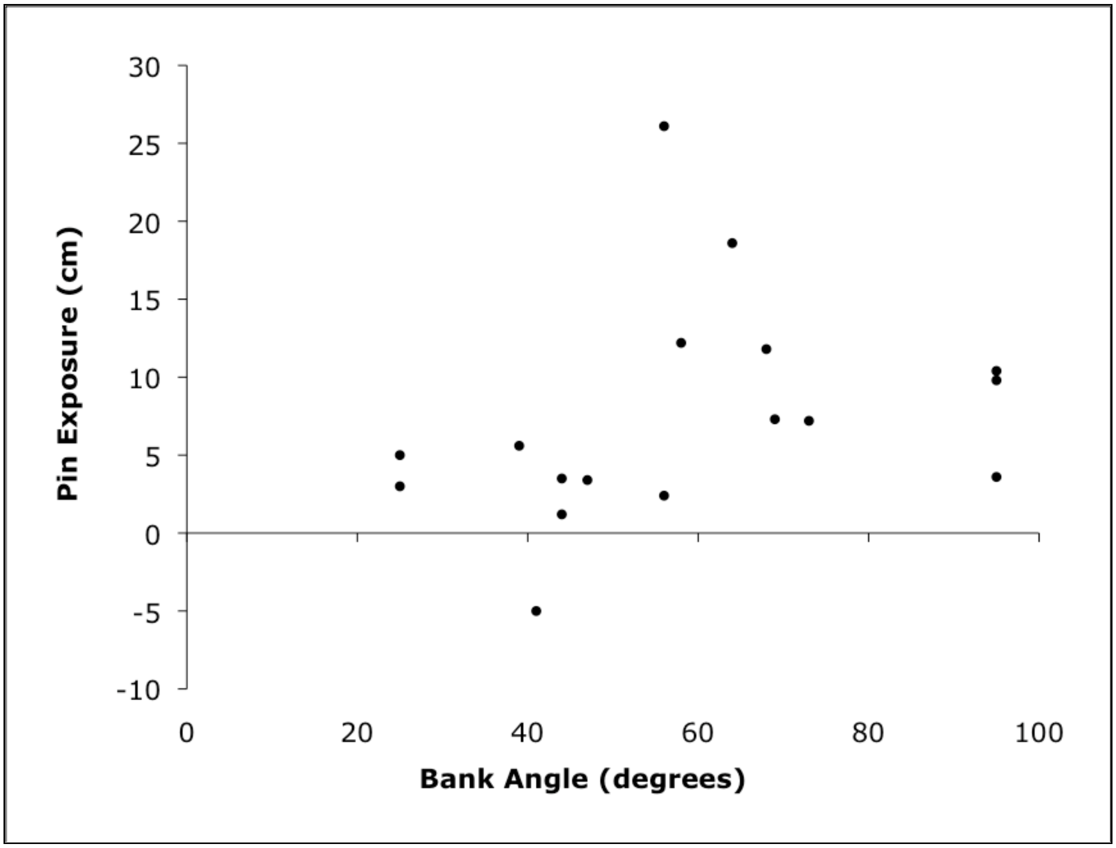

Figure 4.8 Relationship between bank angle and pin exposure where soil texture is clay.

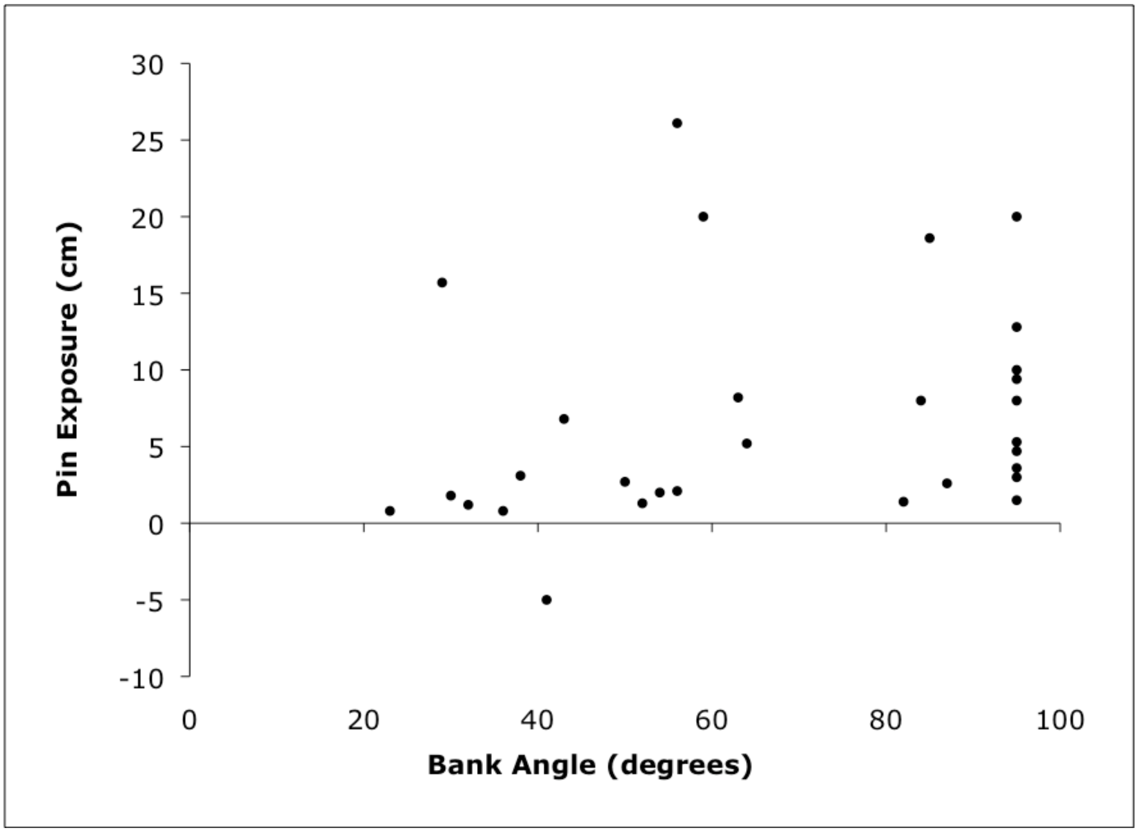

Figure 4.9 Relationship between bank angle and pin exposure on banks classified as undercut.

Table 4.6 Representativeness of bank shape at erosion-pin monitoring sites.

Monitoring Site by Streambank	Shape at Monitoring Site	How many profiles had shape of monitoring site?	Is Monitoring Site Representative?
CaC2 right	undercut	3	yes
CaC2 left	undercut	2	no
CrC1 right	moderate	2	no
CrC1 left	moderate	4	yes
CrC3 right	steep	5	yes
CrC3 left	steep	1	no
CrC4 right	steep	3	yes
CrC4 left	undercut	3	yes
CrC5 right	undercut	1	no
CrC5 left	steep	3	yes
EC2 right	steep	5	yes
EC2 left	undercut	2	no
EC3 right	steep	3	yes
EC3 left	steep	3	yes
EC5 left	steep	3	yes
EC6 right	steep	2	no
EC6 left	steep	5	yes
NC1 right	undercut	4	yes
NC3 right	steep	3	yes
NC3 left	steep	5	yes
NC4 right	gentle	4	yes
NC4 left	undercut	3	yes
PC1 right	moderate	4	yes
PC1 left	steep	1	no
PC2 right	steep	4	yes
PC2 left	steep	4	yes
PC3 right	undercut	4	yes
PC3 left	undercut	3	yes
PC6 right	steep	4	yes
PC6 left	steep	3	yes
PC7 right	gentle	4	yes
PC7 left	moderate	4	yes

Chapter Five

5. Discussion

5.1 Bank Erosion Rates

Erosion pins have proven to be a useful tool for monitoring erosion in the Little River watershed. The erosion pins used for this study were installed primarily in perennial headwater streams, although they can also be implemented in lowland or ephemeral streams. Erosion pins can be inserted into many different bank materials (Midgley 1975), but Thorne (1978) was unsatisfied with their usage in unconsolidated materials. The simplicity of erosion pins is perhaps their greatest lure for potential researchers. The erosion pins employed were inexpensive, easy to emplace, required little maintenance, and could be monitored quickly. In most cases, a network of erosion pins at a site was monitored in a few minutes with no more than a pair of waders, a ruler, and a notebook.

Erosion pins were chosen not only for their simplicity but also because they offer a fine-resolution measure of lateral channel change. Erosion pins can detect change to the nearest millimeter and are more accurate than other commonly used resurvey methods such as repeated cross-profiling and planimetric resurvey (Lawler 1993). This high level of sensitivity makes erosion pins particularly well suited for small or less active tributaries where erosion rates are generally low (Lawler 1993), such as those in the Little River watershed. The ability of erosion pins to record changes at high spatial and temporal resolutions is especially useful for process-based studies (Twidale 1964). For example, in this study, it was possible to interpret variation in pin exposure as resulting from different erosion processes (*e.g.*, accretion, deposition and/or swelling).

The data indicate that the median change in erosion-pin exposure over the course of two years was 1 cm (approximately 0.5 cm per bank per year). In comparison, retreat rates observed in other studies that utilized erosion pins range from millimeters per year (Leopold *et al.* 1966) to more than 1 m per year (Hooke 1979; Simon 1989). As expected, pin #4, below the water line, detected the greatest amount of change. This makes sense given my field observations that maximum hydraulic shear occurred at the bank toe. Although losses were greatest at pin #4, two-thirds of pins with losses of 3 cm or more were located above the water line. Thus erosion is actively occurring at all vertical segments of the bank. Unexpectedly, pins recorded consistent erosion even during a period of drought. This could be due to subaerial processes such as dry raveling, which loosens and even releases streambank materials from the bank face (Couper and Maddock 2001; Wynn *et al.* 2008). When higher flows do occur under these circumstances, they are more likely to detach and entrain soil particles. While most pins recorded positive erosion, approximately 20% detected negative erosion. Positive values imply streambank soil loss, while negative values could have resulted from accretion or swelling of the bank (Harden *et al.* 2009).

A limitation of erosion pins is that each pin records changes at only one point. While more erosion pins would allow for more data across a range of physical stream conditions, data collection is time intensive and access becomes an inhibiting factor as you travel up or down stream away from a roadside entry. Because only a limited number of pins are installed, data extrapolation becomes necessary. Extrapolating rates of bank erosion from one reference point to a broader bank area or a different stream reach must be done with caution. Streambank characteristics such as bank angle and shape may vary spatially and complicate data extrapolation.

5.2 Bank Angles of Little River Tributaries

In this research, I measured bank angles at erosion pins to determine what relationship might exist between bank angle and erosion rates. Streambank angles have frequently been used as a parameter in determining bank stability. For example, Pfankuch (1978) used bank angle as one of several factors to evaluate the stability of mountain streams in Montana. Pfankuch and other researchers (*e.g.*, Platts 1987; Rosgen 2001) interested in streambank stability have traditionally measured the angle of the bank as a whole. Specifically, one streambank angle is measured from the bottom of the bank to the top of the bank. In contrast, I measured angles of 10 cm bank segments centered at each erosion pin. This method allowed for direct comparison of local bank angle to pin exposure.

The mean bank angle of all erosion pins monitored in this study was approximately 55°, with angles ranging from 10° to 95°. Angles varied by pin position, with the highest mean and median angle at pin #3. Angles were not equally distributed among tributaries or monitoring sites. In other words, the mean angles are statistically different between sites. These findings are not surprising given the uniqueness of each location. For example, bank angles are higher at Carr Creek, where the only pin-monitoring site is located next to a farm. It is very likely that this stream reach was channelized at some point in the past, perhaps explaining the higher angles that were observed. Evidence for this can be found in the fine soil textures that comprise the streambanks of the study area (Morris 2008).

I found a weak, positive relationship between local bank angle and pin exposure that was highly significant. This suggests that bank angle is one of many factors that contribute to streambank erosion on the studied tributaries in the Little River watershed. When considering only higher bank angles, those ≥ 30°, the relationship becomes stronger. This suggests that the association between bank angle and erosion is weakest where banks are gently sloped, and becomes stronger as banks steepen. Due to gravitational forces, an obvious assumption is that streambank particles are more likely to be detached from steeper slopes and deposited on gentler slopes. This agrees with Zonge *et al.* (1996), who studied streambanks in California during drought conditions. They found net erosion to be highest on steeper bank segments, while deposition occurred on more moderately sloped portions.

One limitation of my field methods was that the Abney level could only measure angles between 0 and 90°. Angles over 90° were assigned a value of 95°. Based on my field observations, this value is a close estimate of the actual angle. However, the abundance of 95° values skewed the data set, and thus I also ran correlation analysis without those values. The correlation was significant, but lower than for the entire data set. In the future, a more accurate method of determining obtuse angles should be implemented.

When I sorted the data by pin position (height on bank), bank shape, and soil texture, several relationships stood out. At pin positions just above the ordinary water line (pin #3) and 15 cm below the ordinary water line (pin #4), bank angles were significantly correlated to pin exposure; however, correlations at pin #1 and #2 were not significant. Thus the relationship between bank angle and pin exposure is stronger lower on the bank. This could be due to more active fluvial processes that can cause scouring of the slope toe (Pizzuto 2008). When I sorted the data by soil texture, correlations between bank angle and erosion-pin exposure were only significant when considering clayey soils. Clayey soils are more cohesive than other soils and have a greater capacity to shrink and swell (Day 1994). Shrinking and swelling often leads to the formation of tension cracks. These cracks may lead to geotechnical failure, especially when bank angles are steep (Pizzuto 2008). When I sorted the data by bank shape, the correlation between bank angle and pin exposure was only significant for undercut banks. These findings are consistent with observations made in the field and suggest that where banks are overhanging, higher bank angles will be associated with increased erosion rates. In addition, research suggests that undercut banks are more susceptible to mass failure due to stronger gravitational forces that override the resisting forces of friction and cohesion (Pizzuto 2008). In the future, researchers may consider controlling for these factors (pin position, soil texture, bank shape, and bank angle) to better determine how each independently affects erosion rates. Regression analysis may facilitate better understanding of the interaction of these factors and their combined importance in contributing to streambank erosion in the Little River watershed.

Given that bank angle and erosion-pin exposure are only weakly correlated, it is likely that other factors must also be considered. Land-use changes related to agriculture, forestry, mining, and urban development substantially increase the amount of sediment entering U.S. streams (Wilson 1902; Waters 1995; Wang *et al.* 1997; Walling 1999). The clearing of vegetation and impervious surface construction result in higher peak flows, leading to channel enlargement through bed and bank erosion (Graf 1977; Jacobson *et al.* 2001). In the Little River watershed, the relationship between erosion caused by land-use changes and increased sediment is likely to be significant. For example, Hart (2006) reported that subwatersheds consisting of a forested land cover in the Little River watershed had lower concentrations of total suspended solids (TSS) than drainage areas classified as either agriculture or urban.

5.3 Bank Profile Shapes

5.3.1 Determining Bank Profile Shapes

I used a laser range finder to develop streambank profiles at each monitoring site. This method offers an inexpensive and fast alternative to traditional profiling methods such as cross-profiling. Whereas conventional profiling methods involve cumbersome equipment that cannot be easily moved from stream to stream, my method employs very lightweight equipment that can quickly document profiles. Five different bank areas were profiled in a 20 m reach to determine if the monitoring sites were representative in terms of profile shape; profile measurements were then taken three times at each 10 cm vertical increment. This replication was done to minimize error, as even with the bubble level installed on the stadia rod, it was still possible that movement occurred during laser measurements. Repeated measurements were almost always within a 0-5 millimeter range, suggesting a high degree of precision. A possible drawback of my bank profiling method is that no permanent markers were emplaced where I collected my profile data. In the future, profiling benchmarks should be established to allow researchers to allow for temporal analyses of changes in bank profiles.

My profiling methods enabled me to characterize 160 bank shapes in the Little River watershed. I determined that bank shapes are variable throughout the study area, and that even within a single stream reach, diverse bank shapes (*e.g.* gently sloping and undercut) occur. Although bank shapes vary, approximately three-fourths of all banks were classified as either undercut ($n = 45$) or steeply sloping ($n = 70$). Because these banks erode faster (Pizutto 2008), the predominance of steep and undercut banks rather than gently or moderately sloping banks may contribute to higher sediment levels in the Little River watershed.

5.3.2 Representativeness of Monitoring Sites

An important factor in any field-based study is site selection. As part of this study, I evaluated the representativeness of bank shape at monitoring sites. I found that 25 of the 32 monitoring sites (approximately 78%) shared the same bank shape as the reach in which they are located. At the seven monitoring sites that differed in shape, surrounding banks were typically classified as a bank shape that was only slightly different from the monitoring site in terms of steepness. For example, at CrC5, the right bank at the erosion-pin monitoring site was classified as undercut, while all four of the surrounding profiles were classified as steep. As with profiles on the same bank, profiles on opposing banks were usually in similar shape classes. For example, at CrC1 the right bank was steeply sloping, whereas the left bank was moderately sloping, and there were three instances (CrC5, EC2, and PC6) where one bank was undercut while the other was steep. Two exceptions to the similarity in shapes among monitoring sites were found at NC4 and PC7. At both of these sites, the right bank was gently sloping whereas the left bank was undercut. At NC4, the asymmetry could be explained by a concrete structure upstream of the monitoring site, which may divert stream flow to the opposite bank, causing an undercut. Although variability exists among streambank shapes, in general, these findings suggest that the erosion-pin monitoring sites are reasonably representative in terms of shape.

Bank shape should not be the only factor used to determine representativeness, as monitoring sites may differ from the broader stream area in other ways. As previously mentioned, monitoring sites were sometimes located downstream from fluvial diversions such as bridges or road embankments. These structures divert the natural helical flow and may enhance near bank stress on the bank toe, resulting in increased bank heights and greater instability (Simon *et al.* 1989). In future studies, it might be valuable to separate analyses based on the presence or absence of nearby diversions. Thus data extrapolation from erosion pins to the broader stream area should be done cautiously and take into consideration variability of individual site characteristics.

Chapter Six

6. Conclusions and Recommendations

This study examines streambank angles and shapes and their relationship to erosion-pin exposure in small streams during drought conditions in southern Appalachia. The major findings are:

- Bank angles at erosion-pin monitoring sites averaged approximately 55°. However angles were highly variable by pin position and ranged between 10° to over 90°. Angles also vary significantly between tributaries and individual monitoring sites.
- Streambank erosion is positively associated with bank angle at erosion pins. When the entire data set was considered, angle correlated with pin exposure. In addition, angle and pin exposure were positively correlated where soils were clay, on banks that were classified as undercut, and when considering angles $\leq 90°$ or when considering angles $\geq 30°$. Significant correlations were also found when only considering pins lower on the bank (pin #3 and pin #4). It is likely that other factors such as land use and related changes in riparian vegetation also significantly contribute to streambank erosion.
- In the Little River watershed, streambank shapes differ by location and can be highly irregular. I classified shapes as undercut, gently sloping, moderately sloping, and steeply sloping and found that all of these shapes were common throughout the study area. However, three-fourths of all bank profiles were classified as steeply sloping or undercut.

- The majority of bank shapes in the surrounding reach (25 out of 32) matched those at the monitoring site on that bank. Thus, most monitoring sites are representative of the broader stream reach in terms of shape.

Erosion pins have proven to be a useful tool for monitoring erosion in the Little River watershed, and they indicate that streambank erosion is occurring at a rate of approximately 0.5 cm/year on the banks of Little River tributary streams. The causes of erosion are likely related to many factors and the amount of erosion per site is highly variable. This thesis has demonstrated that significant relationships exist between bank angle and erosion-pin exposure, and that additional site factors, including bank shape, pin position, and soil texture are also correlated to erosional losses. In the future, researchers may consider controlling for these factors to better determine how each independently affects erosion rates.

Additional work is needed to fully understand the dynamic nature of streambank erosion in the Little River watershed. A stationary bank profiling method would add temporal resolution to the study of morphological change on streambanks. Additionally, cross-section profiling, as opposed to bank-only profiling, would give more detailed information regarding stream channel change and other streamflow factors that are related to cross-section shape. Future research could also include an in-depth look at riparian vegetation, which has been shown to have mechanical and hydrological effects on bank stability (Simon and Collison 2002). Large-scale causes of bank erosion, such as higher discharges resulting from changes in land use, also warrant further attention from researchers. Additional research involving near-bank velocities would better explain the influence of fluvial processes on streambank erosion, and a more quantitative assessment of streambank material would allow for a more detailed statistical analysis of the affect of soils on bank erosion. Lastly, future studies on groundwater seepage could shed light on another mechanism that is important to bank stability.

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Appendices

Appendix A Soil texture at Little River streambank erosion monitoring sites, from Morris (2008).

Site	Bank	Pin #	Soil Type	Soil Class
CaC2	L	1	sandy loam	Moderately coarse-textured
CaC2	L	2	sandy clay loam	Moderately fine-textured
CaC2	L	3	clay loam	Moderately fine-textured
CaC2	L	4	sandy loam	Moderately coarse-textured
CaC2	R	1	sandy loam	Moderately coarse-textured
CaC2	R	2	clay loam	Moderately fine-textured
CaC2	R	3	clay loam	Moderately fine-textured
CrC1	L	1	clay loam	Moderately fine-textured
CrC1	L	2	clay loam	Moderately fine-textured
CrC1	L	3	clay loam	Moderately fine-textured
CrC1	R	1	clay loam	Moderately fine-textured
CrC1	R	2	silty clay loam	Moderately fine-textured
CrC1	R	3	clay	Fine-textured
CrC3	L	1	silty clay	Fine-textured
CrC3	L	2	silty clay	Fine-textured
CrC3	L	3	clay	Fine-textured
CrC3	L	4	clay loam	Moderately fine-textured
CrC3	R	1	clay loam	Moderately fine-textured
CrC3	R	2	clay loam	Moderately fine-textured
CrC3	R	3	clay loam	Moderately fine-textured
CrC4	L	1	silty clay loam	Moderately fine-textured
CrC4	L	2	clay	Fine-textured
CrC4	L	3	clay loam	Moderately fine-textured
CrC4	R	1	silty clay loam	Moderately fine-textured
CrC4	R	2	silty clay loam	Moderately fine-textured
CrC4	R	3	silty clay loam	Moderately fine-textured
CrC4	R	4	clay loam	Moderately fine-textured
CrC5	L	1	loam	Medium-textured
CrC5	L	2	loamy sand	Coarse-textured
CrC5	L	3	loamy sand	Coarse-textured
CrC5	R	1	sandy loam	Moderately coarse-textured
CrC5	R	2	clay loam	Moderately fine-textured
CrC5	R	3	clay	Fine-textured
CrC5	R	4	loam	Medium-textured
EC2	L	1	clay loam	Moderately fine-textured
EC2	L	2	clay loam	Moderately fine-textured
EC2	L	3	clay loam	Moderately fine-textured
EC2	L	4	clay loam	Moderately fine-textured
EC2	R	1	clay loam	Moderately fine-textured
EC2	R	2	clay loam	Moderately fine-textured
EC2	R	3	clay loam	Moderately fine-textured
EC2	R	4	loam	Medium-textured
EC3	L	1	loamy sand	Coarse-textured
EC3	L	2	loamy sand	Coarse-textured

Appendix A *continued.*

Site	Bank	Pin #	Soil Type	Soil Class
EC3	L	3	loam	Medium-textured
EC3	L	4	loamy sand	Coarse-textured
EC3	R	1	loam	Medium-textured
EC3	R	2	loam	Medium-textured
EC3	R	3	clay loam	Moderately fine-textured
EC5	L	1	clay loam	Moderately fine-textured
EC5	L	2	clay loam	Moderately fine-textured
EC5	L	3	clay loam	Moderately fine-textured
EC5	L	4	clay	Fine-textured
EC6	L	1	clay loam	Moderately fine-textured
EC6	L	2	clay loam	Moderately fine-textured
EC6	L	3	sandy clay loam	Moderately fine-textured
EC6	R	1	clay loam	Moderately fine-textured
EC6	R	2	clay loam	Moderately fine-textured
EC6	R	3	clay loam	Moderately fine-textured
NC1	R	1	silty clay loam	Moderately fine-textured
NC1	R	2	silty clay loam	Moderately fine-textured
NC3	L	1	silty clay loam	Moderately fine-textured
NC3	L	2	clay loam	Moderately fine-textured
NC3	L	3	clay	Fine-textured
NC3	L	4	clay loam	Moderately fine-textured
NC3	R	1	clay loam	Moderately fine-textured
NC3	R	2	clay loam	Moderately fine-textured
NC3	R	3	clay loam	Moderately fine-textured
NC4	L	1	clay loam	Moderately fine-textured
NC4	L	2	sandy loam	Moderately coarse-textured
NC4	L	3	clay loam	Moderately fine-textured
NC4	R	1	sandy clay loam	Moderately fine-textured
NC4	R	2	loamy sand	Coarse-textured
NC4	R	3	sand	Coarse-textured
NC4	R	4	sand	Coarse-textured
PC1	L	1	clay	Fine-textured
PC1	L	2	clay loam	Moderately fine-textured
PC1	L	3	clay	Fine-textured
PC1	L	4	silty clay	Fine-textured
PC1	R	1	silty clay loam	Moderately fine-textured
PC1	R	2	silty clay	Fine-textured
PC1	R	3	clay	Fine-textured
PC2	L	1	clay	Fine-textured
PC2	L	2	clay	Fine-textured
PC2	L	3	clay	Fine-textured
PC2	L	4	clay loam	Moderately fine-textured
PC2	R	1	clay	Fine-textured
PC2	R	2	silty clay	Fine-textured
PC2	R	3	clay	Fine-textured
PC2	R	4	clay	Fine-textured
PC3	L	1	clay loam	Moderately fine-textured

Appendix A *continued.*

Site	Bank	Pin #	Soil Type	Soil Class
PC3	L	2	sandy clay loam	Moderately fine-textured
PC3	L	3	clay loam	Moderately fine-textured
PC3	R	1	clay loam	Moderately fine-textured
PC3	R	2	clay loam	Moderately fine-textured
PC3	R	3	clay	Fine-textured
PC3	R	4	clay	Fine-textured
PC6	L	1	clay loam	Moderately fine-textured
PC6	L	2	clay loam	Moderately fine-textured
PC6	L	3	clay loam	Moderately fine-textured
PC6	R	1	clay loam	Moderately fine-textured
PC6	R	2	sandy clay loam	Moderately fine-textured
PC6	R	3	clay loam	Moderately fine-textured
PC6	R	4	sandy loam	Moderately coarse-textured
PC7	L	1	clay	Fine-textured
PC7	L	2	clay loam	Moderately fine-textured
PC7	L	3	clay	Fine-textured
PC7	L	4	clay	Fine-textured
PC7	R	1	clay loam	Moderately fine-textured
PC7	R	2	sandy clay loam	Moderately fine-textured
PC7	R	3	clay loam	Moderately fine-textured
PC7	R	4	sandy loam	Moderately coarse-textured

Appendix B Erosion-pin exposure after two years. Modified from Harden *et al.* (2009).

Monitoring Site	Pin #1	Pin #2	Pin #3	Pin #4
CaC2 right[b]	2.1	8	1.2	No Pin
CaC2 left	6.8	6.0	18.6	25.0
CrC1 right	3.4	1.1	1.4	1.4
CrC1 left	2.8	-1.0	-5.0	No Pin
CrC3 right	3.2	2.8	3.3	5.5
CrC3 left	2.9	0.4	1.2	5.2
CrC4 right	5.8	0.8	4.4	11.8
CrC4 left	10.0	-5.0	0.8	-5.0
CrC5 right[b]	25.0	5.2	30.0	15.7
CrC5 left	0.8	1.5	-5.0	-5.0
EC2 right	3.8	2.0	6.3	10.0
EC2 left	3.1	8.2	9.4	12.8
EC3 right	3.1	4.7	-5.0	-5.0
EC3 left	2.1	1.2	0.7	-5.0
EC5 left[b]	2.3	8.6	15.7	9.8
EC6 right	2.4	2.9	2.8	10.0
EC6 left	3.0	3.3	2.2	Lost[c]
NC1 right[b]	3.0	2.0	5.3	No Pin
NC3 right	1.8	2.6	-7.0	-5.0
NC3 left	5.3	3.0	3.4	-5.0
NC4 right	1.7	1.5	-2.0	Lost[c]
NC4 left	2.7	4.7	2.6	No Pin
PC1 right	2.1	3.5	5.6	4.2
PC1 left	2.4	5.0	7.2	4.0
PC2 right[b]	11.8	15.5	5.0	-5.0
PC2 left	10.4	12.2	8.6	3.3
PC3 right	1.8	1.3	3.6	10.0
PC3 left	1.4	1.5	0.8	No Pin
PC6 right	2.7	2.0	3.1	4.6
PC6 left	2.2	2.8	2.4	3.8
PC7 right	4.5	3.9	5.7	5.7
PC7 left	3	2.9	3.5	7.3

Appendix C Streambank angles measured at erosion pins.

Erosion Pin	Bank Angle	Pin Exposure
CaC2R1	56	2.1
CaC2R2	84	8
CaC2R3	32	1.2
CaC2L1	43	6.8
CaC2L2	95	8
CaC2L3	85	18.6
CaC2L4	95	20
CrC1R1	34	3.4
CrC1R2	45	1.1
CrC1R3	59	1.4
CrC1R4	10	1.4
CrC1L1	45	2.8
CrC1L2	43	-1
CrC1L3	38	-5
CrC3R1	45	3.2
CrC3R2	54	2.8
CrC3R3	48	3.3
CrC3L1	27	2.9
CrC3L2	46	0.4
CrC3L3	44	1.2
CrC3L4	14	5.2
CrC4R1	52	5.8
CrC4R2	56	0.8
CrC4R3	74	4.4
CrC4R4	30	11.8
CrC4L1	95	10
CrC4L2	41	-5
CrC4L3	23	0.8
CrC5R1	59	20
CrC5R2	64	5.2
CrC5R3	56	26.1
CrC5R4	29	15.7
CrC5L1	39	0.8
CrC5L2	50	1.5
CrC5L3	36	-5
EC2R1	50	3.8
EC2R2	68	2
EC2R3	66	6.3
EC2L1	38	3.1
EC2L2	63	8.2
EC2L3	95	9.4
EC2L4	95	12.8
EC3R1	40	3.1

Appendix C *continued.*

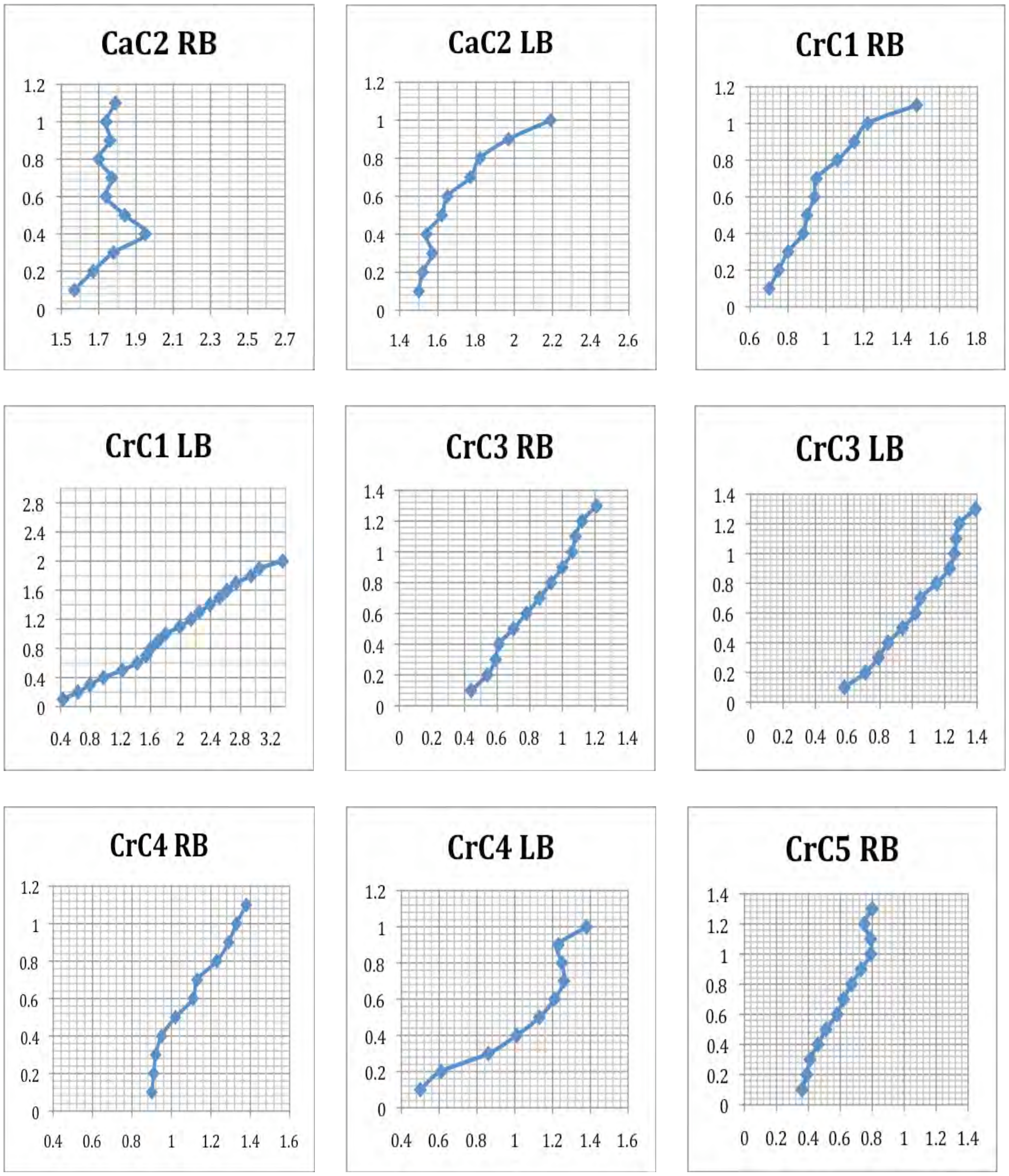
Erosion Pin	Bank Angle	Pin Exposure
EC3R2	90	4.7
EC3R3	95	-5
EC3R4	95	-5
EC3L1	32	2.1
EC3L2	44	1.2
EC3L3	44	0.7
EC5L1	95	2.3
EC5L2	56	8.6
EC5L3	95	15.7
EC5L4	95	9.8
EC6R1	22	2.4
EC6R2	34	2.9
EC6R3	95	2.8
EC6L1	58	3
EC6L2	38	3.3
EC6L3	68	2.2
NC1R1	95	3
NC1R2	54	2
NC1R3	95	5.3
NC3R1	41	1.8
NC3R2	95	2.6
NC3R3	41	-5
NC3R4	14	-5
NC3L1	48	5.3
NC3L2	61	3
NC3L3	47	3.4
NC3L4	12	-5
NC4R1	28	1.7
NC4R2	29	1.5
NC4R3	46	-2
NC4L1	50	2.7
NC4L2	95	4.7
NC4L3	87	2.6
PC1R1	47	2.1
PC1R2	21	3.5
PC1R3	39	5.6
PC1R4	16	4.2
PC1L1	56	2.4
PC1L2	60	5
PC1L3	73	7.2
PC1L4	36	4
PC2R1	68	11.8
PC2R2	50	15.5

Appendix C *continued.*

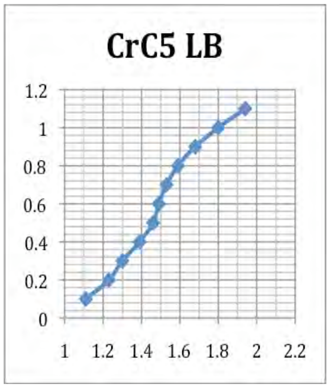
Erosion Pin	**Bank Angle**	**Pin Exposure**
PC2R3	25	5
PC2L1	95	10.4
PC2L2	58	12.2
PC2L3	64	18.6
PC2L4	14	3.3
PC3R1	30	1.8
PC3R2	52	1.3
PC3R3	95	3.6
PC3L1	82	1.4
PC3L2	95	1.5
PC3L3	36	0.8
PC6R1	32	2.7
PC6R2	71	2
PC6R3	74	3.1
PC6R4	95	4.6
PC6L1	65	2.2
PC6L2	95	2.8
PC6L3	75	2.4
PC6L4	43	3.8
PC7R1	20	4.5
PC7R2	19	3.9
PC7R3	14	5.7
PC7R4	95	5.7
PC7L1	25	3
PC7L2	34	2.9
PC7L3	44	3.5
PC7L4	69	7.3

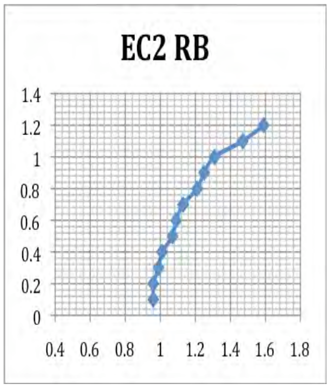
Erosion pins are named by subwatershed (PC), monitoring site (7), left or right bank (L), and pin position (1). Bank angles are in degrees. Pin exposure is reported as cumulative measurements after two years of monitoring.

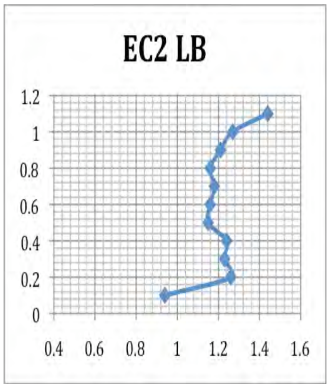
Appendix D Streambank profiles of erosion-pin monitoring sites. The vertical axes represent vertical distance (m) starting at 0.1 m above the water level (at the time of profiling) and extending to what was determined to be the break at the top of the bank. The horizontal axes represent the distance (m) from the stadia rod to the bank. Profiles of the right bank (RB) are viewed in the downstream direction, while profiles of the left bank are viewed in the upstream direction.

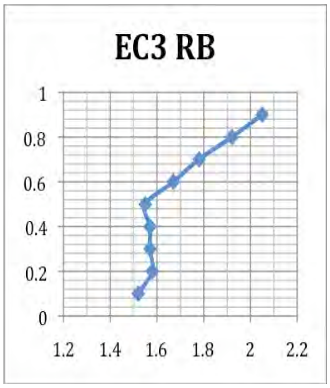


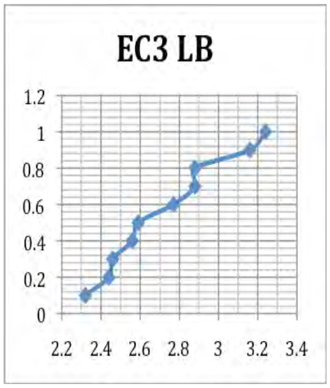
Appendix D *continued.*

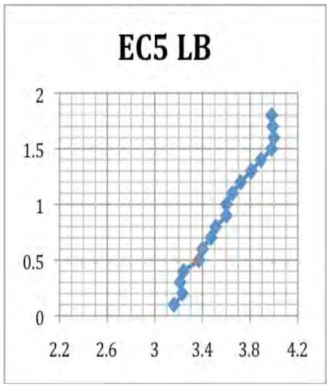


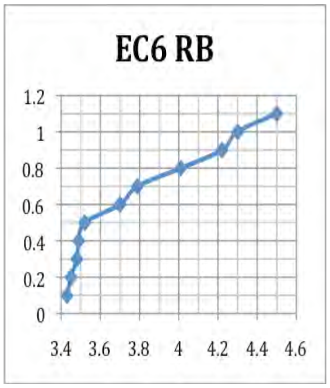


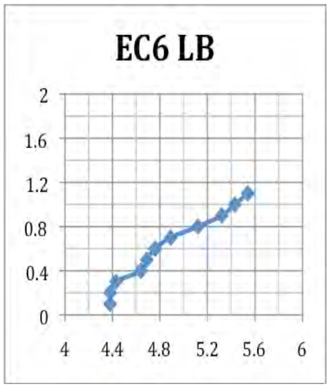


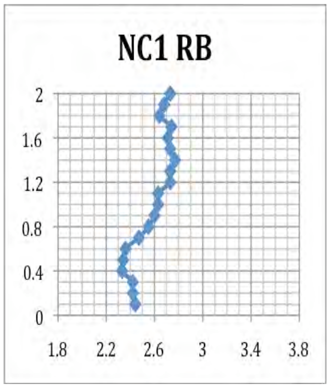




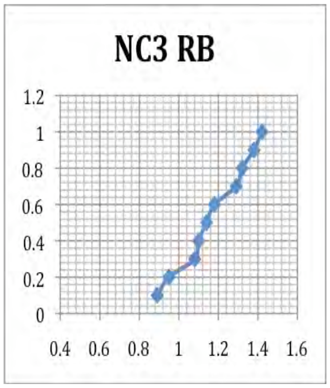


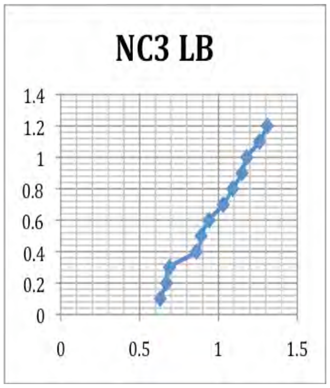


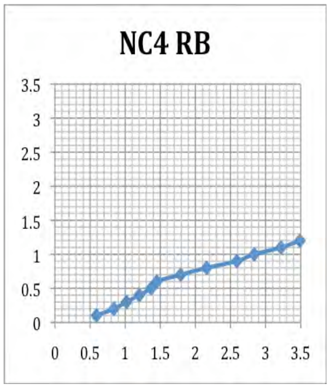


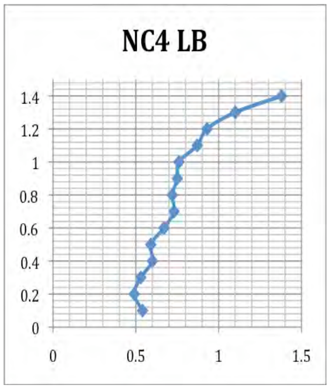


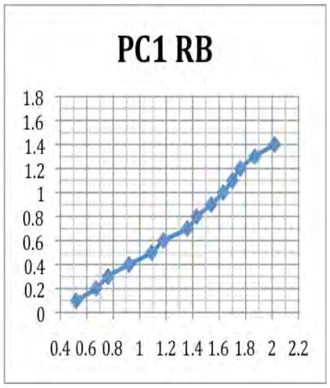
Appendix D *continued.*

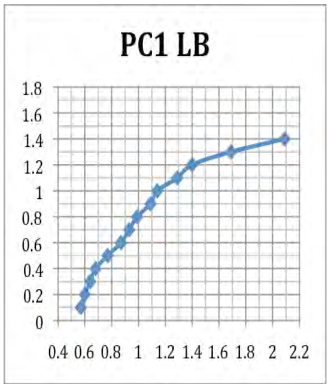


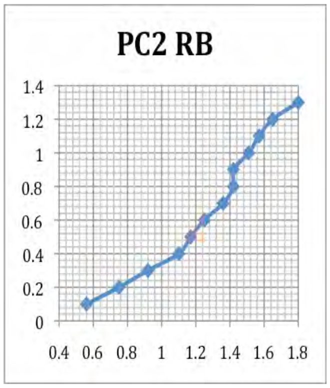


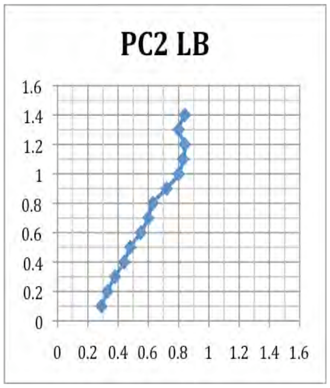


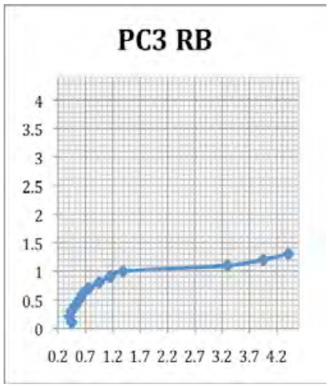












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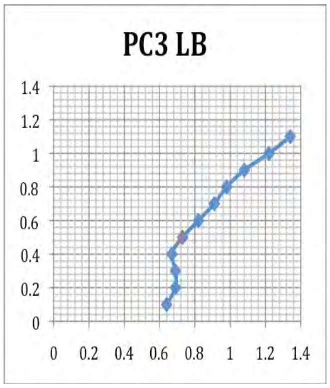

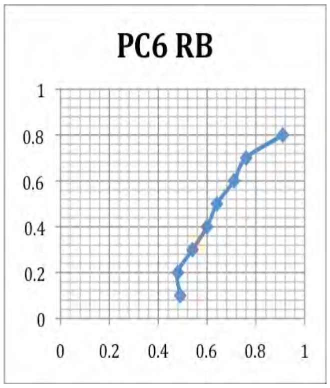

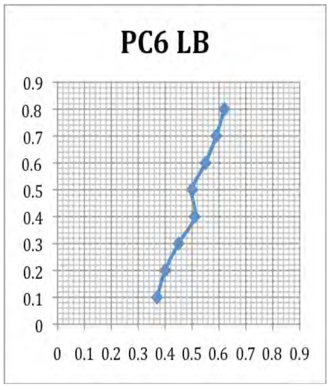

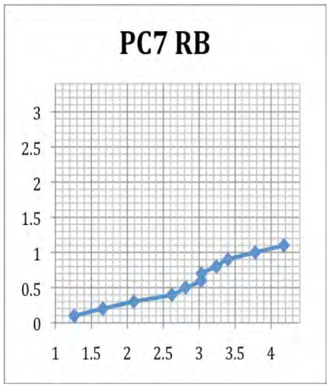

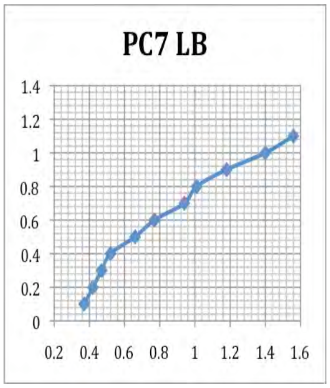

Appendix E Data used to create streambank profiles. The data represent horizontal distance (m) from the stadia rod to the bank. The data are organized from the top to the bottom of the bank. There was 0.1 m vertical distance between each horizontal data point.

CaC2_RB1	CaC2_RB2	CaC2_RB3	CaC2_RB4	CaC2_RB5
4.29	1.79	1.23	3.11	3.28
4.22	1.74	1.19	2.93	2.92
4.17	1.76	1.16	2.69	2.84
4.12	1.7	1.05	2.66	2.71
3.96	1.77	1.12	2.66	2.7
3.89	1.74	1.1	2.62	2.64
3.83	1.84	1.17	2.6	2.59
3.63	1.95	1.19	2.68	2.52
3.59	1.78	1.18	3.02	2.35
3.35	1.67	1.02	2.87	2.26
3.25	1.57	0.95	2.8	1.79

CaC2_LB1	CaC2_LB2	CaC2_LB3	CaC2_LB4	CaC2_LB5
2.57	2.19	2.32	1.58	2.31
2.34	1.97	2.21	1.56	2.13
2.3	1.82	2.19	1.46	2
2.18	1.77	2.16	1.34	1.85
2.03	1.65	2.05	1.16	1.7
1.91	1.62	1.98	1.02	1.55
1.8	1.54	2.01	0.86	1.46
1.69	1.57	2.08	0.78	1.39
1.73	1.52	2.03	0.48	1.31
	1.5	2.03		1.04

Appendix E *continued.*

CrC1_RB1	CrC1_RB2	CrC1_RB3	CrC1_RB4	CrC1_RB5
1.48	2.3	1.24	0.98	1.37
1.22	2.16	1.25	0.99	1.3
1.15	1.99	1.1	0.99	1.15
1.06	1.98	1.02	1.14	1.21
0.95	1.81	0.93	0.95	1.9
0.94	1.69	0.9	0.68	1.85
0.9	1.54	0.85	0.69	1.7
0.88	1.45	0.79	0.65	1.66
0.8	1.22	0.8	0.57	1.49
0.75	1.11	0.81	0.5	1.29
0.7	1.04	0.91	0.44	1.16
	0.95	0.88	0.5	1.02
	0.85	0.81	0.48	0.9
	0.76		0.53	0.75
	0.66		0.48	0.68
	0.72		0.46	0.62
	0.67		0.43	0.58
	0.57			0.56
				0.53

Appendix E *continued.*

CrC1_LB1	CrC1_LB2	CrC1_LB3	CrC1_LB4	CrC1_LB5
1.34	3.36	2.83	3.02	1.54
1.17	3.05	2.55	2.66	1.46
1.08	2.94	2.43	2.55	1.26
1.01	2.74	2.24	2.33	1.22
0.96	2.62	2.15	2.23	1.22
0.84	2.52	2.08	2.21	1.16
0.75	2.39	1.96	2.07	1.15
0.69	2.25	1.85	1.84	1.15
0.58	2.14	1.72	1.73	1.15
0.55	1.99	1.65	1.67	1.1
0.49	1.8	1.62	1.5	0.95
0.37	1.7	1.52	1.43	0.91
	1.6	1.41	1.32	0.82
	1.54	1.36	1.18	0.74
	1.42	1.23	1.09	0.68
	1.22	1.08	1.01	0.59
	0.97	0.92	0.85	0.54
	0.79	0.8	0.74	0.47
	0.63	0.67	0.64	
	0.43	0.51	0.54	
		0.39	0.38	
		0.24		

CrC3_RB1	CrC3_RB2	CrC3_RB3	CrC3_RB4	CrC3_RB5
1.28	1.39	1.56	1.21	2.68
1.32	1.44	1.57	1.12	2.2
1.18	1.28	1.51	1.08	1.92
1.17	1.22	1.44	1.06	1.61
1.1	1.16	1.4	1	1.35
1.02	1.08	1.37	0.93	1.19
0.95	1.05	1.24	0.86	1.1
0.9	1.02	1.17	0.78	0.98
0.82	0.86	1.08	0.7	0.93
0.7	0.76	0.98	0.61	0.83
0.56	0.62	0.9	0.59	0.72
0.41		0.81	0.54	0.55
		0.74	0.44	

Appendix E *continued.*

CrC3_LB1	CrC3_LB2	CrC3_LB3	CrC3_LB4	CrC3_LB5
1.26	1.91	1.88	1.39	0.71
1.28	1.88	1.72	1.29	0.64
1.27	2.1	1.67	1.27	0.65
1.21	2.12	1.61	1.26	0.81
1.17	2.1	1.56	1.23	0.77
1.05	2.08	1.43	1.15	0.74
1.1	2.02	1.38	1.05	0.72
1.05	2.01	1.22	1.02	0.64
0.97	1.98	1	0.94	0.56
0.86	1.97	0.89	0.85	0.53
0.79	1.99	0.73	0.79	
0.69	2.14	0.55	0.71	
0.61			0.58	

CrC4_RB1	CrC4_RB2	CrC4_RB3	CrC4_RB4	CrC4_RB5
1.13	1.09	2.29	1.14	1.38
1.03	1.06	2.25	1.08	1.33
0.99	1.04	2.22	0.95	1.29
0.9	1.05	2.1	0.86	1.23
0.83	1.16	2.06	0.79	1.13
0.77	1.18	1.97	0.71	1.11
0.75	1.11	1.94	0.65	1.02
0.72	1.15	1.9	0.61	0.95
0.6	1.14	1	0.56	0.92
0.43	1.09			0.91
	0.98			0.9

CrC4_LB1	CrC4_LB2	CrC4_LB3	CrC4_LB4	CrC4_LB5
0.99	1.42	0.98	1.17	1.38
0.88	1.25	0.95	1.26	1.23
0.96	1.18	0.83	1.24	1.25
1.04	1.13	0.77	1.21	1.26
1.03	1.15	0.69	1.16	1.21
1.01	1.15	0.63	1.12	1.13
0.94	1.08	0.6	1.05	1.01
0.95	0.99	0.52	0.95	0.86
0.81	0.87	0.47	0.89	0.61
0.63	0.75	0.42	0.82	0.5
		0.42	0.75	

Appendix E *continued.*

CrC5_RB1	CrC5_RB2	CrC5_RB3	CrC5_RB4	CrC5_RB5
1.45	0.84	1.05	1.4	0.8
1.31	0.76	1	1.41	0.75
1.26	0.67	0.83	1.43	0.79
1.15	0.59	0.8	1.4	0.79
1.02	0.57	0.74	1.35	0.73
0.91	0.57	0.7	1.29	0.67
0.85	0.56	0.63	1.14	0.62
0.76	0.5	0.6	1.03	0.58
0.68	0.47	0.55	0.9	0.51
0.6	0.45	0.48	0.73	0.46
0.55	0.3	0.46	0.63	0.41
		0.41	0.45	0.39
		0.29		0.36

CrC5_LB1	CrC5_LB2	CrC5_LB3	CrC5_LB4	CrC5_LB5
0.62	1.07	1.66	1.85	1.94
0.57	0.94	1.55	1.7	1.8
0.54	0.88	1.49	1.57	1.68
0.49	0.75	1.43	1.49	1.59
0.48	0.64	1.39	1.49	1.53
0.52	0.5	1.35	1.41	1.49
0.53	0.45	1.28	1.34	1.46
0.51	0.39	1.27	1.34	1.39
0.44	0.36	1.24	1.32	1.3
0.46	0.33	1.26	1.33	1.23
0.39	0.32	1.27	1.25	1.11
0.35	0.33	1.3		
0.38	0.36			
0.41				

Appendix E *continued.*

EC2_RB1	EC2_RB2	EC2_RB3	EC2_RB4	EC2_RB5
2.22	2.99	1.59	2.84	3.31
2.12	2.33	1.47	2.19	2.61
2.08	1.66	1.31	1.99	2.56
2.04	1.54	1.25	1.94	2.54
1.99	1.51	1.21	1.92	2.41
1.93	1.42	1.13	1.9	2.36
1.91	1.37	1.09	1.8	2.35
1.86	1.31	1.07	1.66	2.35
1.65	1.19	1.01	1.66	2.32
1.59		0.99	1.56	
1.36		0.96	1.51	
1.2		0.96	1.34	
0.99				

EC2_LB1	EC2_LB2	EC2_LB3	EC2_LB4	EC2_LB5
2.51	2.65	1.44	1.97	2.24
2.34	2.2	1.27	1.93	2.09
2.28	2	1.21	1.8	1.86
2.14	1.93	1.16	1.77	1.82
2.05	1.81	1.18	1.67	1.72
2.02	1.76	1.16	1.62	1.68
1.93	1.72	1.15	1.58	1.6
1.89	1.72	1.24	1.47	1.56
1.73	1.66	1.23	1.4	1.53
1.7	1.58	1.26	1.34	1.45
1.68	1.52	0.94	1.31	1.48
1.58	1.39			1.49
1.42	1.25			1.43
1.27				

Appendix E *continued.*

EC3_RB1	EC3_RB2	EC3_RB3	EC3_RB4	EC3_RB5
2.05	1.97	3.82	3.28	2.9
1.92	1.81	3.72	3.34	2.78
1.78	1.72	3.69	3.29	2.71
1.67	1.69	3.66	3.2	2.62
1.55	1.64	3.63	3.1	2.52
1.57	1.62	3.57	3.07	2.37
1.57	1.56	3.5	3.02	2.27
1.58	1.53	3.46	3.92	2.21
1.52	1.51	3.38	2.9	2.02
		3.3	2.85	1.88
		3.29	2.73	1.83

EC3_LB1	EC3_LB2	EC3_LB3	EC3_LB4	EC3_LB5
3.24	3.12	3.62	4.36	3.34
3.16	3.03	3.3	4.02	3.13
2.88	2.86	3.24	3.78	2.94
2.88	2.71	3.08	3.54	2.62
2.77	2.56	2.88	2.58	2.34
2.59	2.52	2.73	2.39	2.12
2.56	2.33	2.53	1.58	2.12
2.46	2.27	2.46	1.38	2.15
2.44	2.23	2.38	1.27	2.13
2.32	1.96	2.34		2.05
	1.85	2.21		2.01
		2.16		

Appendix E *continued.*

EC5_LB1	EC5_LB2	EC5_LB3	EC5_LB4	EC5_LB5
3.98	3.44	2.74	3.28	2.62
3.99	3.69	2.95	3.23	2.63
4	3.68	2.89	3.21	2.62
3.98	3.65	2.85	3.06	2.5
3.89	3.59	2.69	2.92	2.36
3.81	3.56	2.62	2.91	2.29
3.72	3.47	2.46	2.83	2.21
3.65	3.39	2.35	2.78	2.18
3.6	3.32	2.33	2.76	2.07
3.6	3.27	2.34	2.68	2.05
3.51	3.18	2.32	2.53	2
3.47	3.08	2.25	2.34	1.9
3.4	3.01	2.21	2.32	1.88
3.37	2.87	2.18	2.26	1.82
3.24	2.74	2.11	2.2	1.7
3.21				1.63
3.23				1.57
3.16				

EC6_RB1	EC6_RB2	EC6_RB3	EC6_RB4	EC6_RB5
1.27	2.85	2.55	3.36	4.5
1.2	2.75	2.39	3.28	4.3
1.15	2.63	2.18	3.17	4.22
1.11	2.56	2	2.97	4.01
1.03	2.62	1.84	2.87	3.79
0.95	2.65	1.77	2.71	3.7
0.89	2.67	1.7	2.62	3.52
0.89	2.65	1.61	2.35	3.49
0.89	2.66	1.47	2.12	3.48
0.86	2.68	1.3	1.85	3.45
0.8	2.63	1.11	1.74	3.43
0.84		0.95	1.63	
0.8			1.62	

Appendix E *continued.*

EC6_LB1	EC6_LB2	EC6_LB3	EC6_LB4	EC6_LB5
1.14	2.37	2.2	4.87	5.54
1.11	2.23	2.21	4.78	5.43
1.06	2.14	2.12	4.58	5.32
1	2.03	2.03	4.47	5.12
0.97	1.98	1.9	4.32	4.89
0.89	1.89	1.8	4.2	4.76
0.77	1.67	1.65	4.06	4.69
0.7	1.59	1.59	3.97	4.64
0.63	1.48	1.49	3.92	4.43
0.57	1.38	1.39	3.86	4.38
0.42	1.28	1.15		4.38
	1.19	1.03		
	0.95	0.95		

NC1_RB1	NC1_RB2	NC1_RB3	NC1_RB4	NC1_RB5
2.73	2.48	4.25	3.61	2.18
2.68	2.09	4.14	3.43	2.01
2.64	1.85	3.98	3.25	1.98
2.74	1.72	3.92	3.04	1.85
2.71	1.7	3.78	2.98	1.82
2.73	1.62	3.6	2.77	1.73
2.77	1.61	3.21	2.58	1.74
2.73	1.56	2.52	2.36	1.66
2.73	1.56	2.27	2.12	1.61
2.63	1.47	2.19	1.85	1.63
2.63	1.38	2.13	1.69	1.56
2.6	1.22	2.09	1.56	1.62
2.55	1.1	2.07	1.53	1.6
2.47	0.79	2.11	1.51	1.55
2.36	0.77	2.12	1.59	1.48
2.34	1.05	2.24	1.65	1.42
2.33	0.93	2.38	1.65	1.42
2.42		2.39	1.66	
2.42		2.39		
2.44				

Appendix E *continued.*

NC3_RB1	NC3_RB2	NC3_RB3	NC3_RB4	NC3_RB5
1.99	1.34	1.05	1.42	1.64
1.67	1.09	1	1.38	1.36
1.42	0.93	0.95	1.32	1.21
1.36	0.84	0.88	1.29	1.19
1.21	0.75	0.81	1.18	1.07
1.02	0.75	0.88	1.14	0.99
0.87	0.72	0.83	1.1	1
0.75	0.69	0.77	1.08	1.01
0.55	0.66	0.76	0.95	1.01
0.45	0.73	0.76	0.89	0.85
0.34	0.76	0.73		0.77
	0.68	0.72		0.55
	0.61	0.69		0.19
		0.69		
		0.54		

NC3_LB1	NC3_LB2	NC3_LB3	NC3_LB4	NC3_LB5
1.52	1.17	2.45	1.31	0.99
1.32	1.1	2.43	1.26	0.95
1.24	1.06	2.35	1.18	0.87
1.17	0.96	2.28	1.15	0.82
1.1	0.88	2.26	1.09	0.69
1.07	0.86	2.13	1.03	0.66
0.98	0.82	2.12	0.94	0.68
0.96	0.76	2.09	0.89	0.64
0.92	0.7	1.94	0.86	0.65
0.88	0.68	1.93	0.69	0.62
0.9	0.57	1.72	0.67	0.53
0.84	0.54	1.53	0.63	0.44
0.77	0.52	1.12		0.4
	0.46	0.46		

Appendix E *continued.*

NC4_RB1	NC4_RB2	NC4_RB3	NC4_RB4	NC4_RB5
3.49	3.86	3.6	3	2.8
3.22	3.55	3.36	2.39	2.64
2.84	3.31	3.12	2.04	2.5
2.59	3.12	2.9	1.92	2.31
2.16	2.67	2.61	1.79	2.26
1.79	2.55	2.49	1.62	2.04
1.45	2.46	2.27	1.5	1.9
1.37	2.33	2.16	1.35	1.8
1.2	2.26	1.97	1.21	1.72
1.02	2.17	1.85	1.11	1.62
0.84	2.03	1.71	1.02	1.48
0.59	1.04	1.46	0.85	1.35
	0.66		0.47	1.03

NC4_LB1	NC4_LB2	NC4_LB3	NC4_LB4	NC4_LB5
1.38	1.27	1.24	1.75	1.93
1.1	1.12	1.06	1.58	1.73
0.93	0.92	0.84	1.44	1.57
0.87	0.85	0.71	1.29	1.38
0.76	0.83	0.66	1.22	1.22
0.75	0.82	0.69	1.1	1.1
0.72	0.76	0.72	1.06	0.86
0.73	0.7	0.68	0.94	0.71
0.67	0.64	0.71	0.89	0.62
0.59	0.6	0.81	0.77	0.54
0.6	0.71	0.76	0.71	0.5
0.53	0.72	0.7	0.68	0.48
0.49	0.73	0.77		0.41
0.54				

Appendix E *continued.*

PC1_RB1	PC1_RB2	PC1_RB3	PC1_RB4	PC1_RB5
2.31	2.02	2.08	1.73	1.84
2.08	1.87	1.99	1.67	1.69
2.05	1.76	1.94	1.61	1.62
1.95	1.7	1.84	1.61	1.58
1.88	1.63	1.79	1.53	1.53
1.79	1.54	1.7	1.51	1.4
1.72	1.43	1.6	1.44	1.26
1.67	1.36	1.53	1.39	1.2
1.56	1.18	1.46	1.36	1.04
1.45	1.09	1.31	1.22	0.91
1.35	0.92	1.26	1.07	0.83
1.25	0.76	1.13	0.96	0.66
1.1	0.67	0.95	0.83	0.58
0.9	0.52	0.66	0.63	0.46
0.72			0.48	0.37

PC1_LB1	PC1_LB2	PC1_LB3	PC1_LB4	PC1_LB5
2.09	4.2	2.86	2.35	3.05
1.69	3.73	1.83	2.09	2.73
1.4	3.09	1.54	1.93	2.53
1.29	2.7	1.42	1.69	2.25
1.14	2.48	1.28	1.38	2.18
1.09	2.36	1.06	1.19	1.98
0.99	1.96	0.91	1.08	1.84
0.93	1.39	0.77	0.94	1.69
0.87	0.71	0.72	0.79	1.56
0.77	0.61	0.61	0.61	1.37
0.68	0.56	0.55	0.56	1.21
0.64	0.5	0.55	0.47	0.88
0.6	0.58		0.34	0.55
0.57				0.34

Appendix E *continued.*

PC2_RB1	PC2_RB2	PC2_RB3	PC2_RB4	PC2_RB5
1.99	1.59	1.8	1.45	0.72
1.71	1.41	1.65	1.32	0.76
1.65	1.27	1.57	1.21	0.76
1.52	1.02	1.51	1.14	0.73
1.4	0.93	1.42	1.07	0.74
1.32	0.86	1.42	0.99	0.72
1.22	0.8	1.36	0.98	0.67
1.18	0.76	1.25	0.88	0.61
1.19	0.72	1.17	0.8	0.56
1.14	0.68	1.1	0.75	0.45
1.04	0.54	0.92	0.68	0.41
0.87	0.49	0.75	0.6	
0.72	0.44	0.56	0.44	
	0.28			

PC2_LB1	PC2_LB2	PC2_LB3	PC2_LB4	PC2_LB5
1.32	0.84	1.79	3.48	2.76
1.26	0.8	1.39	2.79	2.51
1.05	0.84	1.21	2.45	2.19
0.91	0.83	1.13	2.09	2.06
0.85	0.8	0.96	1.89	1.89
0.81	0.72	0.77	1.84	1.84
0.8	0.63	0.75	1.78	1.82
0.71	0.6	0.66	1.72	1.8
0.69	0.55	0.62	1.62	1.81
0.69	0.48	0.7	1.54	1.74
0.66	0.44	0.69	1.45	1.59
0.61	0.38	0.51	1.35	1.28
0.56	0.33	0.36	1.03	0.99
0.56	0.29		0.57	0.27
0.36				

Appendix E *continued.*

PC3_RB1	PC3_RB2	PC3_RB3	PC3_RB4	PC3_RB5
1.78	4.41	4.53	2.89	0.58
1.62	3.95	4.39	2.31	0.54
1.39	3.3	4.41	1.77	0.68
1.28	1.39	3.4	1.4	0.67
1.2	1.15	0.97	0.96	0.69
0.96	0.95	0.76	0.79	0.69
0.88	0.76	0.69	0.64	0.67
0.76	0.65	0.57	0.53	0.67
0.74	0.59	0.49	0.46	
0.7	0.52	0.47	0.46	
0.85	0.44	0.45		
	0.41	0.53		
	0.45			

PC3_LB1	PC3_LB2	PC3_LB3	PC3_LB4	PC3_LB5
1.71	1.34	1.22	1.77	1.12
1.56	1.22	1.11	1.66	1.17
1.52	1.08	1.02	1.62	1.14
1.5	0.98	0.97	1.54	1.12
1.44	0.91	0.92	1.34	1.12
1.44	0.82	0.74	1.22	1.09
1.36	0.73	0.66	1.13	1.05
1.37	0.67	0.57	1.04	1.05
1.17	0.69	0.54	0.91	1
1.02	0.69	0.52	0.81	0.95
	0.64	0.6	0.75	0.85
		0.6	0.72	

Appendix E *continued.*

PC6_RB1	PC6_RB2	PC6_RB3	PC6_RB4	PC6_RB5
1.3	1.1	0.91	0.8	0.76
1.04	1	0.76	0.7	0.65
1.01	0.95	0.71	0.63	0.6
0.99	0.78	0.64	0.59	0.58
0.97	0.7	0.6	0.59	0.57
0.98	0.65	0.54	0.57	0.57
0.86	0.65	0.48	0.55	0.48
0.78	0.59	0.49	0.44	0.43
	0.69		0.34	

PC6_LB1	PC6_LB2	PC6_LB3	PC6_LB4	PC6_LB5
0.93	0.74	0.62	1.2	0.89
0.78	0.66	0.59	1.1	0.76
0.66	0.61	0.55	0.93	0.62
0.57	0.56	0.5	0.76	0.53
0.54	0.59	0.51	0.63	0.49
0.45	0.63	0.45	0.54	0.44
0.44	0.66	0.4	0.47	0.36
0.4	0.67	0.37	0.43	0.32
0.36			0.34	

PC7_RB1	PC7_RB2	PC7_RB3	PC7_RB4	PC7_RB5
4.48	3.75	4.18	4.11	1.73
4.28	3.49	3.78	3.77	1.53
4.14	3.35	3.4	3.65	1.39
3.94	3.27	3.24	3.52	1.31
3.68	3.05	3.03	3.26	1.16
3.15	2.63	3.03	3.13	1.06
2.57	2.38	2.81	2.81	0.93
2.02	2.33	2.62	2.41	0.89
1.7	1.84	2.09	1.46	0.83
1.14	1.38	1.66	0.97	
1.04	1.03	1.26	0.63	

Appendix E *continued.*

PC7_LB1	PC7_LB2	PC7_LB3	PC7_LB4	PC7_LB5
1.86	1.75	1.56	1.7	2.14
1.73	1.4	1.4	1.51	1.86
1.64	1.14	1.18	1.4	1.64
1.45	0.99	1.01	1.36	1.45
1.16	0.9	0.94	1.22	1.13
1	0.76	0.77	1.03	0.83
0.97	0.64	0.66	0.87	0.69
0.94	0.58	0.52	0.71	0.69
0.68	0.5	0.47	0.54	
0.59		0.42	0.4	
0.68		0.37		

Vita

Ryan Foster was raised on a farm near Clinton, TN. As an adolescent, he spent much of his time exploring the forests and streams of rural Anderson County. It was during this time that he began to grow an appreciation for nature. As an undecided college undergrad at the University of Tennessee, Ryan took courses that interested him and invited him to see the world from different perspectives. Ryan chose Geography as his major because it promotes an interdisciplinary approach. After receiving his Bachelors of Arts degree in 2003, Ryan spent a couple of months backpacking in the wilds of the Northern Rockies. Upon returning home to Tennessee, he worked with a land survey crew, and then with a landscaper specializing in native plants. Feeling unchallenged, Ryan decided to further his formal education with a focus on watersheds. While in graduate school, he was given the opportunity to contribute to a wide array of research projects in differing disciplines. But, through his fieldwork in the Little River watershed, he was able to watch study sites change over time, during the ups and downs of wet and dry years. After repeated visits to the field, and one worn-out pair of waders later, Ryan truly began to recognize the dynamic nature of these systems. In August of 2010, he was awarded a Master of Science degree in Geography from the University of Tennessee, Knoxville. Ryan hopes to have a career where he can utilize his past experiences and develop new skills and interests. For Ryan, true enjoyment comes from his interactions with the natural world. If he can make a living by understanding and contributing to ecosystem health and functionality, then he will consider his life well lived.