DISSERTATION

BIOTIC CONTROLS ON POST-GLACIAL FLOODPLAIN DYNAMICS IN THE COLORADO FRONT RANGE

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2011

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ABSTRACT

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A recent surge in ecogeomorphic research has shed light on the numerous feedbacks and couplings between physical and biotic processes in developing geomorphic and ecologic process and form. Recent work has shown the critical importance of vegetation in altering overall channel form and developing meandering channel systems. This dissertation expands on planform classifications and the understanding of biotic-physical couplings through examining two components of post-glacial floodplain evolution in broad headwater valleys in the Colorado Front Range. First, I evaluate the role of beaver in Holocene floodplain evolution in low-gradient, broad headwater valleys to understand the historical range of variability of sedimentation processes and to determine the role of beaver in altering channel complexity and how that contributes to spatial heterogeneity of sedimentation processes. These objectives were carried out in Beaver Meadows and Moraine Park in Rocky Mountain National Park through analysis of subsurface sediment, geomorphic mapping, and aerial photography analyses. Second, I examine the role of various riparian species in stabilizing streambanks in order to determine the relative importance of bank versus root characteristics in stabilizing streambanks and to develop a functional classification of riparian vegetation in stabilizing streambanks. Data for this portion of the project were collected in three study sites along an elevation gradient in the Colorado Front Range: Phantom Canyon on the North Fork Poudre River (1920 m), North Joe Wright Creek (3000 m), and Corral Creek (3100 m), all of which are located in the Cache la Poudre drainage. For fourteen species (4 trees, 3 shrubs, 3 graminoids, and 4 herbs), root tensile strength, root size distribution, and root morphology were characterized. Streambank geometry and stratigraphy from Moraine Park were combined with vegetation characteristics in a physically-based bank stability model to determine the role of various physical bank characteristics and root characteristics in stabilizing streambanks.

Examination of Holocene sedimentation processes in these broad, low-gradient headwater valleys, which are fairly disconnected from their hillslopes, lends support to the beaver-meadow complex hypothesis that uses beaver dams as the mechanism to explain the accumulation of fine sediment in glacial valleys. In the study valleys, sediment associated with beaver dams account for a significant (30-50%) portion of the relatively thin alluvium overlaying glacial till and outwash. Sedimentation rates were temporally and spatially heterogeneous across the floodplain, with higher rates associated with beaver pond sedimentation. Fluvial complexity, in terms of multi-thread channels, islands, and channel bifurcations, increases with beaver populations and number of ponds, and magnifies the potential for beaver damming because of increased channel length, which accelerates the development of fluvial complexity and valley sedimentation.

Bank stability modeling determined that although bank and root characteristics are interrelated, physical bank characteristics play a larger role in determining bank stability than root characteristics. However, within similar streambank types, vegetation type is a strong predictor of overall streambank stability, and streambanks without vegetation were consistently the least stable. The presence of rhizomes, the maximum root diameter, the root tensile strength, and the lateral root extent of each species are the most important root characteristics in determining streambank stability. Riparian shrubs (willows) and riparian trees are the best streambank stabilizers. Upland trees and graminoids are mid-level bank stabilizers, and herbaceous species are mid/low-level bank stabilizers.

In addition to sediment and flow regimes, the two biotic processes studied interact to form the overall channel planforms that dominate these broad headwater valleys. Assuming a relatively snowmelt-dominated flow regime and a gravel-bed channel system in the headwaters, four planform regimes are identified based on low to high beaver populations and the abundance and presence of xeric or riparian vegetation. Without beaver or bank-stabilizing vegetation, a braided channel planform will likely develop. With bank stabilizing vegetation but without a sustainable beaver population, a single-thread meandering channel will form, which only has a thin riparian vegetation strip and small fluvial influence on the overall valley ecological and geomorphic processes. With a sustainable beaver population and riparian vegetation along the streambank, a stable multi-thread channel system will form which has implications for the ecological and physical form and process of the valley. A valley with abundant beaver but little to no bank-stabilizing vegetation is impossible under natural conditions, because riparian vegetation is necessary to sustain a beaver population and their dam-building. However, a narrow, incised channel may be observed as a legacy effect from beaver removal. The probable planform regimes can be inferred over the range of Holocene climate conditions in the Colorado Front Range, and understanding of these biotic-physical interactions should be a crucial component of any management decisions for geomorphic or ecologic conditions.

ACKNOWLEDGEMENTS

Although completing a dissertation, after several summers of field work and years concentrating on a complex question, feels like a great personal accomplishment, it would not have been possible without financial support, academic guidance, research assistance, and emotional support from others. First, I would like to thank the U.S. Forest Service for funding this project and supporting this research to gain a better understanding of riparian areas on USFS lands. Additional funding, especially for field work, was provided by the Colorado State University Department of Geosciences Graduate Research Fund and a Geological Society of America Graduate Research Grant. Additionally, I would like to thank several agencies for allowing access to field sites and supporting field work and research: Clifford Hoelscher with the City of Fort Collins for allowing access to Phantom Canyon below Halligan Dam, Rocky Mountain National Park, and the Arapahoe-Roosevelt National Forest.

I am very grateful to my advisor Ellen Wohl, whom it has been an honor and joy to work with. After five years, many field outings together, and many pieces of humbly-given advice from Ellen, I feel more like a colleague and friend than simply a student. I am extremely thankful for the quick returns she has given me on edits and comments on dissertation drafts (and many other types of drafts through the years), which has allowed me to finish writing on such a short timeline. Her support has been one aspect of graduate school that has always given me clarity and reduced my stress levels. I am thankful not

only for the direct education she gave me, but also for exposing to me to such varied field work, encouraging me to attend many conferences, and giving me opportunities to co-author papers with her. I want to thank Dave Merritt for his energy and dedication in acting almost as a co-advisor through the years. Our meetings were always very productive with interesting philosophical discussions, and I look forward to continued collaboration. I am thankful to Sara Rathburn and Brian Bledsoe for their time and energy serving on my committee and in helping me to develop as a scientist.

I had many great, motivated field assistants that were essential for obtaining all the data necessary during field seasons and were great company during long, hot, cold, rainy, sunny, and snowy days. Benton Line, Ben Mayer, and Kelly McElwaine each contributed at least a full field season of work, in addition to Kyle Grimsley and Dave Dust who were great helps for a few days each. My field dog Ceci helped keep morale high whenever I was not working on in the national park.

I want to thank Jason Sibold, a forest geographer in the Anthropology Department at CSU, and his graduate student Ali Urza for allowing me to us their dendrochronology lab and teaching me how to mount and count tree cores to obtain ages of the tree specimens for which I obtained root data. I want to thank Natasha Pollen-Bankhead and the entire USDA National Sedimentation Laboratory, for help in making and setting up the RootPuller, and providing feedback and guidance in developing my research questions.

I want to thank the fluvial geomorphology group at CSU for a stimulating and fun environment, and where I have met several life-long friends. Through the years, many geomorphology graduate students have been vital additions to Ellen in helping learn field methods, bounce off ideas, edit drafts, and listen and critique talks. In writing my dissertation, I especially want to thank Jaime Goode and Gabrielle David for helping provide edits and constructive comments. Additionally, I want to thank Natalie Kramer, whose Masters thesis provided valuable geophysical data to better constrain Holocene sedimentation, for an enjoyable summer of field work, brainstorming sessions, and help boofing on the river.

Finally, I want to thank my friends and family for emotional support and providing much-needed, fun diversions from focusing too much on work. I have a developed a great network of friends in Ft. Collins and around the country that have always been there to listen, attempted to remember how to say ‘fluvial geomorphology,’ and always been available to go skiing, running, or kayaking with. I am very thankful to have all of you in my life to keep it more balanced. Thank you to my family, including my aunt Sigrid, my dad Esko, brother Martin, stepsister Adrienne, and stepfather Cliff, for being a fabulous and loving support net. Thank you to the memory of my mother Gunnel, who is still with me when I need her most. And last but definitely not least, thank you to my husband Kevin for supporting me with love and calm energy in all of my ventures—the stressful moments and the joyous ones.

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CHAPTER 1: INTRODUCTION

The field of ecogeomorphology, which examines the interactions and feedbacks between ecological and geomorphic processes, has seen a large increase in interest and publications over the last decade. The Binghamton Geomorphology Symposium has hosted three conferences related to ecogeomorphology in the past 10 years (2011: Zoogeomorphology and Ecosystem Engineering, 2009: Geomorphology and Vegetation: Interactions, Dependencies, and Loops, 2005: Geomorphology and Ecosystems), as compared to only one in the previous 30 years (1995: Biogeomorphology, Terrestrial and Freshwater Systems). An analysis of results from Web of Science supports this observation. There are no articles under the topic ecogeomorphology before 2001 and 18 from 2001 to 2011; 14 articles were published before 2001 under the topic biogeomorphology and there were 63 from 2001-2011.

1. Overview of Ecogeomorphology

Links between geomorphology and biotic processes or controls have been recognized since the late to middle-late nineteenth century when geomorphology was recognized as a separate discipline (Viles, 1988). Researchers recognized that biota, such as vegetation and burrowing mammals, played a role, although usually delegated as a minor or rare phenomenon, in shaping landform processes. During the mid-twentieth century when geomorphologists focused on creating conceptual and quantitative models of landform and fluvial processes, biotic processes were largely ignored and processes were assumed to occur in a solely abiotic environment. However, the recent focus on ecogeomorphology has incorporated biota and ecological processes into the general understanding of landscape form and change. Feedbacks and couplings between biotic and morphologic processes have been recognized in particular with the transition between braided and meandering channels (Murray and Paola, 2003; Tal and Paola, 2007).

Several terms have been used to describe this discipline (Wheaton et al., 2011), starting with Viles (1988) whose term ‘biogeomorphology’ was meant for geomorphology that explicitly considers the role of organisms. ‘Biomorphodynamics’ was proposed by Murray et al. (2008) to specifically refer to processes with two-way couplings between biotic and abiotic processes. I prefer to use the term ‘ecogeomorphology’ (Hupp et al., 1995; Osterkamp and Hupp, 2010), which does not restrict ideas only to feedbacks, although abiotic-biotic feedbacks are probably responsible for the formation of various landforms, but at the same time expands thinking from a single organism to ecological systems. However, these terms in addition to others have been, and will likely continue to be, used interchangeably in the literature (Wheaton et al., 2011).

1.1 Ecogeomorphic Research

Research within ecogeomorphology spans spatial and temporal scales, includes flora and fauna, and investigates effects in multiple geomorphic settings from fluvial- to aeolian-dominated environments. Each biotic-geomorphic interaction can be classified into one of three categories and classified as active or passive: bioconstruction, bioprotection, and bioerosion based on the biotic effect on the geomorphic environment (Naylor et al., 2002). On the basin scale, terrain and topography can be products of the hydrologic effects of vegetation (Ivanow et al., 2008 a, b; Yetemen et al., 2010) and sediment movement by trees (Roering et al., 2010). On the hillslope level, the effect of treethrow and bioturbation on sediment movement and hillslope evolution has been quantified (Norman et al., 1995; Heimsath et al., 2002; Roering et al., 2002; Gabet et al., 2003; Embleton-Hamann, 2004; Phillips and Marion, 2006).

A substantial amount of work has focused on the fluvial environment, from the floodplain to the channel, focusing on in-channel processes at the grain-level to planform changes at a channel segment scale (*sensu* Frissell et al., 1986). It has been widely accepted that floodplain vegetation increases roughness and reduces flow velocities (Chow, 1959), but, recently, fine-scaled measurements have determined the role of different types of vegetation in influencing flow dynamics and affecting scour and sedimentation (e.g., Bouma et al., 2005; Hopkinson and Wynn, 2009; Bouma et al., 2009; Shafroth et al., 2010). Vegetation has long been recognized as a natural remedy for bank erosion and this has been extensively quantified and modeled through testing of root tensile strengths and understanding the role of bank properties and hydrologic processes in bank failure (Simon and Collison, 2002; Pollen-Bankhead and Simon, 2009). Additionally, these mechanisms have been applied to the role of exotic plants in causing or accelerating channel change (Pollen-Bankhead et al., 2009; Dean and Schmidt, 2011; Jaeger and Wohl, 2011). On the planform scale, the addition of riparian vegetation has been shown to cause braided channels to form meandering channel systems or less dynamic multi-thread channel systems with an increase in stable islands, using evidence from numerical models (Murray and Paola, 2003), physical experiments (Tal and Paola, 2007 & 2010; Braudrick et al., 2009), the geologic record (Davies and Gibling, 2010 a, b), and field observations of the effects of instream wood (Collins and Montgomery, 2002; Jeffries et al., 2003; Gurnell and Petts, 2006).

Investigations into faunal interactions with fluvial processes have focused on the role of beaver on reach-scale channel and floodplain processes and fish and macroinvertebrates within the channel substrate. Beaver have received attention for altering floodplain groundwater hydrologic processes, attenuating flood discharges, increasing in-channel sedimentation, and contributing to complexity (Naiman et al., 1986; Gurnell, 1998; Persico and Meyer, 2009; Westbrook et al., 2010; Burchsted et al., 2010). Salmon, in addition to crayfish, have been shown to have a measurable impact on substrate disturbance and movement (Statzner et al., 2000; Statzner et al., 2003; Statzner and Peltret, 2006; Statzner and Sagnes, 2008; Hassan et al., 2008). Conversely, macroinvertebrates and biofilms can contribute to cohesion between grains (Nunokawa et al., 2008; Salant, 2011).

In other geomorphic environments, vegetation has been shown to cause erosion by concentrating flows in wetlands and through the alteration of sedimentation patterns to act as an ecosystem engineer in marshes (Temmerman et al., 2007; Bouma et al., 2005; Brun et al., 2009). In aeolian environments, vegetation can stabilize dunes (Reitz et al., 2010). In prairie settings, animals such as bison and prairie dogs create wallows, which may change drainage patterns (Coppedge et al., 1999; Coppedge and Shaw, 2000; Trager et al., 2004; Butler, 2006).

1.2 Future Directions in Ecogeomorphology

Several review papers on biogeomorphology and ecogeomorphology have evaluated the progress and future research demands within this relatively young sub-discipline. In terms of interactions between fluvial processes and vegetation, Osterkamp and Hupp (2010) suggest research directions in interactive effects between vegetation and soil genesis, influence of flow regime on floodplain biota, effects of invasive exotic plants on native communities, and possible effects of climate change. The interdependency of vegetation patterns and geomorphic processes makes identifying influencing factors difficult but will be necessary in upcoming research. In the broader field of biogeomorphology, Naylor et al. (2002) proposed seven research focii: 1) extending observations of bioprocesses across larger spatial and temporal scales; 2) investigating the previously difficult to study processes of bioconstruction and bioprotection; 3) fully investigating complexities between ecologic-geomorphic interactions in-depth in one area; 4) understanding how an interaction of processes, including bioprocesses, create landforms; 5) solving scale issues and using modeling to obtain meaningful insights; 6) using theoretical advances in geomorphology, such as non-linear dynamic systems and self-organization to understand biogeomorphic processes; and 7) making better use of conceptual and process models. These review papers focus on one-way interactions and allude to the need to examine complex interactions between biotic and geomorphic processes. Biomorphodynamic processes, which explicitly deal with two-way couplings and feedbacks of biotic and physical processes, are seen as the next step in ecogeomorphic research, according to Murray et al. (2008). They suggest examining the possibility of two-way couplings in environments where previously only unidirectional impacts have been recorded. Additionally, field data of ecological and geomorphic processes should be collected at large scales to complement small-scale, short-term field and experimental data. To add to this list of future ecogeomorphic research directions, I suggest that ecogeomorphic interactions and processes become an integrated portion of all geomorphic studies. Although studies are still needed to isolate the effects and feedbacks between ecologic and geomorphic processes, the role of ecologic interactions should be evaluated in any study that aims to evaluate geomorphic processes or history. Additionally, effort should be placed into revisiting previous studies and asking whether biotic processes may also be playing a role, particularly in cases of erosion and transport of sediment and in the magnitude or location of sediment accumulation.

The question has been raised of whether there is a permanent or unique effect of life on landforms. The hypothesis of a topographic signature of life was explored by Dietrich and Perron (2006); however, they concluded that although life may increase the occurrence of certain landforms, there are no unique landforms that can only form in the presence of biotic interactions. The cumulative effects of the higher probability occurrence of landforms created by interactions with ecologic processes have not been fully investigated. To understand the role of biotic processes in shaping landforms, Dietrich and Perron (2006) propose the inclusion of biological processes in geomorphic transport laws. Additionally, the idea of evolutionary geomorphology, the possibility that geomorphic landforms tied to biotic processes have evolved and/or disappeared with the evolution of life, has been raised by Corenblit and Steiger (2009). These two proposed hypotheses raise more questions of the role of ecogeomorphic processes and in particular biomorphodynamic feedbacks: is there a topographic signature of life at various temporal or spatial scales? Does the greater occurrence of a certain biotically influenced geomorphic form create feedbacks to ecological systems? Has the probability of occurrence of various geomorphic forms changed throughout time with biological evolution?

Several reviews mention the concept of competing time scales of geomorphic and ecologic processes (Naylor et al., 2002; Murray et al., 2008). Feedbacks between ecologic and geomorphic systems will only occur if processes occur at relatively similar time scales. Vegetation growth in braided channels can cause channel change because the time scale of vegetation growth is of the same temporal order of magnitude as the occurrences of flooding, bank failure, cutoff creation, and avulsions. The importance of competing time scales in determining the resulting geomorphic form is an area ripe for further exploration.

2. Dissertation Objectives

The gaps in the ecogeomorphic research literature presented above are numerous and provide exciting opportunities for researchers for many decades. By focusing on a specific geomorphic setting in a particular region; namely, low-gradient headwater valleys in the Colorado Front Range, I will add to the conceptual understanding of ecogeomorphic processes. The research presented in this dissertation fills several of the functions of future research needs proposed above. First, I expand the understanding of influences of biota on geomorphic form to a longer temporal scale of several thousand years. Second, through understanding effects of beaver and vegetation in influencing bank stability and long-term channel change and how the geomorphic change can affect further ecologic processes, I add to two-way coupling and conceptual feedback models.

This dissertation examines the role of two biotic influences, beaver and riparian vegetation along streambanks, in contributing to floodplain evolution at a range of spatial and temporal scales. I examine diverse spatial scales, from processes affecting bank failure at a single bank profile to the effect of beaver in transforming channel complexity and floodplain aggradation at the valley scale. However, the findings related to riparian vegetation along streambanks can be extrapolated to reach- and valley-scale implications. Similarly, beaver-related valley form is a function of bank erosion and channel migration at the sub-reach scale. I also investigate the influence of biotic processes on geomorphic form at a range of temporal scales, from bank failure that occurs under specific hydrologic conditions on a snowmelt hydrograph to sedimentation and channel change that occur over 100s to 1000s of years.

Biomorphodynamic models have shown the profound effect of vegetation on transforming braided channels to anastomosing or meandering channels (Murray and Paola, 2003; Tal and Paola, 2007; Tal and Paola, 2010). However, these experimental studies have focused on the effect of only one type of vegetation in transforming the channel planform. I present bank stability data on several species in multiple vegetation categories that will facilitate conceptual modeling of planform change based on overall vegetation change. Additionally, I integrate ideas of beaver-influenced sedimentation and beaver-influenced complexity from past studies with new results from headwater valleys to understand two-way coupling between beaver and channel dynamics. By understanding biotic interactions and feedbacks with floodplain processes, I can better understand long-term floodplain dynamics. Incorporating results from vegetation effects on bank stability and beaver sedimentation and interactions with fluvial complexity, I present a process-based conceptual model of planform change.

The dissertation is organized into two separate studies focusing on different aspects of biotic influences and feedbacks with geomorphic processes (Figure 1). Chapter Two evaluates the role of beaver in Holocene floodplain evolution in low-gradient, broad headwater valleys, which are the sediment accumulation centers and recorders of disturbance within the erosional context of headwater streams. Two sets of objectives are presented in this chapter: 1) understanding the historical range of variability of sedimentation processes by determining whether there is net storage or transport of sediment and whether sedimentation occurs at a constant rate or in conjunction with episodic events; and 2) determining the role of beaver in floodplain processes by determining the spatial extent of beaver-related sediment throughout the floodplain and in the subsurface and whether beaver dams alter channel complexity. Chapter Three examines the role of various riparian species in stabilizing streambanks. The objectives for this chapter are to: 1) determine the relative importance of vegetation and bank characteristics in stabilizing streambanks; and 2) develop a functional classification of riparian vegetation in stabilizing streambanks based on root characteristics and bank stability modeling.

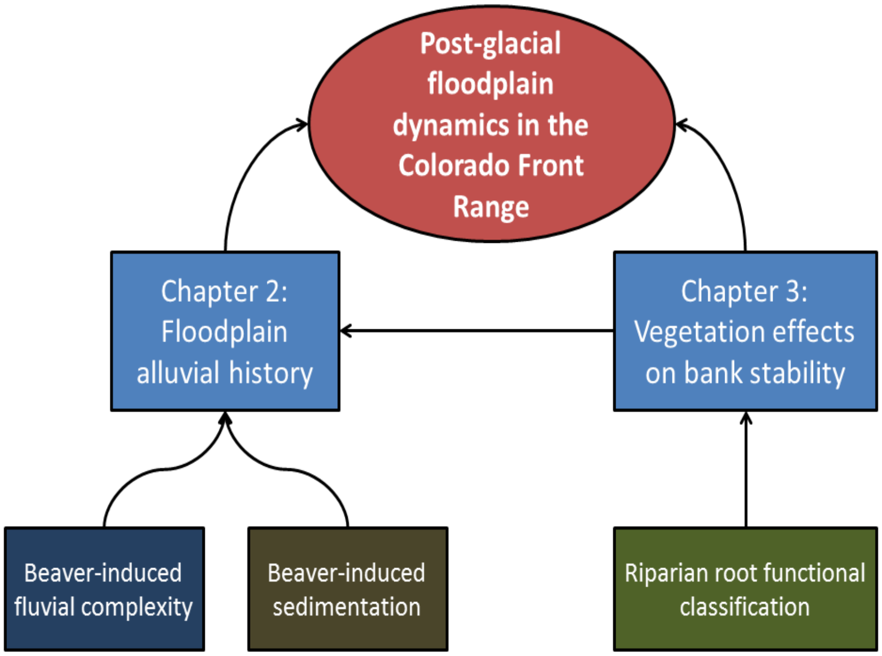

Figure 1. Dissertation organization flow diagram.

In the Synthesis in Chapter Four, I integrate Chapter Two and Chapter Three to present conceptual models of channel changes based on changes in vegetation and beaver populations. The streambank profiles and textural characteristics data for bank stability modeling in Chapter Three were obtained from Moraine Park, which was one of the two sites where I examined Holocene alluvial history in Chapter Two. This was done purposefully to link vegetation effects with Holocene channel planform change and thus floodplain evolution.

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CHAPTER 2: THE ROLE OF BEAVER IN HOLOCENE FLOODPLAIN EVOLUTION, COLORADO FRONT RANGE

1. Introduction

1.1 Valley Sedimentation

Within the fluvial basin, erosion and transportation of sediment is centered in the mountainous headwaters (Schumm, 1977). Removal of sediment from the basin complicates interpretation of the history of geomorphic drivers. The interplay of erosional drivers, depositional settings, and fluvial transport determines the sedimentary record present and also records the biotic and abiotic influences on sedimentation. Low-gradient, unconfined valleys present an ideal location to study alluviation processes and thus the historical range of variability of geomorphic processes. These broad valleys with low stream energies act as temporary sediment sinks within an overall erosional environment.

Valley bottom processes drive channel and watershed evolution. Spatial and temporal variability in sediment delivery, biotic interactions, and hillslope influence interact to shape the landforms present. These landforms create the physical template for riparian zones and human activity commonly concentrates in valley bottoms. This study provides a clearer understanding of the driving processes in valley bottoms and the role of biota, in particular beaver, in determining valley form and processes. This chapter of the dissertation examines sediments stored in selected valley bottom segments of the Rocky Mountains in northern Colorado as a means of inferring processes of sediment storage and removal following the retreat of Pleistocene valley glaciers circa 10,000 years ago.

Valley bottoms record watershed-scale landscape processes through sediment storage and removal over varying time scales. By examining valley bottom sediment, we can answer several questions: 1) Do episodic or gradual processes drive valley bottom alluviation? 2) What is the relative importance of fluvial process, e.g., flooding and lateral channel movement, compared to hillslope processes, e.g., mass movements or wildfires, in floodplain sedimentation? 3) What is the role of biological processes in driving floodplain evolution, in particular beavers, which cause sediment storage behind dams and transport when dams are breached? I examine sediment stored in two valley bottom segments of the Rocky Mountains in northern Colorado to determine the chronology and processes driving post-glacial alluviation. By inferring the relative importance of these processes, we can 1) understand post-glacial landscape processes in the Rocky Mountains and 2) make management recommendations by understanding the natural range of variability of sedimentation rates and processes.

1.2 Beaver-meadow Complex

Beaver (*Castor fiber* in Europe and *Castor canadensis* in North America) are large rodents that build low dams of sediment and wood across stream channels. Although beaver can occupy any portion of a forested stream network, the animals tend to prefer unconfined, low-gradient (<6%) alluvial channels, without coarse or bedrock substrates, and below a stream power threshold (McComb et al., 1990; Gurnell, 1998;

Pollock et al., 2003; Persico and Meyer, 2009). Woody vegetation is a necessary food source, including willow, alder, and maple, but with a strong preference for aspen (Gurnell, 1998).

Beaver are considered ecosystem engineers and their ecological importance is well documented in numerous studies across a range of forested, temperate environments (Naiman et al., 1986, 1988; Wright et al., 2002; Rosell et al., 2005). Their geomorphic significance is less well established. Studies of contemporary beaver dams indicate that beaver activity can alter longitudinal profiles, create localized sediment storage and high magnitudes of sediment transport during potentially catastrophic dam failures (Butler and Malanson, 1995; Gurnell, 1998; Pollock et al., 2003, 2007), and increased extent and duration of overbank flooding and associated alluvial groundwater recharge (Westbrook et al., 2006). John and Klein (2004) showed how beaver dams can increase the potential for channel avulsions; this has been suggested to cause a multi-thread channel network downstream of the dam (Woo and Waddington, 1990; Burchsted et al., 2010). While a beaver dam is active, rates of sediment aggradation behind dams exceed those in adjacent undammed segments of the stream and floodplain (Butler and Malanson 1995). The relative importance of beaver-induced geomorphic changes over hundreds to thousands of years, however, remains uncertain (Persico and Meyer, 2009).

The beaver-meadow complex has been proposed as a mechanism for accumulating significant magnitudes of sediment and maintaining broad, flat valleys in headwater segments. While a beaver dam is active, high rates of sediment aggradation behind dams occur; however, the long-term importance of this aggradation throughout the Holocene is uncertain (Butler and Malanson 1995; Persico and Meyer, 2009). The phrase ‘beaver-meadow complex’ was coined by several workers in the early 1900s who proposed beaver as the cause of fertile low-gradient valleys. Ruedemann and Schoonmaker (1938) suggested beaver as the agent responsible for creating broad plains draining small streams in upstate New York. Previously, these plains had been interpreted as filled glacial lakes. Almost concurrently, Ives (1942) disputed the interpretation of broad wet meadows in northern Colorado as silted up glacial lakes and introduced the idea of a beaver meadow complex. According to Ives (1942), beaver would trap sediment behind dams, form deltaic-like beds, and eventually fill up the valley, while decreasing the gradient and broadening the valley. In contrast to a filled glacial lake, these beaver pond deposits are not spatially extensive, suggesting spatially and temporally variable deposition. Additionally, Rutten (1967) used beaver rather than braided channels to explain aggradation and the formation of subhorizontal flat-bottomed glacial valleys. However, these studies of the beaver-meadow complex are largely inferential and lack systematic data collection of geomorphic forms or volumes of sediment resulting from different depositional processes. It is important to note that all of these workers accepted that glaciation formed the original valley geometry of a broad, low-gradient valley; however, they offered new explanations of the in-filling of these valleys.

There has been little quantitative evaluation of the hypothesized beaver-meadow complex until recently. In addition, the importance of beaver aggradation relative to other alluviation processes has not been quantified for mountainous unconfined valleys, the wide, low-gradient valley segments that store the largest volume of sediment in glaciated, mountainous river networks (Wohl, 2010). Several studies demonstrating the efficiency of current beaver ponds in trapping sediment (Bigler et al., 2001; Bulter and Malanson, 1995; Meentemeyer and Butler, 1999) support the central role accorded to beaver dams in the beaver-meadow complex hypothesis. Quantifying the importance of different depositional processes in valley segments with substantial debris-flow deposition, however, Persico and Meyer (2009) noted only minor effects of beavers in aggradation (<2 m). Persico and Meyer disputed the ability of beaver to cause vertical stacking of beaver-pond packages, and estimated that tens of meters of sedimentation would be necessary to create broad, flat valley floors as Ives (1942) suggested. However, Persico and Meyer did not focus on lower gradient glacial troughs. Beaver-pond sediment does not need to be vertically stacked and spatially extensive in order to be significant. Spatially heterogeneous sediment patches can form over time from cycles of beaver colonization and abandonment (Westbrook et al., 2011). If relatively shallow post-glacial alluvium overlies thicker glacial deposits, then even a few meters of patchy beaver-induced sedimentation can constitute a significant percentage of this alluvium.

As the moniker ‘ecosystem engineers’ suggests, beaver play a significant role in transforming geomorphic processes and landforms. Beaver activity can cause alteration of longitudinal profiles, high magnitude of sediment transport during potentially catastrophic dam failures (Gurnell, 1998), and increased groundwater recharge (Westbrook et al., 2006). John and Klein (2004) showed how beaver dams can increase the potential for channel avulsions and this has been suggested to cause a multi-thread channel network downstream of the dam (Woo and Waddington, 1990; Burchsted et al., 2010).

1.3 Importance of Historic Range of Variability

As previously mentioned, mountainous headwaters tend to act as sediment sources (Schumm, 1977; Milliman and Syvitski, 1992), with relatively minor sediment storage relative to lowland portions of a drainage basin. Mountainous headwaters also display substantial longitudinal variability in valley geometry, with limited wider, lower gradient portions of the river network that are capable of substantial sediment storage (Wohl, 2000, 2010). Low-gradient, unconfined valleys thus present an ideal location to study alluvial processes and the historical range of variability of geomorphic processes. In the context of this study, I define historical as encompassing the period between about 5 ka and the initial exploration of the region by people of European descent during the first decade of the 19th century. Given the climate variability during the late to middle Holocene, fluvial and biotic conditions are more likely to have been comparable for this 5000 year period. Many of the valley bottoms in the Colorado Rockies have been extensively altered by diverse land uses during the past two centuries. Characterizing historical range of variability for these landscapes becomes particularly important as resource managers seek to restore riparian ecosystems.

The magnitude and rate of post-glacial sedimentation resulting from beaver activity likely reflect Holocene hydrology and sediment yield, which in turn are a function of climate, vegetation, and hillslope processes. All of these parameters varied during the Holocene. Beaver populations and dam-induced sedimentation and multi-thread channels also presumably varied during the Holocene, creating some range of historical variability prior to when fur trappers began removing beaver from the study area during the first decade of the 19th century. With the reduction of beaver populations, the beaver-meadow complex changes and may lose significance in valley or channel formation. Without beavers, the geomorphic and ecological systems can change to an alternative stable state that is fundamentally outside of the range of historic variability (Sutherland, 1974). For river and ecosystem restoration, the trajectory of the current and past valley formation determines the available habitat template and possibilities for future geomorphic process. Natural range of variability ecosystem management is based on the concept that past processes provide context for management of ecological systems and that disturbance-driven heterogeneity is an important attribute of any ecological system (Landres et al., 1999). Therefore, an understanding of historical, natural patterns of sedimentation and channel complexity can be used as a model of how ecological and geomorphic systems have evolved together (Veblen and Donnegan, 2005).

1.4 Objectives

1.4.1 Valley Holocene Sedimentation Hypotheses

Many studies have quantified rates of floodplain sediment accumulation using a variety of different techniques; e.g., morphosedimentary unit interpretation and dendrochronology (Boucher et al., 2006), or nuclear bomb fallout isotopes (He and Walling, 1996; Soster et al., 2007; Amos et al., 2009). Commonly, floodplain stratigraphies are documented for floodplains of large, low-gradient river systems, such as the Rhine (Hoffman et al., 2009), but smaller, steeper drainage basins have also been used to record different periods of sedimentation, attributed to different climates and land uses (Leigh and Webb, 2006).

In order to describe the depositional processes in contemporary time as well as temporal changes during the recent Holocene and changes in later extent of these processes, four objectives will be addressed. First, mapping of the geomorphic depositional features is used to determine any hillslope contributions, evidence of buried beaver dams, existing or in-filled ponds, and extent of current or abandoned fluvial channels. Second, the stratigraphic signature of these different depositional environments in modern features is described in order to recognize the features in the subsurface. Third, the volume and depth of the upper most layer of fine sediment, termed the near-surface fine unit, that caps coarser sediment from glacial outwash, is characterized and quantified. Finally, ages and rates of deposition are quantified for the near-surface fine unit. Late Holocene history can be constrained through the development of a chronology and estimation of sedimentation rates for the near-surface fine unit.

Two main sets of hypotheses address the sedimentation supply, rates, and processes. The first set of hypotheses addresses the relative transport versus sediment supply in these glacial troughs. Note that these hypotheses can be tested at various temporal time scales: averaged over the entire Holocene, averaged over a shorter time period, or at the scale of a single disturbance or geomorphic event.

$H1_0$: The floodplain is in a steady state, with the transport capacity being approximately equal to the sediment supply, so there is no net storage of sediment.

In a steady state system, sediment can still be stored, but an equal amount of sediment would be transported out of the system. This hypothesis may be supported if dating of organic material yields mostly recent dates or mostly very old dates.

H1$_{a1}$*: The transport capacity exceeds the sediment supply entering the valley, so there is no new storage or older sediment is being removed.*

If transport capacity exceeds sediment supply, the channel may meander through a thin veneer of Holocene sediment. In that case, I would expect to see little to no modern sediment with a basal date for the fine unit of approximately 10,000 y B.P. or just after a more recent neoglacial time, e.g., 3000 y B.P (Elias, 1996). Because of the low stream power in these low-gradient valleys, it is unlikely that the channel is transporting glacial outwash sediment of large grain sizes out of the glacial trough.

H1$_{a2}$*: The floodplains have a greater sediment supply than transport capacity and thus accumulate and store sediment on the floodplain.*

In these low-gradient, unconfined valleys, there are more processes that could contribute to sediment storage from low transport capacities than higher transport capacities. The glacial troughs likely act as reservoirs for watershed sediment. Various external and fluvial processes can cause transport or storage of sediment in unconfined, low-gradient valleys. External causes of transport include beaver dam breaches or climatic changes. It is unknown, however, if a beaver dam breach will have large consequences in these low-gradient reaches, and dams may not be breached often, but instead, abandoned because of infill of sediment. Possible climatic changes during neoglacial times could increase flooding magnitude. Fluvial causes of transport include lateral channel movement resulting in net erosion and a destabilized base level. These valleys are bounded by high-gradient channel segments formed in bedrock or very coarse alluvium, which would resist a base level change. Storage of sediment can be caused by five external factors: colluvium, fire, beaver dams, riparian vegetation, and climatic changes. Increased sediment input to valley bottoms from colluvial sources such as debris flows is not likely important because these valleys are fairly disconnected from hillslopes. Increased sediment input from hillslope and tributary catchment erosion following fire may not occur frequently enough to be significant at these elevations. Climatic changes that reduce transport capacity may cause increased sedimentation. Beaver dams, causing impoundment of fine sediment and increasing overbank flows, likely contribute to sediment storage. The expansion of riparian vegetation will further reduce velocities of overbank flows in these low-gradient systems and reduce bank erosion, contributing to net aggradation. Fluvial processes that promote sedimentation include lateral channel movement that would cause lateral accretion and overbank flooding causing vertical accretion.

The second set of hypotheses addresses the rate and type of alluviation processes, in terms of constant rates, episodic events, and overall magnitude. The depth to bedrock has been constrained by Kramer (2011) through seismic and ground-penetrating radar imaging. These results set a constraint on the amount of sediment that is stored and are presented in Section 2.5.

H2$_0$*: The floodplain is built via a constant rate of accretion from overbank flood deposits.*

Following glacial outwash from the Pinedale glaciation at about 10-15 ka in the study areas (Madole, 1980; Madole et al., 1998), fluvial processes dominated alluviation through overbank flooding accretion. If episodic events are rare because colluvium is not introduced, beavers play a small role in sediment storage, and fires are infrequent in this area, then the nearly annual snowmelt-driven overbank flooding will dominate sedimentation.

H2$_{a1}$*: The floodplain was built rapidly from glacial outwash with a thin veneer of Holocene sediment.*

Contrary to the first hypothesis, the floodplain was built very rapidly from glacial outwash sediment and only contains a thin veneer of Holocene sediment. Figure 2 shows the two end members of the continuum of rapid to gradual sedimentation of the floodplain.

H2$_{a2}$*: Episodic events such as beaver fluctuations, wildfire, or rare large floods (dam breaks) dominate alluviation of glacial troughs.*

There may be a constant rate of gradual sedimentation resulting from the fluvial processes of lateral channel movement and overbank flooding. However, episodic events, such as beaver dam sedimentation, riparian vegetation expansion, fire, and colluvial inputs, will interrupt the background rate with rapid sedimentation (Figure 2).

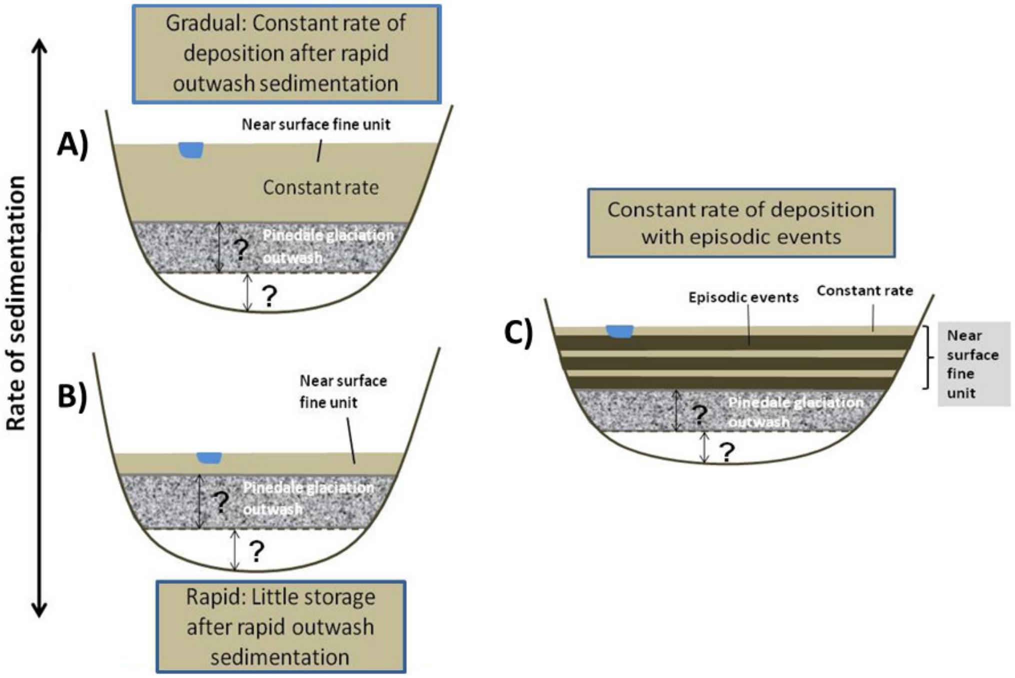

Figure 2. Schematic diagram of three possible Holocene sedimentation scenarios, which are presented in a set of hypotheses above. Each schematic shows cross-section of valley geometry, with various stratigraphies, and modern channel shown in blue. The null hypothesis ($H2_0$) is shown in schematic (A), the first alternate hypothesis ($H2_{a1}$) is in schematic (B), and the second alternate hypothesis ($H2_{a2}$) is shown in schematic (C).

1.4.2 Holocene Beaver Aggradation Hypotheses

Sediments deposited in valley bottoms record watershed-scale landscape processes through sediment storage and removal over varying time scales. The role of beaver through the Holocene is examined to answer the following questions: 1) What is the role of beaver in driving floodplain evolution, and how spatially and temporally discontinuous is sedimentation? and 2) Do beaver dams alter channel complexity and promote greater magnitudes of sedimentation throughout a valley? Answering these questions will constrain the processes driving post-glacial alluviation and the chronology of this alluviation. I will determine the historical range of variability of valley-bottom processes and be able to make management recommendations of the importance of beaver. Additionally, the beaver-meadow complex hypothesis will be revisited to determine whether beaver have fundamentally changed processes in post-glacial alluviation by altering sedimentation or channel form.

Two sets of hypotheses are tested in relation to the role of beaver in valley aggradation. The first set of hypotheses tests whether the beaver-meadow complex is a valid explanation for the aggradation of fine sediment in low-gradient, broad valleys. The second set of hypotheses addresses whether beaver alterations to the channel affect fluvial complexity.

$H3_0$: Beaver-induced sedimentation is an insignificant amount (<25%) of the total post-glacial alluvial sediment.

If beaver-related sediment comprises a small percentage of the total post-glacial alluvium, it can be inferred that beaver had a less significant impact on sedimentation than other hillslope and valley processes. Therefore, it would be unlikely that beaver-meadow complexes dominated the valley landscape and contributed to valley sedimentation. If the null hypothesis is supported, the beaver-meadow complex hypothesis as described by previous workers (Ruedemann and Schoonmaker, 1938; Ives, 1942; Rutten, 1967) is not supported.

H3$_a$: Beaver-induced sedimentation is a significant amount (>25%) of the total post-glacial alluvium sediment.

If the amount of beaver-related sediment within the post-glacial alluvium is a relatively significant percentage, then it can be concluded that a beaver-influenced fluvial network has occupied the valley over a significant time period through the Holocene, or that beaver-induced sedimentation is sufficiently persistent to dominate the Holocene record. Support of the alternative hypothesis would also lend validation to the beaver-meadow complex hypothesis for a mechanism to explain the accumulation of fine sediment. Note that a large depth or volume of beaver-related sediment is not necessary for the beaver-meadow complex to be supported, but simply a significant percentage of the post-glacial alluvium

H4$_0$: The beaver activities of building dams, creating ponds, and excavating canals do not increase fluvial complexity in the study area or alter the system from a single- to a multi-thread planform.

With low beaver activity and thus a relatively small number of beaver dams and associated ponds, there may be little alteration to the overall fluvial network in a broad valley. There likely exists a threshold of beaver population or activity for changes to affect the entire fluvial planform in a valley. Additionally, beaver activities may not cause changes in fluvial complexity if the fluvial processes, including streambank processes of erosion and retreat, have a stronger signal than manipulations of the channel by beaver.

H4$_a$*: The beaver activities of building dams, creating ponds, and excavating canals increase fluvial complexity in the study area by promoting bifurcation and islands, and by altering the system from a single- to a multi-thread planform.*

Dams built by beaver are leaky systems that allow some movement of water and sediment through the dam (Burchsted et al., 2010) and can cause channels to avulse or the main channel to bifurcate. Canals built by beavers provide a flow path for flooding induced by dams and can be incorporated into the channel network. Through these processes, a more complex channel network with multiple threads can form through a broad valley. With greater fluvial complexity, there is greater potential channel length for beaver damming and thus the original added complexity begets more complexity. A valley system with multiple channels, each with several beaver dams trapping sediment, would further support the beaver-meadow complex by increasing the effect of beaver-related sediment over a lateral and longitudinal spatial scale rather than only temporal scales.

2. Study area

2.1 Geographic location and characteristics

Several episodes of glaciation formed the valleys of the Colorado Front Range. This provided the template of the valley geometry for Holocene processes. The most recent glaciation, known as the Pinedale glaciation, extended down to approximately 2300 m (Madole et al., 1998) and retreated approximately 10,000 years ago (Madole, 1980), but the study areas, which are situated close to the terminal moraine, were probably deglaciated by 15,000 y BP. Holocene wildfire chronology has been documented using fire scars on ponderosa pines (Laven et al., 1980). Streamflows for the past 300-600 years have been reconstructed for the upper Colorado and South Platte River basins using dendrochronologic methods (Woodhouse and Lukas, 2006), and mid to late Holocene paleoclimate has been constrained in the Southern Rocky mountains (e.g., Elias et al., 1986). In addition, there is no documented tectonic activity or river response to base level fall and minimal terrace development has been observed within the last 5,000 years in the study area, when the climate has been relatively stable. Holocene climate and thus flow regime, disturbance (fire, debris flows, and floods), and glacial history control sediment supply and transport capacity. However, we lack knowledge on the rates, magnitude and processes driving valley bottom alluviation. A summary of glacial and Holocene conditions is found in Table 1 and a more detailed review of the literature is presented in Sections 2.2 through 2.5.

Table 1. Summary of Pleistocene glacial and Holocene environmental conditions in the Colorado Front Range and Rocky Mountain National Park.

Environmental condition	**Time Period**	**Condition**	**References**
Glaciation	1800-300 ka: Pre-Bull Lake glaciation	Pre- Bull Lake glaciation(s)	Richmond, 1960; Madole, 1976; Madole, 1980; Chadwick et al., 1997; Madole et al., 1998; Braddock and Cole, 1990
	300-130 ka: Bull Lake glaciation	Bull Lake glaciation	
	30-10 ka:Pinedale glaciation	Pinedale glaciation	
Climate	10 ka: Post-glacial warming	Post-glacial warming	Benedict, 1979; Short, 1985; Elias, 1986; Elias, 1996; Benedict et al., 2008
	~7-6 ka: Holocene altithermal	Holocene altithermal	
	3ka (warmer period)	Warmer period	
	1600s-1850: Little Ice Age	Little Ice Age	
Drought	1705-1710	Drought period	Woodhouse and Lukas, 2006
	1844-1852	Drought period	
	1884-1890	Drought period	
	1951-1955	Smaller magnitude drought period	
	1965	Smaller magnitude drought period	
Forest fires	1700-1789	Increase in fires in subalpine	Laven et al., 1980; Sibold et al., 2006
	1800-1850	Fire-free period in subalpine	
	1851-1919	Increase in fires in subalpine	
	1920-1972	Period of fire suppression by management	
Beaver population	pre-European settlement	60- 400 million beaver in N. America	Packard, 1947; Stevens and Christianson, 1980; Mitchell et al., 1999
	1700s- 1800s	Extensive beaver trapping	
	1940	315 in Moraine Park (MP); 36 in Beaver Meadows (BM)	
	1964	92 in MP	
	1980	12 in MP; 0 in BM	
	1999	6 in MP	

I focus on two broad, unconfined valleys on the eastern side of the Continental Divide in Rocky Mountain National Park: Moraine Park and Beaver Meadows (Figure 3; Figure 4), located along the Colorado Front Range at approximately 2440 m elevation. Moraine Park is bounded by two lateral moraines and was glaciated in the Pinedale as well as the earlier glaciations. Moraine Park is approximately 3 km long and 1 km wide. The Big Thompson River, which flows through Moraine Park, drains an area of 103 km^2 at the park and is a pool-riffle stream with an active channel 8-15 m wide and a bed gradient of ~1.5 %. Beaver Meadows is bounded by one of Moraine Park's lateral moraines to the south and by bedrock, consisting of granite, gneiss, and schist (Braddock and Cole, 1990) to the north. Beaver Meadows is 2.5 km long and 75-300 m wide. Beaver Brook drains an area of 15 km^2. Beaver Brook is 0.2-1.5 m wide with a bed gradient of 0.2-0.8%. These two valleys have similar glacial histories with the exception of the last glacial maximum, when Beaver Meadows was not glaciated. Surveys of beaver populations throughout RMNP indicate that beaver were present in both valleys during the 20th century, although no active beaver colonies presently exist in either location.

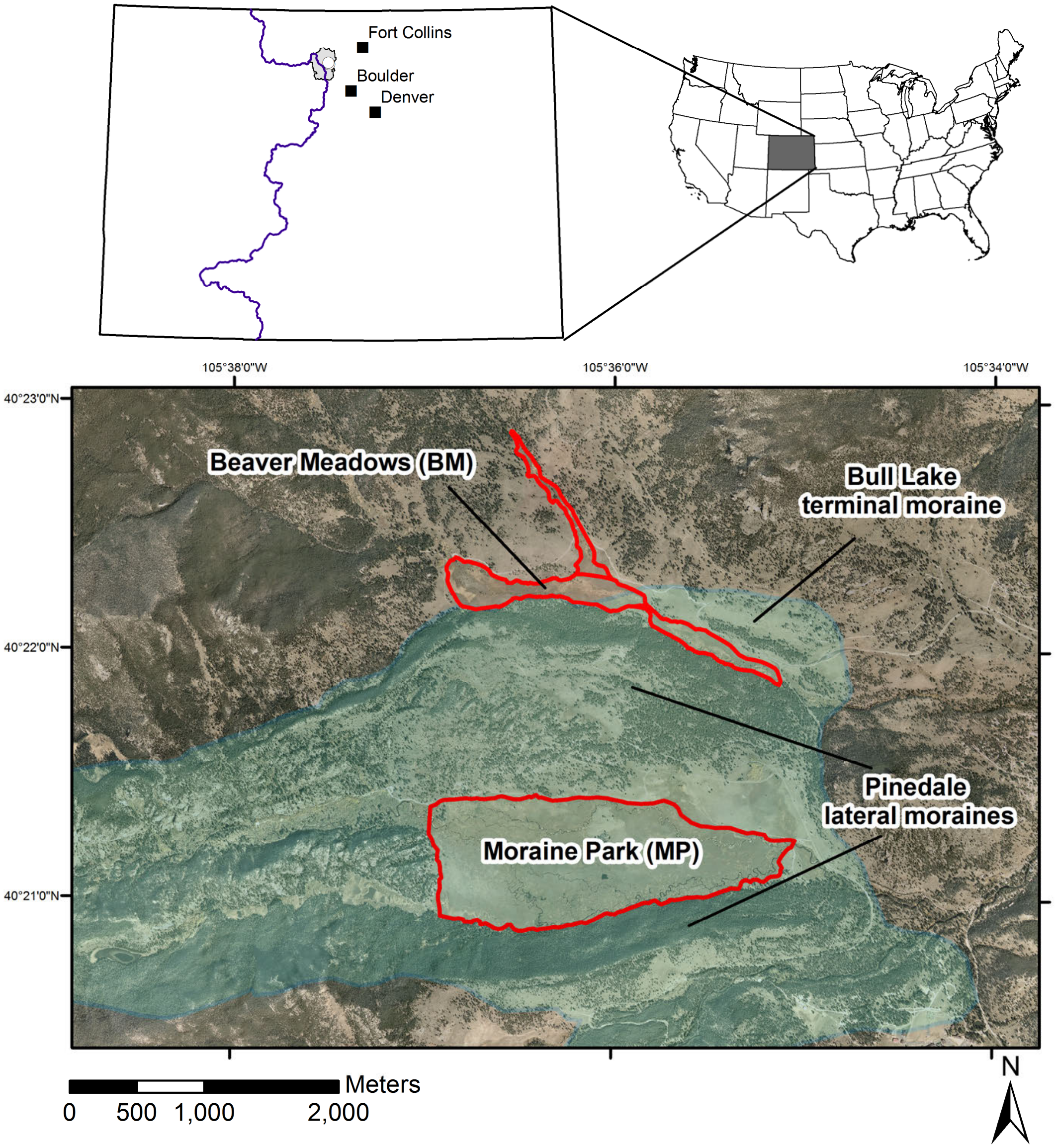

Figure 3. Location map of the two study valleys, Beaver Meadows and Moraine Park in Rocky Mountain National Park (RMNP) in north-central Colorado. In the map of Colorado, the north-south line represents the Continental Divide, and the boundary of RMNP is shown; the two circles represent the locations of the study valleys. The study valleys are shown on the 2001 aerial photograph with a hillshade DEM below; the shaded area represents the maximum cumulative extent of glaciation.

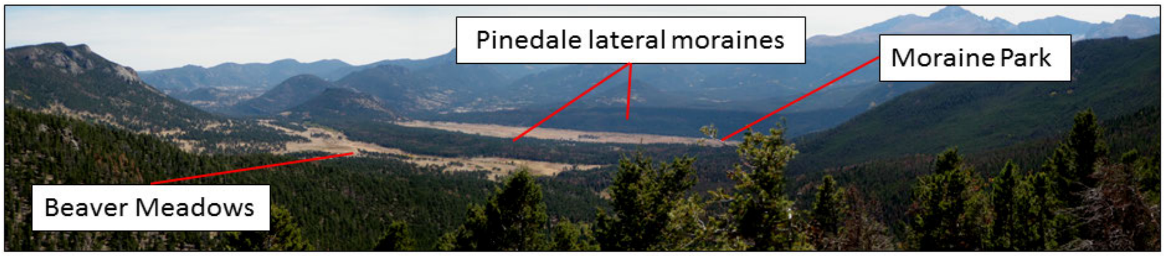

Figure 4. Oblique photo of Beaver Meadows and Moraine Park, showing lateral moraines from Pinedale glaciation.

2.2 Climate and Vegetation

These valleys are located within the montane ecozone (Marr, 1964), with hillslope forests dominated by ponderosa pine (*Pinus ponderosa*), and with some lodgepole pine present (*Pinus contorta*). Vegetation in the valleys consists of xeric and mesic species. Because the channel in Beaver Meadows is incised and the channel is restricted to certain parts of Moraine Park, the contemporary channel, overbank flooding, and the associated shallow alluvial aquifer likely do not have a large influence over most of each valley. Xeric vegetation that has recently encroached on the valley bottoms includes small ponderosa pines, native and non-native thistles, graminoids and herbaceous species. The main mesic vegetation is water birch (*Betula occidentalis*) and gray alder (*Alnus incana*). Few to no willows (*Salix* spp.) are present in either valley, although historical ground photographs and descriptions suggest that they were present during the 20th century.

2.3 Pleistocene glacial and post-glacial climate timeline in RMNP

Several cycles of alpine glaciation are recorded in the southern Rocky Mountains. Pre-Bull Lake glaciation, extending from 1800 to 300 ka, incorporates several glacial maxima without clear signatures on today's landscape (Richmond, 1960; Chadwick et al., 1997). Bull Lake glaciation occurred from 300-130 ka. Pinedale glaciation extended down to ~2300-2400 m elevation, lasted ~20,000 yr, and ended circa 10-15,000 years ago, depending on elevation (Madole, 1980; Madole et al., 1998). Because Moraine Park and Beaver Meadows are located within 1 km of the terminal moraine (Braddock and Cole, 1990; Madole et al., 1998), the study sites are assumed to be deglaciated ~15 ka (Madole, 1976; Madole, 1980). Although there were significant gaps between glacial episodes, during which alluvial processes dominated in the study valleys, this study focuses on the sedimentation history since the end of the Pinedale glaciation.

Post-glacial warming followed the recession of Pinedale glaciation approximately 10 ka and lasted ~1000 years, with warmer than modern summer and winter temperatures (Elias, 1996). Until 3 ka, mean July temperatures were above modern levels and mean January values were below modern levels, and treeline stood about 145 m higher than today in the early to mid- Holocene, indicating warmer temperatures (Elias, 1996; Benedict et al., 2008). This warmer, drier Holocene Altithermal lasted from 6500-3500 y BP as confirmed through beetle assemblages, pollen records, fossil ice-wedge polygons, and excavated spruce trees within the current alpine zone (Benedict, 1979; Short, 1985; Elias et al., 1986; Elias, 1996; Benedict et al., 2008).

Several periods of drought affected the region, as was reconstructed using tree rings extending to the early 18th century (Woodhouse, 2001). Using five-year averages, the three significant periods of drought were during 1705-1710, 1844-1852, and 1884-1890. Smaller magnitude droughts occurred during 1951-1955 and 1965, which is during the time period for which aerial photos exist for my study areas. The subalpine forests in RMNP, which are located at a higher elevation than the study areas, are affected by infrequent but extensive stand-replacing fires (Sibold et al., 2006). However, even though these fires do not occur directly on the hillslopes above the valleys studies, Moraine Park has a significant catchment area in the subalpine zone (above 2700 m). There was an increase in subalpine fires from 1700-1789, followed by a fire-free period from 1800-1850, followed by another increase from 1851-1919 before the human policy of fire suppression from 1920-1972 (Sibold et al., 2006). In the montane zone, prior to fire suppression, frequent surface fires occurred in ponderosa pine forests in the Colorado Front Range; however, at approximately 2400 m, ponderosa pine is mixed with Douglas-fir and lodgepole pine and fires at this transition zone are much less frequent but include extensive stand replacing events (Veblen et al., 2000).

2.4 RMNP Beaver Populations

Regular surveys of beaver populations, or the proxies of beaver lodges, were conducted in RMNP throughout the 20th century. The beaver population in Moraine Park decreased by 70% from 1940 to 1964, with the number of beavers dropping from 315 to 92 (Packard, 1947; Stevens and Christianson, 1980; Mitchell et al., 1999). In the following twenty years, there was a further 87% decrease in the number of beavers to only 12 in 1980. In 1999, only 6 beavers were present and no beaver activity was recorded during this study in the summers of 2009 and 2010. In Beaver Meadows, 36 beaver were surveyed in 1940 and by 1980 none were present. No other surveys were conducted in Beaver Meadows between 1940 and 1980. The Beaver Meadows population even in the 1940 survey may be an overestimate because the delineation of Beaver Meadows is not clear from the survey reports and likely includes a larger area than my study area, which is referred to as Upper Beaver Meadows in RMNP (Packard, 1947).

The dramatic decline in beaver has been attributed to competition with elk for willow, an important winter food source for beaver (Baker et al., 2005). Elk numbers have increased with the removal of their main predator, the wolf (Ripple and Beschta, 2003). Packard (1947) noticed that Beaver Meadows and Moraine Park were already being overgrazed by elk and deer, although he did not believe that the willow population in Moraine Park could be exhausted. Simply excluding elk and reintroducing willow and beaver may not return the valleys to their original state because of an altered hydrologic state without beaver (Westbrook et al., 2006; Wolf et al., 2007).

Although no paleontologic data on the Holocene history of beaver exist for RMNP, beaver are known to have been present throughout the contiguous United States, except Florida and the desert of Arizona, until the arrival of European fur trappers (Naiman et al., 1988). Wood-cutting, semi-aquatic mammals in the Castoridae family, of which *Castor canadensis* is a part, evolved as early as 25 million years ago (Rybczynski, 2007). This suggests that beaver have cut trees and built dams, potentially altering riparian corridors and geomorphic process, at least through the Pleistocene, which is the time period during which the study area has experienced glaciation. Therefore, beaver were likely present in RMNP whenever climatic and ecological conditions allowed. Most importantly, beaver prefer unconfined, low-gradient (<6%) alluvial channels, without coarse or bedrock substrates, and below a stream power threshold (McComb et al., 1990; Gurnell, 1998; Pollock et al., 2003; Persico and Meyer, 2009). In the Colorado Front Range, aspen, a preferred food source for beaver (*Populus tremuloides*) are found from the montane through the subalpine zones and willows (*Salix* spp.), another food source of beaver, are found up to the alpine zone (Marr, 1964; Veblen and Lorenz, 1991).

2.5 Supporting Geophysical Data

The overall subsurface sediment geometry in Beaver Meadows has been described in detail through the use of the shallow geophysical techniques of near-surface seismic refraction (SSR) and ground penetrating radar (GPR) (Kramer, 2011; Kramer et al., in press). In this study, Beaver Meadows was divided into three regions: East Beaver Meadows (EBM), which is bounded by glacial till to the north and south, West Beaver Meadows (WBM), which is bounded by bedrock to the north and till to the south, and North Beaver Meadows (NBM), which is the tributary valley that joins Beaver Meadows at the eastern end of WBM (Figure 5). Geophysical techniques were used to differentiate glacial deposits, post-glacial alluvium, and beaver pond sediments. The crystalline basement was delineated from the glacial deposits using SSR. Glacial deposits were delineated from alluvium, and beaver pond deposits were distinguished within alluvium, using GPR. Mean total valley fill (including alluvium and glacial deposits) was 16 m in EBM, 10 m in WBM, and 1.3 m in NBM. The maximum and mean alluvial thicknesses in EBM, WBM, and NBM are 2.5 and 0.7 m, 6.0 and 1.8 m, and 3.5 and 1.3 m, respectively (Kramer et al., in press). From isopach maps, the percentage of alluvium in the valley fill was only 5% in EBM, 19% in WBM, and 100% in NBM. Using type facies from sediment beneath surface features interpreted as buried beaver dams, Kramer et al. (in press) estimated the percent volume of alluvium attributed to beaver dams and ponds as 64% in EBM, 28% in WBM, and 38% in NBM.

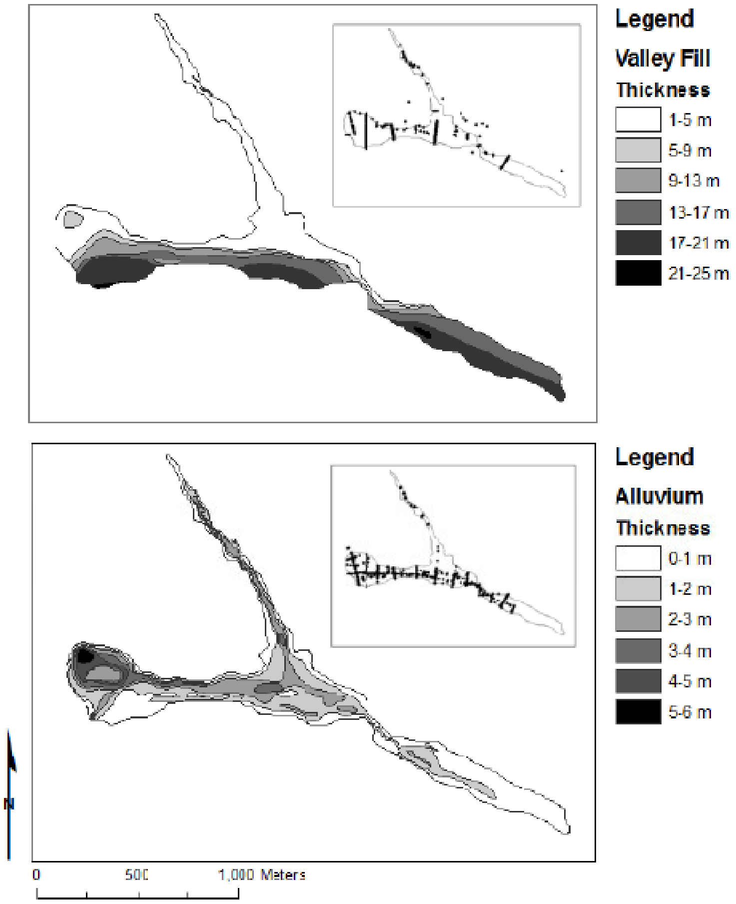

Figure 5. Isopach maps of valley fill and alluvium. Valley fill includes glacial till and outwash and alluvium (Kramer, 2011; Figure 3.7).

In Moraine Park, SSR has been used to determine the depth to bedrock, which ranges from 5-30 m (N. Kramer, unpublished data; Figure 6). The total volume of glacial and alluvial fill is approximately 24 million m^3, compared with 5.3 million m^3 in Beaver Meadows (including EBM, WBM, and NBM). When standardizing for the valley area, however, the total valley fill is quite similar; 10.7 m^3/m^2 in Beaver Meadows and 12.6 m^3/m^2 in Moraine Park.

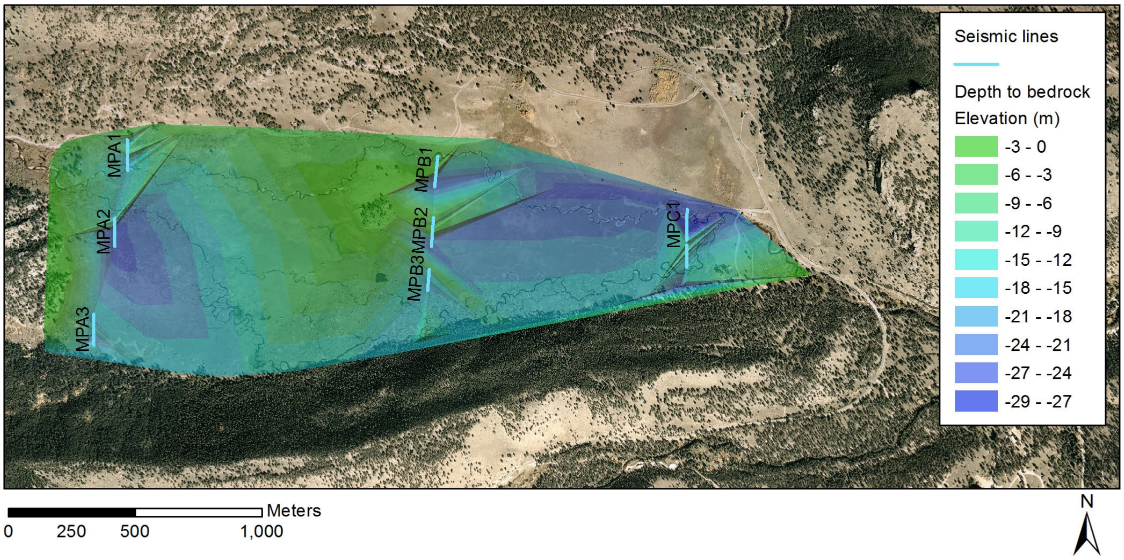

Figure 6. Triangulated irregular network (TIN) of depth to bedrock in Moraine Park created from eight seismic lines and observations of bedrock throughout the valley (figure modified from unpublished data, N. Kramer, *personal communication*, August 2011).

These data provide the template from which the Holocene stratigraphy, timeline of aggradation, and importance of beaver in aggradation can be deduced. In evaluating the beaver-meadow complex hypothesis, whether or not beaver have played a significant role in sediment aggradation needs to be determined. Because alluvium only reaches a depth of ~1.5 m, I do not need to invoke tens of meters of beaver-related sedimentation to support the beaver-meadow complex hypothesis, as suggested by Persico and Meyer (2009).

3. Methods

I used three primary lines of evidence in addition to near-surface geophysical data to evaluate the influence of beaver on post-glacial sediment accumulation at the study sites. I quantified sediment texture and age within 2 m of the surface at numerous locations in both study areas, I mapped contemporary landforms across each valley bottom, and I measured the extent of beaver ponds and channel planform on aerial photographs spanning several decades.

3.1 Sediment Characterization

Because I worked in a public area of a national park, the methods used to analyze near-surface sediment, defined as the sediment within 2 m of the surface, were non-invasive. This sediment was accessible along cutbanks and in ~2 m-deep hand-augered cores (Figure 7). I recorded sediment texture, sorting and angularity, presence of organic material, such as wood, leaves or roots, color of sediment as an indicator of past anoxic or aerobic conditions, and depth of layers and type of boundary between each layer. The depth of the water table was also recorded. The auger reached a depth of ~1.9 m; cores either ended at this depth, when impenetrable substrate was encountered, or when too much infilling occurred, usually with a rounded, well-sorted sand below the water table. At the bottom of each core, I recorded the substrate encountered as: similar to previous layer; coarse gravel to cobbles; or large cobbles, boulders, or bedrock. Using the auger, it is possible to feel whether the sediment moves but cannot be picked up (coarse gravel to cobbles) or is completely impenetrable (cobbles to bedrock). Descriptions of cutbanks included more detailed stratigraphy. In Beaver Meadows, the channel throughout most of the valley is incised up to 1-2 m, which allowed for detailed observations of stratigraphy including boundaries between layers not preserved within cores. Samples were taken of characteristic sediment types. Sediment samples were sieved and a hydrometer test was used to determine the clay and silt fraction of the remaining sediment smaller than 4 φ (0.0625 mm) (Gavlak et al., 2003). In order to interpret depositional environment, I collected samples of modern sediment in known depositional environments, including the hillslope and the pools and riffles of the channel. Because there were no active beaver ponds or dams in either Beaver Meadows or Moraine Park, beaver pond sediment was collected from two proxy locations: 1) in Moraine Park, in what is interpreted to be an abandoned beaver pond that is currently a dried, marshy pond, currently 5-10 m from an active channel, and 2) in active beaver ponds along Corral Creek valley, located north of RMNP in the headwaters of the Cache la Poudre River, with channel and valley dimensions roughly between that of Beaver Meadows and Moraine Park. Because hydraulic conditions and sediment characteristics vary between and even within beaver ponds, these proxies sediments can verify the classification of sediment as beaver-pond sediment if the sediment interpreted as beaver-pond sediment is as fine as, or finer than, that found in the proxy ponds. Samples of silt- and clay-rich sediment were analyzed for organic content by measuring mass before and after burning off all organic material.

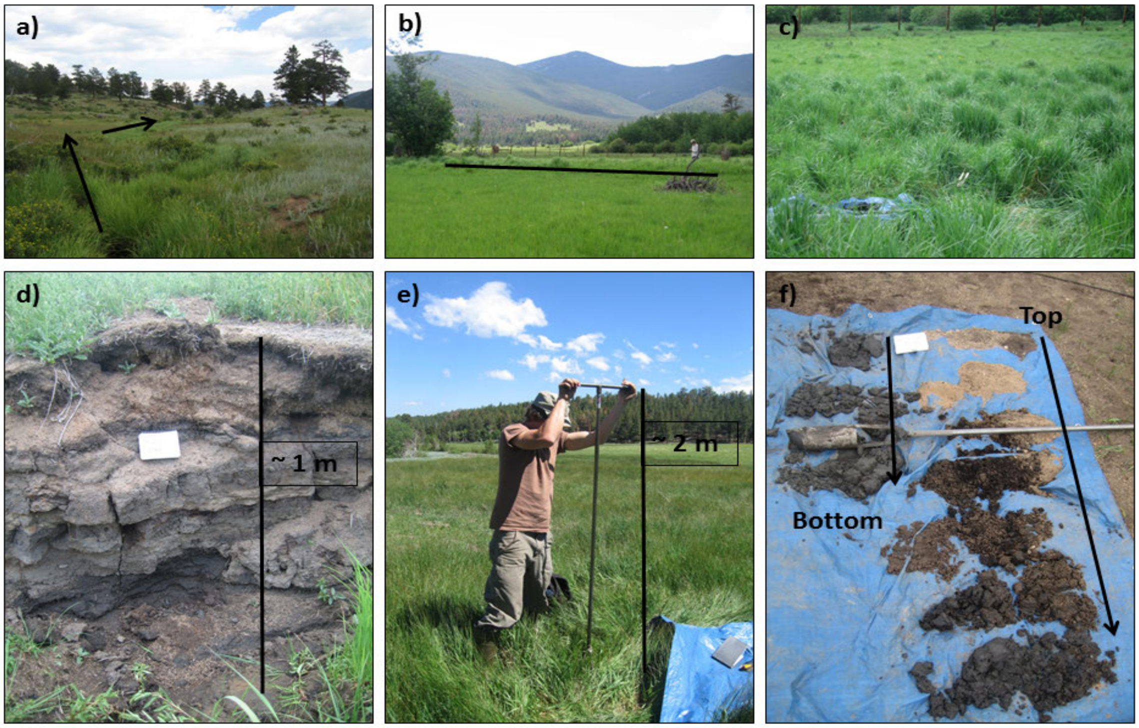

Figure 7. Photographs of field work and various surface features in Beaver Meadows. A) Constricted portion of valley where till from Bull Lake glaciation forms mound on channel right; valley edge is located close to channel on river left; arrows show flow direction of channel. B) Looking upstream at ramp-like feature (~1 m in height) that is surface expression of buried beaver dam (delineated by horizontal black line). C) Hummock surface features ~30-50 cm in height common upstream of buried beaver dams where sediment directly below surface is fine-grained. D) Cutbank along Beaver Brook where charcoal samples were collected for BM07 (see Table 3) at ~0.7 m depth (8 x 13 cm notecard). E) Photograph of hand auger being used to obtain core sediment; auger spoon is directly below surface. F) Example of core sediment obtained from hand auger for analysis; auger spoon is shown next to sediment on photo left. Sediment texture transitions from coarse fluvial material to fine-grained clay to fine sands below water table.

Radiocarbon dating was used to obtain dates of wood and charcoal samples, of which 16 were from Beaver Meadows and 3 from Moraine Park (Table 3 in Section 4.3). Four cores had two samples dated from different depths (BMO1 and BM02; BM09 and BM10; and BM11 and BM14) and two samples from approximately the same depth in a core (BM03 and BM04). Calibration of the conventional radiocarbon date results in various age ranges. I used the weighted mean of the calibrated probability distribution of ages with 2σ ranges to obtain a single age for each dated sample that could be used to calculate aggradation rates (Telford et al., 2004). Net, average aggradation rates were calculated by simply dividing the depth at which the sample was found by the age. Six organic samples of wood and charcoal were dated using the University of Arizona Radiocarbon Lab via standard analyses; 13 samples were dated by Beta Analytic Inc. using accelerator mass spectrometry.

3.2 Geomorphic Mapping

Using a 2001 aerial photograph as a template, I mapped landforms including the active floodplain, hummocky landforms, glacial deposits, and steps in the valley profile perpendicular to the valley axis, which were interpreted as abandoned beaver dams. I surveyed the valley geometry with a total station to determine valley length and widths, channel sinuosity, and valley and channel gradient. Twelve valley cross-sections were surveyed in Beaver Meadows and the entire valley and channel longitudinal profiles were surveyed (APPENDIX X). Because of the large size of Moraine Park, it was divided into three study reaches, approximately 250 m long. For each reach, I surveyed a valley cross-section, and a valley and channel longitudinal profile.

In Moraine Park, evidence of beaver influence is still prevalent in the form of abandoned beaver dams and beaver-chewed wood deposited in the channel. I walked the entirety of the main channel and all of the side channels in Moraine Park and noted any occurrences of abandoned beaver dams, beaver-chewed wood, or instream wood without evidence of beaver influence. Abandoned beaver dams were distinguished from simply beaver-chewed wood using the criteria that abandoned dams showed a set structure of interwoven wood and sediment that was anchored in one or both streambanks, whereas beaver-chewed wood showed clear evidence of beaver chewing, but a dam structure could not be identified. It is possible that beaver-chewed wood could be located at the site of an abandoned dam, but dam identification was designed to reduce false identification. For each wood observation, the local in-channel geomorphic structure was recorded: channel splits and junctions; islands, which were smaller in width than the combined channel widths of the two side channels; a cutbank or point bar; or a sharp bend, which is where the bend around a point bar was 90° or less.

3.3 Aerial Photograph Analyses

I used historical aerial photographs to assess the historical presence of beaver dams or ponds and to quantify channel planform change. I obtained a series of aerial photographs of Beaver Meadows and Moraine Park from the late 1930s to 2001, some of which were in black and white (BW) and others in color (C). Full coverage of Beaver Meadows was available for the years 1947 (BW), 1964 (C), 1969 (C), 1987 (C) & 2001 (C) and only partial coverage for 1938 (BW) and 1971 (BW); and full coverage of Moraine Park was available for 1947 (BW), 1964 (C), 1969 (C), 1987 (C), and 2001 (C) and partial coverage for 1938 (BW), 1961 (BW), 1965 (C), 1971 (C). In Beaver Meadows, no historical beaver ponds were present and only one other channel was present, but I could identify linear features with pond-like shapes up-valley.

In Moraine Park, historic multiple channels and ponds were abundant and apparently dynamic during the time of the aerial photo series. For the Moraine Park photos, I digitized ponds and calculated total area and number of ponds for each year of photographic coverage. Channel complexity was determined in two ways: all the channels were digitized and I calculated total channel length, and a braiding index was calculated (Bridge, 1993). Although the stream in Moraine Park has not, in fact, been braided during the time of the aerial photographs, the braiding index provides a metric for quantifying the number of separate channels in this multi-thread system. The braiding index was determined by counting the number of stream channels that crossed 19 valley-wide transects, which were spaced ~250 m apart; the mean and standard deviations for each year were compared. The braiding index and total channel length were compared to trends in the number or area of ponds.

4. Results

4.1 Near-surface Sediment Interpretation

Sediment textures at both sites were comparable, although larger grain sizes were found in Moraine Park. Grain sizes ranged from clay to coarse gravel in Beaver Meadow, and clay to small cobbles in Moraine Park. Most sand- to cobble-sized sediment was sub-rounded to well-rounded. Alternating layers of fluvial sands, gravels, and cobbles with layers of clay to fine sand were commonly seen in cutbanks and cores. Ten sediment texture categories were identified and used to classify sediment in cores and cutbanks; these include organic soil, fluvial sands and gravel, very fine grained sediment, and oxygenated and anoxic clays through gravel (Table 2).

Table 2. Sediment categories identified in Beaver Meadows and Moraine Park.

Abbr.	Layer name	Color	Texture	Organics	Depositional Environment
OS	Organic soil	Dark brown	Clay to fine sand	Abundant roots	Modern soil formation
CS	Very fine grained	Dark brown- black	Very fine grained; mostly clay and silt; possibly minor sand	Minimal to extensive	Pond behind beaver dam
CSS	Fine grained	Dark brown- black	Fine grained; Clay, silt, and fine sands	Minimal to extensive	Pond behind beaver dam
CSG	Clay to fine gravel	Light- dark brown	Clays, silt, sand & gravel; sands and gravels are subrounded- subangular	Minimal to none	Pond or floodplain
CSG+O	Oxygenated clay through gravel	Light- dark brown & red/ orange pods	Clays, silt, sand & gravel; sands and gravels are subrounded- subangular	Minimal to extensive; oxygenated	Pond or floodplain
CSG+A	Anoxic clay through gravel	Light- dark brown & grey/blue/green pods	Clays, silt, sand & gravel; sands and gravels are subrounded- subangular	Minimal; anoxic	Pond or floodplain
SS	Silt and fine sand	Light-medium brown	Silts & fine sands	Minimal to none	Floodplain or channel
FSG	Fluvial sands & gravel	Light-medium brown	Well sorted, subrounded sands and fine gravels	Minimal to none	Fluvial channel
FG	Fluvial gravels	Tan- light brown	Well sorted, subrounded fine to medium gravels	Minimal to none	Fluvial channel
FGC	Fluvial gravels & cobbles	Tan- grey	Well sorted, subrounded medium gravels to small cobbles	Minimal to none	Fluvial channel

4.2 Interpretation of Depositional Setting of Sediment Layers

Using modern analogs, I interpreted a range of possible depositional settings for each sediment category. A 100-particle point count of sediment in the channel within Beaver Meadows showed a D_{50} of 3 mm, and sieving a grab sample of thalweg sediment revealed a D_{50} of 6 mm, which confirms an average median grain size of very fine to medium gravel. These sediments were sub-rounded to sub-angular; fluvial sediments within this valley do not necessarily show significant rounding because of the small drainage area. From six 100-particle point counts conducted within the main channel in Moraine Park, the D_{50} varied from 27 to 48.5 mm, with ranges from 2-75 mm up to 2-900 mm; the in-channel sediment in Moraine Park was much more rounded than that of Beaver Meadows. No active beaver pond sediment was available in Beaver Meadows or Moraine Park, but in Moraine Park I found an off-channel, partially dried, marshy area bounded by berms that I interpreted as a recently abandoned beaver pond. Sediment sampled from this location has a D_{50} of fine sand, a trace amount of gravel and 4.3% silt.

Sediment was also sampled from active beaver ponds in a similar environment in Corral Creek valley, where median grain size of grab sample ranges from very fine to medium sand; <1 % of sediment is very fine to fine gravel and 2-9% is composed of silt and clay.

I interpret any very fine-grained sediment in the subsurface as being deposited in a pond behind a beaver dam. Other possible causes for fine-grained sediment were eliminated in these study areas. Log jams and debris flows could cause damming of water and sediment and thus deposition of fine-grained sediment. However, these broad valleys are relatively disconnected from the hillslopes, thus reducing wood recruitment into the channels. If any long-lasting instream wood is recruited, the low channel gradients (<1 %) would limit transport and formation of a jam. Additionally, I have observed elsewhere in the river network that wood from deciduous riparian species that enter the channel (birch, alder, willows) disintegrates quickly and will not form jams. No evidence of debris flows was observed and hillslopes have low gradients and are fairly short, limiting mobilization of hillslope sediment by intense rain or snowmelt. Addtionally, these fine-grained sediment packages are correlated with areas of up-ramped stratigraphy from a concurrent ground-penetrating radar study (Kramer, 2011), which is consistent with beaver dams and not oxbows or cutoffs.

Packages of possible pond sediment range from 0.05-1.2 m thick in Beaver Meadows, with an average thickness of 0.25 m (sd: 0.17), and in Moraine Park these sediment packages range in thickness from 0.05-1.1 m, with an average of 0.25 m (sd: 0.21). Fluvial sediment in Beaver Meadows was abundant and commonly formed most of a core of cutbank, showing coarsening upwards or downwards that records channel migration. Core sections with distinctly different textures were measured separately even if they were collectively interpreted as fluvial sediment. These sections ranged from a few centimeters, when bounded by clay layers as a sand lens, to over 0.5 m, with an average of 0.21 m (sd: 0.12). Fluvial sediment packages that I could core through had smaller thicknesses: 0.05- 0.45 m, with an average of 0.17 m (sd: 0.11). However, all of the cores in Moraine Park ended at a coarse fluvial sediment layer of unknown thickness, comprised of coarse gravels and cobbles, at an average depth of 0.66 m (sd: 0.36).

Cores in Beaver Meadows showed characteristic sequences of alternating fluvial and ponded sediment, especially close to the channel and up-valley of any linear berms, which also usually coincided with hummocky surface features (Figure 8; Figure 9). In cores closer to the valley edge and at the upstream end of the valley, little to no silt and clay were present, contemporary soils were better developed, and mostly fine to coarse sand and fine gravel occurred in the remainder of the core. Cores and cutbanks throughout the valley in Moraine Park showed alternating sequences of fine, cohesive sediment with mostly silt and clay and minor sand, and clearly fluvial sediment ranging from well-sorted sand to gravels and cobbles (Figure 8). The percent organic material in the fine grained sediment, interpreted as beaver pond sediment, ranged from 4.9- 23.2% with an average of 14.5%.

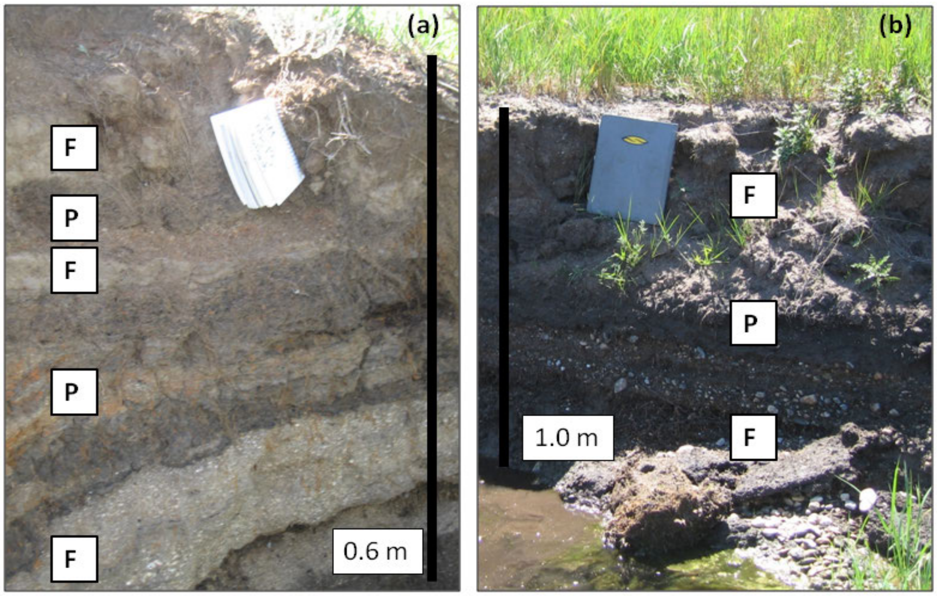

Figure 8. Photgraphs of cutbanks in Beaver Meadows (a) and Moraine Park (b) showing typical sequence of fluvial (F) and ponded (P) sediment. In photograph (a), a ~13 x 18 cm notebook is shown for scale, and in photograph (b), a clipboard is shown for scale.

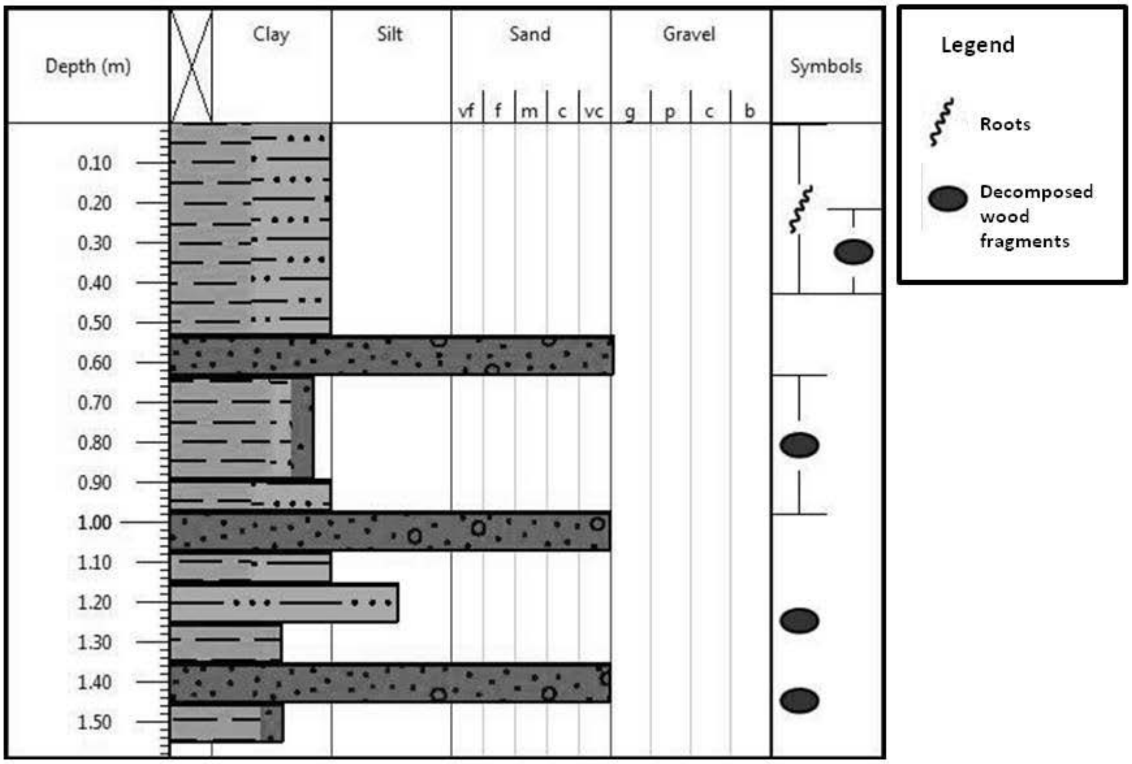

Figure 9. Sediment stratigraphy of core in northern valley of Beaver Meadows, representative of cores in areas of abandoned beaver ponds. Horizontal lines represent clay; horizontal lines with dots represent silt; randomly spaces dots represent sand; randomly spaced dots with circles represent gravel.

Ranges of sediment that was deposited in four different depositional settings were determined, based on the range of depositional environments for each sediment category present in Beaver Meadows and Moraine Park and the thicknesses of each of these sediment layers. In Beaver Meadows, descriptions from 39 cores and cutbanks were used, and I identified the depositional settings of ponded sediment, fluvial channel sediment, abandoned channel sediment, and floodplain sediment as described in Table 2. Ponded sediment consisted of 33-50% of all near-surface sediment. Fluvial channel sediment composed 28-40% of alluvium. Floodplain sediment composed 2-23% of alluvium.

Abandoned channel sediment deposited by slow, intermittent and ephemeral flows in secondary channels composed 0-3% of sediment. Sediment analysis from 22 near-surface cores in Moraine Park showed that 32-41% of sediment was deposited in ponds, 4-52% in a channel, and 0-6% on the floodplain.

4.3 Organic Material Dating

Radiocarbon ages ranged from 180 to 4340 y BP, with a median of 360 y BP and an average of 945 y BP (Table 3). Assuming constant aggradation, aggradation rates vary over an order of magnitude from 0.023 to 0.473 cm/y, with a median of 0.219 cm/y. Local aggradation was calculated for three cores where two samples were collected at various depths. These rates also vary over an order of magnitude: BM01 and BM02 have an aggradation rate of 0.075 cm/y over 0.11 m, BM09 and BM10 have a rate of 0.041 cm/y over 0.72 m; and BM11 and BM14 have an aggradation rate of 0.950 m over 0.19 m. Aggradation rates tend to decrease with larger time interval and follow a linear relationship in log-log space (Sadler, 1981; McShea and Raup, 1986), and thus we can plot these variables for relatively short timespans, over only two orders of magnitude, using a power relationship (Figure 10a). The residuals of actual aggradation rates from the calculated rates should be randomly distributed around zero and have relatively low values if these data truly follow this observed trend of a decrease in aggradation rates when measured over larger time-scales. However, there is a large amount of variability in residuals, especially for ages <500 y BP (Figure 10b). This indicates large temporal variability in sedimentation rates even at small timescales, which may reflect spatial variability in processes across the valley at any given time. Long-term aggradation rates are in agreement at ~0.05 cm/y, which can be used to estimate sedimentation depths over long time-periods. Using the calculated aggradation rates for the five samples older than 1000 y BP, there is an average of 2.2 m (range of 1.2-3.0 m) of net aggradation over 5,000 y, 4.4 m (2.3-6.0 m) in 10,000 y, and 6.5 m (3.5-8.9 m) in 15,000 y. The total net aggradation over 10,000 and 15,000 years, which is the approximate time since the recession of glaciers in these valleys (Madole, 1980), is in agreement with the total alluvial sediment above glacial sediment determined through geophysical analyses (Kramer et al., in press).

Table 3. Descriptions of wood and charcoal samples that were dated using Carbon-14. . The lab number was assigned by either University of Arizona (A) or Beta Analytic (B). The aggradation rates assumes a constant rate of aggradation based on the weighted average of calibrated years BP (IntCal09 curve in OxCal 4.1 used for calibration) and the depth of the sample.

ID	Lab number	Location	Observation	Depth (m)	Material	Conventional date (yrs BP)	Calibrated ages and % probability (yrs BP)	Weighted average (Cal Yrs BP)	Aggradation rate (cm/yr)	Sediment description
BMO1	B288589	BM	Core	1.30	Wood	310 +/- 40	**350-550 (95.4)**	**450.0**	0.289	Clay, silt, fine sand; dark brown- black
BMO2	A15351	BM	Core	1.41	Wood	505 +/- 90	379- 452 (9.3), **486- 725 (86.1)**	**590.0**	0.238	Clay, silt, fine sand; dark brown- black; organic
BMO3	B288590	BM	Core	0.99	Charcoal	170 +/- 40	56-97 (17.5), 124-178 (12.9), **184-291 (46.5)**, 303-355 (18.4)	**210**	0.471	High clay content mixed with fine to medium sand; grey- black
BMO4	B288591	BM	Core	0.99	Wood	140 +/- 40	61-105 (16.1), 116-213 (36.3), **227-343 (43)**	**210**	0.471	High clay content mixed with fine to medium sand; grey- black
BMO5	B288592	BM	Cutbank	0.67	Charcoal	920 +/- 40	**802-984 (95.4)**	**890**	0.075	Clay and silt mixed with minor fine to coarse sand
BMO7	B288593	BM	Cutbank	0.66	Charcoal	2040 +/- 40	1958-1973 (3.1), **1980-2178 (92.3)**	**2080**	0.032	Clay lense within sand and gravel layer; black
BMO8	A15353	BM	Cutbank	0.28	Charcoal	<130	**60-380 (93)**, 443-445 (0.1), 451-486 (2.3)	**230**	0.122	Clay, silt, fine sand layer between sand and gravel layers; grey-black
BMO9	B288594	BM-N	Core	0.43	Wood	110 +/- 40	**50-210 (62.5)**, 233-238 (0.8), 245-332 (32.1)	**180**	0.239	Clay and silt; dark brown- black
BM10	A15355	BM-N	Core	1.15	Wood	1925 +/- 70	**1764-2103 (95.4)**	**1930**	0.060	Clay and silt layer between coarse sand to gravel layers
BM11	B288595	BM	Core	0.76	Wood	110 +/- 40	**50-210 (62.5)**, 233-238 (0.8), 245-332 (32.1)	**180**	0.419	Silt and fine sand; within a layer coarsening downwards; grey-black
BM12	B288596	BM-N	Core	1.37	Wood	3140 +/- 40	3325-3369 (11.6), **3378-3509 (83.8)**	**3430**	0.056	Clay and silt; dark grey to black
BM13	B288597	BM	Core	0.84	Wood	110 +/- 40	**50-210 (62.5)**, 233-238 (0.8), 245-332 (32.1)	**180**	0.467	Clay and silt with minor sand; dark brown to black
BM14	B288598	BM	Core	0.95	Wood	130 +/- 40	66-107 (15.5), **114- 212 (40.2)**, 230- 340 (39.7)	**200**	0.473	Silt and sand coarsening downwards to fine gravel
BM15	B288599	BM	Core	0.22	Wood	110 +/- 40	**50-210 (62.5)**, 233-238 (0.8), 245-332 (32.1)	**180**	0.122	Clay and silt with minor sand
BM16	B288600	BM	Core	0.60	Wood	1280 +/- 40	1148- 1169 (2.8), **1185-1353 (92.6)**	**1270**	0.047	Clay, silt, sand, and minor gravel; transition between clay/silt and fluvial sand and gravel
BM17	B288601	BM	Core	0.60	Wood	70 +/- 40	**77- 205 (69.3)**, 274- 328 (26.1)	**180**	0.333	Clay and silt; dark brown- black
MPO1	A15355	MP	Core	0.97	Wood	855 +/- 100	632-638 (0.3), **712- 1023 (95.1)**	**870**	0.111	Silt and clay with minor amount of fine sand; dark brown to black
MPO2	A15356	MP	Cutbank	0.38	Charcoal	265+/-85	56- 103 (6.8), 130- 177 (4.1), 191-290 (19.2), **304- 563 (65.4)**	**360**	0.106	Silt and sand layer directly above contact with rounded cobbles; medium brown
MPO3	A15357	MP	Cutbank	1.00	Wood	3850 +/-55	4155-4186 (3.6), **4205-4480 (91.8)**	**4340**	0.023	Silt and clay layer; dark brown

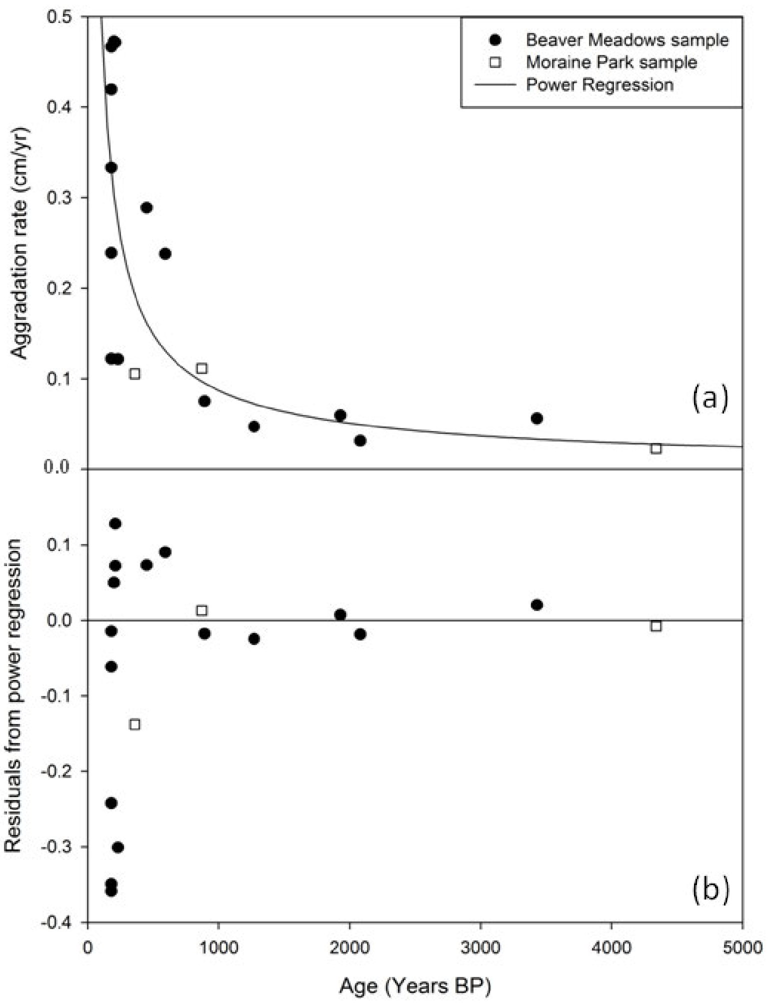

Figure 10. Plots of aggradation rates and residuals versus sample ages. (a) Plot of ages versus calculated aggradation rates of sampled wood and charcoal (see Table 3) in Beaver Meadows and Moraine Park, and the power function fit to the data. (b) The residuals of the sampled dates from the power function to show general agreement in long-term aggradation rates and high variability in short-term rates.

A surface feature interpreted as an abandoned, partially buried beaver dam revealed, through a series of cores along a longitudinal transect, a sequence of fluvial sands and gravels and fine-grained ponded sediment (Figure 11). Several disintegrated wood fragments were found in each core, usually at the top of a fluvial coarse-grained layer. Because the buried beaver dam is still expressed as a surface feature, this must be a relatively recently abandoned dam. This is confirmed through the dating of four wood fragments (BM11, BM13, BM14, and BM15), which have dates of 180 cal y BP or 200 cal y BP. This sequence is interpreted as a beaver dam influencing this area, either downstream or at the main break in slope (at ~5 m down valley in Figure 11) for at least 200 years. The dams and the surface feature have more likely been present for up to 500 years, because there are two sets of ponded material and the top set dates to ~200 y B.P., and the channel and dam location was likely laterally mobile between the deposition of the first and second set of pond and fluvial sequences. Fluvial sediment was either deposited when an original dam was breached or simply through spatial heterogeneity of the main flow through the beaver pond. Because a beaver dam allows some flow by creating a patchy, discontinuous environment (Burchsted et al., 2010), coarser-grained fluvial sediment may be deposited within the pond, depending on the flow dynamics upstream of the pond.

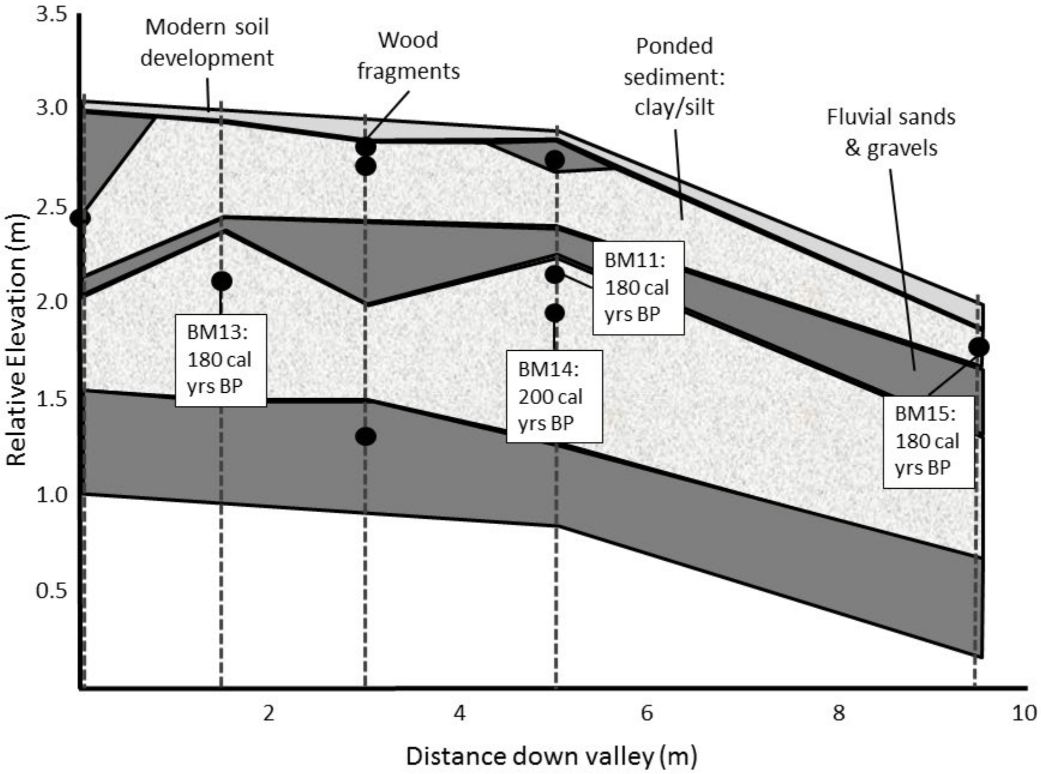

Figure 11. Stratigraphy of buried beaver dam. Schematic down-valley cross-section of topographic berm in main valley of Beaver Meadows, interpreted as buried beaver dam. Schematic compiled from five cores taken along the same longitudinal transect. Four wood samples from these cores were taken and radiocarbon dated. Transect was taken along berm shown in Photo B in Figure 7.

4.4 Beaver Dams and Channel Complexity

Aerial photographs in Moraine Park and Beaver Meadows show significant changes in channel planform, ponding, and vegetation type and extent from the late 1930s to the present (2010). Currently, there are very few small willows and only scattered birch and alder in Beaver Meadows. In 1938, large patches (up to 300 x 50 m) of shrubs, which are most likely willows, are present, and somewhat more fragmented patches are seen in 1947. Through the 1960s these willow patches became more linear and present only in discontinuous areas along the channel. The 1987 and 2001 aerial photographs show similar conditions to those during field visits in 2010; woody vegetation is sparse and only found along the channel.

4.4.1 Beaver Meadows

From the 2001 aerial photograph, lighter-colored vegetation areas in Beaver Meadows correspond to hummocky, wet areas in the field with the top layer of sediment commonly composed of cohesive clay and silt with grasses and sedges growing on top of the hummocks. Hummocks, which range from 0.3-0.5 m in height, were usually found in areas directly upstream of an abandoned beaver dam feature (Figure 7c). Typically, a linear feature bounds these vegetation areas along the down-valley boundary, and the area tapers in the up-valley side; in that case, I interpreted these as former beaver ponds. The berms or down-valley boundaries, interpreted as locations of beaver dams, could be more clearly delineated than the entire pond boundary and were identified for a series of five aerial photographs (1938-1987). On the most recent aerial photograph (2001), I mapped linear features for which there was geomorphic field evidence of buried dams (Figure 12). A general decreasing trend exists in the presence of features representing buried beaver dams, which corresponds with beaver surveys of Beaver Meadows that show a population of 36 in 1940 and none present in 1980 (Section 2.4). Relict beaver dams identified in the aerial photographs numbered 6 in the main valley (MV) and 4 in the north valley (NV) in 1938, which only had partial photographic coverage; these numbers become 8 and 4, respectively, in 1947, 5 and 3 in 1964, and 1 and 3 in 1969 and 1987. The total topographic features identified in the field in 2009 that were interpreted as buried beaver dams were 10 in the main valley and 7 in the north valley.

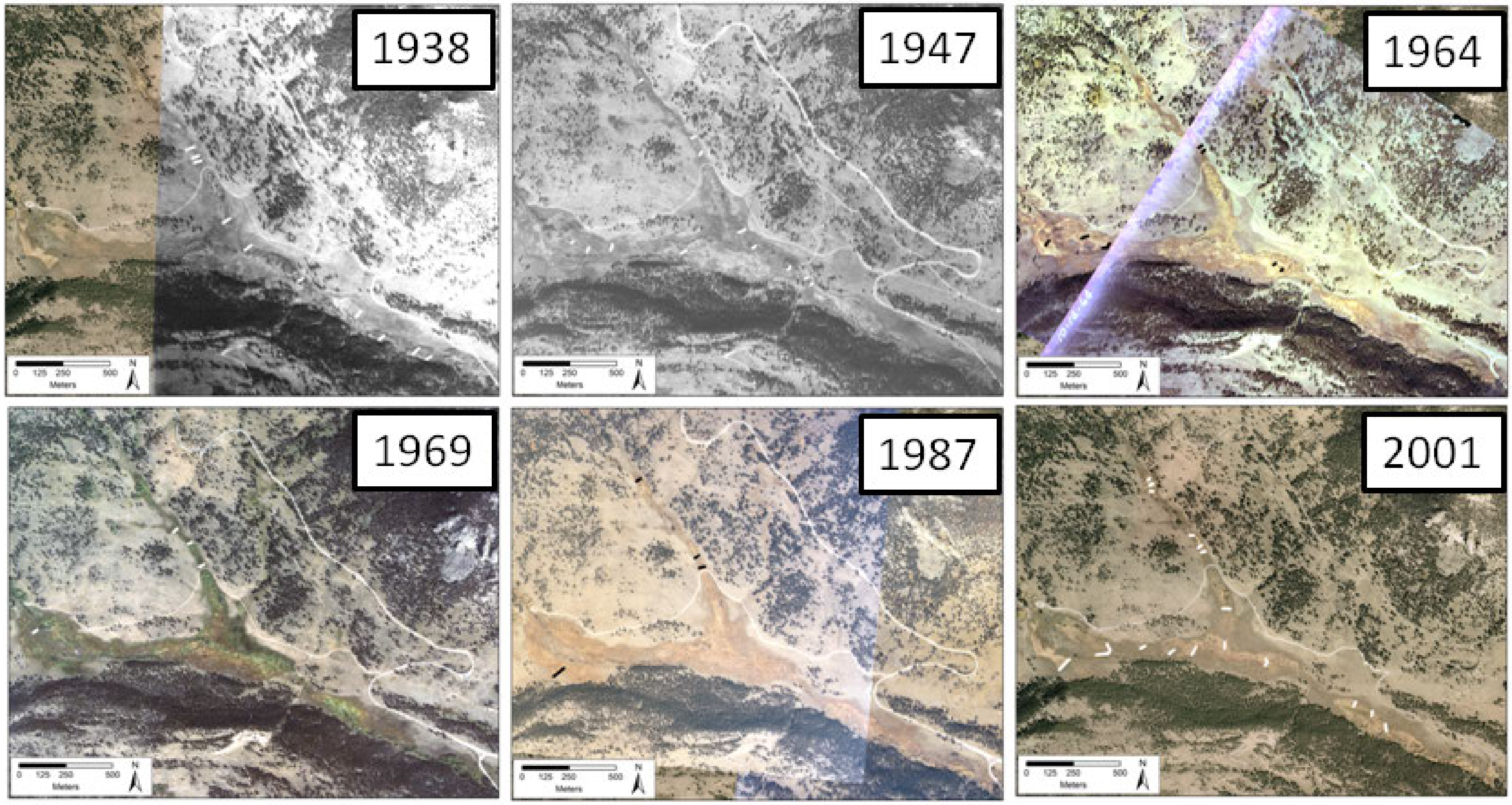

Figure 12. Aerial photograph series of Beaver Meadows from 1938-2001. Photos from 1938-1987 show black or white lines (depending on photograph darkness) that represent interpreted active or abandoned beaver dams. White lines on the 2001 photograph are located where there was photographic or field evidence (in 2009-2010) of buried beaver dams. Where there is incomplete coverage of the valley (1938 and 1964), the 2001 aerial photograph is in the background.

4.4.2 Moraine Park

A qualitative review of the aerial photograph series from Moraine Park clearly shows a dramatic decrease in the complexity of the channel network. Currently, the channel splits at the upstream end of the valley into two main channels and rejoins at the downstream end of the valley; there are a few other side channels on each main fork. Aerial photographs from the 1940s and 1960s show an extremely complex network of channels, where braidplains, meander belt widths, and significant riparian vegetation occupy ~50% of the valley area. In the 1987 and 2001 photographs, these areas make up <25% of the valley area.

The number of ponds and the total channel length generally decrease with time through the twentieth century, but both metrics spike in 1969, which could reflect a mild drought in the beginning of the 1960s and higher than normal discharge at the end of the 1960s (Woodhouse, 2001). Even with a decreasing beaver population in the 1960s, the increased abandoned channels would accommodate the increase in flow and appear as an increase in the number of active channels in the aerial photograph. The number of ponds range from 64 in 1947, up to 96 in 1969, decreasing to only 4 in 2001 (Figure 13). The total channel length ranges from approximately 30 km in the 1940s and 1960s and drops off to less than 15 km in 1987 and 2001. Several channels that were active in the 2001 photograph were found to be abandoned during field work in 2009-2010. The braiding index for the channels, as measured from the number of channels per valley width in 18 valley-wide transects, also increases slightly for the 1960s, but the spike is in 1964 rather than 1969. According to an ANOVA comparison of braiding indices, there are two significantly different groups of means, 1947-1969 and 1987-2001, where the means are 0.0110 (1947), 0.0125 (1964), and 0.0123 (1969), versus 0.0051 (1987) and 0.0038 (2001).

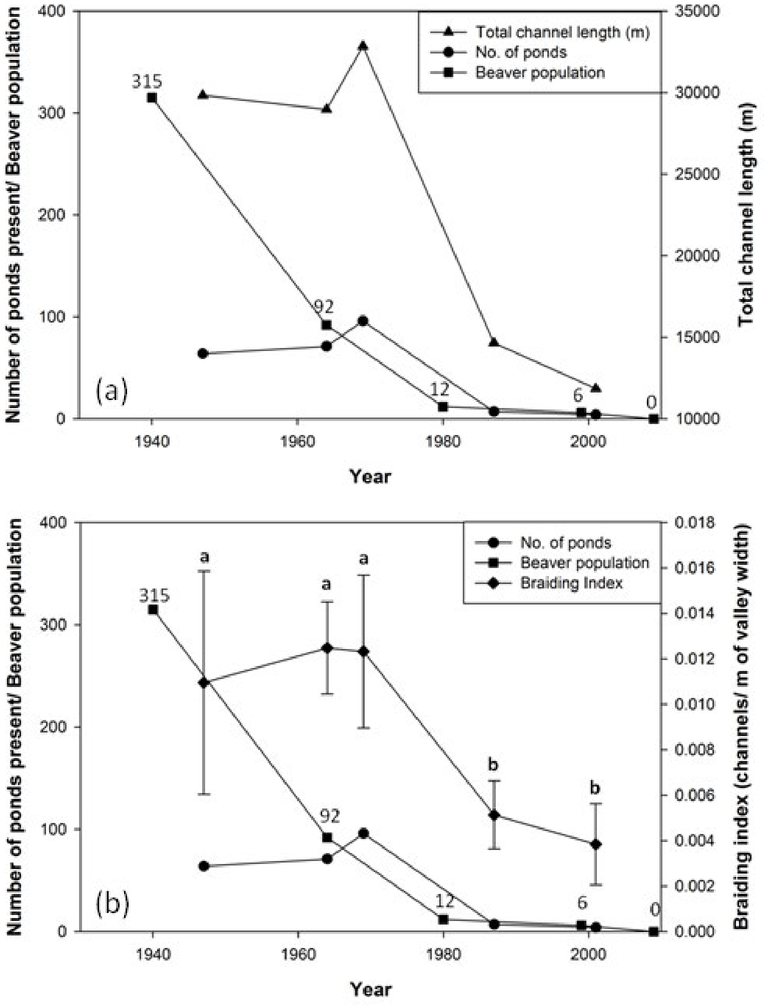

Figure 13. Relationship between channel complexity and number of ponds (circles) in Moraine Park. Actual beaver populations are shown on the graph, as determined from surveys conducted in RMNP (squares). Channel complexity is represented by total channel length (a) and braiding indices (b). Note that there is a general correspondence in trend of changes in channel complexity (total channel length and braiding index) and number of ponds.

Field reconnaissance of evidence of beaver dams or beaver-chewed wood indicates that in over half of the observations of abandoned beaver dams, there is an island that has formed directly downstream (Figure 14; Figure 15). If there was no island downstream, the channel split (~25% of observations) or there was a sharp bend in the channel. After the dam is abandoned, the channel migrates and incorporates the relict dam into the streambank, where the bank is highly reinforced and acts as a type of geotechnical bank reinforcement (Figure 14f). Where only beaver-chewed wood was present, this may be a disintegrated dam or simply transported beaver-chewed wood. In the vicinity of most of these observations, islands are formed, and the rest of the beaver-chewed wood seems to be randomly distributed on various in-channel geomorphic structures. Nonetheless, there is strong field evidence of the presence of channel splits or islands, which increase channel complexity and would increase the braiding index, where abandoned beaver dams or beaver-chewed wood is present (Figure 14; Figure 15).

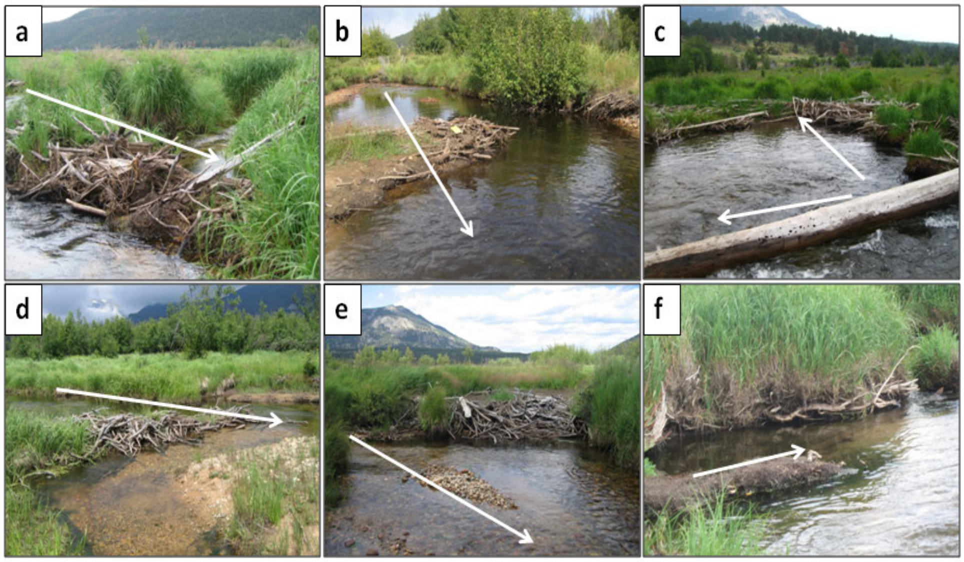

Figure 14. Examples of beaver- influenced channel form in Moraine Park. Photos a, c, and e show channel avulsions or splits where an abandoned beaver dam is present. Photos b and d show island formation at the site of an abandoned beaver dam. Photo f shows a bank reinforced by beaver chewed wood, possibly an abandoned dam, which caused a sharp meander bend. White arrows indicate main flow direction.

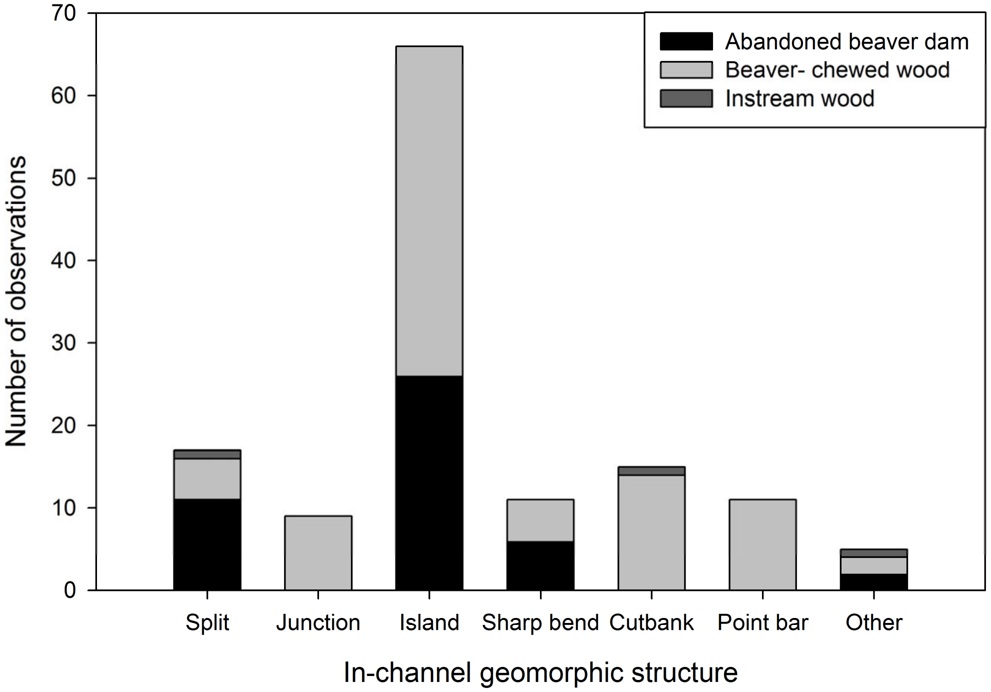

Figure 15. Geomorphic channel form associated with different types of wood in channel throughout Moraine Park. For each type of wood observation made (abandoned beaver dam, beaver-chewed wood, or instream wood without any evidence of beaver influence), the main proximal channel form was characterized. Splits and junctions are where a side channel splits or rejoins; an island is smaller in width than the combination of the two side channels; a sharp bend is 90° or less.

5. Discussion

Four hypotheses were tested in relation to floodplain sedimentation and the role of beaver in floodplain aggradation (Table 4). Unconfined, low-gradient valleys in the high-elevation Colorado Front Range are net sediment storage sinks. There is a low rate of constant sedimentation from fluvial in-channel deposition that is incorporated into the floodplain with channel migration. A significant component of sediment is beaver-induced fine-grained sediment. Higher rates of sedimentation occur in association with beaver dams, which are also responsible for added channel complexity.

Table 4. Summary of results of hypotheses presented in Section 1.3. Letters ‘R’ and ‘A’ indicate whether the hypothesis is rejected or accepted, respectively.

$H1_0$	Floodplain is in steady state, with the transport capacity approximately equal to the sediment supply, so there is no net storage of sediment.	**R**	Sediment is stored on the floodplain from at least the last 4000 years, according to ^{14}C ages. Sequences of fluvial and ponded sediment record temporal changes at a point in floodplain conditions.
$H1_{a1}$	Transport capacity exceeds sediment supply entering valley; there is no new storage and older sediment is removed.	**R**	
$H1_{a2}$	Floodplains have greater sediment supply than transport capacity and store new sediment on floodplain.	**A**	
$H2_0$	Floodplain is built via constant rate of accretion from overbank flood deposits.	**R**	There is a relatively thin veneer of Holocene sediment. Holocene sediment consists of relatively slow background rates of overbank or in-channel sedimentation and relatively fast, episodic beaver ponding sedimentation.
$H2_{a1}$	Floodplain was built rapidly from glacial outwash with a thin veneer of Holocene sediment.	**A**	
$H2_{a2}$	Episodic events dominate alluviation of valleys, such as beaver fluctuations, wildfire, or rare large floods (dam breaks).	**A**	
$H3_0$	Beaver-induced sedimentation is an *insignificant* amount (<25%) of the total post-glacial alluvium sediment.	**R**	Beaver- induced sedimentation consists of 30-50% of near- surface sediment.
$H3_a$	Beaver-induced sedimentation is a *significant* amount (>25%) of the total post-glacial alluvium sediment.	**A**	
$H4_0$	Beaver activities of building dams, creating ponds, and excavating canals *do not increase* fluvial complexity or alter the system from a single- to a multi-thread planform.	**R**	Beaver- formed features, such as dams and beaver-chewed wood, are often associated with islands and channel bifurcations. Channel length and braiding indices decreased with beaver population and number of ponds over the past century.
$H4_a$	Beaver activities of building dams, creating ponds, and excavating canals *increase* fluvial complexity by promoting bifurcations, islands, and by altering the system from a single- to a multi-thread planform.	**A**	

5.1 Sedimentation Types

Near-surface alluvial sediment in Beaver Meadows and Moraine Park create a relatively thin veneer above glacial outwash or till (Kramer et al., in press). Within this sediment layer exists a spatially heterogeneous layering of sediment types within a vertical section and across a lateral extent. However, the various sediment types reflect a defined set of environments: fluvial channel, beaver pond, and possible floodplain sediment. Common sediment packages have alternating packages of coarse fluvial sediment (sands and fine gravel in Beaver Meadows and gravels and small cobbles in Moraine Park) and fine-grained ponded sediment (clay, silt, and fine sands). Sediment from beaver ponds consists of mainly 0.1 m segments, up to ~1 m thick in some places, but combined consists of a significant proportion of the entire sampled sediment. In Beaver Meadows, beaver pond sediment consists of 33-50% of sediment, and in-channel sediment consists only of 28-40% of the sediment. Conversely, in Moraine Park there is 40-50% in-channel sediment and slightly less ponded sediment (32-41%). These values are supported by the geophysical analyses of Beaver Meadows, where 32-38% of alluvium was interpreted as beaver pond sediment (Kramer et al., in press).

The majority of sediment was interpreted as being deposited in relation to a beaver dam or within a channel. Minor amounts of sediment (2-23% in Beaver Meadows, 0-6% in Moraine Park) were interpreted as overbank deposition. Additionally, no other major sources of sediment were observed, including debris flows or peat accumulation. Therefore, I interpret the main floodplain processes in Beaver Meadows and Moraine Park as being a function of the interplay between fluvial and beaver pond processes.

5.2 Rates of Sedimentation

Sedimentation rates in Beaver Meadows and Moraine Park vary over an order of magnitude. Long-term rates agree at ~0.05 cm/y over several thousands of years. However, short-term rates vary considerably, indicating high temporal variability in aggradation over time and spatial variability in sedimentation processes and rates throughout the valley at any given point in time. Recent rates of sedimentation (within 300 cal y BP) range from 0.1-0.5 cm/y, which is still considerably lower than that of measured beaver pond aggradation rates for contemporary beaver ponds. Butler and Malanson (1995) measured rates of 2-28 cm/y (mean: 9.6, sd: 8.14) in several successive beaver ponds in Montana. Similar studies have obtained rates within a similar order of magnitude: John and Klein (2004) measured a mean rate of 8.02 cm/y (sd: 3.71) and Meentemeyer and Butler (1999) measured a mean rate of 15.25 cm/y (sd: 12.6) in beaver ponds in Germany and Montana, respectively. Ives (1942) suggested a rate of <1 cm/y, which is consistent with the highest rates measured in Beaver Meadows and Moraine Park; however, this is an estimate from observations of rising water levels over 20 years. The lower rates observed in Beaver Meadows and Moraine Park confirm the temporal variability in sedimentation. The two main sedimentation processes recorded in Beaver Meadows and Moraine Park are beaver-ponded sediment and fluvial deposition, either from a channel or overbank floodplain deposition. The slow settling of fine sediment constitute the periods of relatively high sedimentation rates. Fluvial sedimentation, although fast and more dramatic while it is occurring, is slow and episodic over longer time spans.

The glacial troughs on the eastern side of the Continental Divide in RMNP are an ideal location for examining beaver-induced sedimentation. Compared to sites on the western slope of the divide, Beaver Meadows and Moraine Park have limited sources of sediment, according to a similar study along the headwaters of the Colorado River in RMNP at the Lulu City wetland, where human induced debris flows have severely altered fluvial and ecological processes over the past decade (Rubin, 2010). In the Lulu City wetland, less than 10% of sediment was attributed to beaver pond sediment, and the remainder was split fairly evenly between debris flows, overbank or sorted debris flow, and peat. Even with additional sediment sources, aggradation rates in the Lulu City wetland are consistent with those in Beaver Meadows and Moraine Park, ranging from 0.04-0.15 cm/y, with more recent rates up to 0.4 cm/y. In a site more similar to Moraine Park, Horseshoe Park on the eastern slope of RMNP shows sedimentation rates varying throughout the Holocene: 0.025 cm/y directly after glaciation to 8200 y BP, 0.089 cm/y during 8200-6075 y BP, and 0.035 cm/y from 6075 y BP to present (Rainey, 1987). The average of these values (0.05 cm/y) coincides exactly with the long-term average aggradation rates in Beaver Meadows and Moraine Park.

5.3 Holocene Alluviation

We are presented with the conundrum of a time gap in sediment since deglaciation in Beaver Meadows and Moraine Park, because the oldest dated organic material is only 3430 cal y BP in Beaver Meadows at a depth of 1.37 m, and 4340 cal y BP in Moraine Park at 1 m depth. However, given the long-term aggradation rates of ~0.05 cm/y, 10,000 yrs of aggradation can be accounted for in the depth of alluvium (~2-6 m; average of 1.5 m) determined by Kramer et al. (in press). With the proximity of the terminal moraine to the downstream end of both of these valleys, these valleys were probably deglaciated by ~15,000 y BP; averaged aggradation at the same rate over 15,000 years would exceed the measured amount of alluvial sediment by 1-3 m. Therefore, there is a gap of deposited sediment of ~5,000 rather than 10,000 years. Because sediment older than 5,000 years old was not accessed, I present three possible scenarios of Holocene aggradation: 1) Episodic sedimentation was prevalent since deglaciation, but significant sedimentation only coincided with a significant beaver population. Although paleontological evidence is not available to determine beaver presence in RMNP, based on the current distribution of beaver, I can infer that beaver would be present when a food source is available and geomorphic characteristics are favorable (see section 2.4). In Yellowstone National Park, gaps in the beaver sediment record were found for several centuries from 700-1000 and 1800-2200 cal y BP, which was inferred to reflect periods of severe drought and warmer temperatures (Persico and Meyer, 2009). Directly following deglaciation, a warming period at ~10,000 y BP might have changed vegetation and flow dynamics in RMNP (Elias, 1996). Instead of reducing flows as during a drought, this warming period may have had the opposite effect and significantly increased flows from the receding glaciers, thereby creating a braided system with glacial outwash, which also would have inhibited beaver activity. 2) Possible higher flows directly following deglaciation that coincided with a warming period, combined with an absence of beaver ponds, would allow for higher stream power, and additional sediment would be transported out of the system rather than deposited. Similarly, occasional flushing could occur from outburst floods, from either breached beaver dams or upstream events of other breached natural dams such as large log jams (Butler, 1989; Butler and Malanson, 2005). 3) Finally, both Beaver Meadows and Moraine Park are bounded at the downstream end by base level controls of high-gradient reaches. Downstream of Moraine Park, the Big Thompson River reaches a gradient of ~5% with cascade bedforms created by large cobbles and boulders and lined by bedrock; the lower portion of Beaver Brook in Beaver Meadows exceeds a gradient of 2% with gravel to small boulder sized substrate. Because the sediment thickness cannot exceed that of the base level elevation formed by the bottom of the valley, the possible valley gradient is controlled by the base level elevation. An internal gradient threshold will cap the thickness of the sediment wedge that develops, so the first period of time recorded in sediment may be removed by erosion (Schumm, 1979). With the presence of beaver, the channel gradient can be artificially lowered in relation to the valley gradient, so the internal gradient threshold may be increased. However, under this scenario, I would expect to see a gap in dates in the middle rather than the beginning of the Holocene, and only very recent dates in the top layer of sediment. Each of these three scenarios are plausible, but there was likely a combination that acted to limit the net aggradation, where beaver-induced sedimentation was occasionally limited and sediment was evacuated in conjunction with outburst events, and downstream controls limit the potential sediment accumulation.

5.4 Beaver, Channel Complexity, and Sedimentation Positive Feedback Loop

The presence of beaver dams increases the complexity of the channel network through promoting avulsions, promoting multiple flow paths, and discontinuous flows (Woo and Waddington, 1990; John and Klein, 2004; Burchsted et al., 2010). In Moraine Park, a dramatic decrease in the braiding index and total channel length from the 1930s to the present was concurrent with a surveyed decrease in beaver population and a decrease in the number of ponds present. These data, in conjunction with field evidence of islands or channel splits downstream of relict beaver dams, support the hypothesis that beaver promote the formation of a multi-thread channel network. The multi-thread network influences complexity in other spheres, such as the vegetated riparian area, groundwater flow, and sedimentation. Past studies have noticed similar changes over shorter time spans (Woo and Waddington, 1990; John and Klein, 2004), and in Moraine Park we see the extended result of the removal of beaver and reduction of multiple flow paths on channel planform and the resultant transformation in riparian vegetation zones to xeric environments. The reduction of beaver furthermore removes the current floodplain processes from the range of historical variability of sedimentation.

In terms of beaver pond sedimentation in a beaver-meadow complex hypothesis, the increase in channel complexity forms a positive feedback. A multi-thread channel network, a product of beaver dams, increases the potential channel length for further damming, thus increasing the area that can be occupied by beaver ponds and increasing the volume of beaver pond sediment trapped in a valley (Figure 16). With relatively few beaver dams, complexity will be reduced and the potential of beavers in trapping sediment will be minimal. There is likely a threshold population of beaver that will alter channel planform and will exponentially increase possible dam sites and thus beaver population. Even though sedimentation is spatially heterogeneous due to the different processes acting on a broad valley at any given point in time, beaver ponds can exist at multiple locations laterally and longitudinally throughout an extensive valley like Moraine Park at any given time.

The importance of the beaver meadow complex hypothesis in explaining the development of broad valleys has been debated for over a half a century (Ives, 1942; Persico and Meyer, 2009). Although the hypothesis may not be applicable in all settings and where other processes dominate, Beaver Meadows and Moraine Park represent ideal setting where beaver do have a large impact on sediment aggradation. Given the high percentage of beaver sediment (~50%) in the thin veneer (~1-5 m) of alluvial sediment and the role of beaver in enhancing their habitat potential not only through creation of ponds but also a multi-thread channel network, these valleys have been built up and future streambank material has been deposited as a result of beaver activities.

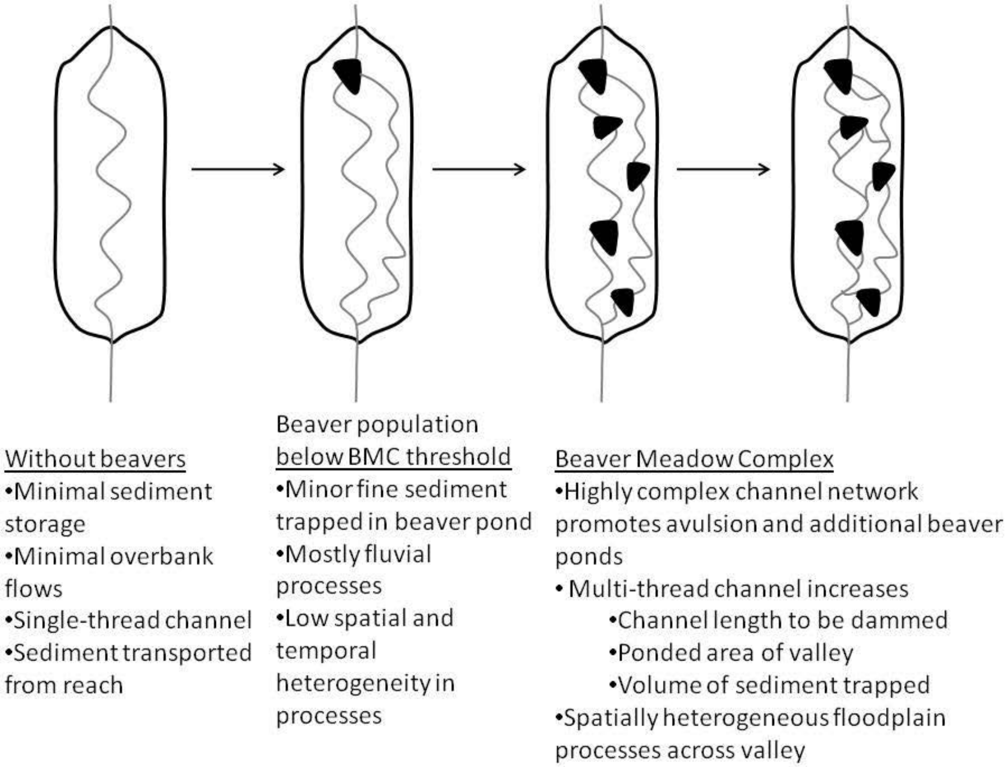

Figure 16. Illustration of creation of beaver-meadow complex through additional beaver ponds and added complexity from a multi-thread system.

5.5 Historical Range of Variability of Beaver Pond Deposits

Given the scenarios of future climate change, the usefulness of understanding the historical range of variability may be limited because the governing processes, including discharge, which is controlled by precipitation and temperature regimes, are moving into non-stationarity (Milly et al., 2008). For stream or ecological restoration, novel scenarios may need to be considered, rather than restoring to historical condition. However, given the interaction of multiple geomorphic and biotic processes in producing the current valley form, understanding HRV illuminates a template of normal processes from which current conditions were formed. The role of biotic processes in shaping channel form and valley evolution has largely been ignored in the past. This study has shown how beaver can compound their own effects on the valley through creating a more complex channel network and thus allowing more potential stream length to be dammed where sediment can be trapped. Without the added complexity of a beaver-influenced channel network, not only will less fine sediment be trapped but, without the beaver-induced lower gradient, more sediment will be evacuated from the system (Gurnell, 1998).

In this type of headwater stream there are few segments where fine sediment will deposit. From the watershed-scale view of sediment movement, headwaters are erosional centers (Schumm, 1977); however, these broad, low-gradient valleys act as temporary storage depots for sediment in its overall movement towards base level. Without mechanisms such as beaver dams that slow the movement of sediment, hillslope and upstream disturbances will be felt more rapidly and at a greater magnitude in downstream reaches. Hydrologically, beaver dams dampen the effect of floods (Gurnell, 1998, Westbrook et al., 2006), and in the same respect, the beaver-meadow complex in broad, low-gradient headwater valleys dampens sediment movement. On a smaller scale, this is analogous to sediment trapped by log jams, supplying nutrients and possibly storing carbon.

Additionally, the fine sediment trapped in beaver ponds will become part of streambanks following channel migration, forming cohesive streambanks. Because of high gradients and coarse substrates, cohesive streambanks are rare in headwater streams. This furthers the beaver legacy on channel form by increasing bank stability and influencing channel form with steeper streambanks.

Given that pre-European settlement estimates of beaver populations in North America range from 60 to 400 million and current populations are only 6 to 12 million (Naiman et al., 1988), beaver-meadow complexes would have been much more common. Butler and Malanson (2005) estimated that the number of ponds ranged from 15 to 250 million versus only 1.5 to 7.7 million in pre- versus post-European settlement, respectively. Because beaver-meadow complexes are composed of several ponds, the number of complexes will be less but would still have decreased by at least 50%. Beaver-meadow complexes significantly contribute to the development of the floodplain in unconfined, low-gradient valleys, which are often disproportionately impacted by human development, thereby further altering the floodplain processes from a historical range of variability throughout North America.

6. Conclusions

Unconfined, low-gradient headwater valleys are important centers for temporary sediment storage, within the larger space and time scales of sediment transport from headwaters to the mouth of a catchment. In Beaver Meadows and Moraine Park in RMNP, I have shown the importance of beaver in trapping and storing a significant amount of fine sediment throughout the Holocene. Because the alluvium that covers the glacial till and outwash is relatively thin, sediment deposition induced by beaver does not need to be on the order of tens of meters to be significant and to support the beaver-meadow complex in explaining the development of relatively flat, broad valleys with abundant fine sediment. Temporal heterogeneity in aggradation rates reflects spatial heterogeneity in fluvial and beaver-ponded processes throughout the floodplain. These study valleys were ideal locations for examining the role of beaver in floodplain processes, but relatively low sedimentation volumes by beaver may be overshadowed in landscapes with strong signals from debris flows or sediment pulses from frequent forest fires.

6.1 Historical Range of Variability of Beaver Sedimentation

Beaver were abundant in the RMNP area pre-European settlement, which caused a positive feedback in the volume of sediment aggradation through the formation of a complex channel network. The current ecological and geomorphic condition without beaver exhibits a single thread channel with a higher gradient, which will not only trap less sediment but with a higher stream power will incise and transport additional sediment. This condition likely falls outside of the historical range of variability in channel form and sedimentation rates found during much of the Holocene in these valleys, and certainly differs from conditions during the past 1,000 years. Historically, a multi-thread channel network maintained by successive beaver dams trapped a nearly equal amount of beaver pond and in-channel sediment. Fine sediment, which ordinarily would be flushed out of headwater reaches, is trapped and incorporated into the floodplain and streambanks after channel migration. The faster and larger magnitude of sediment evacuation translates into higher connectivity between disturbances in the headwaters and downstream reaches.

The ecological management of these headwater valleys will require an understanding of the historical channel conditions in addition to change in vegetation and elk-beaver interactions. With the reduction in beaver population, the change in channel form into a simpler single-thread system has affected riparian vegetation, sediment trapping and the potential for supporting a larger beaver population.

6.2 Beaver-meadow Complex

The beaver-meadow complex has been invoked as a mechanism for filling unconfined, low-gradient valleys with fine sediment (Ruedemann and Schoonmaker, 1938; Ives, 1942). These researchers did not provide quantitative measurements of beaver-related sediment, which offers this subject as an open area for research. Although they did not suggest a minimum quantity or percentage of fine sediment for a valley to be designated as a beaver-meadow complex, their idea was meant as a conceptual model to counter the earlier explanations of fertile valleys filled with mostly fine sediment as silted-up glacial lakes. The premise that the original geometry of these valleys was formed through glaciation is accepted, and the beaver-meadow complex is not meant to explain the original formation of the broad valley, as suggested by Persico and Meyer (2009). Through their work examining Holocene beaver-related sediment in Yellowstone National Park, Perscio and Meyer (2009) discount the beaver-meadow complex hypothesis, under the assumption that tens of meters of beaver-related sediment are necessary to transform an originally V-shaped valley to one that is broader and disconnected from its hillslopes.

The results presented from this study provide quantitative support for the conceptual ideas presented by Ruedemann and Schoonmaker (1938) and Ives (1942).

Although only a thin veneer of Holocene sediment exists above post-glacial Pinedale outwash and older Bull Lake till, a significant percentage of the sediment is deposited as a result of beaver damming. The beaver-related sediment deposited not only adds to floodplain aggradation, but contributes finer-grained sediment than is normally deposited in this headwater environment. Other mechanisms for trapping fine sediment, including log jams and debris flows, are ruled out in these valleys. The signal of sediment from beaver dams can be overshadowed by debris flows, highly productive wetlands forming peat, or forest fires delivering large amounts of hillslope sediment in other environments (e.g., Rubin, 2010). In addition to providing field support for the previously proposed beaver-meadow complex hypothesis, this study furthers the concept by adding the idea of beaver-induced complexity that creates added potential for beaver damming and thus sediment trapping.

6.3 Colorado Front Range Sedimentation

The results and discussion from this study have established the importance of beaver in storing sediment and shaping valley processes in Beaver Meadows and Moraine Park in Rocky Mountain National Park. These processes should not be unique to the two study locations, however, and likely occur where several conditions are met. 1) Conditions must be favorable for beaver to establish dams: there must be a sufficient and sustainable food source for beaver, which includes willow and aspen, and stream power must be low enough so that dams withstand removal (e.g., Gurnell, 1998). 2) Valley geometry must provide a wide enough valley bottom for the channel to migrate, avulse, and create a multi-thread channel system (Wohl, 2011). 3) Other sedimentation processes must not overshadow beaver-induced sediment or overwhelm the system so that beaver dams cannot be maintained or add only minor amounts of sediment to the total alluvium stored in the valley bottom. Where debris flows are more common, in valleys with steep hillslopes, and/or highly weathered bedrock, and intense rainfall, beaver-influenced sedimentation will not likely contribute as large a percentage to the overall sediment stored. Debris flows may wash out beaver dams, and therefore portions of the valley will not have locally decreased gradients, causing sediment storage to be less likely.

A thorough survey of valleys throughout the Colorado Front Range could determine what percentage of the valleys was conducive to historical beaver-meadow complex formation. However, a cursory examination of the east side of Rocky Mountain National Park suggests only three other valleys meeting these criteria: Hidden Valley, which is similar in size to Beaver Meadows, Horseshoe Park, which is similar in size to Moraine Park, and Wild Basin meadows, which is between Beaver Meadows and Moraine Park in size. Although the Lawn Lake alluvial fan terminates in the upper portion of Horseshoe Park, most of the valley is clear of debris flow evidence. Given the relative paucity of these valley types, their importance within the entire Front Range in terms of function is magnified.

The beaver-meadow complexes serve several functions, at short time scales while beaver dams are active and there is an established multi-thread network, and over longer time scales where magnitude and types of sediment storage become important. At the shorter time scales, the added complexity has ecological importance by providing a larger riparian width through increased overbank flooding and a higher water table (Westbrook et al., 2006). At longer time scales, beaver-meadow complexes provide storage sinks for sediment and organic material. The trapped fine sediment also provides the template for the channel to carve through and creates the potential for more cohesive banks and less bank failure and thus sediment loss over time (Thorne, 1982).

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CHAPTER 3: FUNCTIONAL CLASSIFICATION OF RIPARIAN VEGETATION FOR BANK STABILITY

1. Introduction

This chapter of the dissertation evaluates the effects of various riparian plant species native to the Colorado Front Range on bank stability. Two main objectives are addressed in this component. The first objective is to use metrics of riparian species' roots and bank characteristics and conduct a sensitivity analysis of a bank stability erosion model, BSTEM, to determine whether vegetation or physical bank characteristics have a larger control on bank stability values. The second objective is to develop a classification for riparian plant species describing their functional role in stabilizing streambanks. Root tensile curves and morphologic descriptions are presented for several species. These species' characteristics are used to develop a simplified species root classification. The integrated properties of the roots, in addition to bank properties that are tested in the bank stability model, are also used to refine the species classification.

1.1 Background

1.1.1 Types of Bank Failure

Streambank erosion occurs by two main processes: 1) fluvial entrainment caused by hydraulic forces generating shear stress directly on the bed or bank, and 2) through complete failure of the bank when shear strength of the bank, as determined by the Coulomb equation, is overcome by pore-water pressure and other driving forces defined by the bank geometry and confining pressure from the channel (Thorne, 1982). The background material presented and objectives of this study focus almost exclusively on the latter process. The relative importance of physical bank properties, including bank geometry, sediment texture, and pore-water pressure versus mechanical influences of riparian vegetation in regards to bank stability are discussed.

Regardless of the relative importance of vegetation and bank characteristics, hydrology remains the primary controlling factor in streambank retreat and thus migration. The basal endpoint of the streambanks ultimately controls bank stability, and there are three states of basal endpoint control. 1) *Impeded removal* occurs when bank failures supply new material to the base of the bank faster than it is removed and results in a decreased bank angle and height and thus decreases the rate of bank failures. 2) In *unimpeded removal*, the rates of bank failure and removal of sediment from the base of the streambank are in balance. 3) *Excess basal capacity* occurs when the rate of removal of material exceeds the rate of bank failure; however, because the base of the streambank is lowered, the bank height and angle increase, causing more bank failure from undercutting and sloughing (Thorne, 1982). Although both of the endpoint scenarios (impeded removal and excess basal capacity) cause the banks to move toward greater equilibrium, there can be a hydrologically-induced increase or decrease in bank failure. For the sake of simplicity in modeling under which conditions bank failure occur, I assume that there is unimpeded removal for the bank stability situations presented in this chapter.

Banks fail differently with non-cohesive versus cohesive material (Thorne, 1982). Failure of non-cohesive banks occurs by removal of individual grains or along a shallow slip plane or slightly curved surface. Cohesive banks, on the other hand, are subject to two different types of failure, depending on bank geometry. Slab-type failure of low-steep banks or rotational slip failure occurs on high but less steep banks and the curved failure surface usually passes close to or just above the bank toe (Thorne, 1990). More complex types of bank failures occur on stratified banks with a combination of non-cohesive layers, which usually erode more quickly, and cohesive layers. The curved or planar failure surfaces may be within one layer or cut across multiple layers.

1.1.2 Use of Riparian Vegetation for Bank Stabilization

Planting of riparian vegetation is commonly used for stream restoration projects. Willow planting is common by transplanting entire shrubs or by simply using vegetative reproduction by cut stems. According to Watson et al. (1997), Roseboom of the Illinois State Water Survey (1992) pioneered the use of the willow post technique for stream stabilization. Willow posts serve many functions in erosion control, ranging from reducing soil water by evapotranspiration, mechanical soil reinforcement, and reducing stream velocity, to increasing sedimentation (Watson et al., 1997).

Stream restoration projects typically use these techniques to facilitate the establishment of a riparian zone for habitat and to stabilize streambanks and reduce bank erosion (e.g., Shields and Knight, 2003; Pezeshki and Shields, 2006). Guides for harvesting, storing and planting willow cuttings are common (Roseboom, 1992). Given that stream restoration projects have increased at an exponential rate over the past 15 years (Bernhardt et al., 2005), there is a relatively small amount of literature related to bank stabilization properties of various species or even the commonly used willow. Although it is accepted that willows are fast growing and relatively easy to plant, few quantitative studies have shown the added benefit of using willows in relation to other riparian species. Because willow require moist conditions, alternative species could be advantageous, because a high water table may not be available in a degraded system.

Riparian restoration is intrinsically tied to stream restoration, because the processes maintaining streambanks, which control the basal endpoint, ultimately stem from geomorphic and hydrologic processes (Goodwin et al., 1997). Therefore, planting riparian vegetation for bank stability is futile under conditions with excess basal capacity. Nonetheless, many stream or riparian restoration projects proceed with planting of riparian vegetation without regard to physical processes (Bernhardt et al., 2005). Stream restoration relies on riparian planting, especially of willows, for improving bank stability. Because one of the top five reported goals of restoration projects is to stabilize streambanks (Bernhardt et al., 2005), it would behoove land managers from a wide array of agencies to have a better understanding of which types of riparian species provide the best bank stabilization.

Although bank stabilization is a common goal for stream restoration projects, it is important to note that bank erosion is an integral part of stream processes, allowing for the formation and propagation of meandering and braided channels. Bank erosion allows for succession of riparian plants and creates dynamic habitat patches for aquatic organisms (Florsheim et al., 2008). However, when anthropogenic reach- or watershed-scale disturbances have altered equilibrium stream processes, so that the system is in a state of impeded removal (*sensu* Thorne, 1982), bank reinforcement may be necessary.

The examination of the role of riparian plants in stabilizing streambanks in this dissertation should not be interpreted as advocating stable banks in all stream systems. When vegetation is used for bank reinforcement, however, quantitative knowledge should inform the decision on what type of vegetation should be used.

Abundant evidence exists, however, on the effects of riparian vegetation on shifting channel planform because of the vegetation’s ability to stabilize streambanks and decrease the rate of channel migration. With the addition of vegetation, braided channels tend to form a meandering or multi-thread planform (Murray and Paola, 1997; Tal and Paola, 2007, 2010). The rate of avulsions decreases and flow is concentrated in a central channel with more vegetation. Braudrick et al. (2009) were able to create a meandering channel in a flume by planting riparian vegetation (alfalfa sprouts) on the floodplain and adding fine sediment.   Additionally, field evidence has shown that, with the invasion of the non-native willow to New Zealand, braided streams in which flows have been reduced by dams and flow regulation have lost channel complexity (Michal Tal, *personal communication*, August 2010). This has serious consequences beyond interesting academic questions of interactions between channel planform, bank stability, and vegetation, because the reduced flow capacity has increased the magnitude and frequency of flooding, affecting nearby towns.

Non-native invasive riparian vegetation can cause significant geomorphic change, because vegetation can affect flow dynamics by changing roughness, and prevent or promote channel migration, depending on the previous vegetation type. The invasive tamarisk has contributed to a positive-feedback loop together with an altered flow regime to create a narrower channel, disconnected from its floodplain (Dean and Schmidt, 2011). Bank stability modeling of streambanks in Canyon de Chelly, Arizona, which has seen large-scale geomorphic change since the introduction of tamarisk during the 20th century, indicates that more bank failure would occur with the removal of tamarisk (Pollen-Bankhead et al., 2009).

1.1.3 Mechanics of Riparian Vegetation Bank Stabilization

Vegetation has numerous positive and negative effects on soil stability. Simon and Collison (2002) divide these into mechanical and hydrologic effects. I focus the discussion below on the mechanical strengthening of streambanks, the most commonly studied effect of vegetation. The fibrous roots of riparian vegetation, which are strong in tension but weak in compression, add strength to streambanks, because soil is strong in compression but weak in tension (Thorne, 1982). However, vegetation also increases the normal stress of a streambank by adding mass to the top of the soil and thus increasing the shear strength. This commonly causes a destabilizing effect on the streambank due to steep shear surfaces. Hydrologically, vegetation can stabilize streambanks by increasing matric suction when pore-water pressure decreases. Soil water is transpired by the vegetation or vegetation intercepts rainfall that would otherwise infiltrate into the bank. Conversely, vegetation can concentrate rainfall through stemflow and create higher local pore-water pressures. In addition, roots and associated biological activity can create macropores that can concentrate flow and contribute to bank failure (Simon and Collison, 2002).

Cohesion in soils on landslide-prone slopes increases with tree roots (Wu et al., 1979). Although riparian vegetation has been used as a geotechnical bank reinforcement, until recently little work has shown this quantitatively. Abernethy and Rutherfurd (2001), in an Australian study of two riparian species, showed that root strength, friction between the roots and the soil, and the distribution of roots within the soil control the streambank root reinforcement. The root area ratio (RAR), which quantifies the density of roots as the ratio of the sum of the cross-sectional area of the roots intersecting the profile wall to the cross-sectional area of the wall, declined rapidly with distance below the surface and proved important in describing tree-root distribution. Root tensile strengths ranged from tens to hundreds of megapascals, whereas soil shear strengths are normally in the tens of kilopascals. Abernethy and Rutherfurd (2001) concluded that interspecies differences in tensile strength have a smaller impact than interspecies variability in root distributions for the shear strength of a streambank. However, this study only compared two riparian trees species and not differences between different vegetation types, such as trees, shrubs, graminoids, and herbs.

The modeled added bank reinforcement by vegetation in the Lake Tahoe region of California and Nevada caused reductions in sediment load of ~53% when root reinforcement was in the top meter of the bank. Added reinforcement values ranged from

~3 kPa for young Lemmon's willow, to 16.5 kPa for a wet meadow with sedges and grasses and >20 kPa for a mature lodgepole pine (*Pinus contorta*). Goodwin Creek, a commonly modeled stream in Mississippi, was able to withstand bank failure during a wet spring because of added shear strength from vegetation (Pollen et al., 2004).

1.1.4 Classification of Riparian Vegetation

Previous work has established that vegetation adds cohesion to streambanks and that vegetation is frequently used for stream restoration projects. However, few studies have classified riparian vegetation in terms of differences in stream stabilization characteristics and capabilities. In fact, a thorough literature review resulted in no peer-reviewed studies classifying riparian vegetation based on bank stabilization properties. Measuring the tensile strength of many species can be time intensive and prohibitive to most because the equipment to measure root tensile strength is not readily available. The U.S. Forest Service (USFS), which is charged with monitoring and restoring streams for 8.5% of the total land in the United States (http://www.fs.fed.us), currently partially relies on a rating system of riparian vegetation developed by Winward (2000). This rating system ranks over 90 different riparian species, and assemblages of these species, based on their ability to buffer erosive forces along the streambank. Species were ranked from 1 to 10 based on their resistive capabilities. Barren ground is ranked as '1,' and most sedges were given a ranking of '8' or '9.' Certain willow-sedge communities were given a ranking of '10,' and anchored logs or boulders were also ranked as a '10.' Winward (2000, p. 39) claims that the stability class rating was

> “developed based on several years of observations and study of various successional sequences as well as in-field evidence of their abilities to withstand the erosive forces of water. Information from various research studies also was used where it was available. A few values have been adjusted slightly in this document as continuing field experiences and recommendations from other riparian ecologists have demonstrated a need for such modifications.”

However, these observations were not described nor cited. Although there is certainly some validity to this ranking, it is not based on any quantifiable functional or morphologic characteristic.

This ranking system of riparian vegetation for bank stability has some valid advantages for USFS managers, yet fails to capture some of the complexity of vegetation-bank interactions. The species ranking is simple and easy to understand, and it includes an extensive list of species. For a single streambank, managers can easily compare species to be used for stream restoration projects or evaluate the potential stability of a streambank. The drawbacks of this ranking system, however, are numerous. First, the ranking of the various species is entirely subjective; no field studies are referenced, nor are quantitative measures of root characteristics reported. Additionally, non-vegetative factors that contribute to bank stability (bank geometry, sediment texture, pore pressure) are not taken into account. Finally, no guidance is given on how to rank species or assemblages not included in this ranking system. Managers working in national forests with different riparian species assemblages than those included in Winward (2000) would find this ranking system useless, because it does not give the rationale for the ranking or measurable characteristics to compare with other species.

1.1.5 Root Descriptors and Classifications

Classification systems of organisms have been used to simplify the understanding of a system or the possible consequences of a disturbance (Boutin and Keddy, 1993). Classifications started in the 1930s, when Du Rietz (1931) introduced the idea of classifying plant species according to type rather than only taxonomic similarity. Raunkiaer (1934) classified plants according to life-form adapted to the unfavorable season, based on the elevation of vegetative buds in relation to the ground. Root traits are not commonly used as a classification method for plants because they are not easily visible. However, workers have recently realized the importance of understanding root morphology and corresponding function or identifying features. Leva et al. (2009) determined that root traits can be used to recognize species and can reflect a major ecological group of species. Roots were measured and characterized according to color, hair abundance, diameter, tensile strength, spatial density and maximum root length (Leva et al., 2009). Roumet et al. (2008) conducted a study to determine whether root traits differed between three major plant families and whether this related to root function. Taxonomic plant classification did reflect differences in root morphology and architecture, but root functions of respiration and exudation were not related to root architecture or morphology. The authors suggest that measurements made at the whole root system level may obscure the functional relationship between root traits and their functions of interest -- respiration and exudation. Functional classifications should be based on the morphological attributes that pertain to the functions being studied. To study the root function of plant roots adding strength to stream banks, the whole root system should be characterized and studied.

1.1.6 Bank Stability Modeling

Models of bank failure have been evolving for the past 20 years, with elements of riparian root strength being incorporated within the last 10 years. Simon et al. (2000) developed a bank-stability algorithm, known as BSTEM, incorporating two different failure criteria for the saturated and unsaturated parts of the failure surface. Three other forces are also taken into account: 1) matric suction force on the unsaturated part of the failure surface, 2) hydrostatic-uplift force due to positive pore-water pressures on the saturated part of the failure plane, and 3) hydrostatic-confining force provided by the water in the channel. BSTEM was chosen for bank stability modeling, because it is a physically based model that takes into account multiple aspects of physical, hydrological, and vegetative resisting and driving forces that allows for comparison of these three aspects in determining overall bank stability. Additionally, this model has been thoroughly validated with field data (e.g., Simon et al., 2000).

RipRoot, an important addition to BSTEM, is a tensile strength model that calculates added cohesion from roots (Pollen et al., 2004; Pollen and Simon, 2005). Wu et al. (1979), who introduced an earlier model to calculate added cohesion from roots, made several simplifying assumptions. Wu et al. (1979) supposed that roots are perpendicular to the slip plane. However, the angles of the roots are in fact important, because they determine the maximum tensile strength possible before root failure occurs as a result of the stress distribution within the root volume. Also, the assumption was made that roots are always well anchored and always fail through tension and not by pull out, which happens when roots slip out of the soil due to bond failure between the root and soil. Most importantly, this previous root failure model assumed that when the full tensile strength of roots is reached, all of the roots would fail simultaneously. To address these assumptions, Pollen and Simon (2005) use a fiber bundle model to model root failure. This method allows roots to have different tensile strengths and break progressively during failure of a bank, and redistributes the stresses to the remaining roots after the failure of one root.

These bank and root failure models have been applied to practical stream management problems and have been verified using field data. The effects of removing tamarisk and Russian olive were determined at individual cross-sections in Canyon de Chelly National Monument, Arizona (Pollen-Bankhead et al., 2009). Testing the tensile root strength of these two species and modeling bank failure using BSTEM indicated that tamarisk and Russian olive have a significant impact on bank stability and bank failure frequency. On a larger scale, these methods can be applied to an entire river reach. BSTEM was used iteratively for an entire year's hydrograph for several cross-sections, and these results were extrapolated over an entire reach to determine sediment loading into Lake Tahoe modeled for existing conditions and with toe protection (Simon et al., 2009). Using this method, the magnitude of channel bank erosion can be modeled in relation to hydrologic versus vegetative change.

1.2 Objectives and Hypotheses

In this section of the dissertation, I will address two main objectives. First, I will determine the relative importance of vegetation versus bank characteristics in determining bank stability and whether a bank will fail, as simulated in BSTEM. As shown above, previous riparian vegetation classification schemes assumed bank stability is an inherent characteristic for a given species and does not vary based on physical bank or hydrologic characteristics (Winward, 2000). This study determines whether differences in species or physical characteristics contribute greater variability to bank stability. Second, I develop and present a functional classification of species based bank stability capability and root characteristics. This classification is created under the assumption that species cause more variability than bank characteristics; otherwise, the classification examines the species variability within a certain bank type.

1.2.1 Objective 1: Relative Importance of Bank Versus Vegetation Characteristics

Bank characteristics, vegetation characteristics, and interactions between the two factors determine the overall stability of a streambank. However, the relative contribution of these factors is unknown. For a functional classification of species to be applicable, it must be determined either that vegetation type provides greater variability than bank type or that the classification is only applicable within similar bank types. Because the Winward (2000) classification of bank stability by riparian vegetation (described in Section 1.1.5) simply ranks species without regard to bank characteristics, it implicitly assumes that bank stability is an inherent characteristic of the species.

The first objective will test whether bank characteristics or vegetation characteristics have a greater control on bank stability with the types of streambanks and riparian species observed in the Colorado Front Range. Each species should have a range of bank stabilizing effects, taking into account the variation in streambank texture, bank height and angle, and hydrologic conditions.

Although there will be different interactions between plant roots and a fine-grained cohesive bank versus a bank composed of pure sand, I expect to see variation between species. For example, a shallow root with low tensile strength may add less bank cohesion in a cohesive bank than a spatially dense, deep root with high tensile strength in the sandy bank. Figure 17 shows a schematic of relative contribution of species or species groups to bank stability. Several factors can influence the range of variability of the bank stability contribution of a species, including streambank texture, bank angle, pore-water pressure, root-soil friction, and specimen spatial density (Figure 17). Species can have a broad range (species group D in Figure 17), either in terms of where they will grow and are found or in terms of contribution to bank stability because the root interacts with the streambank properties. Narrow ranges (species group E in Figure 17) may reflect either very specific requirements of where the species will grow, or very little interaction with bank properties and therefore a consistent contribution to bank stability. Using this schematic, species will have a varying degree of contribution to bank stability, but some species groups can still be distinguished. For example, the range of species group I does not overlap with A, B, C, E, or F, and could therefore be distinguished from them regardless of streambank properties or conditions.

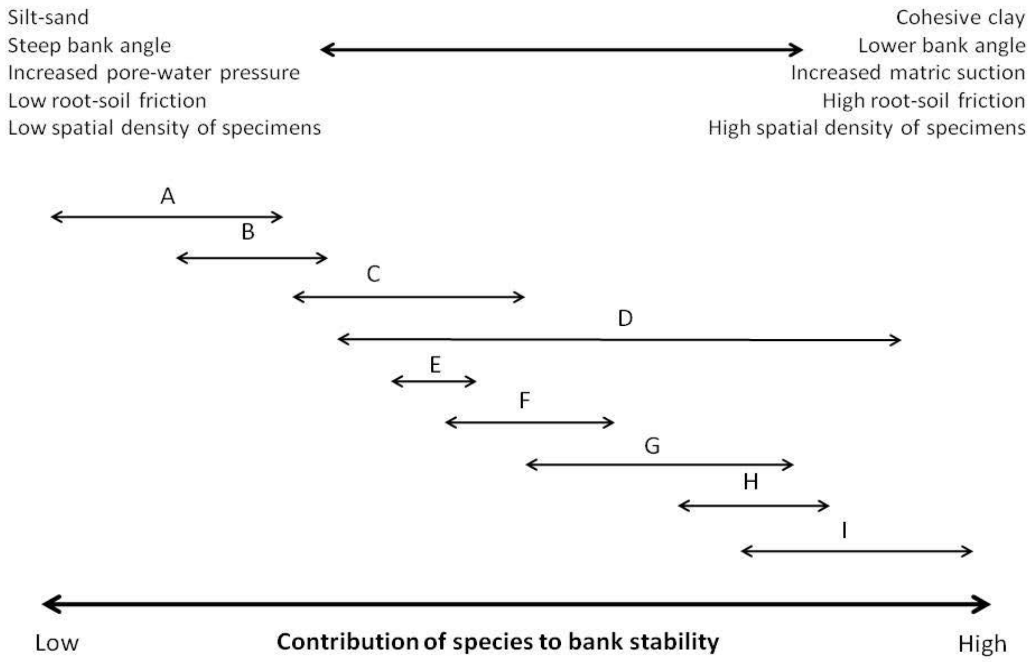

Figure 17. Shematic showing low to high contribution of riparian roots to bank stability. Ranges show bank stability resulting from species' roots and variation of interaction with streambank characteristics. Streambank factors that would contribute to the varying bank stabilization contribution are shown at the top of the figure.

The following hypotheses will be tested for the objective of determining the relative contribution of bank characteristics and vegetation to bank stability:

$H1_0$: There are no differences in the ability of riparian species to stabilize streambanks.

Two conditions may be present for there to be no apparent difference in the bank stabilization properties of various species. If there is very little contribution of the vegetation to erosional resistance and most of the resistance results from bank properties and characteristics, then there will be little difference between species in bank stability. Second, if the interactions between the vegetation and streambank overwhelm any vegetation-specific bank stabilization effects, little difference may be evident between species. In this case the individual species or species groups shown in Figure 17 would overlap and not show any distinct ranges.

$H1_a$: There are distinct differences in the ability of riparian species to stabilize streambanks.

There will be distinct differences in the ability of riparian species to stabilize streambanks if 1) individual riparian species or species groups have greater erosional resistance than the streambank characteristics and 2) species or species groups have distinctly different erosional resistance. In this case, the species or species groups represented in Figure 17 will show distinctly different ranges from one another.

Alternatively, a combination of the null and alternate hypotheses may be present. Riparian species may create erosional resistance that interacts with the streambank resistance, and therefore some species or species groups will show distinct ranges of bank stabilization and others may overlap.

This objective is fulfilled through bank stability modeling using BSTEM. The purpose of using the bank stability model is to determine the factor of safety while integrating bank and vegetation characteristics and to determine the frequency of bank failures. The analyses presented in this dissertation are a sensitivity analysis of the model, however, because these scenarios are hypothetical simplifications of real-world situations. Even if the model results should not be taken as reflections of true situations, they should still represent valid comparisons between species and bank conditions.

1.2.2 Objective 2: Functional Classification of Vegetation for Bank Stability

A functional classification of vegetation for bank stability will provide a deeper understanding of the vegetative characteristics that actually provide bank stability. This classification should be applicable to a large range of species using a small amount of field data to compare to the functional classification presented here. Because I am only focusing on a subset of Colorado Front Range species, this constitutes a first-order approximation of a species classification. However, a skeleton of a classification should still show the range of root characteristics present and allow future studies to fill in gaps using less-extensive field techniques. The classification should also be applicable to other regions with different species assemblages using available root characteristics. This functional classification of vegetation for bank stability is only valid if vegetation characteristics are more important than bank characteristics in determining bank stability. Otherwise, the functional classification can still be used but only for similar banks under similar hydrologic conditions.

A morphological root classification will simplify the understanding of root contribution to bank stability. Rather than testing every possible species in a riparian zone for its effect on bank stability, a morphological root classification may simplify bank stability characterization. The three-dimensional diagram proposed in Figure 18 shows the three characteristics hypothesized to be most important in classifying riparian roots with respect to bank stability. Species or species types could be plotted in the root-characteristic space defined by this diagram.

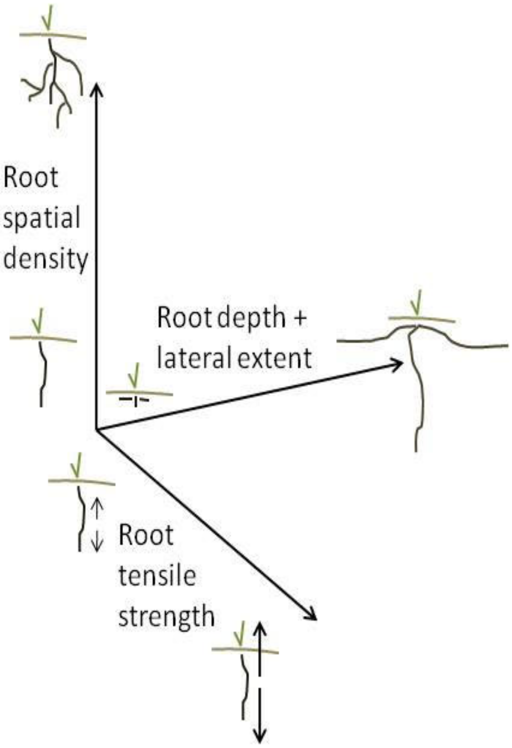

Figure 18. Proposed ternary diagram of riparian species showing three root characteristics hypothesized to be most important in determining bank stability.

In creating this ternary diagram of root characteristics, several questions are presented: 1) What is the range in root morphologic variability for Colorado Front Range species?, 2) Where are common Colorado Front Range riparian species found along this ternary diagram? And, after the bank stability relative classification is completed, (3) Is this approach useful for predicting bank stability? A set of hypotheses is tested pertaining to the functional riparian root classification.

$H2_0$: Inherent characteristics of riparian roots, including morphology and root tensile strength, do not correlate with the vegetation's effect on bank stability.

If $H1_0$ is rejected, I will determine whether root morphologic and tensile strength characteristics correlate with the species or species group's ability to stabilize streambanks. This hypothesis will be supported if no characteristics of riparian roots, including root spatial density, lateral extent and depth of roots, maximum root diameter, and root tensile strength correlate with the vegetation's effect on bank stability. Instead, a complex interaction of various root characteristics that cannot be explained through a root classification may serve to influence how banks are stabilized. Alternatively, species-specific characteristics, unrelated to the roots, may drive inter-species variability in contribution to bank strength. Possible above-ground factors include surcharge, which is the weight of the specimen, its height, and how the specimen is branched, which could alter the distribution of weight or interactions with flow dynamics.

This hypothesis proposes that certain intrinsic root characteristics serve to stabilize streambanks. I hypothesize that the following three characteristics are most important in determining bank stability: root tensile strength, which is quantified as the coefficient and exponent of root-tensile strength power function curves, root spatial density of a single specimen, and the root's combined lateral extent and depth (Figure 18). From this ternary diagram, I can create categories of root types and use those to correlate with the vegetations' (species of species group) bank stability contribution. This ternary diagram is designed so that increasing values on each axis reflect increased bank stability. Root spatial density, defined as the branching of the roots for any one specimen, should increase bank stability because it essentially increases the root-area-ratio

(Abernethy and Rutherfurd, 2001). Increases in depth and lateral extent will lengthen the area of bank stabilized by the root. Increases in root tensile strength will increase the shear stress the root can be exposed to before root failure (Pollen et al., 2004).

2. Study Area

Vegetation root samples and data were collected from three study sites in the Colorado Front Range, ranging from montane to subalpine zones, in order to obtain a range of riparian species (Figure 19). All three sites are situated within Precambrian metamorphic and igneous bedrock, and upstream portions of each respective basin are composed only of crystalline rocks (Tweto, 1979). Two main processes shape the valley form in the Colorado Front Range: the extent of glaciation and the boundary of two hydroclimatic zones, both of which occur at the elevation of 2300 m. Terminal moraines of the Pinedale glaciation, which ended ~10,000 y BP, are located at approximately 2300 m in the Front Range (Madole, 1980; Madole et al., 1998). The flow regimes above and below 2300 m differ greatly: above 2300 m, hydrographs are mainly snowmelt dominated, and below 2300 m hydrographs are snowmelt- and rain-dominated with flood peaks strongly controlled by high-intensity rainfall events (Jarrett, 1990). The Colorado Front Range exhibits relatively dry conditions with large temperature differences between summer and winter (Veblen and Lorenz, 1991). Mean annual precipitation increases with elevation (Barry, 1972); however, the highest rainfall intensities are associated with convective storms at lower elevations (Jarrett, 1990).

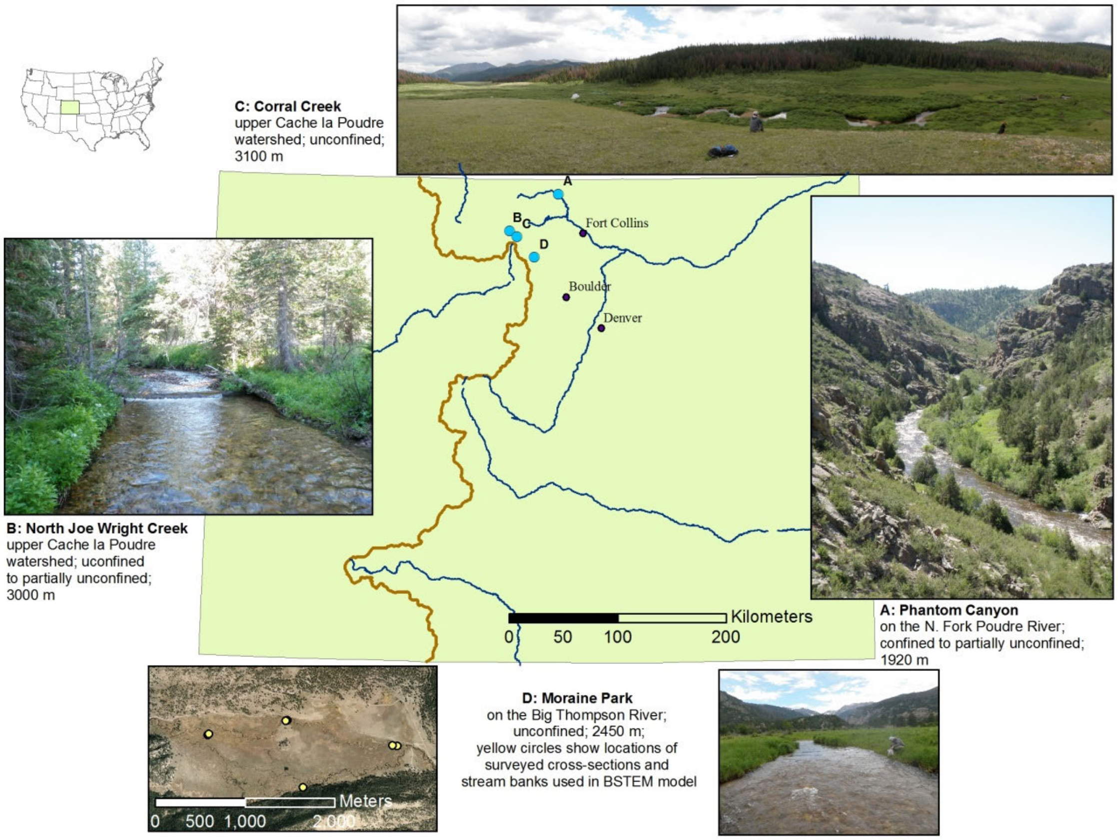

Figure 19. Map with locations and pictures of four study locations, which are all located in the Colorado Front Range. Brown line shows location of Continental Divide within Colorado.

The lowest elevation site, at 1920 m, is in the upstream reaches of Phantom Canyon along the North Fork Poudre River, directly downstream of Halligan Dam, with a drainage area of 919 km^2. U.S. Geological Survey gauge 06751150 is located within the reach. Phantom Canyon is a confined to partially confined valley (*sensu* Polvi et al., 2011), with intermittent bedrock constrictions. The channel is ~10 m wide with pool-riffle to plane bed morphology (Montgomery and Buffington, 1997). Riparian width ranges from <1 m directly adjacent to the channel to 3-5 m in more unconfined sections of the valley. Woody vegetation in the riparian zone consists of *Alnus incana* (gray alder), *Betula occidentalis* (water birch), *Salix exigua* (sandbar willow), and *Juniperus virginiana* (eastern redcedar). The upland is sparsely vegetated with *Juniperus virginiana*, *Artemisia tridentata* (big sagebrush), *Chrysothamnus viscidiflorus* (yellow rabbitbrush), and *Pinus ponderosa* (ponderosa pine). Vegetation nomenclature follows the USDA Plants Database (USDA NRCS, 2011). Phantom Canyon was chosen as a site for vegetation collecting because it was an easily accessible site with low-elevation montane riparian and upland species (Marr, 1964). Access was granted to excavate and sample vegetation below Halligan Dam by the City of Fort Collins because there are plans to expand Halligan Reservoir by moving the dam further downstream. Previous research along the North Fork Poudre River has established controls on pool spacing and dimensions (Wohl and Legleiter, 2003), sediment dynamics and transport (Wohl and Cenderelli, 2000; Rathburn and Wohl, 2001; Rathburn and Wohl, 2003), and the role of hydrochory in establishing vegetation patterns (Merritt and Wohl, 2006). Halligan Reservoir, which acts as a seed-trap for hydrochorically-dispersed species (Merritt and Wohl, 2006), in conjunction with an altered flow regime from Halligan Dam, have likely changed the vegetation composition in the reach below the dam. The bank stability work presented here may prove useful for managers in determining and managing channel change caused by the dam.

Two sites are located in the subalpine zone: North Joe Wright Creek and Corral Creek. North Joe Wright Creek is a tributary of Joe Wright Creek, which is a major tributary of the Cache la Poudre River and follows CO Highway 14 upstream of the confluence with the Cache la Poudre River. Vegetation was sampled along North Joe Wright Creek within 1 km (west of CO 14) of the confluence with Joe Wright Creek at an elevation of ~3000 m, with a drainage area of 7.8 to 9 km^2. This section of channel, which is 3-5 m wide, ranges from a pool-riffle to a step-pool channel in a partially unconfined to confined valley. Vegetation roots were only sampled and tested where they were easily accessible in the pool-riffle and plane bed reaches, located in partially unconfined valley segments. The riparian zone in the partially unconfined valley segments ranges from ~2 to over 20 m, and riparian vegetation is diverse, ranging from conifers to willows with an abundant understory. Common riparian species are *Picea engelmannii* (Engelmann spruce), *Salix monticola* (mountain willow), *Salix geyeriana* (Geyer willow), and *Ribes* spp.; several sedge and rush species are also commonly present, along with a diverse herbaceous community. North Joe Wright Creek was chosen as a site for vegetation sampling to obtain a range of species available at mid-high elevation sites in partially confined valley segments. Several different species, within all four vegetation types, were sampled along two reaches in North Joe Wright Creek, which is representative of many low-order mountain streams.

Corral Creek is the highest elevation site at 3100 m, located in the upper Cache la Poudre watershed. The 3-5 m wide pool-riffle channel is situated in an unconfined valley, with a drainage area of 11.6 km^2. The riparian zone is quite extensive, reaching > 50 m on each side of the channel, and is maintained by several active beaver dams, the corresponding ponds, and many smaller side channels. The vegetation is dominated by one willow, *Salix geyeriana* (Geyer willow), and a sedge, *Carex aquatilis* (water sedge), and a small number of other herbaceous and graminoid species are present. Because of the legacy of beaver activity in this valley, multiple abandoned channels with minimal flow and incised reaches (from breached beaver dams) are present and facilitate access to riparian roots along exposed cutbanks. However, it proved difficult to find cutbanks with only *S. geyeriana*, separate from *C. aquatilis,* to accurately count root density. Corral Creek provided a site with a high-elevation, unconfined valley, where I could expand the species selection sampled.

Streambank profile characterization was completed in Moraine Park in Rocky Mountain National Park, which was also described extensively in Chapter 1 of this dissertation (Figure 19). The Big Thompson River flows through Moraine Park, an expansive (~1 x 3 km), low-gradient valley (~1 %). The river has a drainage area of 103.1 km^2 at the downstream end of the valley, according to a USGS gauge (USGS 402114105350101) at the site. The pool-riffle channel has a gradient of ~0.5 %, and as shown in Chapter 1 currently has two main channels through the valley but was historically a complex multi-thread channel network. With the reduction in channel complexity and valley area directly connected to an active channel, the riparian vegetation has dramatically decreased. In the 1940s to 1960s riparian vegetation composed ~50% of the valley area, and from aerial photography from 1987 and 2001, riparian vegetation made up <25% of the valley area (see Chapter 2).

Moraine Park was chosen for bank profile characterization for two reasons: 1) Moraine Park has bank stratigraphy fairly representative of low-gradient, small streams (<15 m wide) in the CO Front Range. Streambanks rarely exceed 1 m and are composed of layers of non-cohesive (fluvial sand and gravel) and cohesive (sandy loam to loam with organic clays) sediment. I was able to identify, survey, and characterize a representative sample of these bank profiles in Moraine Park.

3. Methods

3.1 Field Measurements

I quantified tensile strength curves for a broad range of species native to and commonly found in riparian zones of the Colorado Front Range. Fourteen species were tested, of which four were trees, three were shrubs, three were graminoids (rushes and a sedge), and four were herbaceous species (including *Equisetum*) (Table 5). The species were chosen according to their overall abundance in the riparian areas of the Colorado Front Range (Polvi, 2009) as well as abundance along a streambank in one of the three study sites.

Table 5. List of species sampled and the study area(s) where specimens were sampled.

Latin name	Abbreviation	Common name	Vegetation type	Riparian designation[1]	Study area(s)	
Alnus incana	*AI*	grey alder	Tree	Riparian	Phantom Canyon	
Betula occidentalis	*BO*	western birch	Tree	Riparian	Phantom Canyon	
Caltha leptosepala	*CL*	marsh marigold	Herbaceous	Riparian	N. Joe Wright	
Carex aquatilis	*CA*	water sedge	Graminoid	Riparian	N. Joe Wright	Corral Creek
Equisetum arvense	*EA*	field horsetail	Herbaceous	Riparian	Phantom Canyon	
Equisetum hyemale	*EH*	scouringrush horsetail	Herbaceous	Riparian	Phantom Canyon	
Juncus arcticus	*JA*	arctic rush	Graminoid	Riparian	Phantom Canyon	
Juncus drummondii	*JD*	Drummond's rush	Graminoid	Riparian	N. Joe Wright	
Juniperus virginiana	*JV*	red cedar	Tree	Upland	Phantom Canyon	
Picea engelmannii	*PE*	Engelmann spruce	Tree	Upland	N. Joe Wright	
Salix exigua	*SE*	sandbar willow	Shrub	Riparian	Phantom Canyon	
Salix geyeriana	*SG*	Geyer willow	Shrub	Riparian	N. Joe Wright	Corral Creek
Salix monticola	*SM*	mountain willow	Shrub	Riparian	N. Joe Wright	
Saxifraga odontoloma	*SO*	brook saxifrage	Herbaceous	Riparian	N. Joe Wright	

1: Riparian designation according to Polvi (2009)

The root tensile strength was characterized in the field using a Root Puller provided by the National Sedimentation Lab in Oxford, Mississippi. The Root Puller, designed by Abernethy and Rutherfurd (2001), consists of a metal frame (~40 cm x 40 cm) attached to a winch that protrudes ~45 cm from the frame (Figure 20). To find a suitable location for the Root Puller, specimens were either found along a cutbank, a cutbank was cut into a shallower bank using shovels, or a trench (up to 1 m deep) was dug on the valley-side of a specimen. The depth of the water table in the trenches or water surface elevation along the banks occasionally limited the depth to which roots could be measured. Once the Root Puller was attached to a cutbank or trench face, using rope tied around a tree stem, variously sized U-bolts were attached to roots protruding from the face. For some smaller specimens where it proved difficult to find or cut a face with sufficient roots, the specimen was completely excavated and removed. In this case, the Root Puller was attached to a tree on the floodplain or to a lab table using C-clamps, and a field assistant securely held one end of the roots while each root was being pulled using the Root Puller. Care was taken to ensure that U-bolts were only attached to single-stemmed roots protruding from the bank and not to the end of a branched root, because branched roots would tend to break at the branching point, which is a weaker point of connection. The U-bolts were attached to a tension-calibrated load cell (100 lb), which was connected to the winch. The winch was slowly turned at a rate of ~1 full turn per 4 seconds. At the point at which the root breaks, the maximum load is recorded by a data logger connected to the load cell. The diameter of the root at the breaking point was measured using digital calipers and any comments about the breaking process were recorded. Comments include whether the break occurred at a branch point or directly at the U-bolt, and whether the root was stripped from the U-bolt, or if the root pulled out of the trench face of the cutbank, which happens if the root is not pulled from the end of the root but rather from the inner edge of the root. I later determined that roots that broke at the U-bolt did not break with a different force than normal breaks by plotting the results from ‘normal’ breaks with ‘U-bolt’ breaks together, so these results were incorporated in the tensile strength curves. To obtain the tensile strength curves for each species, the tensile strength (MPa) was calculated by dividing the force required to break the root (N) by the area of the root at the breaking point (m^2) and plotted against the diameter of the root (mm). The coefficient (TSA) and exponent (TSB) of the power relationship are used to characterize the tensile strength curves.

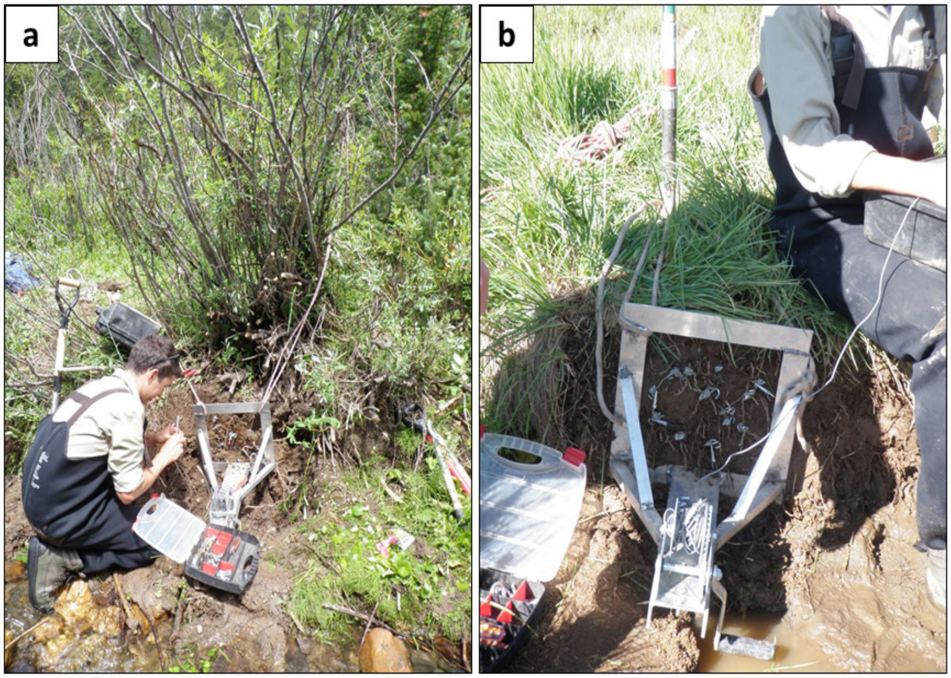

Figure 20. Photographs showing Root Puller attached to low cutbanks. U-bolts are attached to roots before being pulled. (a) Below *S. monticola* specimen along N. Joe Wright Creek. (b) On a cleaned face below dense *C. aquatilis* patch along a side channel of Corral Creek.

The distribution and number of root sizes were quantified along the root face using a 0.5 x 0.5 m PVC grid containing 10 x 10 cm grid squares constructed from bungee cord (Figure 21). The grid was placed on the cutbank or trench face directly below the stem of the plant. In each of the 50 grid squares, each root diameter was measured using digital calipers. The grid was moved down and the count was continued as long as the roots and cutbank continued deeper. Care was taken to ensure that roots were only counted and measured from the species of interest; this was done by examining root color and texture and by selecting locations for the grid where only species was present. The root distribution was used as a factor in determining root depth, maximum root diameter, and as input for the root area ratio in the RipRoot portion of the BSTEM model, which requires the number of roots in various size classes per square meter.

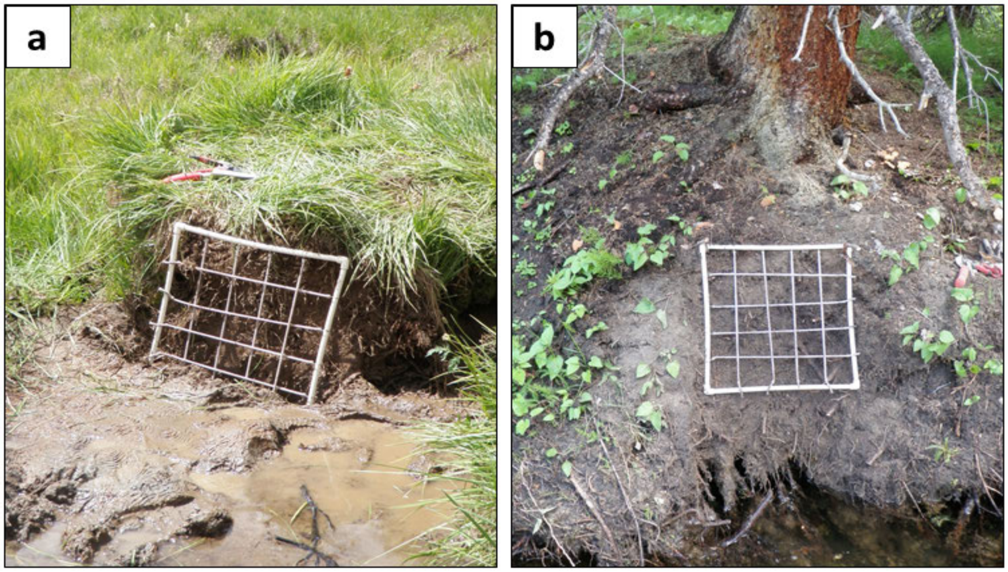

Figure 21. Photographs showing method for counting root density and size distribution. A 0.5 x 0.5 m pvc frame with 10 x 10 cm squares was used for counting the root area ratio, which determines the number, diameter, and location of roots. Photograph (a) is located along an abandoned side channel along Corral Creek under *C. aquatilis*; (b) is underneath *P. engelmannii* along N. Joe Wright Creek.

The root distribution was not characterized for species that were not abundant or not situated along a cutbank, which were all of the herbaceous and graminoid species except *C. aquatilis*, which was extremely abundant along nearly all cutbanks along Corral Creek. For three of these species (*J. drummondia*, *C. leptosepala*, and *S. odontoloma*), above-ground stem densities were counted using the same grid used for the root density counts along a trench or cutbank. Using the branching densities (root tips per stem), the number of roots per square meter could be easily calculated. The number of roots in each size class was determined using the distribution of root sizes obtained during the tensile strength measurements, for which I strived to measure a representative range of root sizes. For three other species (*E. arvense*, *E. hyemale*, and *J. arcticus*), the specimens were very sparse, and a grid count would not provide a sufficient count to be even slightly significant for adding cohesion to the streambank. Therefore, three scenarios were created for each species, where there were 10, 50, or 100 stems per square meter, and as with the species described above, the root size distribution was obtained from the tensile strength data. These three stem densities were chosen to represent a range of possible densities. Observations indicate that for these three species no more than 50 stems were present per square meter but a scenario with a greater number of stems (100 stems per square meter) was also tested in order to account for measurement errors and determine if a doubling in observed stem densities would affect bank cohesion. These three stem density scenarios are labeled as the two letter Latin species name abbreviation followed by a number indicating the number of stems per square meter.

Additional root morphology characteristics were obtained for each specimen in the field. Root depth was measured along the cutbank, by excavating smaller herbaceous or graminoid species. In the case of trees (*A. incana* and *B. occidentalis*) not situated along a tall cutbank, the trench was dug at least 1 m deep to determine root depth. Because very few cutbanks in the Colorado Front Range exceed 1 m in height, the root depth was capped at 1 m. Lateral root extent was measured similarly to root depth.

Species with rhizomes, or underground stems connecting separate rametes of the same genetic makeup, were noted and the lateral root extent of rhizomatous species was capped at 1 m if it was unclear to which specimen the roots belonged. The extent of root branching was characterized for each species to differentiate those with a clear dendritic root pattern and those that were more linear with very few branches. Branching extent was categorized as 1) minimal, where the roots have less than 3 splits per 10 cm of root length and the root is mostly linear; 2) moderate, where there are 3-5 splits per 10 cm of root length and few bifurcations on secondary roots; and 3) extensive branching, which has >5 splits per 10 cm of root length. The *Equisetum* spp. and *Juncus* spp. specimens showed minimal root branching; in fact, the *Equisetum* species' roots rarely bifurcated once in the 0.5 m root depth. The *Juncus* species' roots from several hundreds of individual specimens were joined together with a thick rhizome, but the ratio of root to stems was approximately 1.5. All of the *Salix* species specimens branched moderately. Thick rhizomes connected individual willow specimens. Thick (~1 cm in diameter) tap roots and other thick lateral roots had medium to small roots extending from them, but these smaller roots rarely bifurcated, nor did the thick taproots.

Ages of woody specimens were determined by cutting stem slices of willow specimens and collecting tree cores from tree specimens. If a tree had multiple stems, the two largest stems were cored, ages were determined for each, and the oldest age of the multiples cores was recorded as the specimen age. If the pith could not be identified in the core, the germination year was estimated using measurements of the oldest visible rings.

Bank profile geometries and sediment textures were required for the bank stability modeling described below. The bank profile geometry and sediment layer characteristics were obtained from Moraine Park, which was one of the two study areas in Chapter 1. This study location was used 1) because bank profiles in Moraine Park are representative of those in low-gradient valleys in the Colorado Front Range, and 2) so that the bank profile and vegetation combination scenarios presented in this section can be used to understand long-term floodplain dynamics in Moraine Park. I surveyed fifteen bank profiles on 7 cross-sections throughout Moraine Park using a Topcon total station and Carlson data logger (Carlson Software, 2008). The cross-sections were located within one of the three reaches (A, B, or C) surveyed in Moraine Park (see Chapter 2). Two cross-sections were surveyed in reach A and C, and three cross-sections were surveyed in reach B. Along the bank profile, the following bank features were noted: top of bank, top of bank toe, bottom of bank toe, and the end point, which was usually located in the thalweg.

For each bank profile, significant sediment layers were identified and boundaries were marked on the profile survey. The sediment texture was described in the field, and sediment samples were taken for further lab analyses. If I determined in the field that a sediment layer had a similar texture to a layer in a nearby bank profile, only one sediment sample was taken. In the lab, sediment samples were first dried then sieved using whole-number sieve sizes from -4 φ (16 mm, coarse gravel) to +4 φ (0.03125 mm, very fine sand). Prior to sieving, coarse organic material was removed and the sample was weighed to the nearest hundredth of a gram. The sediment fraction from each sieve was weighed and the percentage weight and cumulative weight percent of each sieve fraction was determined using the total mass. The sediment fraction below the +4 φ sieve, which contained only silt and clay, was retained for hydrometer analyses. Hydrometer analyses determined the percentage of sand, silt, and clay in the remaining fraction after sieving.

3.2 Modeling Procedures

The Excel-based model BSTEM and built-in model RipRoot were used to determine added cohesion by species and the factor of safety for various scenarios of bank profiles, water surface and water table elevations, and vegetation types. First, RipRoot was used to determine the added cohesion from each species for six different sediment textures. The parameters for each species were determined in the field and described above in section 3.1. The coefficient (TSA) and exponent (TSB) of the tensile strength curves are required to determine the tensile strength for a given root diameter. The root size distribution, given as the number of roots in seven root size categories per square meter, is used in conjunction with the tensile strength parameters to run the fiber-bundle model. The seven root size classes are capped at 40 mm (0-1 mm, 1-2 mm, 2-3 mm, 3-5 mm, 5-10 mm, 10-20 mm, and 20-40 mm); measured roots that exceeded 40 mm in diameter were placed in the 20-40 mm category. The RipRoot module needs an input of sediment type in order to determine the added cohesion, because the threshold between pullout versus breakage forces varies with sediment size. The effective cohesion, effective angle of internal friction, and saturated unit weight were input for six soil textures, as determined by Simon et al. (2011), except for the sandy loam, which is an average of the sand and loam values (Table 6).

Table 6. BSTEM sediment texture parameters. Table shows values used to parameterize sediment textures to obtain added cohesion from RipRoot and model bank stability. Table modified from Simon et al. (2011).

Soil Type	**c' (kPa)^1**	**ϕ' (degrees)^2**	**γ_{sat} (kN/m^3)^3**
Gravel (uniform)	0.0	36.0	20.0
Sand and gravel	0.0	47.0	21.0
Sand	0.4	30.3	18.5
Sandy loam	2.4	28.5	18.3
Loam	4.3	26.6	18.0
Clay	8.2	21.1	17.7
1: effective cohesion			
2: effective angle of internal friction			
3: saturated unit weight of soil			

BSTEM is a physical model that calculates the factor of safety of a streambank, where a value below 1 is unstable, between 1 and 1.3 is conditionally stable, and above 1.3 is stable. The bank profile inputs to the model include the bank profile geometry, the thicknesses of up to five horizontal layers, and sediment texture parameters of each individual layer, as well as the toe of the bank. These parameters were obtained from detailed bank profile surveys conducted in Moraine Park, as outlined in Section 3.1. Additionally, the pore-water pressure and confining pressure were determined by the model by either measured saturation of the bank, or by simply inputting the depth of the water table, and the height of the water surface elevation.

Based on the number of layers and sediment textures of the layers in each of the bank profiles, the profiles were placed into five categories, and one representative bank profile from each category was used for the bank stability modeling (A-E) (Table 7; Figure 22). The modeled streambanks represented a range of bank heights, textures and layers: Bank A, at ~0.9 m high, has a non-cohesive layer over a semi-cohesive layer; Bank B has an undercut and a cohesive over a non-cohesive layer; Bank C consists of only cohesive sediment ~1 m high; Bank D consists of non-cohesive sediment ~1 m high; and Bank E consists of semi-cohesive sediment only 0.6 m high. Five layers were determined for each bank profile, where vegetation rooting depth and depth of breaks between sediment layers coincided with the bottom of a layer, and additional layers were evenly spaced to the bottom of the bank profile. Layer thicknesses differ for each bank profile and species combination, depending on root depth and stratigraphy (Appendix A). This allowed me to model not only the added cohesion from the roots of a species to a streambank, but also to incorporate the rooting depth. By running the RipRoot module as part of the BSTEM to model bank stability, it is not possible to directly take into account the root depth. Instead, the modeler must first determine the added cohesion for a given sediment texture and then add this to the cohesion value for the sediment layers that contain roots. Below the rooting depth, the effective cohesion value for the sediment layers only reflects that of the sediment texture. Therefore, it is important to select lower boundary depths for the sediment layers that not only reflect changes in the sediment texture, but the rooting depth as well. The depth of the layers for each bank profile had to be configured differently for each species to reflect varying root depths.

Table 7. Bank profiles surveyed in Moraine Park classified into five groups based on number and cohesion of layers. One representative bank profile from each group was chosen to be modeled in BSTEM.

Group		Bank Profile			Top Layer			Bottom Layer		
	BSTEM modeled bank	*X-sxn*	*Bank*	*Bank type*	*Cohesivity*	*Sediment texture*	*Depth at bottom (m)*	*Cohesivity*	*Sediment texture*	*Depth at bottom (m)*
A	**X**	XSA1	Left	Undercut	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.50	Semi-cohesive	Sandy loam (85% sand; 15% silt & clay)	0.93
B	**X**	XSB3_400	Right	Undercut	Cohesive	Sandy loam (85% sand; 15% silt & clay)	0.20	Non-cohesive	Sandy gravel (60% gravel; 35% sand)	0.90
B		XSB3_500	Right	Undercut	Cohesive	Sandy loam (85% sand; 15% silt & clay)	0.50	Non-cohesive	Sandy gravel (60% gravel; 35% sand)	0.65
B		XSB3_200	Right	Undercut	Cohesive	Sandy loam (85% sand; 15% silt & clay)	0.80	Non-cohesive	Sandy gravel (60% gravel; 35% sand)	0.90
C	**X**	XSB3_300	Right	Undercut	Cohesive	Sandy loam (85% sand; 15% silt & clay)	1.02	---------------		
D	**X**	XSA1	Right	Undercut	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.97	---------------		
D		XSA2	Left	Cutbank	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.70	---------------		
D		XSB1	Right	Cutbank	Non-cohesive	Gravelly sand (~30% gravel; 65% sand)	1.05	---------------		
D		XSB2	Right	Cutbank	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.77	---------------		
D		XSC1	Left	Cutbank	Non-cohesive	Sandy gravel (60% gravel; 35% sand)	1.38	---------------		
D		XSA2	Right	Gradual	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.33	---------------		
D		XSB1	Left	Gradual	Non-cohesive	Sand (~95% sand; minor silt & gravel)	0.55	---------------		
E	**X**	XSB2	Left	Cutbank	Semi-cohesive	Loamy sand (~90% sand; 7% silt & clay)	0.61	---------------		
E		XSC1	Right	Cutbank	Semi-cohesive	Loamy sand (~90% sand; 7% silt & clay)	0.55	---------------		
E		XSC2	Left	Gradual	Semi-cohesive	Loamy sand (~90% sand; 7% silt & clay)	0.39	---------------		

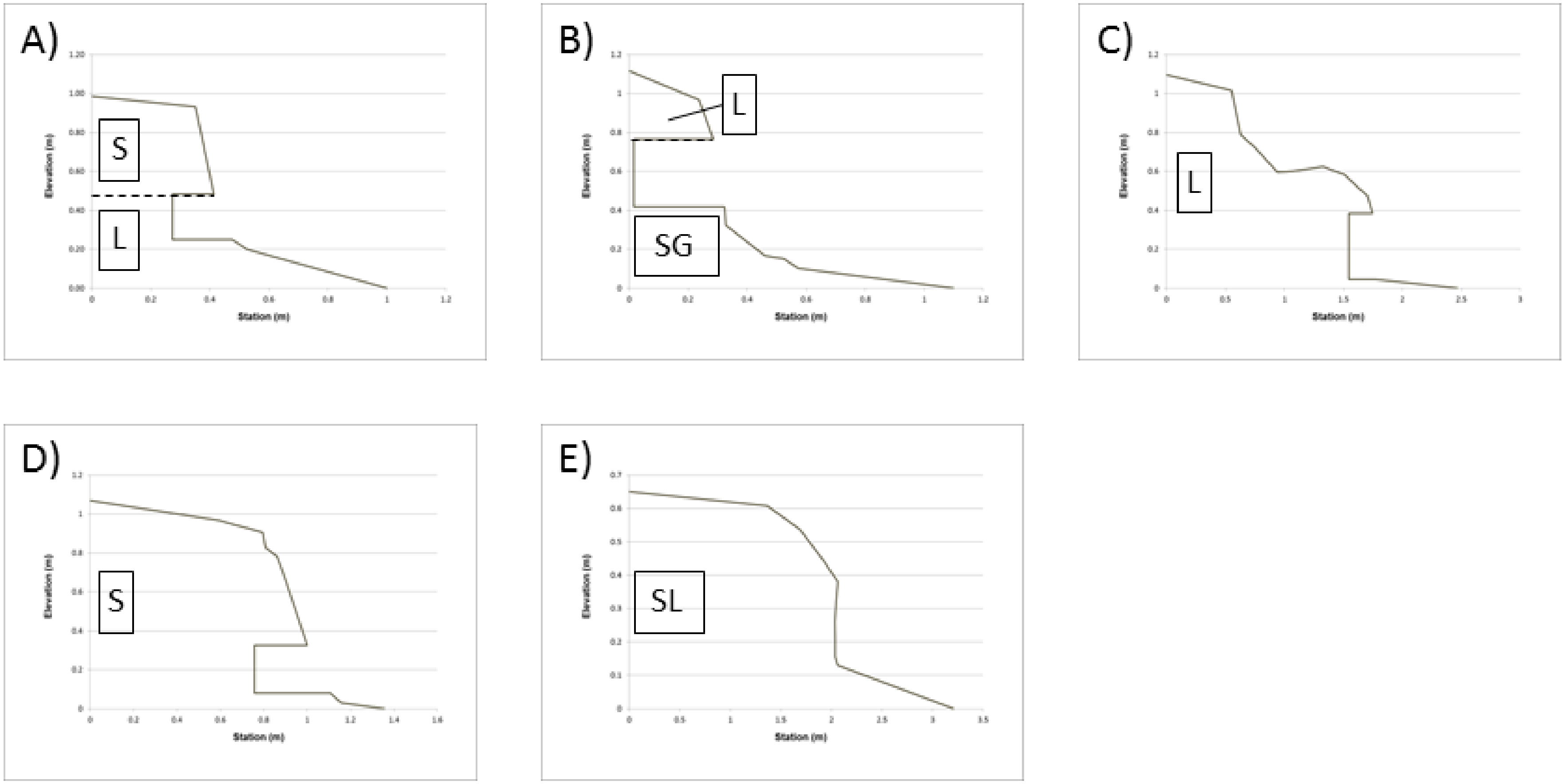

Figure 22. Representative bank profiles (A-E) surveyed in Moraine Park used for bank stability modeling. Bank geometry shown with sediment used for BSTEM modeling, where SG is sand and gravel, S is sand, SL is sandy loam, and L is loam. Sediment texture of sandy loam in sediment characterization (Table 7) was modeled with sediment characteristics of loam (L) (Table 6) as in bank profile XSB3_300-Right. Sediment texture of loamy sand is modeled as sandy loam (SL) as in bank profile XSB2-Left.

For each bank profile and species combination, six scenarios of the water surface elevation and groundwater table were modeled. The height of the water surface elevation determines the confining pressure from the channel, and depth of the water table allows calculation of the pore-water pressure. The water table was modeled at three locations: top of the bank, middle of the bank, and bottom of the bank. The water surface elevation was only modeled at two locations: the middle and bottom of the bank and not at the top of the bank, because there would never be any failure when the water surface elevation is at the top of the bank and providing pressures that fully confine the streambank. Modeling scenarios when the water table is higher than that of the water surface elevation more closely resemble field conditions on the receding limb of snowmelt runoff during the summer or large storms. The model output for each scenario is the factor of safety, which is a value determined from the ratio of resisting to driving forces.

3.3 Analyses

The analyses and results are presented in two sections. First, I present the connections between the physical attributes of the 14 species samples, in addition to the differences between the 4 taxonomical groups of trees, shrubs, graminoids and herbaceous species. Of the four tree species sampled, two (*A. incana and B. occidentalis*) were classified as riparian by Polvi (2009) and the other two species (*J. virginiana* and *P. engelmannii*) were classified as upland species. All of the shrub species are willows (*S. exigua*, *S. geyeriana*, and *S. monticola*), which represent the majority of riparian shrubs at a range of elevations. Three graminoids, which consist of two rushes (*J. arcticus* and *J. drummondia*) and a sedge (*C. aquatilis*), are common in riparian areas. *J. arcticus* is most common at low elevations (found at Phantom Canyon study area) and *J. drummondia* is more common at high elevations (N. Joe Wright). *C. aquatilis* is a prolific sedge at high elevation (N. Joe Wright and Corral Creek). The four herbaceous species are a sample of herbaceous species found in riparian areas in low and high elevation. There are no dominant herbaceous species, so those that were present and accessible were tested. Two species in the Equisetaceae family were included in the herbaceous group, because although they are not very extensive, they are commonly found along streambanks in low and high elevation sites in the Colorado Front Range.

The simple taxonomical classification of trees, shrubs, graminoids, and herbaceous species was used as an *a priori* root characteristic classification. If distinctions are found between these broad plant groups, this can be a first-order level of distinction between root types and their ability to stabilize streambanks. Because this classification is used by botanists and ecologists with the added benefit of being recognizable by a lay person, significant physical root differences between these groups will facilitate understanding of species contributing to bank stability and give a functional classification greater intuitive appeal with the public.

Comparisons between these four taxonomic groups are presented in terms of the following physical characteristics: root depth, lateral root extent, the coefficient (TSA) and exponent (TSB) of tensile strength curves, maximum root diameter, and whether the species is rhizomatous. Then, I compare the added cohesion resulting from the vegetation roots and the total cohesion for roots and sediment for six different sediment types: gravel, sand and gravel, sand, sandy loam, loam, and clay. Finally, I compare the resulting classification from the taxonomic group comparisons to the factor of safety values determined from modeling results. By first determining differences in physical attributes followed by comparison of modeling results, agreements in the two lines of reasoning can be used for a stronger classification scheme.

To determine which model parameters correlated most strongly or could be used to predict factor of safety values (FS), several statistical techniques were analyzed using the software SAS (SAS Software, 2002-2008). First, Pearson and Spearman correlation coefficients were examined. Then, model selection techniques were used to determine a model with the most explanatory power of the FS. Parameters with Pearson correlation values (ρ) >0.6 were determined to be collinear and only the parameter with the greater ρ with FS was included as a possible parameter in the model selection. Mallow's Cp was used as a selection criterion to determine the best model; Akaike's Information Criterion (AIC) and the adjusted R^2 values were also analyzed for agreement with Cp values (Akaike, 1973; Simonoff and Tsai, 1999). Parameters were only included in the model if they were significant at $\alpha=0.05$. Differences between FS values for categorical groups (species and vegetation groups) were determined using an ANOVA and visualized using boxplots. Additionally, an ANOVA was used to determine differences in physical root characteristics between the vegetation groups. Differences were deemed to be significant at $\alpha=0.05$. The multiple comparison penalty, Tukey's Honestly Significant Difference (HSD) test, was used to reduce the Type II error.

4. Results

4.1 Quantification of Physical Root Attributes

The vegetation types of trees, shrubs, graminoids, and herbaceous species have characteristic, and occasionally unique, ranges of physical root attributes. Five root characteristics were hypothesized to be an important factor in determining a plant's role in contributing to bank stability: root depth, root lateral extent, maximum root diameter, and the two parameters of the root tensile strength curve power-relationship, the coefficient (a), which determines the intercept, and exponent (b), which determines the slope (

Table 8; Table 9). In addition to the lateral root extent, whether a species is rhizomatous will be important in determining the ability of a specimen to withstand being removed by hydraulic forces or bank failure. Although rhizomes are not considered a part of the root network, the underground stem network, connecting genetically linked specimens to one another, will nonetheless add cohesion to the bank and prevent specimen pullout. Table 10 shows the ages of the specimens sampled that were determined by ring counts from cores and slices. Although care was taken to obtain a varied range of ages, the results and conclusions from these data should not be extrapolated to specimens of much younger or older ages than those sampled here.

Table 8. Root tensile strength curve parameters for each species. Refer to Eq. 1 for explanation of parameters. R^2 value describes fit of power-relationship curve to data; n is the number of roots tested.

Species	a	b	R^2	Min root diameter (mm)	Max root diameter (mm)	n	Max TS (MPa)	Min TS (MPa)	TS for mean root size (2.5 mm)
Alnus incana	16.78	-0.42	0.22	0.21	6.63	60	32.3	7.6	11.4
Betula occidentalis	25.05	-0.79	0.58	0.10	8.14	81	155.5	4.7	12.1
Caltha leptosepala	9.06	-1.49	0.87	0.03	1.40	40	1655.0	5.5	2.3
Carex aquatilis	20.25	-1.14	0.76	0.10	3.40	75	277.6	5.0	7.1
Equisetum arvense	10.93	-1.23	0.46	1.21	2.96	14	8.6	2.9	3.5
Equisetum hyemale	6.44	-0.46	0.52	0.04	3.60	17	28.7	3.6	4.2
Juncus arcticus	14.66	-0.72	0.60	0.12	3.91	61	66.7	5.5	7.6
Juncus drummondii	9.62	-1.03	0.31	0.10	0.82	55	102.6	11.8	3.7
Juniperus virginiana	20.40	-0.81	0.21	0.10	4.45	85	132.0	6.1	9.7
Picea engelmannii	12.36	-1.17	0.49	0.22	5.31	39	72.2	1.8	4.2
Salix exigua	14.71	-0.80	0.58	0.17	11.25	85	60.6	2.1	7.1
Salix geyeriana	12.20	-0.58	0.26	0.11	8.59	84	43.6	3.5	7.2
Salix monticola	12.80	-0.82	0.45	0.12	3.77	60	73.0	4.3	6.0
Saxifraga odontoloma	5.31	-1.48	0.81	0.05	0.64	29	440.7	10.3	1.4

Table 9. Root characteristics of species sampled, including field characteristics and those obtained from the USDA Plants Database.

	Field Characteristics						USDA Plants Database Characteristics[5]							Root depth	
Species	Depth (m)[1]	Depth observation limit[2]	Lateral extent (m)[3]	Maximum root diameter (mm)	Root form	Branching[4]	Adapted to coarse soils	Adapted to fine soils	Adapted to medium soils	Anaerobic tolerance	Min root depth (m)	Duration	Group	Root depth range (m)[6]	Average depth (m)
Alnus incana	0.4	BH	0.5	28.07	Single	Extensive	Yes	Yes	Yes	High	0.61	Perennial	Dicot	0.4-0.6	0.50
Betula occidentalis	0.5	MR & BH	1	52.71	Single	Extensive	Yes	Yes	Yes	Medium	0.51	Perennial	Dicot	0.5	0.50
Caltha leptosepala	0.4	MR	0.4	1.40	Rhizomes	Moderate	Yes	No	Yes	Medium	0.20	Perennial	Dicot	0.2-0.4	0.30
Carex aquatilis	0.5-0.6	BH	0.5	8.23	Rhizomes	Extensive	No	Yes	Yes	High	0.36	Perennial	Monocot	0.36-0.6	0.48
Equisetum arvense	0.5	MR	0.1	2.96	Single	Minimal	Yes	Yes	Yes	Medium	0.15	Perennial	Horsetail	0.15-0.5	0.33
Equisetum hyemale	0.5	MR	0.1	3.60	Single	Minimal	-------	-------	-------	-------	-------	Perennial	Horsetail	0.5	0.50
Juncus arcticus	0.3	MR	0.1	3.91	Rhizomes	Minimal	No	Yes	Yes	High	0.51	Perennial	Monocot	0.3-0.5	0.40
Juncus drummondii	0.4	MR	0.1	0.82	Rhizomes	Minimal	Yes	No	Yes	Medium	0.36	Perennial	Monocot	0.4	0.40
Juniperus virginiana	0.4-1.0	MR & BH	1	54.22	Single	Extensive	Yes	Yes	Yes	Low	0.51	Perennial	Gymnosperm	0.4-1.0	0.70
Picea engelmannii	0.5-0.8	MR & BH	0.5	21.45	Single	Extensive	No	Yes	Yes	None	0.51	Perennial	Gymnosperm	0.5-0.8	0.65
Salix exigua	0.3-0.4	MR	1	19.68	Rhizomes	Moderate	Yes	No	Yes	High	0.51	Perennial	Dicot	0.3-0.5	0.40
Salix geyeriana	0.3-0.4	MR	1	18.75	Rhizomes	Moderate	Yes	Yes	Yes	Low	0.15	Perennial	Dicot	0.15-0.4	0.28
Salix monticola	0.5-0.6	MR	1	46.88	Rhizomes	Moderate	Yes	No	No	High	0.91	Perennial	Dicot	0.5-0.9	0.70
Saxifraga odontoloma	0.4	MR	0.4	0.64	Single	Moderate	-------	-------	-------	-------	-------	Perennial	Dicot	0.4	0.40

1- Observed depth limited to 1 m

2- BH: bank height was limiting factor for determining root depth; MR: maximum root depth was visible above bottom of bank; MR & BH: root depth extends to bottom of bank

3- Observed lateral extent of roots limited to 1 m

4- Extent of observed root branching: minimal root branching are almost straight roots with <3 splits per 10 cm; moderate branching has 3-5 splits per 10 cm and few bifurcations on secondary roots; extensive branching has >5 splits per 10 cm

5- Root characteristics as listed by USDA Plants Database (USDA, 2011); two species (E. hyemale *and* S. odontoloma*) did not have detailed root data*

6- Root depth range includes observed root depth and minimum root depth according to USDA (2011), if the minimum depth is greater than the observed depth

Table 10. Ages of specimens for which tensile strength or root distribution data were collected. Samples are labeled with the study location, followed by the species abbreviation (refer to Table 5 for abbreviation explanations), and a number indicating different specimens. Horizontal lines separate different specimens and species. A letter suffix indicates two different cores taken from the same specimen. If there are different diameters for the two cores, two different stems were sampled. The oldest age of multiple cores was taken as the specimen age.

Sample	Species	Diameter (cm)	Germination year	Age	Specimen age
HD_AI1	AI	6.2	1997*	13	**13**
HD_AI2	AI	13.5	1985	25	**25**
HD_AI3_A	AI	14.0	1970	40	**40**
HD_AI3_B	AI		1987	23	
HD_BO1_A	BO	10.0	1988	22	**22**
HD_BO1_B	BO	7.5	1992	18	
HD_BO2_A	BO	7.5	1993	17	**29**
HD_BO2_B	BO	7.5	1981	29	
HD_BO3_A	BO	7.0	1989	21	**21**
HD_BO3_B	BO	7.0	1992	18	
HD_JV1_A	JV	33.5	1974	36	**36**
HD_JV1_B	JV		1978	32	
HD_JV2	JV	15.2	1978	32	**32**
HD_JV3_A	JV	19.0	1963	47	**49**
HD_JV3_B	JV		1961	49	
NJW_PE1_A	PE	46.5	1886	124	**124**
NJW_PE1_B	PE		1911	99	
NJW_PE2	PE	10.0	1978*	32	**32**
NJW_SM2_1	SM	5.0	1988†	22	**22**
NJW_SM2_2	SM	4.0	2000†	10	
HD_SE2_A	SE	2.0	2008†	2	**4**
HD_SE2_B	SE	2.0	2008†	2	
HD_SE2_C1	SE	4.0	2006†	4	
HD_SE2_C2	SE	4.0	2006†	4	
HD_SE2_C3	SE	4.0	2006†	4	
HD_SE2_C4	SE	4.0	2006†	4	

*Pith was identified; non-asterisks are those where pith could not be identified and an estimated germination year was determined from measurements of the oldest visible ring

†Age was determined from slices taken from bottom of stems

Tensile strength curves were developed for each species and compared among and between vegetation type groups, visually and using the coefficient (a) and exponent (b) in the power relationship (Equation 1). R^2-values range from 0.21 to 0.87, with a mean and median agreeing at ~0.5. The b-values vary little, with a range from -1.49 to -0.46. The a-values vary over a larger range, from 5.31 to 25.05. Because the b-value controls the slope of the curve and the a-value determines the intercept, or magnitude of the tensile strength for any given root diameter, the a-value is expected to be a more significant determinant of a root's addition to bank tensile strength.

$$TS = aD^b \qquad \text{Eq. 1}$$

where, TS is the tensile strength in MPa,

a is the tensile strength curve coefficient,

D is the diameter of the root in mm,

and b is the tensile strength curve exponent

A qualitative comparison of the root tensile strength curves reveals differences between the four vegetation group types (Figure 23; Figure 24). The trees appear to have the highest tensile strength for any given root diameter, with the riparian species *B. occidentalis* showing the highest tensile strength values. The graminoids have tensile strengths among or just below that of the trees. The willows have low to average tensile strengths, and the herbaceous species have the lowest tensile strength values.

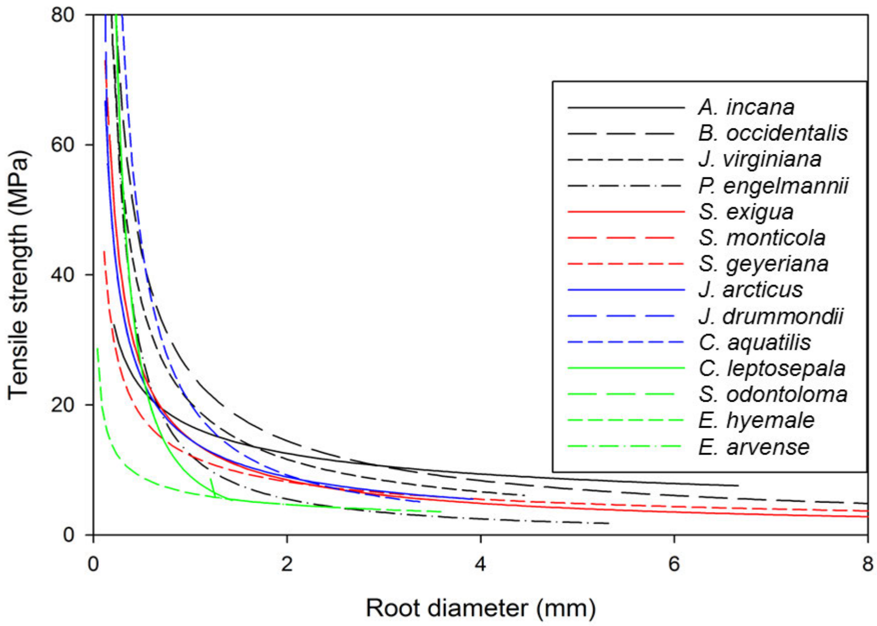

Figure 23. Tensile strength curves of all 14 species sampled, color-coded by vegetation type, where trees are black, shrubs are red, graminoids are blue, and herbaceous species are green.

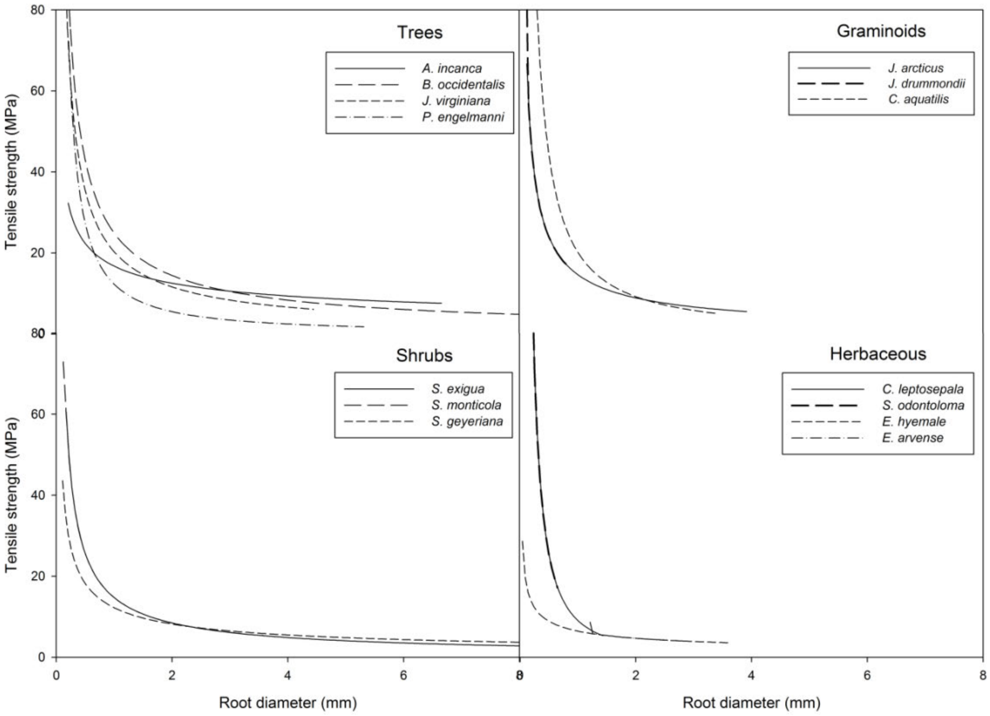

Figure 24. Tensile strength curves for fourteen species sampled divided by vegetation type.

The distribution and number of various root diameter classes for each species were quantified by the root-area-ratio. Several interesting trends emerge through investigation of the root size distributions (Figure 25-Figure 29). First, *C. aquatilis* has an order of magnitude more roots per square meter than any other species sampled. The willow species (*Salix* spp.) have a relatively low number of roots per square meter, but *S. geyeriana* has a much larger number of large roots, especially in the 10-20 mm class, than any other species. The trees have a greater root density than shrubs, and in fact the upland tree species (*J. virginiana* and *P. engelmannii*) have a greater root density than the riparian trees (*A. incana* and *B. occidentalis*).

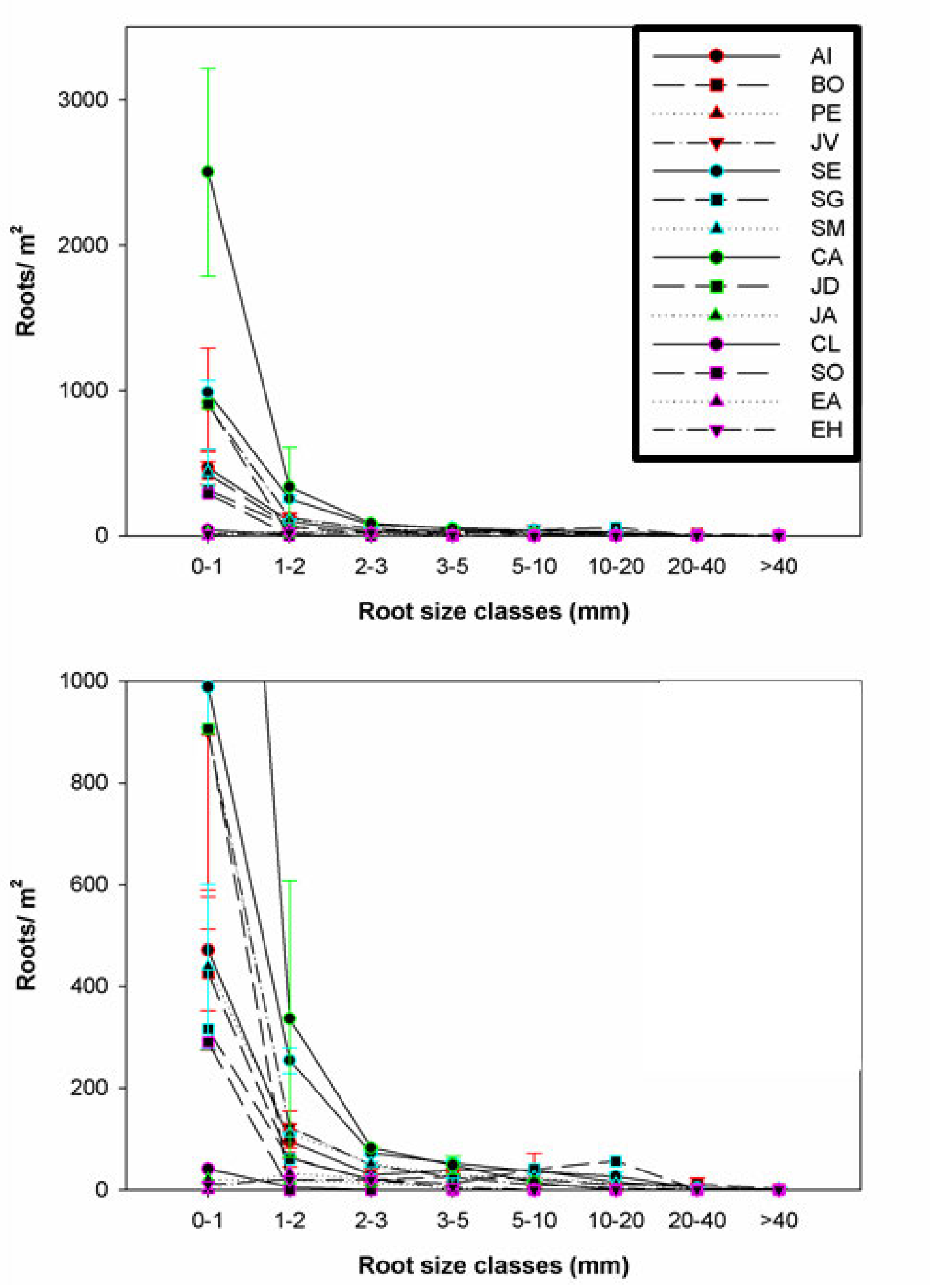

Figure 25. Root size distributions for all fourteen species sampled. Error bars of standard deviation shown for species with more than one specimen sampled for root area ratio on separate cutbanks or trenches. Symbols with pink edges are trees, light blue edges are shrubs, light green edges are graminoids, and pink edges are herbs.

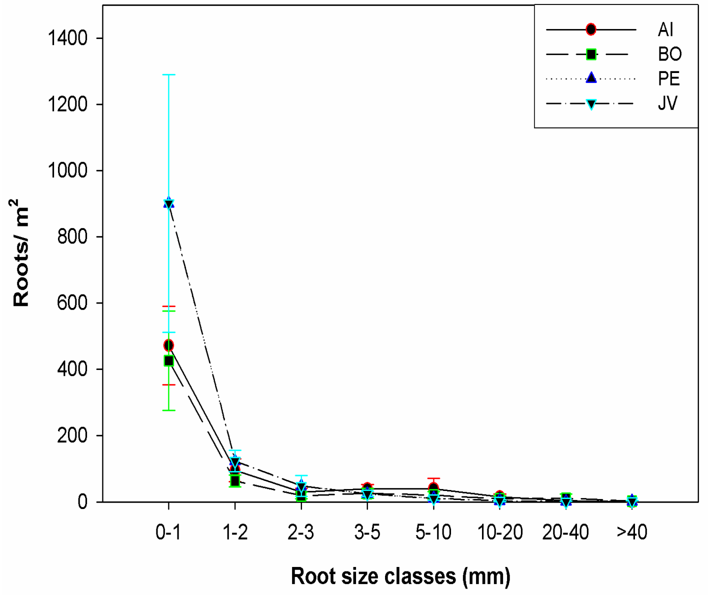

Figure 26. Root size distribution of tree species. Error bars show the standard deviation of root numbers per size class.

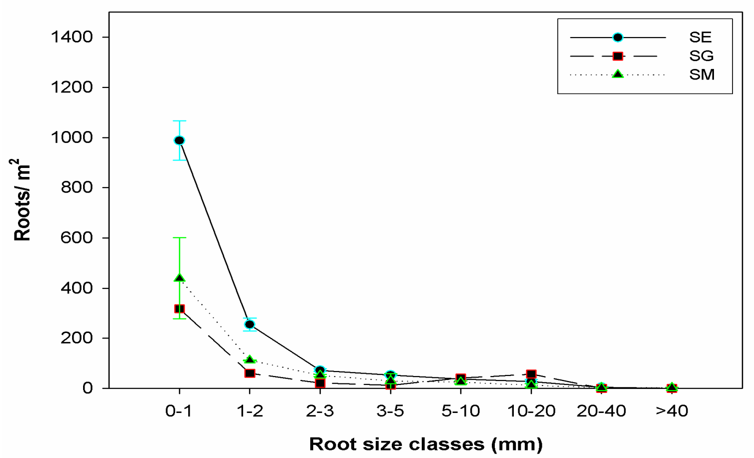

Figure 27. Root size distributions of shrub species. Error bars show the standard deviation of root numbers per size class.

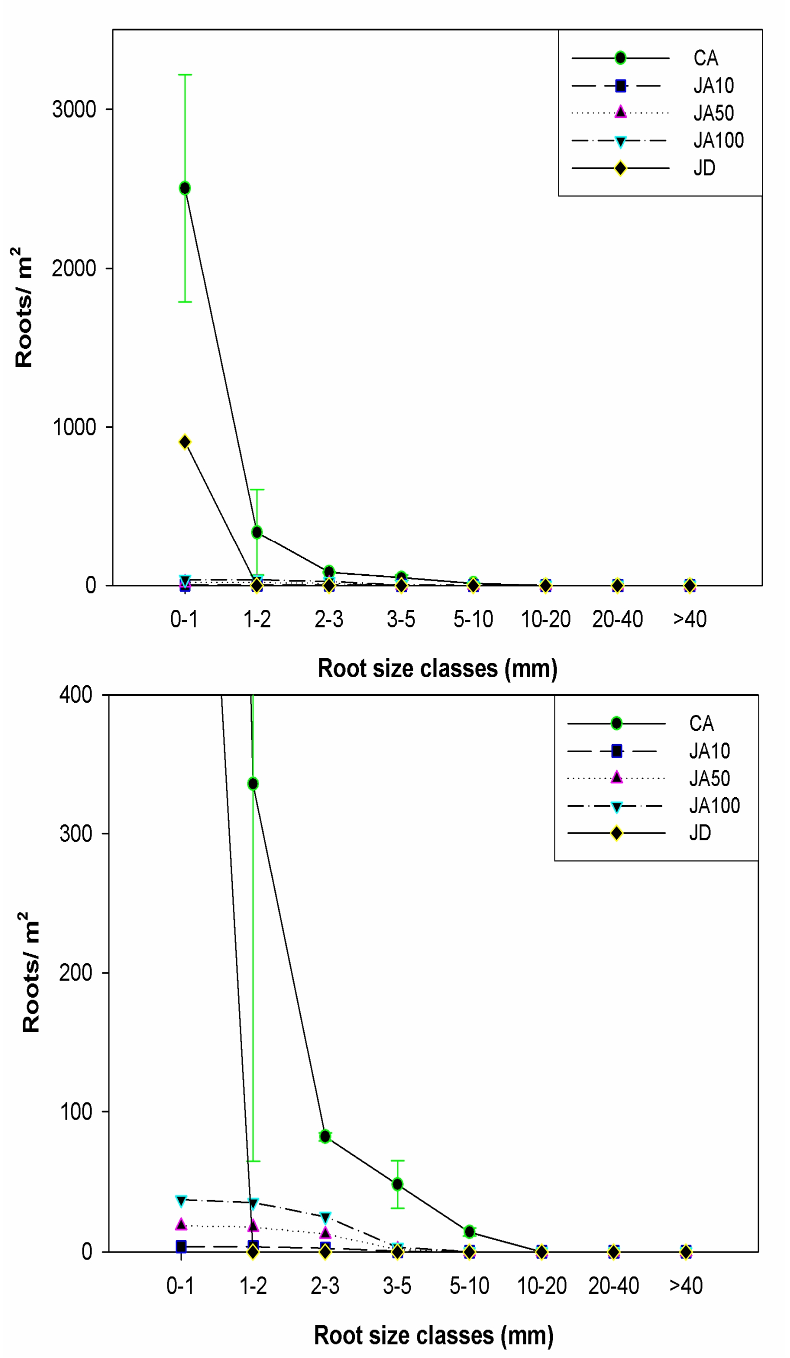

Figure 28. Root size distribution of graminoid species, with various stem densities per square meter shown for *J. arcticus*. Error bars of standard deviation shown for species with more than one specimen sampled for root area ratio on separate cutbanks or trenches. Two graphs have different ranges on y-axis to allow comparisons of low values.

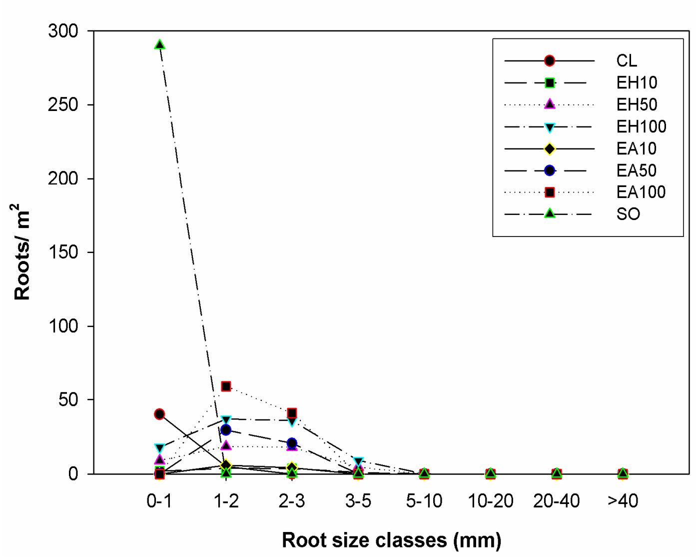

Figure 29. Root size distribution of herbaceous species, with various stem densities per square meter shown for *E. arvense* and *E. hyemale*.

4.2 Root Architecture

Root branching density is described in Table 9 by the categories of minimal, moderate, and extensive. Some species have characteristic root architecture that may impact bank stability and are described below by vegetation type. All of the trees sampled had fairly dendritic branching patterns: roots bifurcate regularly and progressively decrease in diameter with each bifurcation. The willows (*Salix* spp.) do not bifurcate regularly and therefore do not have a very extensive root network. Willows have thick (~1 cm) rhizomes in addition to thick vertical and lateral roots. The thick main roots do not bifurcate regularly but rather taper into a slightly narrower root towards the end. Thinner roots (a few mm) extend directly from the main thick roots, and bifurcation is sparse or uncommon in these roots. The root architecture of graminoids varies by genus. The sedge, *Carex aquatilis*, contains extensively branching fine roots, which are connected by thin rhizomes to other specimens. The two *Juncus* species have minimal branching and commonly have one single root, with one or no bifurcations, per stem. All of the roots extend from a massive rhizome comb. *Juncus arcticus* grows along a linear rhizome comb ~5-20 cm long, as opposed to *Juncus drummondii*, which grows in from rhizomes extending from a circular clump, ~10-20 cm in diameter. Additionally, the *Juncus* species have roots with a loose spiral form, causing a slight elasticity in the roots. The herbaceous species have moderate to minimal branching. The *Equisetum* species show very interesting root morphology that mimics the stem architecture. Similarly to how the stems are formed by interlocking segments at joints, the roots also have joints where root segments join, and there are bifurcations located at these joints in a minor percentage of the roots sampled.

4.3 Comparison of Physical Root Attributes

There are significant differences between the four vegetation groups for the lateral root extent (F= 10.66, p= 0.0019), maximum root diameter (F= 8.77, p= 0.0038), and the tensile curve coefficient (a) (F= 4.72, p= 0.0267) (Table 11). There is no significant difference between the means of the vegetation groups for the root depth or tensile strength curve exponent.

Table 11. Statistics of physical root parameters categorized by vegetation type. P-value shown for each parameter tests the null hypothesis that there is no difference between the means of the groups. Bolded p-values are significant at α=0.05.

Vegetation Type	**Root depth (m)**				**Lateral root extent (m)**				**Maximum root diameter (mm)**				**Tensile strength curve coefficient (a)**				**Tensile strength curve exponent (b)**			
	Min.	Max.	Mean	Range	Min.	Max.	Mean	Range	Min.	Max.	Mean	Range	Min.	Max.	Mean	Range	Min.	Max.	Mean	Range
Tree	0.4	1.0	0.59	0.6	0.5	1.0	0.75	0.5	21.45	54.22	39.11	32.77	12.36	25.05	18.65	12.69	-1.03	-0.42	-0.80	0.61
Shrub	0.2	0.9	0.46	0.8	1.0	1.0	1.00	0.0	18.75	46.88	28.44	28.13	12.20	14.71	13.24	2.51	-0.82	-0.58	-0.73	0.24
Herbaceous	0.3	0.5	0.38	0.2	0.1	0.4	0.25	0.3	0.64	3.60	3.86	2.96	5.31	10.93	7.93	5.62	-1.49	-0.46	-1.16	1.03
Graminoid	0.3	0.6	0.43	0.3	0.1	0.5	0.23	0.4	0.82	8.23	2.04	7.41	9.62	20.25	14.84	10.63	-1.14	-0.81	-0.96	0.33
p-value[1]				0.1808				**0.0019**				**0.0038**				**0.0267**				0.3500

1- p-value for the test of the null hypothesis that all means of four vegetation type means are equal; significant values at α=0.05 are in bold

In general, the trees and shrubs have significantly different root parameters than the graminoid and herbaceous species. In terms of the maximum root diameter and the lateral root extent, the trees and shrubs form a significantly different group from the graminoids and herbaceous species (Figure 30). As for the tensile strength curve coefficient, only the trees and herbaceous species are significantly different.

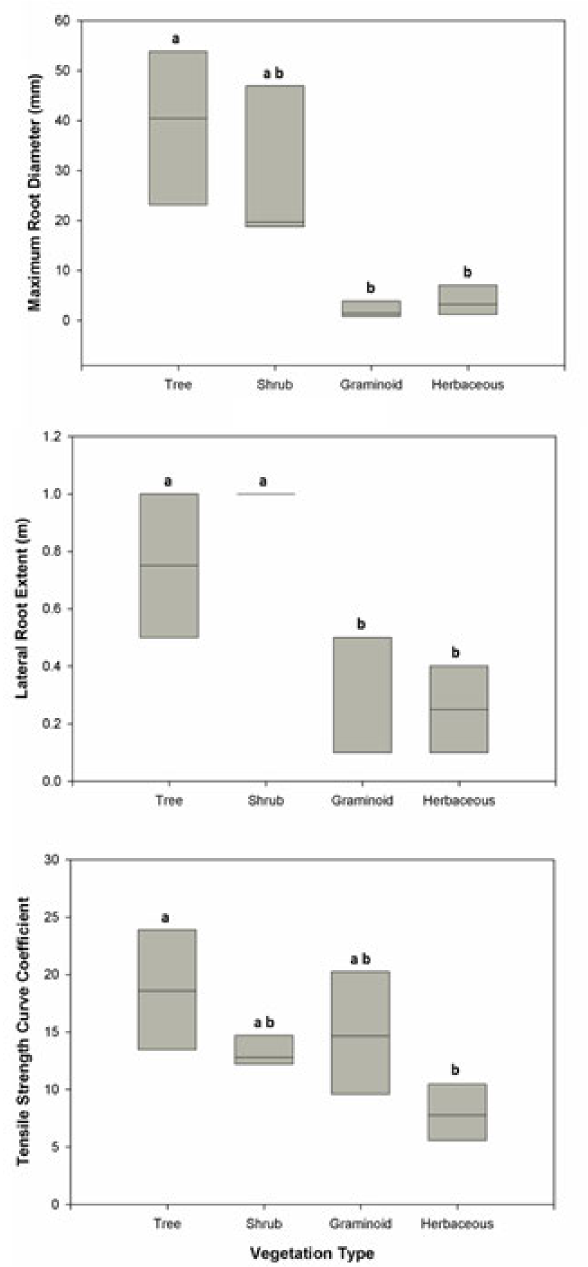

Figure 30. Box plots of physical root parameters by vegetation type for those parameters that had significant differences between means. Letters show significantly different groups at α=0.05.

Additionally, scatter plots of where species plot in three-dimensional space of various physical parameters show differences in the four vegetation types (Figure 31; Figure 32). In the scatter plot of TSA, maximum root diameter versus lateral root extent, all of which had significant differences between the means (Figure 30), show that the trees and shrubs plot in unique and separate space compared to the graminoids and herbs. In all of these plots, species that plot furthest to the left, back and to the top (i.e., with the highest values of any of the physical parameters) should provide the greatest contribution to bank stability, because an increase in any of these parameters corresponds to greater root contribution to bank stability in terms of added cohesion (tensile strength coefficient and maximum root diameter), and the vertical and lateral extent of roots. The points plotted on the graphs also indicate whether the species do or do not have rhizomes. The lateral root extent indicates the estimated root extent of a single specimen capped at 1.0 m, but those species with rhizomes are connected to a much larger root network and will reduce the chance of removal of the roots from the streambank. The roots and shrubs always plot separately from the herbaceous species in all three three-dimensional plots (Figure 31; Figure 32). The graminoids also plot separately from the trees and shrubs except in the plot with TSA, maximum root diameter, and root depth, where there is some overlap with the trees and shrubs. The graminoids group always coincides slightly with the herbaceous species, but the graminoids always have higher combined parameter values than the herbs. Additionally, all of the graminoids sampled have rhizomes, whereas only one of the four herbs has rhizomes, so the graminoids should have even higher bank stability capabilities based on physical parameters. Similarly, all of the shrubs have rhizomes and none of the trees have rhizomes; therefore, the willows should be moved upward compared to the trees on the plots. These scatter plots provide a simple visual analysis of how species separate in the space of physical root parameters that can affect the root's addition to bank stability. This assessment, combined with the above box plots and ANOVA, will be compared with the results from the BSTEM model, including the added cohesion from roots and the factor of safety analysis using various bank profiles.

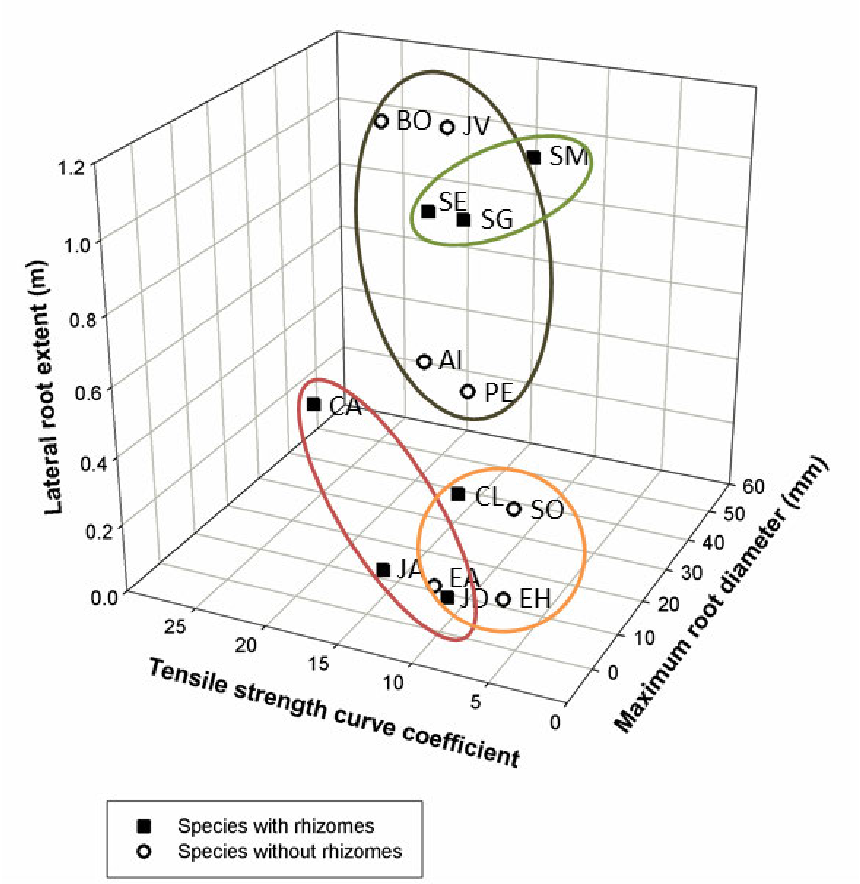

Figure 31. Three-dimensional scatter plot of tensile strength curve coefficient, maximum root diameter, and lateral root extent, showing location of each species (shown as two letter genus- species abbreviations) plotted along the three axes. The highest addition to bank stability would occur in the back, top-left corner. Species are distinguished by those with (black squares) and without (hollow circles) rhizomes. These three parameters showed significant differences between vegetation group types. The ovals encompass the different vegetation types: brown are trees, green are shrubs, red are graminoids, and orange are herbs.

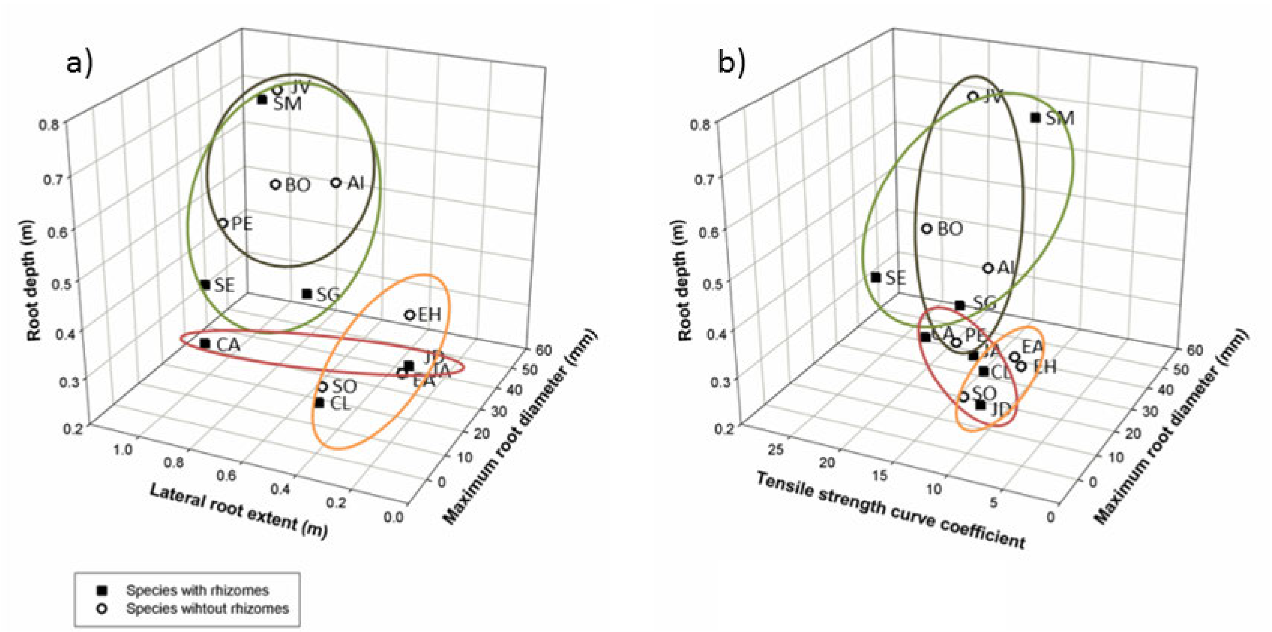

Figure 32. Three-dimensional scatter plots of species plotted in space of three different physical parameters. Unlike three-dimensional scatter plot in Figure 31, not all of the parameters have significantly different means between the four vegetation groups. Species are distinguished by those with (black squares) and without (hollow circles) rhizomes. The ovals encompass the different vegetation types: brown are trees, green are shrubs, red are graminoids, and orange are herbs. Graph (a) shows no overlap between the trees or shrubs and the graminoids or herbs.

4.3 Modeling Results

4.3.1 RipRoot Results

Added cohesion varied for each species by the type of bank material. For species without field-collected root density data, three scenarios of stem density were used and added and total cohesion values are reported for each stem density (Figure 33). The values from the three stem density scenarios were averaged and the values are reported by species in Figure 34. Added cohesion is greatest for the sand and gravel texture or the clay textures. Overall, the species with the lowest average added cohesion also have the smallest ranges of added cohesion. By far, the highest added cohesion values are from the willow species, *S. geyeriana*, which is a factor of the large number of large roots (see Figure 27). However, the other two willow species have rather low added cohesion values over a very small range. Other than the willow with high values, the two riparian trees, *A. incana* and *B. occidentalis*, and one of the juncus species, *J. drummondii*, have the highest average added cohesion values. Additionally, the graminoid *C. aquatilis* has a similar added cohesion value for clay textures but lower values for the remaining textures. The total cohesion values show similar trends between the species but with lesser differences between species because the added cohesion values are added to the same sediment texture values for all species. For all species, the total cohesion values are greatest for clay textures followed by loam textures, and the non-cohesive textures have similarly low values. Although each species follows similar trends in terms of the total cohesion by sediment texture, the range and spread of values differ.

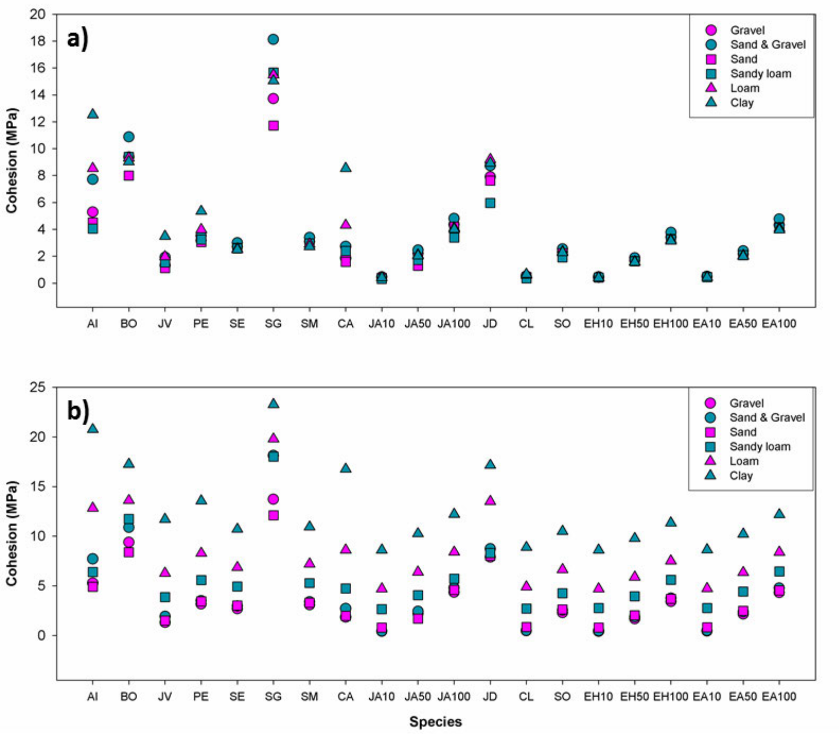

Figure 33. Added cohesion (a) and total cohesion (b) for each species and species density combination based on sediment texture.

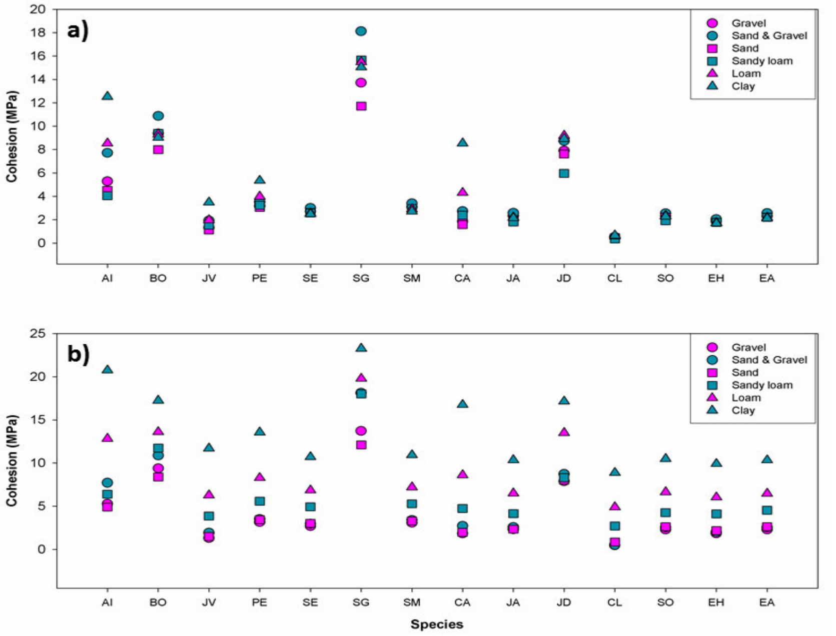

Figure 34. Added cohesion (a) and total cohesion (b) for each species based on sediment texture.

Differences in added cohesion and total cohesion were found between the vegetation lifeform groups (added cohesion: F= 7.97, p = 0.0001; total cohesion: F= 4.16, p = 0.0086). The added cohesion for the shrubs and trees was significantly higher than that of herbaceous species but not different than that of the graminoids (Figure 35). The only significant difference for the total cohesion was between the shrubs and herbs (Figure 35). Significant differences were also present for added and total cohesion between species (added cohesion: F= 51.57, p < 0.0001; total cohesion: F= 6.10, p < 0.0001). In terms of added cohesion, *S. geyeriana* forms a significantly different group from all other species, with the highest added cohesion values (Figure 36). The three species with the next three highest added cohesion values also form a group that is significantly different from all other species: *A. incana*, *B. occidentalis*, and *J. drummondii*. The species with the lowest added cohesion values form a combination of two significant groups (c, cd, and d). The only species that are significantly different from one another are *C. aquatilis* and *P. engelmannii*, which are different than *C. leptosepala*. There are fewer significantly different groups of species for the total cohesion values, but the overall differences are similar. *S. geyeriana* is significantly different than all other species except for the next three highest species mentioned above. *C. leptosepala*, with the lowest values, is significantly different than *S. geyeriana* and *B. occidentalis*.

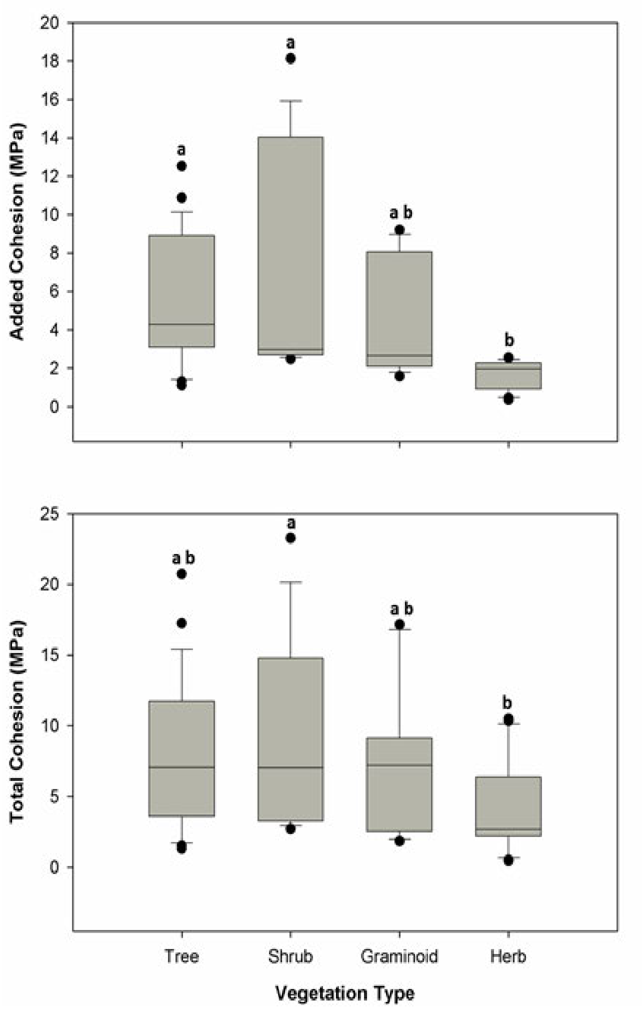

Figure 35. Boxplots of added and total cohesion based on vegetation type. Letters above boxplots show significant different groups at α = 0.05 with a Tukey's HSD adjustment.

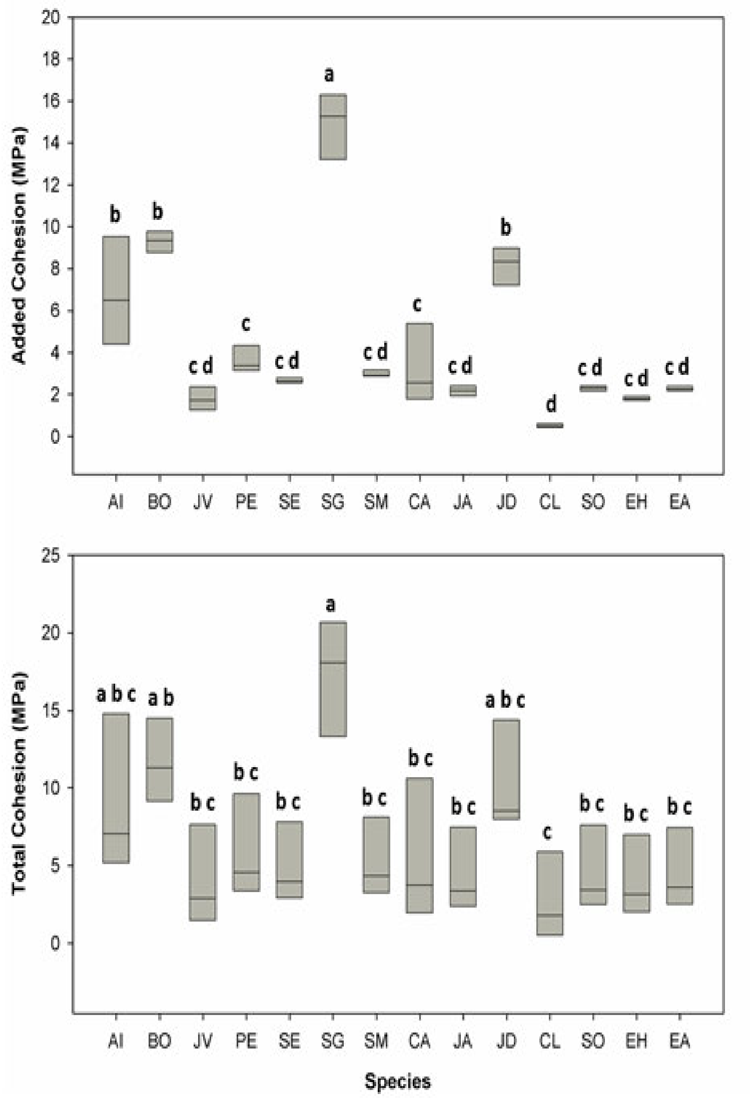

Figure 36. Boxplots of added and total cohesion based on species. Letters above boxplots show significant different groups at α = 0.05 with a Tukey's HSD adjustment.

4.3.2 BSTEM Results (Factor of Safety)

Modeling Results

Modeling bank stability of one of the five bank profiles proved to be unsuccessful. Bank B, which was modeled as a loam above a sand and gravel layer, consistently provided extremely high values for factor of safety (FS). I attempted to use bank B by altering the bank profile within the model so that the loam layer was thicker than the non-cohesive layer and by removing the undercut, but the bank stability output consistently either provided infinitely high values or values several orders of magnitude higher than those of the other banks. Although these are unrealistic values, I interpret these results as indicating that bank B is more stable than the other banks, according to the possible analyses in this model. Field tests would probably show differences between species and hydrologic conditions within bank B. I did not include the model results using bank B in the statistical comparisons of results between banks, species, or vegetation type presented below, because comparisons or trends would not be accurate with the unrealistic factor of safety values.

The added and total cohesion results integrate the tensile strength of each species and the root size distribution and density with various sediment textures. This provides some insight to the varying amounts of bank stability provided by different species. However, to further understand the relative contribution to bank stability by species and bank characteristics, bank stability modeling was required. The results from these models integrate the added cohesion with root depth, together with the physical characteristics of bank profile geometry, sediment layer depths and textures, confining pressure from the channel, and pore pressure in terms of the water table depth.

Factor of safety values varied more by bank profiles than by species (Figure 37). Bank E has much higher factor of safety values than any of the other three bank profiles. However, within each bank type, there is large variability between species.

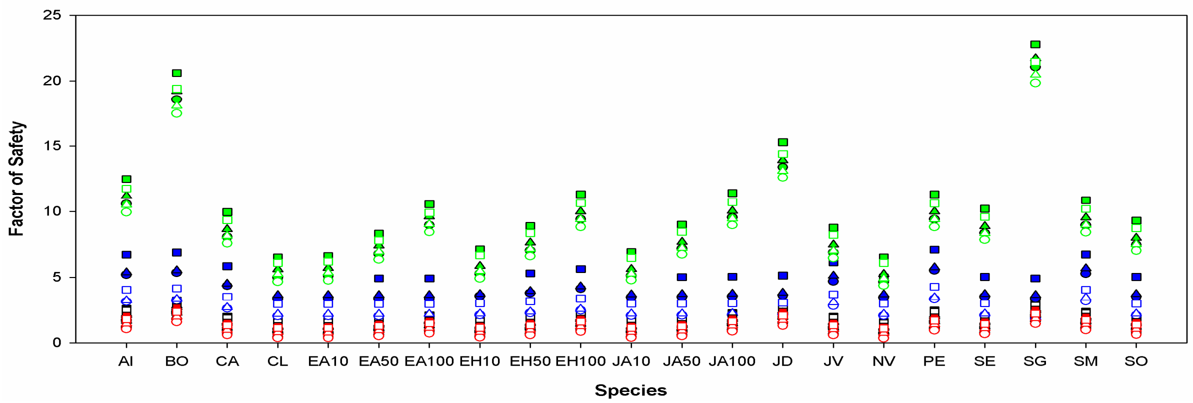

Figure 37. Factor of safety results for all species, bank profiles, and water surface and water table combinations. Black symbols are from Bank A (which are mostly behind red and blue symbols), blue symbols are from Bank C, red symbols are from Bank D, and green symbols are from Bank E. Solid circles: mid-bank water surface elevation (WSEL), and high water table (WT); solid triangles: mid WSEL, mid WT; solid squares: mid WSEL, low WT; open circles: low WSEL, high WT; open triangles: low WSEL, mid WT; open squares: low WSEL, low WT. Note large variability in FS by banks, within which there is variability by species.

Physical comparisons with FS

The categorical physical characteristics showed significant differences for factor of safety values between bank profiles (F= 371.1, $p < 0.0001$) and water table depth (F= 3.72, p= 0.0249), but not for the water surface elevations (F= 3.68, p= 0.0555) at $\alpha = 0.05$. The bank profiles form three significantly different groups for the factor of safety values, with bank E having the significantly higher values than the other three banks, and bank C having significantly higher FS values than banks A and D (Figure 38). Banks A and D have some non-cohesive sediment: Bank A consists of a non-cohesive layer over a semi-cohesive layer, ~ 0.9 tall, and Bank D consists only of non-cohesive sediment, ~ 1 m tall. Bank C consists only of cohesive sediment and is ~1 m high, and Bank E consists of semi-cohesive material and is only ~ 0.6 m high. The low water table depth creates significantly higher values for factor of safety than the high water table depth, but is not different from the mid-bank depth (Figure 38).

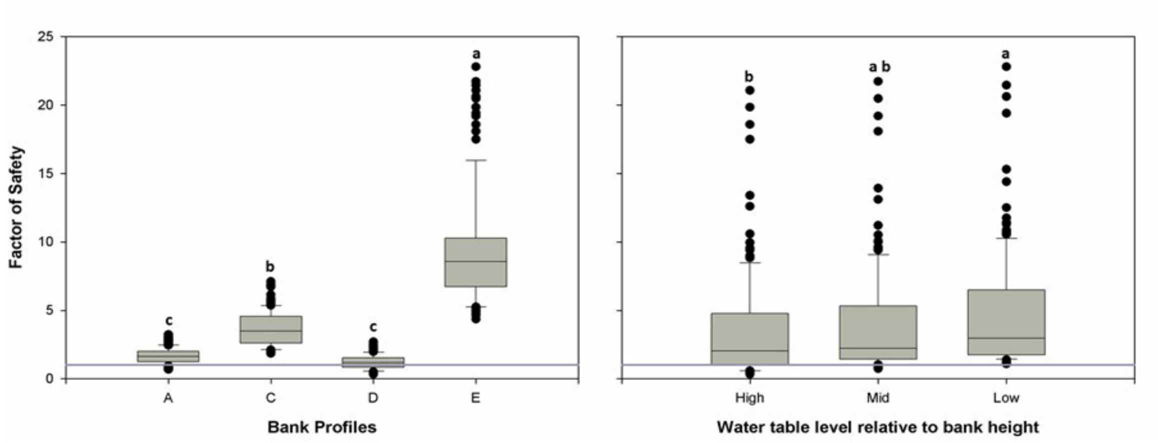

Figure 38. Boxplots of factor of safety by bank profile and water table level. Different letters signify significantly different groups at α = 0.05 with a Tukey's HSD adjustment.

Vegetation comparisons with FS

The species differences in FS values are shown for all species with the varying stem densities in Figure 39 and only by species in Figure 40. Comparing all species with those divided by stem density, there are three significant groups but most species belong to at least two groups and so are not significantly different than many other or any other species. *S. geyeriana* has the highest FS values and is significantly different than six other species with the lowest FS values, all of which are graminoids or herbs, or scenarios with no vegetation.

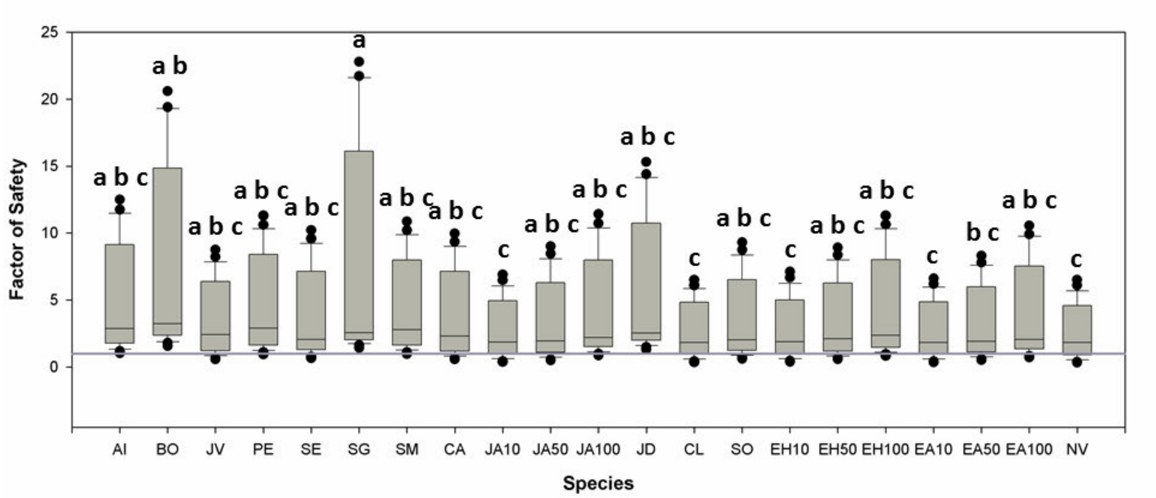

Figure 39. Boxplots of factor of safety values by species, including those with varying root distributions. Different letters indicate significantly different groups. Species are ordered by vegetation type.

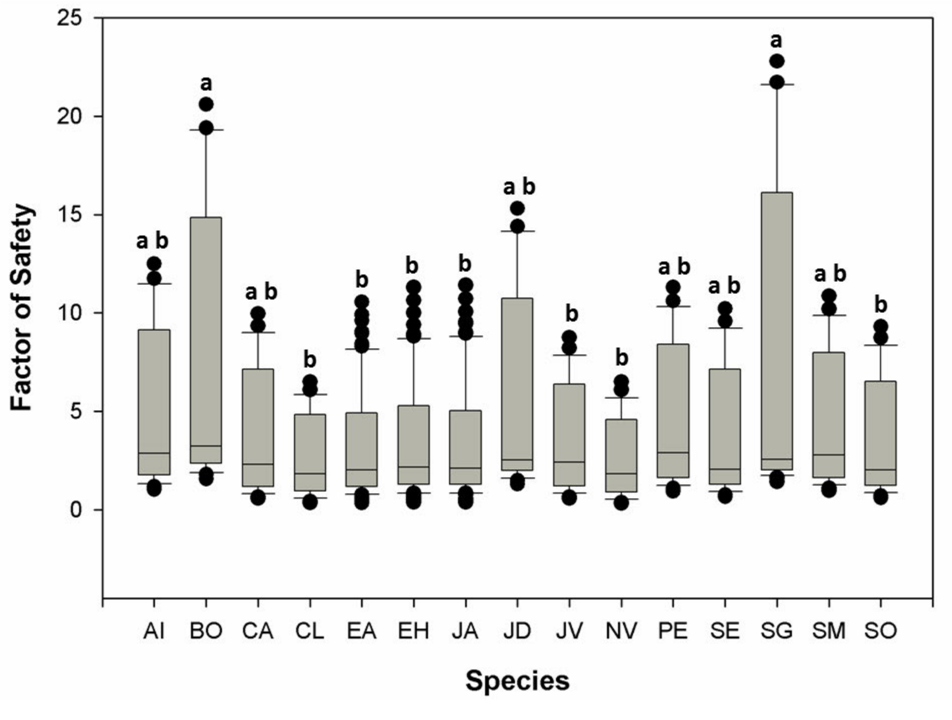

Figure 40. Boxplots of factor of safety by species. Different letters above boxes indicate significantly different groups. Species are listed in alphabetical order.

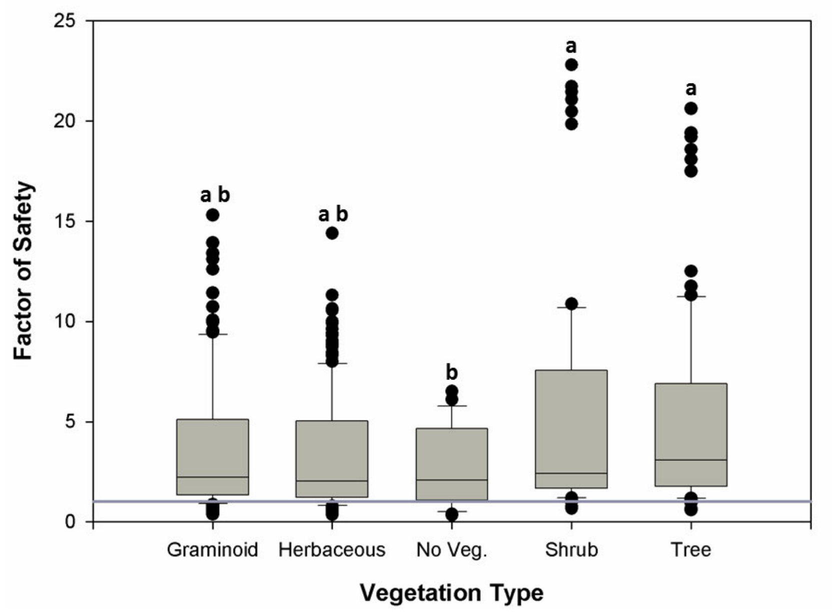

Figure 41. Boxplots of factor of safety by vegetation type. Different letters above boxes indicate significantly different groups.

Bank failure proportions

Comparisons of factor of safety values show the difference in the ratio between the driving and resisting forces acting on the bank as a result of diverse physical and vegetative factors. However, those analyses do not give a clear picture of when actual bank failure occurs. The bar graphs below show the proportion of stable versus unstable scenarios by bank profile, species and vegetation type (Figure 42, Figure 43). Notice that both banks E and C never fail in these model scenarios, even though the factor of safety values differ significantly. A very low proportion of scenarios with either trees or shrubs fail; the largest proportion of bank failure occurs with no vegetation. Bank failure occurred more often with herbaceous species than graminoids, but both occurred more often than trees or shrubs and less often than with no vegetation. There are four species that have no scenarios that produce bank failure: *A. incana*, *B. occidentalis*, *S. geyeriana*, and *J. drummondii*. The herbaceous species *C. leptosepala* has the same proportion of scenarios with bank failure as with no vegetation.

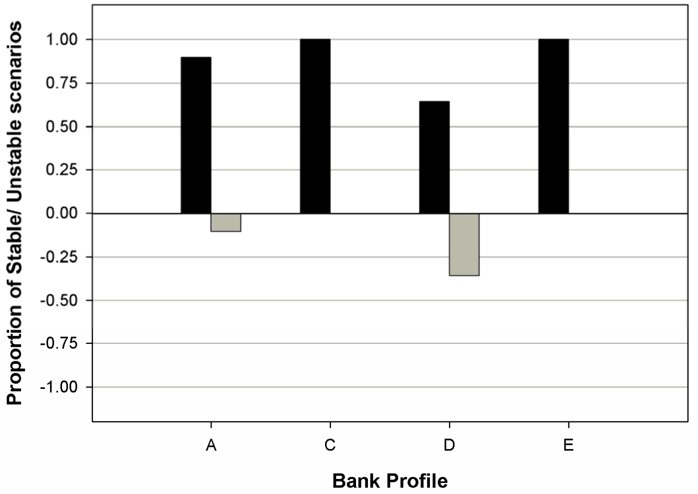

Figure 42. Proportion of stable versus unstable banks for each bank profile. Positive numbers represent the proportion of stable banks and negative numbers represent proportion of unstable banks.

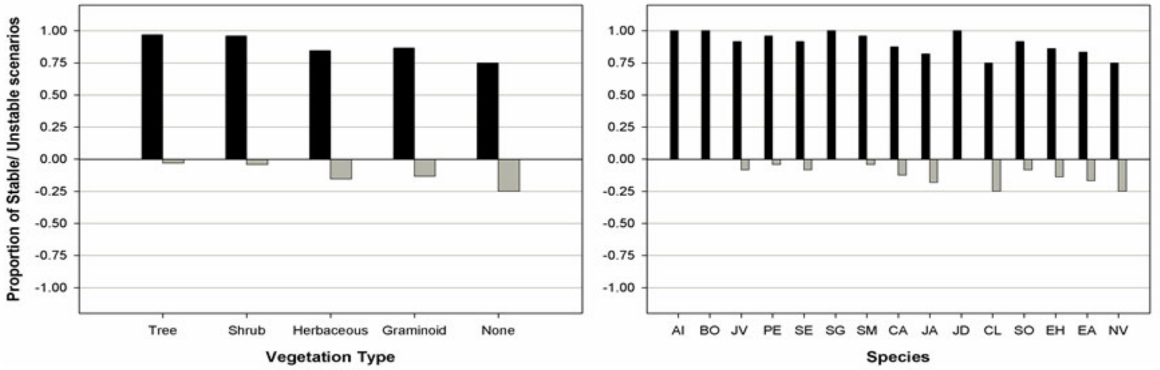

Figure 43. Proportion of stable versus unstable banks for different vegetation types and various species. Positive numbers represent the proportion of stable banks and negative numbers represent proportion of unstable banks.

Correlations of continuous variables with FS

Pearson and Spearman correlation coefficients (ρ) of continuous physical and root characteristics with FS values show several highly correlated variables (Table 12). The physical parameter of bank height is most highly correlated with FS, where ρ = -0.75; the ratio of the root depth to bank height is positively correlated with FS. The two vegetation parameters of the maximum root diameter and tensile strength curve intercept are weakly positively correlated with FS (ρ = 0.16 and 0.15, respectively), but both are highly significant relationships.

Table 12. Pearson and Spearman correlation coefficients of continuous physical and vegetation root parameters as related to FS.

	ρ	Pearson p-value	R^2 value	ρ_s	Spearman p-value
Bank height (BH)	-0.75	<0.0001	0.56	-0.34	<0.0001
RD/BH[1]	0.47	<0.0001	0.22	0.41	<0.0001
Max Rt[2]	0.16	0.0002	0.03	0.15	0.0008
Lat[3]	0.15	0.0006	0.02	0.18	<0.0001
TSA[4]	0.15	0.0007	0.02	0.11	0.0117
RD	0.08	0.0899	0.01	0.12	0.0094
Min Rt[5]	-0.06	0.1699	0.00	0.03	0.4426
TSB[6]	0.03	0.5681	0.00	0.02	0.5813
1: Root depth (RD) to bank height ratio capped at 1					
2: Maximum root diameter (mm)					
3: Lateral root extent, capped at 1 m					
4: Tensile strength curve coefficient (intercept of power regression)					
5: Minimum root diameter (mm)					
6: Tensile strength curve exponent (slope of power regression)					

A multiple linear regression developed a model explaining 58% of variability in FS values (Table 13). The bank height and maximum root diameter were the significant parameters in the model. Root depth (RD) and the root depth to bank height ratio (RD/BH) were highly collinear (ρ_s= 0.82), so only RD/BH was included as a potential variable in the model selection process; however, it was not deemed to be significant for the model. The TSA was highly collinear with maximum root diameter (ρ_s= 0.82) and Lat

(ρ_s= 0.76), so only Max Rt was included in the model selection process because it was most highly correlated with FS. Because Max Rt is a part of the final model, this parameter represents change in Max Rt, TSA, and Lat.

Table 13. Model and parameter statistics for multiple linear regression model that explains most variability in FS.

Model statistics			
R^2	0.5821		
Adjusted R^2	0.5804		
F-value	348.92		
p-value	<.0001		
Parameter statistics			
Variable	Parameter estimate	t- value	p-value
Intercept	19.53	30.58	<.0001
BH	-18.19	-25.8	<.0001
Max Rt	0.04	5.69	<.0001

The correlation values and multiple linear regression results shown above, both of which explain variability in FS, suggest that the physical characteristic of bank height explains more variability than any of the vegetation root characteristics. However, these analyses also elucidate the root characteristics that exert the most influence on bank stability: tensile strength curve intercept (TSA) and the maximum root diameter (Max Rt). This provides another line of evidence for evaluating the difference in species root characteristics examined in section 4.3. Recalling the results of the ANOVAs between vegetation groups and root characteristics, there are differences between vegetation groups for TSA and Max Rt.

5. Discussion

5.1 Modeling and Physical Characteristics Synthesis

Integrating the bank stability modeling results with those of root characteristic differences, the root characteristics that most contribute to bank stability and show greatest differences between species groups can be distinguished. The tensile strength intercept (coefficient; TSA), the maximum root diameter, and lateral root extent are significantly correlated with factor of safety, and, in addition, show significant differences between vegetation groups. Trees show differences from herbaceous species and to a lesser degree graminoids for both the maximum root diameter and tensile strength intercept. Shrubs have higher maximum root and tensile strength intercept values than the graminoids and herbs, although these differences are not significant. In regards to the lateral root extent, both the trees and shrubs have more laterally extensive roots than the graminoids and herbs.

The effect of lateral root extent on factor of safety from the modeling results reflects the collinearity with other root characteristics rather than a true effect on the model, as no parameter quantifying lateral root extent is taken into account in the model. However, the correlation between lateral root extent and factor of safety will still allow for a simpler measurement of the ability of a species to stabilize streambanks. The connection between lateral root extent and factor of safety over the reach scale also has some physical justification, because the root network will add cohesiveness over a longer downstream distance.

Comparison of physical root attributes and modeling results agree that the root characteristics of lateral root extent, tensile strength curve coefficient, and maximum root diameter best describe differences between vegetation groups and most closely predict the bank stability.

5.2 Relative Influence of Bank Versus Vegetative Characteristics

Bank stability modeling of five different banks more strongly supports the hypothesis that there are no differences in the ability of riparian species to stabilize streambanks than the alternate hypothesis that there are distinct differences in the ability of riparian species to stabilize streambanks for the whole population of streambanks and species types. Support of this hypothesis does not imply that there are no differences between species or species groups in bank stability, or that vegetation does not play an important role in stabilizing streambanks. However, based on the species and bank characteristics modeled, there was more variation between physical bank characteristics than species. A visual analysis of factor of safety values by species and bank types show greatest variability between banks, and the correlation coefficients and multiple linear regression describing the factor of safety show that bank height correlates more strongly with factor of safety than any vegetative factor. Between the five bank types, there was large variability between factor of safety values and bank failure occurrences (Figure 40). Within each bank type, however, there is variability between species. The patterns between species between each bank were similar, but the magnitude of difference between species varied by bank type. The bank characteristics, which integrate geometry and texture, have a larger impact on resulting bank stability than vegetation characteristics. A functional root classification of species is only valid within similar bank types and with the caveat that the same magnitude of differences will not be seen across bank types.

Only two of the five streambanks experienced bank failure with any of the water table-water surface scenarios or species combinations. These two banks (A and D) have moderately high banks (~ 1 m) and consist of a thick non-cohesive layer of sediment. Bank A has >0.5 m of sand over a smaller loam layer above the bank toe, and Bank D, which has the lowest factor of safety values of all the banks, is composed entirely of sand. The remaining three banks (B, C, and E) did not have any occurrences of bank failure for all scenarios and species. Bank B, which was not included in the statistical analyses, because it showed consistently unrealistically high or infinite bank stability values, consisted of sand and gravel overlain by loam. Bank E, which was the shortest bank at 0.61 m and consisted entirely of a sandy loam, had significantly higher factor of safety values than any other bank. Bank C contained slightly more cohesive sediment than Bank E but had the highest bank height at 1.02 m. Bank E had lower factor of safety values than Bank C but higher than either Bank A or D.

The integrated variation in bank geometry and texture had a larger effect on the bank stability than the combination of water surface level or water table level scenarios. There was no difference in the means of factor of safety values for the mid or low level of the water surface elevation, although the factor of safety was consistently higher for the mid-elevation water surface, when all other factors are held constant. There is a difference in factor of safety values for low versus high water table depths. All water table depths have some scenarios with bank failure, but the high water table elevations have more than the middle or low elevations. This factor can be thought of as a third-level variable, because it causes variability within the bank and species combinations but does not drive the overall variability.

Factor of safety values, which drive these analyses, are a simple ratio between resisting and driving forces and are widely used to describe bank stability in models and field investigations (Simon et al., 2000; Shields et al., 2008; Simon et al., 2009). Factor of safety values indicate the balance between driving and resisting forces, so values <1 indicate unstable banks and >1 indicate stability. The BSTEM model assigns values from 1- 1.3 as conditionally stable, because a slight change in conditions could move the bank into an unstable zone. However, Hubble (2010) provides a set of nomenclature to further clarify ranges of factor of safety values. Because a factor of safety value of 0.5 implies driving forces two times greater than resisting forces and a value of 1.5 implies resisting forces only 50% greater than driving forces, the scale of factor of safety values is not linear (Hubble, 2010). Therefore, a streambank with a factor of safety value of 2 is as stable as a bank with a factor of safety value of 0.5 is unstable. In regards to the results presented, differences in factor of safety values exceeding 2 are not very meaningful (Table 14). The differences between banks are thus much less if we only focus on the variability below a factor of safety value of 2. Evaluating the data classified by these categories, all of the scenarios with Bank E are ‘stable,’ and all but two scenarios with Bank C are ‘stable,’ both of which are ‘probably stable.’ Additionally more scenarios with Bank A are ‘stable,’ ‘probably stable,’ or ‘moderately stable,’ compared to those with Bank D, which are more likely to be ‘moderately,’ ‘conditionally’ or ‘critically stable’ if the FS >1 (Figure 44).

Table 14. Probable bank stability conditions for factor of safety value ranges (Hubble, 2010).

Factor of safety	Probable bank stabiltiy condition
> 2.00	Stable
1.51-2.00	Probably stable
1.31-1.50	Moderately stable
1.10-1.30	Conditionally stable
1.00-1.10	Critically stable
0.91-0.99	Unstable
0.71-0.90	Very unstable
0.50-0.70	Highly unstable
< 0.50	Extremely unstable

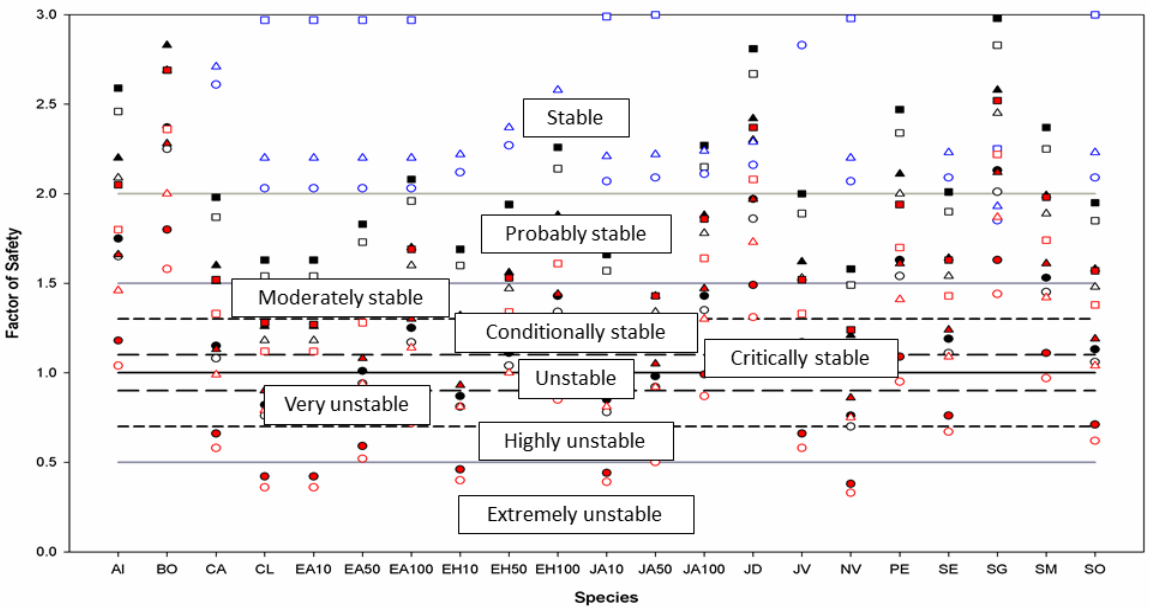

Figure 44. Factor of safety results with Hubble (2010) bank stability conditions. Factor of saftety values shown for all species, bank profiles, and water surface and water table combinations. Black symbols are from Bank A, blue symbols are from Bank C, red symbols are from Bank D. Most of the data points from Bank C and all of those from Bank E are not visible because they have FS values >3. Solid circles: mid-bank water surface elevation (WSEL), and high water table (WT); solid triangles: mid WSEL, mid WT; solid squares: mid WSEL, low WT; open circles: low WSEL, high WT; open triangles: low WSEL, mid WT; open squares: low WSEL, low WT. Lines correspond to factor of safety values that divide stability categories (see Table 14; Hubble, 2010).

Variability in bank stability results from bank characteristics suggests that the cohesiveness of bank sediment and bank height drive differences in bank stability. The bank without any cohesive bank material (Bank D) had twice as many bank failures as a bank with similar bank height that had a sand and loam layer. Although bank C had more cohesive sediment than bank E, it had slightly lower factor of safety values, because of a higher bank height. The following are the most important bank characteristic factors, in order: 1) whether or not there is cohesive sediment present, 2) bank height, 3) degree of cohesive sediment (if it is cohesive), and 4) depth of water table.

This study focused specifically on streambanks along low-gradient streams with moderate drainage areas in the Colorado Front Range. I expect to see greater variability in a similar comparison carried out across more valley types, channel geometries, and drainage sizes. Although species variability follows a similar trend between the bank types in this study, I might expect less variability between species with much higher bank heights. If the bank heights greatly exceed the rooting depths, the proportion of the bank with added cohesion from root strength will be much smaller in comparison to the segment that will behave the same regardless of the type of vegetation. In these cases, the root depth to bank height ratio should be a strong driving factor in determining whether vegetation type will have any effect even after bank characteristics effects are taken into account. In this study area, however, vegetation type and species still contribute significant variability within banks and contribute to a common trend between banks, and therefore warrant the development and use of a functional classification of species for bank stabilization.

5.3 Functional Vegetation Classification

Differences between root characteristics and their significant contributions to bank stability facilitate the creation of a functional species classification for bank stability. This discussion presents a synthesis of results based on the four taxonomic groups and then discusses explicit differences in species. In Section 5.1, vegetation type differences in maximum root diameter, lateral root extent, and tensile strength coefficient were presented. Although only the tensile strength coefficient and not the exponent showed significant differences between vegetation types, analysis of tensile strength curves elucidates differences between species and vegetation types. The species with clearly highest tensile strengths for all root diameters are tree species: *B. occidentalis* and *J. virginiana*. The tensile strength curves of the three willow shrubs nearly overlap and are positioned in an intermediate range compared to other species. The herbaceous species substantially overlap with one another and plot below most other species.

The functional classification proposed here integrates the three main root characteristics that contribute to bank stability. Because there were significant correlations between root traits and factor of safety, the original null hypothesis that inherent characteristics of riparian roots, including morphology and root tensile strength, do not correlate with the vegetation’s effect on bank stability was not supported. I hypothesized that the three traits of tensile strength, root depth and lateral extent, and root density would be the strongest traits in determining differences between species in adding to bank stability (Figure 18). However, slightly different characteristics showed the strongest correlations with factor of safety and differences between vegetation type: lateral root extent, tensile strength coefficient, and maximum root diameter. Two of the originally hypothesized variables are included in this list, and the maximum root diameter is a parameter describing the distribution of root sizes. Figure 45 shows a schematic three-dimensional diagram of the study species grouped by vegetation group along the three axes representing the lateral root extent, tensile strength coefficient, and maximum root diameter. The four taxonomic groups form distinctive groups in the root characteristic space. There is no overlap between the woody (trees and shrubs) and the non-woody (graminoids and herbs) species. The species with rhizomes would provide additional stability to the bank on the scale of a few meters to an entire reach, depending on the extent of the specimens from a single genetic individual.

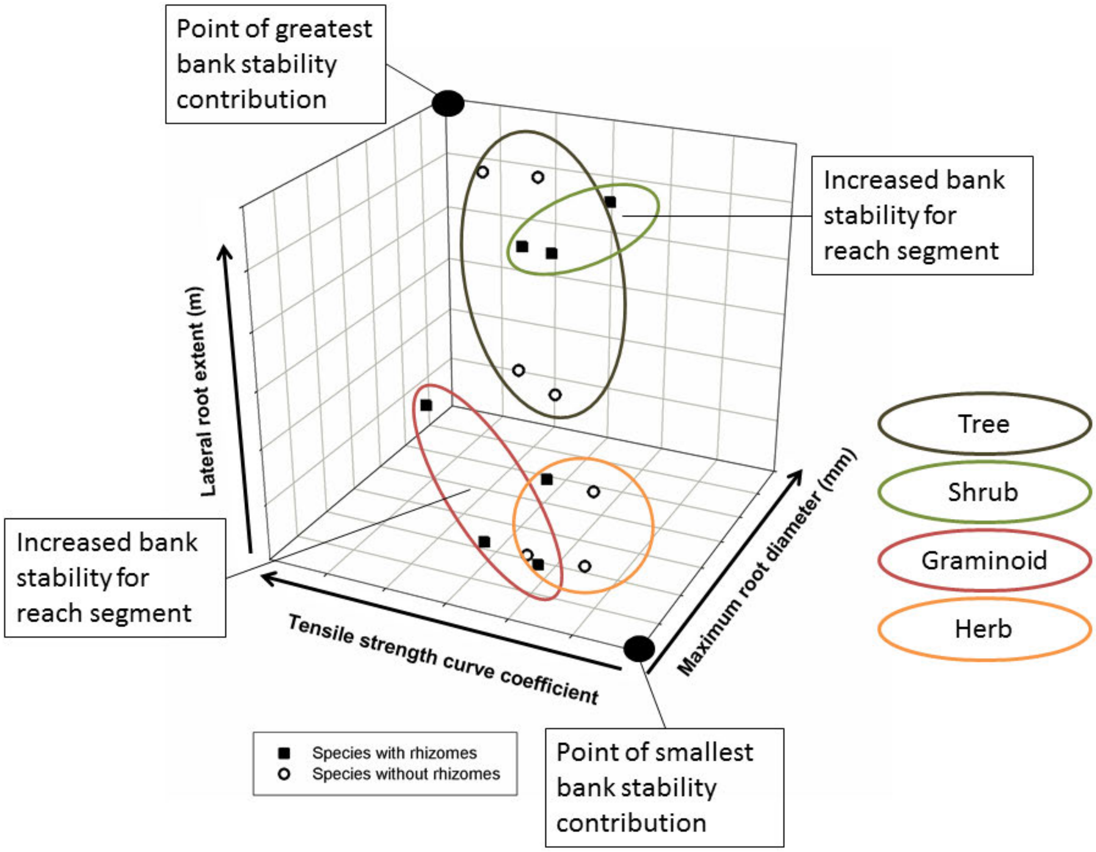

Figure 45. Schematic diagram showing vegetation types plotted in the space of the three most explanatory root characteristics for bank stability. Colored ovals show four taxonomic groups.

Although vegetation type groupings represent the distribution of species well, they are restricted to the taxonomic groupings. Secondary groupings were created based on the level of vegetative bank support (High, Medium, Low) and whether the species has rhizomes (Non or Rhi) (Figure 46; Table 15). These groupings allow visualization of various levels of added bank stability by species and the larger-scale downstream impact of the species. Not all possible groupings are present from these data; the med/low-rhi grouping is not represented. The low groupings for either the rhizomatous or non-rhizomatous groups are not found in these data. However, it is possible that these groupings would be extremely rare in streambank settings, because they would not be able to withstand such a high-disturbance environment.

The classification of each species into the three stability classes was based on its position in root characteristic space, which was adjusted based on bank stability modeling results. The density of roots across size classes, which is an important component of the fiber-bundle model in RipRoot (Pollen et al., 2004), is not shown in the root trait diagram (Figure 46). Additionally, root depth was not significantly correlated to factor of safety but was incorporated in the bank stability modeling, which may also account for some differences in species position on the root trait diagram and factor of safety values. For example, in the diagram, *J. virginiana* plots in close proximity to *B. occidentalis*, but, because *B. occidentalis* has significantly higher factor of safety values than *J. virginiana*, they are assigned to separate groups. *A. incana* plots lower than *B. occidentalis* and in close proximity to *P. engelmannii*, with which it does not have significantly higher factor of safety values. *A. incana* is one of four species that does not have any modeled scenarios with bank failure, however, so it is placed in the ‘high’ category with *B. occidentalis*.

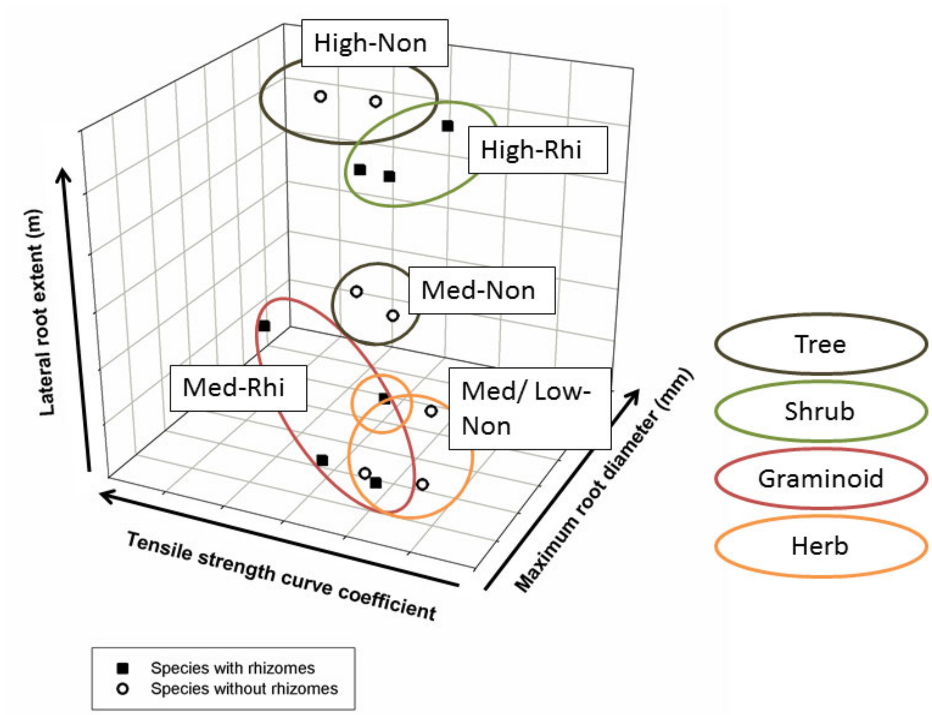

Figure 46. Schematic of vegetation types based on functional classification. Species are plotted in space of three most explanatory root characteristics for bank stability. Groupings are based on taxonomic groups and whether or not the species has rhizomes.

Table 15. Functional classification of fourteen studied species. Classification was determined by placement in three-dimensional space by root characteristics and adjusted by factor of safety modeling results.

	Rhizomatous		**Non-rhizomatous**	
Added stability class	*Vegetation Type*	*Species*	*Vegetation Type*	*Species*
High	Shrub	*S. exigua ,* *S. geyeriana ,* *S. monticola*	Tree	*A. incana ,* *B. occidentalis*
Medium	Graminoid	*C. aquatilis ,* *J. arcticus ,* *J. drummondii*	Tree	*J. virginiana ,* *P. engelmannii*
Med/Low	Herbs	*C. leptosepala*	Herbs	*E. arvense ,* *E. hyemale ,* *S. odontoloma*

Expansion of this functional classification through the addition of more species would be beneficial and require the collection of a moderate amount of field data. In particular, the functional classification should be flushed out with non-willow shrubs, larger riparian trees, and additional graminoids. For each species, measurements of the maximum root diameter, lateral root extent and tensile strength coefficient are necessary to determine the position in the root trait diagram. Obtaining the tensile strength coefficient would require the most intensive field work and specialized equipment; therefore a simpler model using only the lateral root extent and maximum root diameter is proposed as a proxy (Figure 47). There is much less variability in lateral root extent than either of the other two root characteristics, so most species plot in a few distinct clumps along the x-axis.

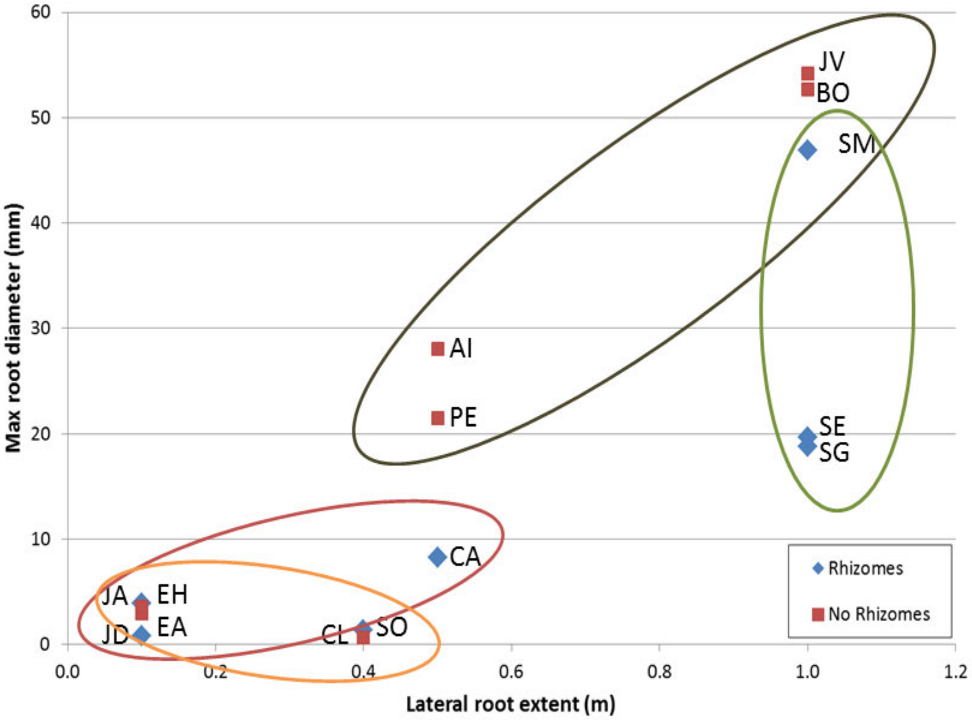

Figure 47. Proxy diagram of important root traits, excluding the more field-intensive root characteristic to collect, tensile strength coefficient.

Even though additional species data would strengthen this classification, specific morphologic data are not required to apply these findings to new species. Species in Table 15 that fall out into separate rhizome/bank stability categories also separate by vegetation type. The two tree species categories separate by riparian and upland species, according to Polvi (2009). The two trees in the 'high' category are both riparian species, whereas the trees in the 'medium' category are upland species. Therefore, species could be simply classified according to their vegetation type and whether they were riparian, in the case of trees, to obtain a general idea of their bank stabilization abilities. Because the root characteristics should be similar within a taxonomic group, this classification should be applicable in other regions with distinct species assemblages.

Other than adding data from new species, common species assemblages should be modeled and plotted in the three-dimensional space by combining traits from multiple species. Field observations indicate that certain assemblages are ecologically common and most likely have unique effects on bank stability. For example, along Corral Creek there are virtually only two species present: *S. geyeriana* and *C. aquatilis*. The two rhizomatous species form an intricate root network. Both of these species showed some unique root attributes: *S. geyeriana* had more large roots than any other species and *C. aquatilis* had twice as many small roots as any other species. This assemblage forms a highly reinforced bank as the willow behaves like a rebar and the sedge like thin netting through bank material.

5.3.1 Comparison with Literature

Several other studies have tested the root tensile strengths of riparian species along streambanks (Abernethy and Rutherfurd, 2001; Pollen and Simon, 2005; Pollen-Bankhead et al., 2009). Comparisons were not made with other studies that did not supply the tensile strength curve parameters (coefficient and exponent), because accurate comparisons could not be made. The species, locations, and root tensile strength curve parameters are shown in Table 16. Other studies have mostly analyzed trees, some shrubs, only two graminoids, and no herbaceous species. In contrast to other studies, this study sampled vegetation that is found in relatively low banks in headwater streams. This study showed consistently lower tensile strength curve coefficients than previous studies

(Figure 48). Because the same methods and equipment were used for collecting data, it is not likely a measurement error. There is slight overlap between tensile strength coefficient values for trees, but not for the shrubs or graminoids and no other herbaceous species had been tested previously. The trees and shrubs tested from other studies show a similar trend of trees having higher tensile strength curve coefficients. This comparison suggests that similar trends are observed between vegetation types in various geographical locations but because of possible differences in environmental conditions, the Colorado Front Range has species with slightly lower tensile strengths.

Table 16. Tensile strength curve parameters measured in this study and other published studies. All other studies used similar methods of testing root tensile strength, with RootPuller and tension-calibrated load cell.

Species			Tensile strength			
Latin	**Common**	**Vegetation Type**	**a**	**b**	**Location**	**Reference**
Melaleuca ericifolia	Swamp paperbark	Tree	49.4	-0.77	Victoria, Australia	Abernethy and Rutherfurd, 2001
Eucalyptus camaldulensis	River red gum	Tree	49.4	-0.77		
Plantanus occidentalis	Eastern sycamore	Tree	50.5	-0.94	Mississippi, USA	Pollen and Simon, 2005
Pinus palustris miller	Longleaf pine	Tree	30.0	-0.99		
Betula nigra	River birch	Tree	45.8	-0.66		
Liquidamber stryaciflua	Sweetgum	Tree	52.1	-1.04		
Salix nigra	Black willow	Shrub	45.9	-1.10		
Tripsacum dactyloides	Gamma grass	Graminoid	43.1	-1.00		
Panicum virgatum	Switchgrass	Graminoid	35.2	-1.78		
Spirea douglasii	Douglas Spirea	Tree	22.9	-0.54	Oregon, USA	
Fraxinus latifolia	Oregon ash	Tree	24.3	-0.50		
Rubus discolor	Himalayan blackberry	Shrub	19.5	-0.69		
Salix exigua	Sandbar willow	Shrub	25.2	-0.68	Kansas, USA	
Populus fremontii	Cottonwood	Tree	18.9	-0.64	Oregon & Kansas, USA	
Elaeagnus angustifolia	Russian olive	Tree	22.1	-1.00	Arizona, USA	Pollen-Bankhead et al., 2009
Tamarix ramosissima	Tamarisk	Shrub	23.6	-0.90		
Alnus incana	grey alder	Tree	16.8	-0.42	Colorado, USA	This study
Betula occidentalis	western birch	Tree	25.0	-0.79		
Juniperus virginiana	red cedar	Tree	20.4	-0.81		
Picea engelmannii	Engelmann spruce	Tree	12.4	-1.17		
Salix exigua	sandbar willow	Shrub	14.7	-0.80		
Salix geyeriana	Geyer willow	Shrub	12.2	-0.58		
Salix monticola	mountain willow	Shrub	12.8	-0.82		
Carex aquatilis	water sedge	Graminoid	20.3	-1.14		
Juncus arcticus	arctic rush	Graminoid	14.7	-0.72		
Juncus drummondii	Drummond's rush	Graminoid	9.6	-1.03		
Caltha leptosepala	marsh marigold	Herb	9.1	-1.49		
Equisetum arvense	field horsetail	Herb	10.9	-1.23		
Equisetum hyemale	scouringrush horsetail	Herb	6.4	-0.46		
Saxifraga odontoloma	brook saxifrage	Herb	5.3	-1.48		

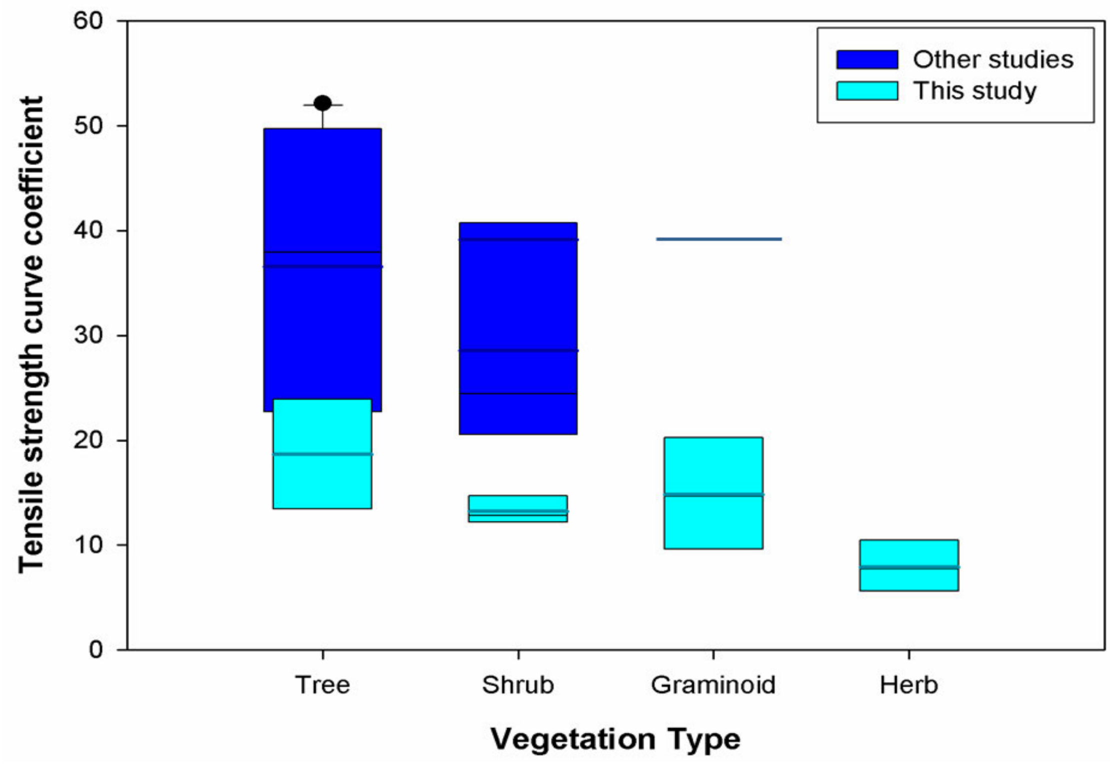

Figure 48. Boxplots of tensile strength coefficients for other studies and this study. Refer to Table 16 for species names, locations, and references. There were only two graminoids tested form other studies; for those, the mean is shown by a single dark blue line. The thick lines inside each box represent the mean values. Only two graminoids were tested in other studies, and thus only the mean is shown from those two values.

5.3.2 Limitations of Classification

The integrated effect of vegetation on bank erosion is the result of multiple effects and feedbacks of vegetation on hydraulic and bank properties. This study only examines one aspect of vegetation effects on bank stability, which are the root morphologic and tensile-strength characteristics. Although this plays a significant role in adding cohesion to streambanks, there are other bank and hydraulic characteristics that riparian species can alter. Vegetation can reduce or increase cohesion by altering the bank moisture properties: matric suction can increase through added transpiration, and conversely, pore-water pressure can increase by directed flow into the soil from stemflow (Simon and Collison, 2002). Larger species can increase the normal force through added surcharge to the bank (Simon and Collison, 2002); this effect should be limited to larger trees, such as the spruce and juniper tested in this study. This study assumes that these additional effects of transpiration, stemflow, or surcharge have negligible effects on soil moisture (Abernethy and Rutherfurd, 1998). Although this study examined vegetation effects on bank failure by static forces, vegetation can also induce changes in hydraulic conditions by affecting surface roughness or concentrating flows and thus shear stresses (e.g., Thorne, 1990; Liu et al., 2010; Zong and Nepf, 2010). Vegetation causes near bank flows to decrease in velocity and thus lowers boundary shear stress; however, the unique effects of different types of vegetation are complicated because of the tendency of some vegetation types to remain stiff and others to flex, which can create an even smoother surface (Thorne, 1990; Hopkinson and Wynn, 2009). Of the species sampled in this study, the graminoids and herbs are most likely to flex and allow high velocities to persist near the banks, as opposed to the shrubs and trees, which are stiffer, and are likely to reduce velocities. Vegetative effects on hydraulics can alter fluvial entrainment of the streambank, which can indirectly accelerate bank stability, but should not directly affect bank failure occurrences.

5.4 Bank and Vegetation Synthesis

5.4.1 Comparison with USFS Classification

The Winward (2000) bank stability classification of species is widely used throughout the USFS, but is not supported by quantifiable root characteristic data that explain how each species contributes to a more cohesive streambank. This study provides root characteristics for a wide range of species and examines how these characteristics tie to the bank stability. By comparing results from this study to the ranking proposed by Winward (2000), the factual basis of Winward's classification can be assessed. Rankings exist in the USFS classification for ten out of the fourteen species sampled and studied in this chapter, and for two of the species that are not ranked (*S. monticola* and *J. drummondii*) there are rankings for other species in the same genus. The average rankings range from 5.8 (*B. occidentalis*) to 9.4 (*C. aquatilis*) (Table 17). Simply from these two endpoint species, it is evident that this ranking does not agree with morphologic data. From the physical root traits and modeling results, *B. occidentalis* consistently has among the highest values of root trait and factor of safety values. And although *C. aquatilis* has a strikingly extensive root system in a rhizomatous network, the combined root traits position this species in a medium range of added bank stability.

Although the Winward (2000) classification is not rooted in quantifiable metrics, it is likely based on some valid observations. Several explanations could account for the difference in the ranking classification by Winward (2000) and the data presented here. First, because the ranking system was based on field observations, sorting vegetation as a cause of bank stability/instability from vegetation growth as an effect of bank type would be problematic. For example, *J. arcticus*, which has a ranking of 9 but very low root trait values in this study, may grow densely along steep, low to high-angled banks, yet have a small effect on long-term bank stabilization. It is necessary to study mechanisms and causes of failure to ensure that species designated as those able to stabilize streambanks are actually the source rather than a reflection of bank type. Second, the ranking classification incorporates species assemblages and may actually incorporate interactions between species' roots or added cohesion from several species with an increased total root density.

Table 17. Winward's stability class rankings of species analyzed in this study.

Latin name	**Vegetation type**	**Winward Stability Class**	**Community type species[1]**	**Latin name**	**Vegetation type**	**Winward Stability Class**	**Community type species**
A. incana	Tree	6	Bench	*S. exigua*	Shrub	6	Barren
		8	*Cornus sericea*			5	Bench
		7	*Equisetum arvense*			7	*Equisetum arvense*
		6-8	Mesic Forb			7-8	Mesic Forb
		6-8	Mesic Graminoid			7-10	Mesic Graminoid
		7	*Ribes hudsonium*			6	*Poa pratensis*
		7	**Average**			8	*Rosa woodsii*
B. occidentalis	Tree	6	Bench			**6.9**	**Average**
		8	*Cornus sericea*	*S. geyeriana*	Shrub	10	*Carex aquatilis*
		7	*Equisetum*			9	*Calamagrostis canadensis*
		6-8	Mesic Forb			10	*Carex utriculata*
		6-8	Mesic Graminoid			7	*Deschampsia cespitosa*
		5.8	**Average**			7-8	Mesic Forb
P. engelmannii	Tree	8	*Cornus stolonifera*			7-10	Mesic Graminoid
		9	*Betula glandulosa*			6	*Poa palustris*
		7	*Equisetum arvense*			6	*Poa pratensis*
		6	*Galium triflorum*			**8**	**Average**
		7.5	**Average**	*S. monticola*	Shrub	**na**	
J. virginiana	Tree	**na**		*C. leptosepala*	Herbaceous	**6**	
C. aquatilis	Graminoid	9		*E. arvense*	Herbaceous	5	
		10	*Salix planifolia*			7	Conifer
		10	*Salix wolfii*			7	*Picea* spp.
		10	*Salix boothii*			8	*Acer negundo*
		10	*Salix geyeriana*			7	*Alnus incana*
		10	*Salix lemmonii*			7	*Salix boothii*
		7	*Betula occidentalis*			7	*Salix exigua*
		9.4	**Average**			**6.9**	**Average**
J. arcticus	Graminoid	**9**		*E. hyemale*	Herbaceous	**7**	
J. drummondii	Graminoid	**na**		*S. odontoloma*	Herbaceous	**na**	

1: Species assemblage, for which bank stability class was assigned, together with primary species.

5.4.2 Bank and Vegetation Integration

Bank stratigraphy and geometry have the largest impact on bank stability; however, vegetation differences are also significant within the bank variability. Additionally, banks without added cohesion from roots were consistently the least stable. Interactions between roots and sediment textures are likely important but were not incorporated here. For example, root densities tend to be lower in highly cohesive sediment (Dunaway et al., 1994). By following the order of importance of various bank characteristics and vegetation types, the degree of overall bank stability can be determined. Five characteristics contribute varying amounts to the overall stability of a streambank. In declining order of importance, these are: 1) presence or absence of cohesive material in the streambank, 2) bank height, 3) degree of sediment cohesiveness, 4) vegetation type based on functional classification, and 5) depth of water table (Figure 49). The relative order of importance of these five bank traits will likely vary by region, because of greater or lesser variability in bank material, geometry, or pore-pressure. The levels may also be re-ordered if a lower level characteristic overwhelms the rest of the system. If the cohesiveness of the sediment is extremely high (only silt and clay, for example), then even a very high bank will retain stability. High pore-water pressures for long periods of time may cause the increased cohesion from vegetation to have negligible importance. These hypotheses should, however, be tested in future studies.

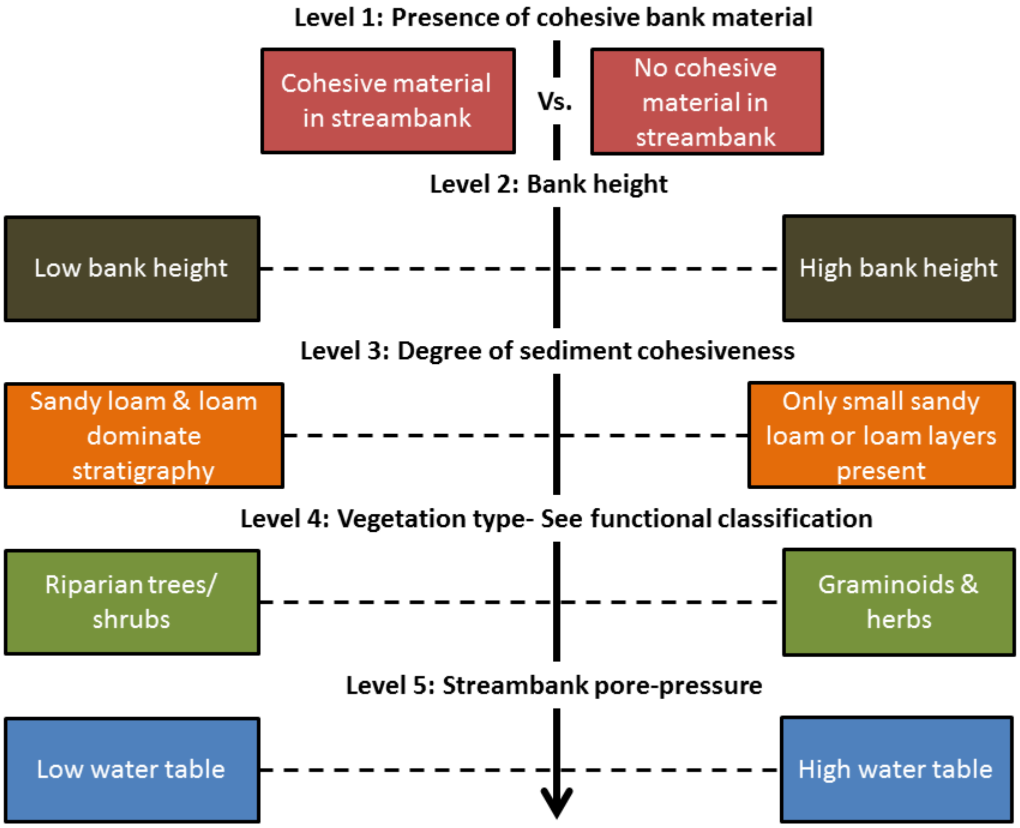

Figure 49. Order of importance of physical bank traits, vegetation type, and bank hydrology in determining overall bank stability. Characteristics that fall on the left of each dichotomy or continuum will contribute to higher bank stability values.

This ranking of physical, hydrologic, and vegetative streambank characteristics are generally consistent with field observations of bank failure. Incidences of bank failure were not directly observed, but I did observe bank slumping and vertical slab separation from the streambank. Because the timing of bank failure was not directly observed, I cannot comment on the importance of streambank pore-water pressure in stabilizing streambanks. Vertical slab separation was observed on higher than lower streambanks, supporting the importance of bank height as a second level determinate of bank stability. A common stratigraphy along streambanks is composed of cohesive sediment overlaying non-cohesive sediment layers. In these cases, undercutting was observed from hydraulic action, but not necessarily increased bank failure. Vegetation differences were most pronounced for riparian and upland trees, where the bank would appear slightly scalloped between trees, indicating localized erosion or bank failure between trees. Bank slumping and failure was also more prevalent between willows where they were common but spaced along the streambank. In Corral Creek, bank failure or slab separation was observed between *S. geyeriana* specimens, where only *C. aquatilis* were present.

5.4.3 Further Bank and Vegetation Classification Applications

The motivation of this study was to provide land managers with guidance for choosing vegetation for bank stabilization measures. Understanding the mechanics of bank erosion will also contribute to a long-term model of channel evolution or planform change. At the simplest level, rates of channel migration are a function of bank stability over an entire reach. Because reaches are seldom composed of only one or even a few species, species assemblages and relative species distributions would be necessary to provide a broader view of the bank processes. The transition from braided to meandering channels, and vice versa, is facilitated by the addition of any or certain types of vegetation. Temporally or spatially extensive observations or experiments can, by definition, take long periods of time or require intensive field measurements. Instead, these bank stability data can assist in development of conceptual or numerical models of stream planform change. Models of bank stability incorporating the interplay between bank types and vegetation may even shed light on hydraulic geometry equations. There have been debates in the literature on the effect of forests versus grasslands on channel width (Hey and Thorne, 1986; Davies-Colley, 1997; McBride et al., 2010), and several factors likely determine the role of vegetation in determining channel width, including drainage area, sediment texture, presence of instream wood, root density, and rooting depth (Anderson et al., 2004). Trees versus graminoid/herbaceous species should have varying effects on bank stability and thus width depending on bank geometry and texture (Dunaway et al., 1994).

5.5. Willows and Stream Restoration

Willows (*Salix* spp.) have a reputation as a successful bank stabilizer and are thus commonly used as an easily accessible tool for the public to participate in stream restoration. Few studies until now have quantified the role of willows in stabilizing streambanks. Native willows (*S. nigra* in these studies) are one of the best species in stabilizing streambanks, but are also sensitive to erosional hydraulic forces and high mortality (as high as 60%) in the first years after planting (Shields et al., 1995; Watson et al., 1997; Pezeshki and Shields, 2006). In addition, regardless of restoration efforts, the hydrologic regime and geomorphic processes may supersede any bank stability measures, as was the case on Little Topashaw Creek in northern Mississippi (Shields et al., 2008). This restoration failure shows again how hydrology is the main driver in bank stability and that banks cannot be stable with an unstable bed (Thorne, 1982; 1990). However, given a stable hydrologic regime and unimpeded removal of bank toe material, the question remains: are willows effective bank stabilization agents for stream restoration?

Three willow species were examined in this study, which reflect different species assemblages over elevation differences in the Colorado Front Range. Tensile strengths of willows fall in the intermediate range compared to the other species sampled. Root densities also fall in average levels, except for *S. geyeriana*, which had more large roots than any other species. These factors combine to determine added cohesion by each species. *S. geyeriana* has very high added cohesion values because of its large roots, but *S. exigua* and *S. monticola* add very low amounts of cohesion over a very small range. Given these results, willows do not seem to live up to their bank stabilizing reputation. However, when examining several root characteristics (maximum root diameter, lateral root extent, and tensile strength coefficient), shrubs such as willows have significantly or at least somewhat higher values than graminoids and herbs. The relatively low rooting depths of the willows further dampen factor of safety values. The willows do not have significantly different factor of safety values from trees, but do add more stability than having no vegetation (unlike graminoids and herbs). It seems that some riparian trees would provide as much if not more stability than willows. Nonetheless, willows are still the preferred bank stabilizer. Although not directly modeled, the rhizome network of willows and fast growth rate favor willows over riparian trees for bank stabilization efforts. The rhizomes can connect willows extending tens of meters away from the bank and downstream along the bank, as observed in Corral Creek valley.

6. Conclusions

6.1 Hypotheses Summary

Determination of bank stability in headwater low-gradient streams in the Colorado Front Range is a function of interactions between bank characteristics and vegetation root characteristics, which can be divided into vegetation groups (trees, shrubs, graminoids, species). In terms of bank stability modeling results, I found that physical bank characteristics, in particular the sediment texture and bank height, determine overall bank stability, and secondly vegetation root characteristics play a role in stabilizing streambanks. Bank geometry and texture have greater effects on bank stability than soil moisture, as defined by the water table level, or confining pressure, determined by the water surface elevation. Five characteristics of bank properties and vegetation type determine the overall stability of a streambank in order: 1) presence or absence of cohesive bank material, 2) bank height, 3) degree of sediment cohesiveness (if cohesive sediment is present), 4) cohesiveness provided by vegetation, and 5) streambank pore-pressure. Extremely high values in a lower level (e.g., pore-pressure) may overwhelm added cohesion from a higher value (e.g., vegetation type).

The model results support the hypothesis that physical bank characteristics have a greater control on bank stability than vegetation type or characteristics. However, the modeling efforts were in essence a sensitivity analysis of the input conditions, and the model did not account for interactions between bank and vegetation characteristics. A functional vegetation classification based on root traits remains valid for distinguishing between vegetation types at a single bank or type of bank. Because of the field- and time-intensive nature of collecting root morphology data, the functional classification presented here is based on only 14 species. This classification provides a template for further studies to develop and test in other regions, including other headwater streams and those with quite different bank geometry, stratigraphy, and texture.

Classification of the cohesiveness provided by vegetation contains three root characteristics: tensile strength curve coefficient, maximum root diameter, and lateral root extent. Three stability classes for species are defined based on where species plot in relation to the three traits mentioned above. These three classes are also divided based on the whether the species is rhizomatous or not. Although the effect of this trait on bank stability was not directly tested, whether or not a species has rhizomes adds a reach-scale dimension to evaluate vegetation's effect on bank stability. Shrubs, which only included willows in this study, are in the high stability class and have rhizomes, and riparian trees are also in the high stability class but without rhizomes. In the medium stability class are graminoids with rhizomes and upland trees without rhizomes. Finally, herbaceous species are found in the medium/low stability class with and without rhizomes.

6.2 Valley and Watershed Implications

I focus on the role of vegetation to stabilize streambanks in low-gradient (<2%) headwater streams. Floodplain evolution, in terms of channel migration, planform development or change, and possible floodplain storage, is directed by the balance of flow conditions and sediment availability. Sediment inputs can originate upstream of the reach, from within the reach, or from colluvial contributions. Given how disconnected many low-gradient streams are from their hillslopes, colluvial input is minimal. Upstream inputs of sediment may have episodic pulses from debris flows or outburst floods in steeper colluvium-dominated reaches. Without a significant climatic change, large changes in background sediment input rates are unlikely and thus the supply and transport of sediment from within the reach is most likely to cause changes in floodplain form and evolution.

Hydrology remains the controlling factor for whether streambanks within a reach are stable or likely to fail (Thorne, 1982). However, if the flow conditions allow for unimpeded removal of sediment from bank failures, then the measure of the volume of sediment provided for reworking the channel and floodplain hinges on the amount of sediment delivered by bank failures. Thus in a reach with a greater number of bank failures, more sediment is available to the reach that may alter the channel planform. With high bank erodibility leading to high sediment supplies, a braided channel form develops (Schumm, 1977; Knighton and Nanson, 1993). If cohesive sediment is a component of streambanks, steeper banks may be retained and an anastomosing or multi-thread system may form rather than a braided planform. Changes in vegetation with climate changes through the Holocene may have caused channel planform changes. During drier periods, upland vegetation, which is commonly non-rhizomatous and non-riparian trees or herbaceous vegetation, may encroach onto the channel's edge. These upland species will contribute less to bank stability than riparian shrubs or trees and can contribute to the formation of a braided or anastomosing channel network.

Within the longitudinal channel network, the role of vegetation in stabilizing streambanks will vary with downstream changes in channel geometry, and in particular bank height (Leopold and Maddock, 1953; Abernethy and Rutherfurd, 1998). Headwater reaches with low banks (up to 1.5 m) are subject to subaerial preparation and fluvial entrainment processes and generally not mass failure processes (Abernethy and Rutherfurd, 1998). Because most species will not have roots deep enough to penetrate an entire bank that may extend over 10 m in high-order stream channels, the ratio of root depth to bank height likely plays a larger role in low-order channels. Within these reaches with relatively low bank heights, the difference between tree roots that can extend the entire depth of the bank and herbaceous species that only reach depths of <0.5 m is comparatively greater than in reaches with high bank heights.

6.3 Management Recommendations

Determining which riparian species contribute most to bank stability is a major responsibility of riparian managers. Stream restoration projects are commonly centered on the goal of stabilizing streambanks (Bernhardt et al., 2005). Paradigms surrounding stream restoration endorse the use of willow plantings for reinforcing streambanks (e.g., Shields et al., 1995; Watson et al., 1997; Shields and Knight, 2003); however, the function of willows in reinforcing streambanks has not been tested quantitatively. The USFS relies on a subjective ranking system developed by Winward (2000), which has two main flaws: 1) it is not based on any quantitative measures of root traits or added bank cohesion, and 2) it assumes that bank stability is wholly a function of vegetation and not of streambank textural or hydrologic characteristics.

Currently, there is demand for understanding vegetation’s role in stabilizing streambanks, but insufficient tools are available for classifying vegetation’s stabilizing ability. Through this study, I provide guidelines for understanding the order of importance of bank and vegetation characteristics. Bank texture and height plays a significantly larger role than vegetation type in determining whether a bank will fail or the relative stability of a bank. Given these findings, managers may find severely erroneous results using a solely vegetation-based bank stability ranking system. If there is one bank is question, then the vegetation functional classification should be a useful tool in determining the relative importance of various vegetation types or species in stabilizing streambanks. However, in reach- or watershed-scale restoration or management efforts, the difference in streambank type needs to be taken into account before differences in vegetation type.

The functional classification provides a solid tool for managers in the Colorado Front Range for a range of species. For regions with different species assemblages or outside of the Colorado Front Range, this study offers a framework for determining the position of other species in the functional classification based on their root trait data. When considering the stability of streambanks along a reach length, whether or not a species is rhizomatous will be an important factor. The importance of rhizomes decreases over progressively deeper sections of the bank and first increases over progressively from a thin vertical slice of the streambank then decreases past reach-length sections of bank.

The ranking system of vegetation for bank stability developed by Winward (2000) gave managers a simple method for understanding vegetation's addition to bank stability. Comparisons between species are straight forward: one can easily decide which species should be planted to increase or decrease bank stability, and examination of a species along streambanks throughout a reach or basin can determine overall stream health. The results from the study presented here have shed light on the complexity of interactions between bank characteristics and root traits that contribute to bank stability; therefore, I do not recommend the use of Winward's (2000) ranking system. Nevertheless, I still provide a relatively simple guideline and functional classification for managers to use, which recognizes the interactions and complexities between bank properties and vegetation roots.

Stream restoration projects often involve bank stability efforts (Bernhardt et al., 2005); however, bank stabilization efforts should not be carried out under the guise of stream restoration. Bank erosion is often a desirable attribute of streams in, for example, dynamic braided and meandering systems, and can contribute to a healthy patchwork for aquatic organisms (Florsheim et al., 2008). Therefore, bank stabilization should only be considered in stream restoration projects when bank erosion has exceeded normative levels for a system in dynamic equilibrium.

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CHAPTER 4: SYNTHESIS OF BIOTIC INFLUENCES ON FLOODPLAIN EVOLUTION

1. Summary of Conclusions

The direction and magnitude of two biotic influences on floodplain processes were examined at various spatial and temporal scales in low-gradient, headwater valleys in the Colorado Front Range. Direct interactions and feedbacks were documented between biologic and physical processes. Impacts of beaver activities on floodplain geometry and composition were measured at the scale of the entire valley; alterations in channel complexity were observed over decades and sediment aggradation was measured over centuries to thousands of years. Vegetation influences on bank stability were quantified over a single streambank profile and over the time scale of a single flow event. Although not directly measured, I expect these two biotic influences to interact and show evidence in the geomorphic landscape.

Floodplain processes altered by beaver affect sedimentation magnitude and channel complexity. I found support for the beaver-meadow complex hypothesis, because sediment associated with beaver dams and ponds accounted for a significant portion (30-50%) of the thin alluvium overlaying glacial till or outwash. Sedimentation rates were temporally and spatially heterogeneous, with higher rates associated with beaver pond sedimentation and background rates consisting of overbank flooding, abandoned channel in-filling, and channel migration. Fluvial complexity, in terms of multi-thread channels, islands, and channel bifurcations, magnifies with an increased beaver population and a greater number of beaver ponds. With a multi-thread channel system, the potential channel length that can be dammed increases, which accelerates the degree of fluvial complexity, or at least maintains the degree of fluvial complexity allowed by valley geometry and sediment and water flow regimes. These biotic-physical interactions show biomorphodynamic feedbacks and two-way coupling in terms of positive feedbacks of beaver dams creating more opportunities for sedimentation.

Although biomorphodynamic processes likely occur between vegetation roots and streambanks, this study focused on the effects of roots on streambanks. Streambank characteristics have a stronger impact on bank stability and the occurrence of bank failure than root characteristics. However, within similar streambanks, vegetation type is a strong predictor of overall streambank stability. The presence of rhizomes, the maximum root diameter or the tensile strength, and the lateral root extent of each species are the most important root characteristics in determining streambank stability. Riparian shrubs (willows) and riparian trees are the best streambank stabilizers. Upland trees and graminoids are mid-level bank stabilizers, and herbaceous species are mid/low-level bank stabilizers. No feedbacks were directly measured between bank-stabilizing vegetation and streambank geometry or failure processes; however, I did determine various magnitudes of importance between vegetation type and streambank characteristics. Feedbacks between biotic and geomorphic processes will occur when timescales of processes are of similar magnitudes. Additionally, the relative effects of each process determine which process will dominate the floodplain processes, whether there will be enhancing feedbacks, or whether one process will dampen the effects of the other.

2. Biotic Controls on Channel Planform

Classification of channel planform has undergone an evolution since Leopold and Wolman's (1957) division between straight, meandering, and braided patterns. Schumm (1977) classified channel patterns based on the type of sediment load and relative stability, and he later introduced fourteen patterns, incorporating the caliber of sediment load and size, relative stability, degree of sinuosity, and multiple flow patterns (Schumm, 1981, 1985). Considering only multi-thread channels, these show a larger range of forms and processes than the braided channel classification introduced by Leopold and Wolman (1957). Traditionally, braided channels are viewed as a product of several conditions (Knighton, 1998): abundant bed load, erodible banks, highly variable discharge, and steep valley slopes. An addition to the cohesion of the streambanks in braided channels, by adding stabilizing vegetation, has been shown to form meandering channels (Murray and Paola, 2003; Tal and Paola, 2007, 2010). In addition to braided channels, multi-thread channels may also consist of anabranching channels, which are 'a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull' (Nanson and Knighton, 1996, p. 218). Six types of anabranching channels were identified by Nanson and Knighton (1996), which are classified in terms of sediment type, lateral mobility, and forms that develop (Table 18). Wandering channels are similar to Type 5 and 6 anabranching channels, in that they have irregularly sinuous channels that split around islands and are sometimes braided (Desloges and Church, 1989).

Table 18. Classification of anabranching channel types according to Nanson and Knighton (1996).

Type	Type of anabranching channel	Characteristics
1	Anastomosing	Cohesive sediment; low gradients & stream powers; low width-depth ratios
2	Sand-dominated, island-forming	Less cohesive bank sediment but require stabilizing vegetation
3	Mixed-load, laterally active	Similar to organo-clastic anastomosing channels but more laterally active
4	Sand-dominated, ridge-forming	Ridges from by stabilizing effects of trees; only observed in arid Australia
5	Gravel-dominated, laterally active	Also referred to as 'wandering'; transitional between meandering and braided; anabranches develop from avulsion channels onto floodplain
6	Gravel- dominated, stable	Similar to Type 5; usually exhibit well-vegetated gravel or boulder islands, with formation usually caused by log jams and sediment accumulation

Multi-thread channels caused by beaver dams and avulsions, as observed through historical aerial photographs in Moraine Park, have not been previously described in any classification of multi-thread channels. Nanson and Knighton (1996) identify two main factors involved with anabranching channels: resistant banks and flow displacement. Resistant banks can form through cohesive sediment or the presence of stabilizing bank vegetation. Flow displacement can be caused by numerous factors, including channel sedimentation, vegetation or ice jams, and ineffective flow or ponding. Log jams have been identified as causing anabranching channels in snowmelt regions of North America (Hickin, 1984; Collins and Montgomery, 2002; Wohl, 2011). Beaver dams are analogous to log jams and will also create ineffective flow patterns, but have not as yet been recognized in geomorphic channel classifications as a cause for anabranching channel patterns, although beaver activity has been tied to channel avulsions (John and Klein, 2004; Burchsted et al., 2010).

Bank stabilizing riparian vegetation and the presence of beaver dams combine to form a unique channel planform in unconfined, low-gradient headwater valleys. The effect of vegetation on stabilizing streambanks has been thoroughly documented, and work presented in this dissertation has determined the relative effects of various vegetation types versus the physical characteristics of the streambanks. Although data are not available on the type of riparian vegetation present throughout the Holocene, we can imagine that drier periods would discourage the growth of riparian shrubs and graminoids that prefer wetter environments. Instead, upland trees and some herbaceous species would dominate, which are poorer bank stabilizers. As discussed in Section 2 in Chapter 2, the Colorado Front Range experienced several warmer and drier periods during the Holocene. In particular, post-glacial warming started 10 ka and lasted ~1000 years (Elias, 1996), and the warmer, drier Altithermal lasted from ~6500-3500 ka (Benedict, 1979; Short, 1985; Elias, 1986; Elias, 1996; Benedict et al., 2008). The drier conditions would probably inhibit riparian vegetation growth, and in turn decrease or altogether diminish beaver populations. No evidence of beaver-ponded sediment older than ~4500 y B.P. was observed in the study area; however, it is unclear whether this reflects a lack of beaver before this time or simply that I did not access older sediment. Beaver may have sustained a healthy population in valley bottoms during periods of climate change, without the presence of other disturbances, through the maintenance of locally raised water tables (Westbrook et al., 2006; Hood and Bayley, 2008). Using inferences of changes in riparian vegetation, and its effects on bank stability, and conclusions regarding Holocene beaver populations and effects on sedimentation and planform, I present the range of potential channel planform across these unconfined, low-gradient valleys throughout the Holocene.

The presence of beaver dams, bank stabilizing vegetation, and hydrology interact to determine overall bank stability and the relative amount of sediment storage or transport out of the valley (Figure 50). Channel gradients reduced by beaver dams affect the local stream power, which traps fine sediment and reduces sediment erosion and transport. Greater amounts of fine sediment are trapped within the channel and on the floodplain. Sediment, especially fine sands, silt, and clay, is trapped in ponds, and alterations in flow dynamics in ponds increase the likelihood of overbank flows, which allows sediment to be trapped in the hydraulically rough floodplain surface. The multiple flow paths encouraged by beaver dams result in lower flow velocities and more sediment accumulation than would occur under the same flow regime without beaver dams (Woo and Waddington, 1990; Figure 51).

This fine sediment provides the raw material available in the floodplain for streambanks to be built from after subsequent channel migration or channel incision after avulsions. The lower stream power not only facilitates sediment accumulation, but limits the removal of sediment from bank toes after bank failure, of which occurrences are also reduced after streambanks have been built by cohesive sediment from beaver ponds. Without beaver dams, and the accompanying lower channel gradient and fine sediment that would be trapped in ponds, processes leading towards increased sediment transport are enhanced.

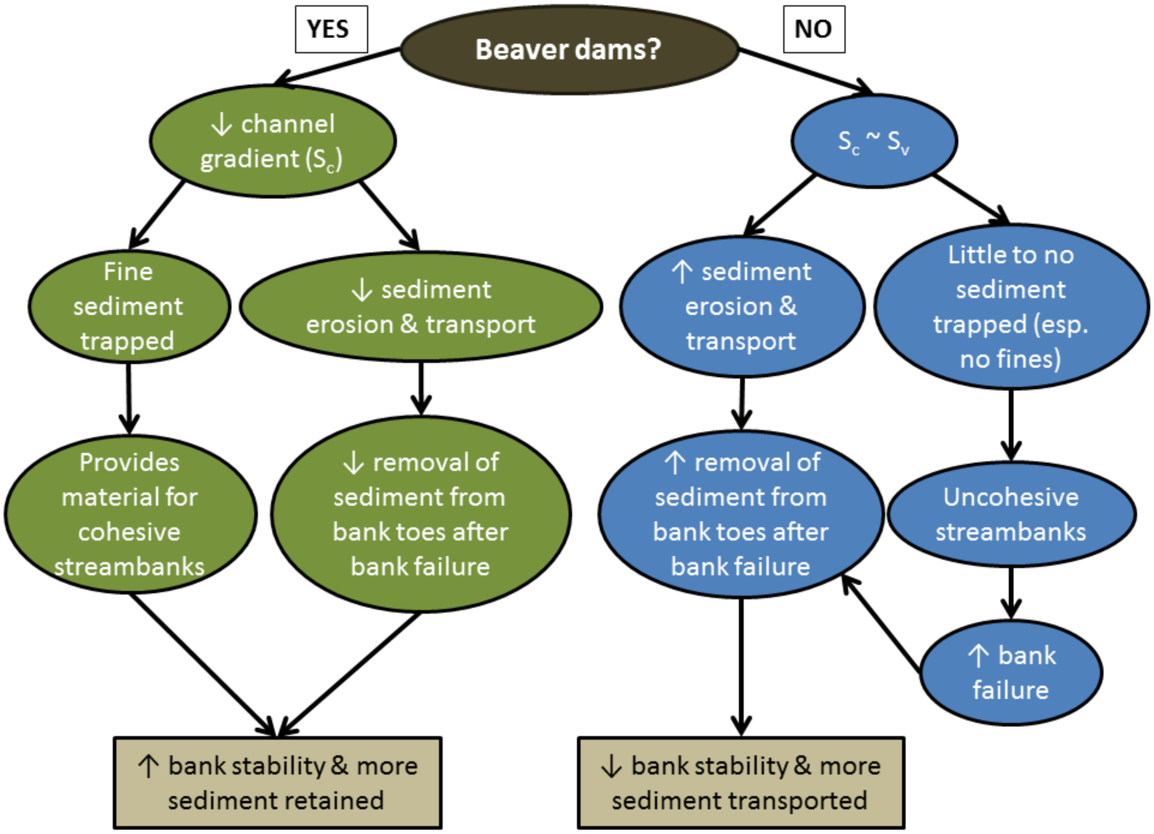

Figure 50. Flow diagram illustrating long-term effects of the presence or absence of beaver dams on bank stability and whether sediment is retained or transported out of the system. With beaver dams, the local channel gradient decreases, causing fine sediment to be trapped, and a decrease in stream power reduces the magnitude of sediment erosion and transport. Beaver dams encourage deposition of fine sediment not only in dams, but there is also enhanced floodplain storage because of increased overbank flows and hydraulically rough vegetated floodplains. The fine sediment creates cohesive streambanks after the channel has migrated into the aggraded pond sediment; cohesive streambanks reduce the likelihood of bank failures providing sediment to the bank toe, and the lower stream power reduces removal of sediment from bank toes after bank failure. Without beaver dams, stream power varies approximately with the valley gradient (S_v); little to no sediment is trapped, especially no fine sediment. Fine sediment is not available to build cohesive streambanks, leading to more bank failures and stream power is higher, so bank toe sediment is removed quickly.

Figure 51. Start of anastomosing approaching beaver dam, showing shallow overbank flow in vegetated, hydraulically rough floodplain. Shrubs are ~2-3 m tall; arrow indicates general flow direction. Photo courtesy of Ellen Wohl, Glacier Creek, RMNP.

Through the addition of vegetation and beaver dam effects, we can build on the channel classifications introduced by Schumm (1977) and Church (1992). Assuming relatively stable conditions of a headwater channel system with a snowmelt-dominated flow regime and a gravel-bed channel system, long-term planform changes should occur under various vegetation and beaver population scenarios. The abundance and type of streambank vegetation will affect the short-term bank stability conditions, in addition to the potential for a sustainable beaver population. The overall, long-term beaver population influences the relative amount of fine sediment available in the floodplain (Figure 50) and the probability of avulsions and formation of a multi-thread channel system. Four planform regimes are identified in Figure 52. Without beaver dams and with sparse or only xeric streambank vegetation, a braided channel system will develop. This was likely the prevalent planform during the post-glacial warming when abundant glacial sediment was available for the channel to work through (Table 19).

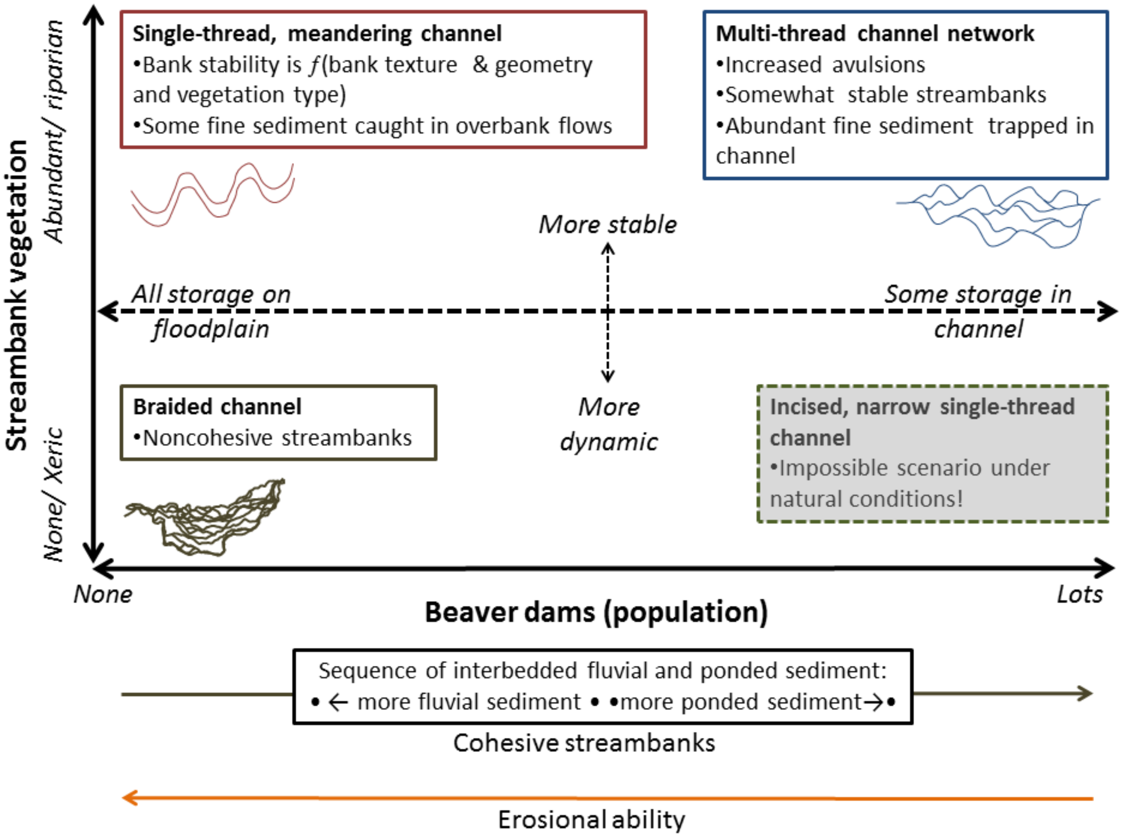

Figure 52. Conceptual diagram of probable long-term planform regimes in low-gradient, unconfined headwater valleys of the Colorado Rocky Mountains based on beaver populations and types of streambank vegetation.

Table 19. Inferred channel planform regime in unconfined, low-gradient headwater valleys based on Holocene conditions in the Colorado Front Range. Direct interpretations are not possible prior to 5000 y B.P.; therefore, several planform regime possibilities are given for this time period. For periods of time where no climate range is given, climate conditions are assumed to be comparable to modern conditions.

Timeline	**Holocene conditions**			**Probable channel planform regime**[1]			
Years B.P.	*Climate*	*Likely vegetation type*	*Beaver population*	*Braided*	*Single-thread meandering*	*Sinuous multi-thread*	*Incised single-thread*
10000	Post-glacial warming	Sparse	Unknown; but likely established after braided channel was colonized by vegetation in early Holocene	●	↑		
9000				↓	│	↑	
8000		Abundant/ riparian			│	│	
7000					│	│	
6000	Altithermal: warmer & drier	Sparse/ xeric in upland; beaver possibly maintained wetland vegetation			│	│	
5000					↓	│	
4000		Abundant/ riparian	Abundant			│	
3000						│	
2000						│	
1000						│	
800-1000						│	
600-800						│	
400-600						│	
200-400	Little Ice Age	Possible riparian decrease	Sharp decline			│	
0 0-200		Abundant/ riparian	Slight rebound followed by decrease after 1960			●	● ↓

1: Lines that start or end in a filled cirlce indicate well-constrained time periods; lines that start or end with an arrow represent unknown starting or ending times.

A single-thread, bed load-dominated meandering channel would likely form if beaver populations had not established, but abundant bank-stabilizing vegetation had taken root. This planform regime is expected during periods that could not sustain beaver populations but when riparian vegetation was at least supported close to the main channel. Because there was no direct evidence of beaver activity within Beaver Meadows or Moraine Park before 5000 y B.P., this planform may have persisted until the end of the Altithermal. Because stratigraphic and geochronologic data were not available for the first half of the Holocene, it is unknown whether beaver were present before or during the Altithermal. If beaver were present prior to the Altithermal, they may have mitigated the effects of climate change in the wetland valley bottoms (Hood and Bayley, 2008).

With a sustainable beaver population, which also maintains abundant riparian vegetation, a multi-thread channel network forms as a result of increased avulsions and relatively stable streambanks. Evidence of spatially heterogeneous ponded sediment extends to >4000 y B.P., suggesting that this planform regime occupied the majority of the historical range of variability (as defined in Chapter 2) in channel and floodplain dynamics. This multi-thread planform regime may have been present through the Altithermal and earlier if beaver established in the early Holocene and were able to maintain a suitable habitat in low-lying valley bottoms during the Altithermal. Given paleontological evidence of the presence of wood-cutting, semi-aquatic beaver in North America for the past 25 million years (Rybczynski, 2007), and ecological evidence of beaver's preferred habitat, which is consistent with that available in headwater streams in the Colorado Front Range (McComb et al., 1990; Gurnell, 1998; Pollock et al., 2003; Persico and Meyer, 2009), beaver most likely populated headwater valleys and especially the unconfined, low-gradient valleys in the Colorado Front Range since glacial retreat. However, beaver establishment would be difficult on a braided channel because of the dynamic nature of sediment movement and channel change. If beaver were available to colonize the study area, there was likely a transition period into a single-thread, meandering channel with the aid of riparian vegetation before beaver established and a multi-thread, meandering system could form.

The final planform regime with sparse or xeric vegetation and abundant beavers is nearly impossible under natural conditions because beaver populations cannot be sustained without riparian vegetation. The scenario of abundant riparian vegetation and few beavers is likely only a legacy effect from beaver trapping or out-competition by ungulates in many valley segments of the study area. During channel adjustment from the changed biotic conditions caused by the absence of beaver, the complex channel system is likely to revert to a single-thread channel system and excess stream power will cause incision into cohesive bank sediment, as observed in Rocky Mountain National Park. However, the trophic cascade of increased elk browsing after the removal of their main predator, wolves, can also cause the channel to revert to a more unstable braided system (Beschta and Ripple, 2008). In this case study by Beschta and Ripple (2008) in Olympic National Park, there was no documented history of beaver damming to cause the cohesive bank material.

Past channel planform classifications have focused on the interplay between sediment caliber and load, stream power, and bank stability (Schumm, 1977; Church, 1992). Through the work presented in this dissertation on the effect of beaver on floodplain aggradation and channel complexity and the role of vegetation type in stabilizing streambanks, I add a biomorphodynamic aspect to the understanding of channel planform and floodplain evolution, incorporating the interacting effects of two biotic processes. Channel planform has traditionally been viewed as a function of the flow regime, sediment supply, and substrate (e.g., Schumm, 1977). Without any biotic controls, this study area would oscillate between a braided and meandering system, according to the early classifications. Recent work has added vegetation as an important mechanism in forming meandering channels (e.g., Tal and Paola, 2007). Meandering channels have, however, been observed without vegetation in bedrock and on Mars (Leopold et al., 1964; Bhattacharya et al., 2005). The formation of stable multi-thread channels in semi-arid headwater valleys, however, requires the interaction of biotic controls. In the absence of beaver and riparian vegetation, the flow and sediment regimes in combination with substrate characteristics will determine channel and floodplain processes, which will most likely only form single-thread channels. The formation of relatively stable multi-thread channels has wide-ranging implications for geomorphic and ecologic process and form (Table 20). The physical and hydrologic processes of overbank flows, avulsions, and channel migration affect sedimentation patterns and riparian zone width and vegetation type, which influences the bank stability. Because bank stability influences channel migration rates, this is not a completely linear chain of events. The feedbacks and thresholds involved in these interactions among biota and channel processes in determining overall channel planform reflect a dynamic, non-linear system

Table 20. Comparison of in-channel and floodplain physical and ecological parameters for meandering, single-thread channels versus stable multi-thread channels with beaver dams and riparian vegetation. These effects focus on headwater valleys with a snowmelt-dominated flow regime.

Parameter	Meandering, single-thread channel	Stable multi-thread channel with beaver dams and riparian vegetation
Overbank flows	•Occurs less often and to lesser degree	•Occurs more often, for longer duration, and larger magnitude
Avulsions	•Rare occurrence •Secondary avulsions may occur during extreme overbank flows	•Main mechanism for channel change •Primary and secondary avulsions occur with new dam construction and during overbank flows
Channel migration	•Main mechanism for channel change •Less cohesive sediment and less stabilizing vegetation create dynamic environment	•Secondary mechanism for channel change •Occurs at similar rate as single-thread channel
Sedimentation	•Most to all sedimentation is on floodplain during overbank flows or in-channel sedimentation preserved after channel migration •Long-term rates are constant •High transport rates out of reach	•More sedimentation in channel deposited behind beaver dams •Increase in fine sediment deposited in floodplain as a result of more frequent overbank flows •Sedimentation is spatially and temporally heterogeneous
Disturbance type	•Higher energy flows through channel and during overbank flows	•Lower energy flows but overbank flows affect larger area and saturate ground
Riparian zone width	•Along narrow corridor parallel to channel	•Riparian zone extends across valley, past channel closest to valley edge •Higher water table across valley supports riparian vegetation
Vegetation type	•Xeric vegetation able to grow closer to channel because floodplain is not often occupied by overbank flows •Mix of riparian trees and shrubs in low-lying areas and upland species along streambanks	•Wetter environment promotes growth of riparian shrubs and graminoids
Bank stability	•More non-cohesive sediment •Riparian trees provide high local stability	•Fine sediment increases bank cohesion •Mix of riparian shrubs and graminoids increase bank stability

3. Management Implications

An understanding of the long-term effects of biotic manipulation of fluvial environments is vital for managing these systems and understanding the effects of human alterations. Managing streams for a sustainable beaver population and healthy associated riparian corridor is not simply a matter of maintaining a beautiful landscape, but will have long-term implications on channel planform that may be difficult to reverse. Managers commonly attempt to alter bank stability, riparian vegetation, and water table levels for beneficial results; however, the channel planform can affect all of these parameters (Table 20). Additionally, when beaver are removed from a multi-thread channel system with beaver dams, the channel may not simply revert to a single-thread meandering system but will typically incise because of increased stream power and cohesive bank sediment. With the loss of beaver, water tables lower, causing gradual drying of the valley bottom that is no longer able to support riparian vegetation and favors the growth of upland conifers. Similar to the ratcheting effect described by Tal and Paola (2007) when a braided channel is colonized by vegetation and transforms into a meandering planform, physical and ecological conditions may change into alternate stable states with or without beaver that will drive reinforcing feedbacks. With a stable beaver population past a certain threshold, the stable multi-thread channel network will propagate itself and maintain a diverse and extensive riparian zone. Removal of beaver will push the planform regime and associated ecological processes to a separate stable state. Management of the valley bottom to provide the ecological functions seen in a multi-thread system will be difficult and require multiple interventions. Process-based management should aim to determine valleys where multi-thread channel systems were located historically and use some artificial techniques to push the channel into a stable state that can support multi-thread channel processes.

4. Recommended Future Work

4.1 Holocene Conditions

In reconstructing planform regimes throughout the Holocene in broad headwater valleys, the conditions before 5000 y B.P. remain uncertain. Because I was working in a public portion of a national park, the methods I used to access subsurface sediment were limited and required to be non-invasive. I would recommend obtaining permission from RMNP to use a vibracorer or a similar instrument in a small, representative portion of Beaver Meadows or Moraine Park to date sediment at the interface between Holocene alluvium and glacial till and outwash. It should be determined whether the lack of beaver-ponded sediment >5000 y B.P. reflects a real absence of beaver in the early Holocene through the Altithermal or whether the methods used in this study simply did not allow access of this older sediment. If RMNP will not support the use of limited invasive methods, an analogous valley outside of the national park boundaries could yield similar useful results. The analog valley must have a similar disturbance regime as Beaver Meadows and Moraine Park, without steep hillslopes to ensure minimal debris flows. Determining whether beaver were present before and through the Altithermal and formed a multi-thread channel system has implications for whether beaver can maintain a wet, multi-thread, beaver meadow system during future climate change scenarios.

4.2 Bank Stability

In addition to roots of riparian vegetation, beaver dams may also contribute to bank stability. As mentioned in Chapter 2 and illustrated in Figure 14, beaver-chewed wood from abandoned beaver dams was found to act as geotechnical reinforcement to streambanks. These reinforced banks were often found at an unusually sharp meander bend. To determine the role of the packed, beaver-chewed wood in locally stabilizing the streambanks and altering channel-meander morphology, the added cohesion should be determined. The Root Puller could be used to determine the force necessary to pull out a piece of wood of a certain diameter and length; in addition to wood density, sediment texture and a packing factor would need to be incorporated, because it should take more force to remove a piece of wood that is packed between several other pieces and wood pull-out would interact with sediment size and cohesiveness. These data would allow comparison of the relative bank stabilizing effectiveness of abandoned beaver dams compared to the vegetation types evaluated in Chapter 3.

The limitations and further work necessary for the functional vegetation classification were discussed in detail in Chapter 3. Characterization of roots of additional species is required to test the validity of the functional classification for a wider range of species. In particular, additional non-willow shrubs should be included. Additional field studies can validate the functional classification and can bolster evidence gathered using bank stability modeling. An observational study of streambanks with varied stratigraphies and geometries would reveal whether unstable banks are more likely to have vegetation and physical bank characteristics with low bank stabilizing capabilities. Also, this large-scale ergodic study should determine whether physical characteristics do in fact trump any vegetation stabilizing effects. Finally, this study provided insight on streambank vegetation root characteristics in relation to physical bank characteristics in determining bank stability in the Colorado Front Range. The conclusions presented here should be applicable in other headwater regions with similar bank and vegetation characteristics, but the interplay between bank and root characteristics needs to be tested for a wider range of bank types in other regions with varied hydroclimatic regimes.

4.3 Planform Regime

The alternate stable states of single- versus multi-thread planform regimes raise additional questions in regards to interactions between biotic and physical processes to create geomorphic form and thus the template for ecologic habitat types and disturbances. First, is there a threshold beaver population, dam or pond number per valley area for the development of a multi-thread channel system? Do the threshold numbers differ for the formation of a multi-thread system as opposed to the maintenance of the system once it is formed and developed? Second, qualitative differences were proposed between a single-thread meandering channel and a complex, stable multi-thread channel system (Table 20); however, quantitative studies should determine the relative magnitude of differences in these parameters between the two planform regimes. For example, how much does the overall riparian zone area and vegetation type differ in the same valley with a single-thread meandering channel versus a complex multi-thread system?

For land managers, the most important questions regarding transitions between single- and multi-thread planform regimes pertain to how best to nudge a system into an alternate stable state. Knowledge of thresholds, as discussed above, may be an important first step in developing management plans for valleys that have transformed into drier single-thread channel systems without beaver. However, it is crucial to understand the underpinning physical and ecological requirements to maintain the system above a certain threshold. For example, beaver introduction may not succeed without the proper water table levels or elk populations. If process-based management solutions are sought, understanding the complex interplay and thresholds of biotic and physical processes for developing geomorphic and ecologic form is required.

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APPENDICES

APPENDIX A

Table 21. Parameter data used for BSTEM modeling. For each species and bank profile combination are parameter data for layer depth and thickness. Layer depths vary for between species for a single bank profile, because the rooting depth was incorporated as the bottom of one layer. Cohesion values represent sediment cohesion in addition to added cohesion from roots. Effective angle of internal friction (ϕ′) and saturated unit weight of soil (γ_s) values are based on sediment texture. Different sediment textures are represented in a change from grey to white shading, and root depth is shown by vertical line.

Bank profile	***Layer parameters***	**BSTEM Layers Cohesion & depth**																													
		A. incana					*B. occidentalis*					*J. virginiana*					*P. engelmannii*					*S. exigua*					*S. geyeriana*				
		1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
A	**Depth (m)**	0.19	0.45	0.50	0.74	0.93	0.19	0.45	0.50	0.74	0.93	0.19	0.45	0.56	0.70	0.93	0.19	0.45	0.56	0.65	0.93	0.19	0.40	0.45	0.74	0.93	0.19	0.30	0.45	0.74	0.93
	Thickness (m)	0.19	0.26	0.05	0.24	0.19	0.19	0.26	0.05	0.24	0.19	0.19	0.26	0.11	0.14	0.23	0.19	0.26	0.11	0.09	0.28	0.19	0.21	0.05	0.29	0.19	0.19	0.11	0.15	0.29	0.19
	C (kPa)	4.92	4.92	12.83	4.30	4.30	8.41	8.41	13.60	4.30	4.30	1.52	1.52	6.28	6.28	4.30	3.45	3.45	8.29	8.29	4.30	3.01	3.01	0.40	4.30	4.30	12.11	12.11	0.40	4.30	4.30
	ϕ' (°)	30.30	30.30	26.60	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60
	γ_s (kN/m^3)	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00
B	**Depth (m)**	0.20	0.39	0.50	0.70	0.97	0.20	0.39	0.50	0.70	0.97	0.20	0.39	0.58	0.70	0.97	0.20	0.39	0.65	0.70	0.97	0.20	0.40	0.58	0.78	0.97	0.20	0.30	0.58	0.78	0.97
	Thickness (m)	0.20	0.19	0.11	0.20	0.27	0.20	0.19	0.11	0.20	0.27	0.20	0.19	0.19	0.12	0.27	0.20	0.19	0.26	0.05	0.27	0.20	0.20	0.18	0.19	0.19	0.20	0.10	0.28	0.19	0.19
	C (kPa)	12.83	12.83	12.83	4.30	0.00	13.60	10.88	10.88	4.30	0.00	6.28	1.93	1.93	1.93	0.00	8.29	3.52	3.52	3.52	0.00	6.86	2.99	0.00	0.00	0.00	19.79	18.12	0.00	0.00	0.00
	ϕ' (°)	26.60	26.60	26.60	26.60	47.00	26.60	26.60	26.60	26.60	47.00	26.60	26.60	26.60	26.60	47.00	26.60	26.60	26.60	26.60	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00
	γ_s (kN/m^3)	18.00	18.00	18.00	18.00	21.00	18.00	18.00	18.00	18.00	21.00	18.00	18.00	18.00	18.00	21.00	18.00	18.00	18.00	18.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00
C	**Depth (m)**	0.20	0.41	0.50	0.82	1.02	0.20	0.41	0.50	0.82	1.02	0.20	0.41	0.61	0.70	1.02	0.20	0.41	0.65	0.82	1.02	0.20	0.40	0.61	0.82	1.02	0.20	0.30	0.61	0.82	1.02
	Thickness (m)	0.20	0.20	0.09	0.32	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.24	0.17	0.20	0.20	0.20	0.21	0.20	0.20	0.20	0.10	0.31	0.20	0.20
	C (kPa)	12.83	12.83	12.83	4.30	4.30	13.60	13.60	13.60	4.30	4.30	6.28	6.28	6.28	6.28	4.30	8.29	8.29	8.29	4.30	4.30	6.86	6.86	4.30	4.30	4.30	19.79	19.79	4.30	4.30	4.30
	ϕ' (°)	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60
	γ_s (kN/m^3)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
D	**Depth (m)**	0.19	0.39	0.50	0.78	0.97	0.19	0.39	0.50	0.78	0.97	0.19	0.39	0.58	0.70	0.97	0.19	0.39	0.58	0.65	0.97	0.19	0.40	0.58	0.78	0.97	0.19	0.30	0.58	0.78	0.97
	Thickness (m)	0.19	0.19	0.11	0.28	0.19	0.19	0.19	0.11	0.28	0.19	0.19	0.19	0.19	0.12	0.27	0.19	0.19	0.19	0.07	0.32	0.19	0.21	0.18	0.19	0.19	0.19	0.11	0.28	0.19	0.19
	C (kPa)	4.92	4.92	4.92	0.40	0.40	8.41	8.41	8.41	0.40	0.40	1.51	1.52	1.52	1.52	0.40	3.45	3.45	3.45	3.45	0.04	3.01	3.01	0.40	0.40	0.40	12.11	12.11	0.40	0.40	0.40
	ϕ' (°)	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30
	γ_s (kN/m^3)	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50
E	**Depth (m)**	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.37	0.49	0.61	0.12	0.24	0.37	0.49	0.61	0.12	0.24	0.40	0.49	0.61	0.12	0.24	0.30	0.49	0.61
	Thickness (m)	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.16	0.09	0.12	0.12	0.12	0.06	0.19	0.12
	C (kPa)	6.40	6.40	6.40	6.40	2.40	11.80	11.80	11.80	11.80	2.40	3.90	3.90	3.90	3.90	3.90	5.60	5.60	5.60	5.60	5.60	4.90	4.90	4.90	2.40	2.40	18.00	18.00	18.00	2.40	2.40
	ϕ' (°)	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50
	γ_s (kN/m^3)	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30

Table 21 (continued).

Bank profile	Layer parameters	BSTEM Layers Cohesion & depth																													
		S. monticola					*C. aquatilis*					*J. arcticus (10)*					*J. arcticus (50)*					*J. arcticus (100)*					*J. drummondii*				
		1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
A	**Depth (m)**	0.19	0.37	0.45	0.70	0.93	0.19	0.45	0.50	0.74	0.93	0.19	0.40	0.45	0.74	0.93	0.19	0.40	0.45	0.74	0.93	0.19	0.40	0.45	0.74	0.93	0.19	0.40	0.45	0.74	0.93
	Thickness (m)	0.19	0.19	0.08	0.25	0.23	0.19	0.26	0.05	0.24	0.19	0.19	0.21	0.05	0.29	0.19	0.19	0.21	0.05	0.29	0.19	0.19	0.21	0.05	0.29	0.19	0.19	0.21	0.05	0.29	0.19
	C (kPa)	3.32	3.32	3.32	7.21	4.30	1.98	1.98	8.61	4.30	4.30	0.80	0.80	0.40	4.30	4.30	1.70	1.70	0.40	4.30	4.30	4.60	4.60	0.40	4.30	4.30	8.02	8.02	0.40	4.30	4.30
	ϕ' (°)	30.30	30.30	30.30	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60
	γ_s (kN/m^3)	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00
B	**Depth (m)**	0.20	0.39	0.58	0.70	0.97	0.20	0.39	0.50	0.78	0.97	0.20	0.40	0.58	0.78	0.97	0.20	0.40	0.58	0.78	0.97	0.20	0.40	0.58	0.78	0.97	0.20	0.40	0.58	0.78	0.97
	Thickness (m)	0.20	0.19	0.19	0.12	0.27	0.20	0.19	0.11	0.28	0.19	0.20	0.20	0.18	0.19	0.19	0.20	0.20	0.18	0.19	0.19	0.20	0.20	0.18	0.19	0.19	0.20	0.20	0.18	0.19	0.19
	C (kPa)	7.21	3.40	3.40	3.40	0.00	8.61	2.74	2.74	0.00	0.00	4.71	0.46	0.00	0.00	0.00	6.40	2.45	0.00	0.00	0.00	8.41	4.81	0.00	0.00	0.00	13.50	8.73	0.00	0.00	0.00
	ϕ' (°)	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00
	γ_s (kN/m^3)	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00
C	**Depth (m)**	0.20	0.41	0.61	0.70	1.02	0.20	0.41	0.50	0.82	1.02	0.20	0.40	0.61	0.82	1.02	0.20	0.40	0.61	0.82	1.02	0.20	0.40	0.61	0.82	1.02	0.20	0.40	0.61	0.82	1.02
	Thickness (m)	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.09	0.32	0.20	0.20	0.20	0.21	0.20	0.20	0.20	0.20	0.21	0.20	0.20	0.20	0.20	0.21	0.20	0.20	0.20	0.20	0.21	0.20	0.20
	C (kPa)	7.21	7.21	7.21	7.21	4.30	8.61	8.61	8.61	4.30	4.30	4.71	4.71	4.30	4.30	4.30	6.40	6.40	4.30	4.30	4.30	8.41	8.41	4.30	4.30	4.30	13.50	13.50	4.30	4.30	4.30
	ϕ' (°)	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60
	γ_s (kN/m^3)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
D	**Depth (m)**	0.19	0.39	0.58	0.70	0.97	0.19	0.39	0.50	0.78	0.97	0.19	0.40	0.58	0.78	0.97	0.19	0.40	0.58	0.78	0.97	0.19	0.40	0.58	0.78	0.97	0.19	0.40	0.58	0.78	0.97
	Thickness (m)	0.19	0.19	0.19	0.12	0.27	0.19	0.19	0.11	0.28	0.19	0.19	0.21	0.18	0.19	0.19	0.19	0.21	0.18	0.19	0.19	0.19	0.21	0.18	0.19	0.19	0.19	0.21	0.18	0.19	0.19
	C (kPa)	3.32	3.32	3.32	3.32	0.40	1.98	1.98	1.98	0.40	0.40	0.80	0.80	0.40	0.40	0.40	1.70	1.70	0.40	0.40	0.40	4.60	4.60	0.40	0.40	0.40	8.02	8.02	0.40	0.40	0.40
	ϕ' (°)	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30
	γ_s (kN/m^3)	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50
E	**Depth (m)**	0.12	0.24	0.37	0.49	0.61	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.40	0.49	0.61	0.12	0.24	0.40	0.49	0.61	0.12	0.24	0.40	0.49	0.61	0.12	0.24	0.40	0.49	0.61
	Thickness (m)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.16	0.09	0.12	0.12	0.12	0.16	0.09	0.12	0.12	0.12	0.16	0.09	0.12	0.12	0.12	0.16	0.09	0.12
	C (kPa)	5.30	5.30	5.30	5.30	5.30	4.70	4.70	4.70	4.70	2.40	2.70	2.70	2.70	2.40	2.40	4.10	4.10	4.10	4.10	2.40	5.70	5.70	5.70	5.70	2.40	8.30	8.30	8.30	8.30	2.40
	ϕ' (°)	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50
	γ_s (kN/m^3)	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30

Table 21 (continued).

Bank profile	Layer parameters	BSTEM Layers Cohesion & depth																													
		C. leptosepala					*S. ondontoloma*					*E. hyemale (10)*					*E. hyemale (50)*					*E. hyemale (100)*					*E. arvense (10)*				
		1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
A	**Depth (m)**	0.19	0.30	0.45	0.74	0.93	0.19	0.40	0.45	0.74	0.93	0.19	0.45	0.50	0.74	0.93	0.19	0.45	0.50	0.74	0.93	0.19	0.45	0.50	0.74	0.93	0.19	0.30	0.45	0.74	0.93
	Thickness (m)	0.19	0.11	0.15	0.29	0.19	0.19	0.21	0.05	0.29	0.19	0.19	0.26	0.05	0.24	0.19	0.19	0.26	0.05	0.24	0.19	0.19	0.26	0.05	0.24	0.19	0.19	0.11	0.15	0.29	0.19
	C (kPa)	0.86	0.86	0.40	4.30	4.30	2.63	2.63	0.40	4.30	4.30	0.81	0.81	4.71	4.30	4.30	2.04	2.04	5.90	4.30	4.30	3.69	3.69	7.52	4.30	4.30	0.85	0.85	0.40	4.30	4.30
	ϕ' (°)	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	26.60	26.60	26.60	30.30	30.30	30.30	26.60	26.60
	γ_s (kN/m^3)	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.00	18.00	18.00	18.50	18.50	18.50	18.00	18.00
B	**Depth (m)**	0.20	0.30	0.58	0.78	0.97	0.20	0.40	0.58	0.78	0.97	0.20	0.39	0.50	0.78	0.97	0.20	0.39	0.50	0.78	0.97	0.20	0.39	0.50	0.78	0.97	0.20	0.30	0.58	0.78	0.97
	Thickness (m)	0.20	0.10	0.28	0.19	0.19	0.20	0.20	0.18	0.19	0.19	0.20	0.19	0.11	0.28	0.19	0.20	0.19	0.11	0.28	0.19	0.20	0.19	0.11	0.28	0.19	0.20	0.10	0.28	0.19	0.19
	C (kPa)	4.90	0.52	0.00	0.00	0.00	6.65	2.55	0.00	0.00	0.00	4.71	0.47	0.47	0.00	0.00	5.90	1.88	1.88	0.00	0.00	7.52	3.77	3.77	0.00	0.00	4.74	0.51	0.00	0.00	0.00
	ϕ' (°)	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00
	γ_s (kN/m^3)	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00
C	**Depth (m)**	0.20	0.30	0.61	0.82	1.02	0.20	0.40	0.61	0.82	1.02	0.20	0.41	0.50	0.82	1.02	0.20	0.41	0.50	0.82	1.02	0.20	0.41	0.50	0.82	1.02	0.20	0.30	0.61	0.82	1.02
	Thickness (m)	0.20	0.10	0.31	0.20	0.20	0.20	0.20	0.21	0.20	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.20	0.09	0.32	0.20	0.20	0.10	0.31	0.20	0.20
	C (kPa)	4.90	4.90	4.30	4.30	4.30	6.65	6.65	4.30	4.30	4.30	4.71	4.71	4.71	4.30	4.30	5.90	5.90	5.90	4.30	4.30	7.52	7.52	7.52	4.30	4.30	4.74	4.74	4.30	4.30	4.30
	ϕ' (°)	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60
	γ_s (kN/m^3)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
D	**Depth (m)**	0.19	0.30	0.58	0.78	0.97	0.19	0.40	0.58	0.78	0.97	0.19	0.39	0.50	0.78	0.97	0.19	0.39	0.50	0.78	0.97	0.19	0.39	0.50	0.78	0.97	0.19	0.30	0.58	0.78	0.97
	Thickness (m)	0.19	0.11	0.28	0.19	0.19	0.19	0.21	0.18	0.19	0.19	0.19	0.19	0.11	0.28	0.19	0.19	0.19	0.11	0.28	0.19	0.19	0.19	0.11	0.28	0.19	0.19	0.11	0.28	0.19	0.19
	C (kPa)	0.86	0.86	0.40	0.40	0.40	2.63	2.63	0.40	0.40	0.40	0.81	0.81	0.81	0.40	0.40	2.04	2.04	2.04	0.40	0.40	3.69	3.69	3.69	0.40	0.40	0.85	0.85	0.40	0.40	0.40
	ϕ' (°)	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30
	γ_s (kN/m^3)	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50
E	**Depth (m)**	0.12	0.24	0.30	0.49	0.61	0.12	0.24	0.40	0.49	0.61	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.37	0.50	0.61	0.12	0.24	0.30	0.49	0.61
	Thickness (m)	0.12	0.12	0.06	0.19	0.12	0.12	0.12	0.16	0.09	0.12	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.12	0.13	0.11	0.12	0.12	0.06	0.19	0.12
	C (kPa)	2.70	2.70	2.70	2.40	2.40	4.30	4.30	4.30	2.40	2.40	2.80	2.80	2.80	2.80	2.40	4.00	4.00	4.00	4.00	2.40	5.60	5.60	5.60	5.60	2.40	2.80	2.80	2.80	2.40	2.40
	ϕ' (°)	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50
	γ_s (kN/m^3)	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30

Table 21 (continued).

Bank profile	*Layer parameters*	BSTEM Layers Cohesion & depth														
		E. arvense (50)					*E. arvense (100)*					*No vegetation*				
		1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
A	**Depth (m)**	0.19	0.30	0.45	0.74	0.93	0.19	0.30	0.45	0.74	0.93	0.19	0.37	0.45	0.74	0.93
	Thickness (m)	0.19	0.11	0.15	0.29	0.19	0.19	0.11	0.15	0.29	0.19	0.19	0.19	0.08	0.29	0.19
	C (kPa)	2.49	2.49	0.40	4.30	4.30	4.56	4.56	0.40	4.30	4.30	0.40	0.40	0.40	4.30	4.30
	ϕ' (°)	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60	30.30	30.30	30.30	26.60	26.60
	γ_s (kN/m^3)	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00	18.50	18.50	18.50	18.00	18.00
B	**Depth (m)**	0.20	0.30	0.58	0.78	0.97	0.20	0.30	0.58	0.78	0.97	0.20	0.39	0.58	0.78	0.97
	Thickness (m)	0.20	0.10	0.28	0.19	0.19	0.20	0.10	0.28	0.19	0.19	0.20	0.19	0.19	0.19	0.19
	C (kPa)	6.35	2.40	0.00	0.00	0.00	8.38	4.77	0.00	0.00	0.00	4.30	0.00	0.00	0.00	0.00
	ϕ' (°)	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00	26.60	47.00	47.00	47.00	47.00
	γ_s (kN/m^3)	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00	18.00	21.00	21.00	21.00	21.00
C	**Depth (m)**	0.20	0.30	0.61	0.82	1.02	0.20	0.30	0.61	0.82	1.02	0.20	0.41	0.61	0.82	1.02
	Thickness (m)	0.20	0.10	0.31	0.20	0.20	0.20	0.10	0.31	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	C (kPa)	6.35	6.35	4.30	4.30	4.30	8.38	8.38	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30
	ϕ' (°)	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60	26.60
	γ_s (kN/m^3)	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
D	**Depth (m)**	0.19	0.30	0.58	0.78	0.97	0.19	0.30	0.58	0.78	0.97	0.19	0.39	0.58	0.78	0.97
	Thickness (m)	0.19	0.11	0.28	0.19	0.19	0.19	0.11	0.28	0.19	0.19	0.19	0.19	0.19	0.19	0.19
	C (kPa)	2.49	2.49	0.40	0.40	0.40	4.56	4.56	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	ϕ' (°)	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30	30.30
	γ_s (kN/m^3)	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50	18.50
E	**Depth (m)**	0.12	0.24	0.30	0.49	0.61	0.12	0.24	0.30	0.49	0.61	0.12	0.24	0.37	0.49	0.61
	Thickness (m)	0.12	0.12	0.06	0.19	0.12	0.12	0.12	0.06	0.19	0.12	0.12	0.12	0.12	0.12	0.12
	C (kPa)	4.40	4.40	4.40	2.40	2.40	6.50	6.50	6.50	2.40	2.40	2.40	2.40	2.40	2.40	2.40
	ϕ' (°)	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50	28.50
	γ_s (kN/m^3)	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30