INFLUENCES OF HARDWOOD RIPARIAN VEGETATION ON STREAM CHANNEL GEOMETRY IN EASTERN FORESTED ENVIRONMENTS

By

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I owe this thesis to early mornings,
strong coffee,
and the music of Bill Evans.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

Vegetation has a number of strong influences on the way Earth's surface changes over time, and the scientific community has expressed a growing interest in the interactions of biological and geomorphological processes. It has been suggested that, in the absence of vegetation, Earth would lack many of the topographic features we observe today [*Dietrich and Perron*, 2006]. Corenblit and Steiger [2009] suggest that the introduction of plants to Earth's surface led to a coevolution of both vegetation physiology and geomorphological regimes, and ecological succession may still promote a continued evolution in geomorphology.

Vegetation and the land surface develop feedbacks between one another, maintaining surface features and biological conditions necessary for continued habitation. For example, Ludwig et al. [2005] assert that vegetation patches attenuate sediment erosion rates and nutrient loss, preserving conditions for biological habitation; and biological-physical feedbacks are a key part of the development of Earth's critical zone [*Anderson et al.*, 2007].

Despite the fact that many of these relationships have been recognized, the links between vegetation and surface processes are still not fully clarified. Characterization of complex natural systems inherently introduces many variables, but an understanding of how these relationships work is important to improve theoretical interpretations of biotic-abiotic interactions and environmental management practices [*Viles et al.,* 2008].

With respect to fluvial systems, vegetation has been recognized as an important factor in bank stabilization and single-thread channel development [*Tal and Paola,* 2010]. The connection between riparian vegetation and stream morphology has given rise to a variety of interrelated questions and practices regarding land use management, water quality, ecosystem health and associated controls on topography, but understanding how plants and streams interact requires an understanding of two seemingly disparate concepts, namely riparian influence on channel flow and alluvial bedform development.

Much of the research published with regard to vegetative influences on pool formation and maintenance focuses on the effects of large woody debris (LWD): trees and branches that fall into the stream and alter geometry and flow [*Piégay and Gurnell,* 1996]. LWD often refers to decaying wood that crosses the channel, damming water and sediment behind it. While much of this work has elucidated the importance of some vegetative controls on channel dynamics, there has been disproportionately less attention paid to the effects that live trees at stream banks and within the channel have on the local flow conditions. Live trees have been recognized as strong stablizing factors for sediment-laden banks, but the effective stabilization depends on the channel size and root depth of the trees [*Biedenharn et al.,* 1997; *Abernethy and Rutherfurd,* 1998]. It can be assumed that the effects of hardwood riparian vegetation will have a greater influence on morphology when vegetation is similar in size to the stream, and transition to having only minor influence on the channel as stream order increases and becomes proportionally larger than the riparian vegetation.

The bedforms of primary interest, pools and sediment bars, have been studied extensively in field and laboratory experiments for the past several decades [*Wilkinson et al.,* 2008; *Fujita and Muramoto,* 1985; *Jaeggi,* 1984]. Features such as alternate bars are often portrayed as forcing agents that stimulate outside bank erosion, providing the conditions necessary for the onset of lateral channel migration [*Jaeggi*, 1984]. In general, these studies have emphasized the formation of the bars, where associated pools are designated as secondary features [*Fujita and Muramoto,* 1985; *Ikeda*, 1984]. There exists little research that explores scenarios where pool formation is the primary process that controls the size and location of bars. It must also be considered that previous experimental studies have been conducted in straight flumes with no irregular features. In a natural channel, riparian trees exist at the stream's banks and on the bed, which may present patches of differing stability. Such changes in erodibility may trigger variations in bed topography and/or resistance to bank erosion, a precursor to channel curvature [*Thorne and Furbish, 1995*].

The motivation to understand how fluvial and biotic processes interact to create aquatic habitats is of special interest to the geomorphological and ecological communities alike. Specifically, the influence of riparian trees on ecosystem complexity deserves greater inspection. It has been documented that greater physical complexity of stream habitats allows for greater species diversity [*Gorman and Karr,* 1978; *Brosse et al.,* 2002], and woody material, both alive and dead, is an important contributor to structural complexity in stream channels [*Opperman et al.,* 2008; *Everett and Ruiz,* 1993; *Frissell et al.,* 1986; *Piégay and Gurnell,* 1996]. Unlike LWD in natural channels, live trees persist longer than dead debris and provide greater stability to the channel, but management practices concerning in-stream wood have not paid ample attention to trees that are still alive [*Opperman et al.*, 2008].

Numerical modeling, laboratory experiments and field assessments have shown that riparian vegetation (reeds, grasses, and trees) cause variation in channel form and bank stability [*Huang and Nanson,* 1996; *Murray and Paola,* 2003; *Tal and Paola,* 2010, *Abernethy and Rutherfurd*, 2000]. Riparian vegetation, both on the banks and within the channel, can promote local increase in sediment deposition and cause stream channels to narrow [*Friedman et al.,* 1996; *Scott et al.,* 1996; *Hupp and Osterkamp*, 1996]. This is of fundamental interest because the ratio between channel width and depth has been observed as a controlling factor of bar instability, a primary process of alternate bar formation and a prerequisite to channel migration [*Lanzoni and Tubino,* 1999; *Ikeda,* 1984; *Jaeggi,* 1984]. In a series of field and experimental studies, Furbish et al. [1998] and Wilkinson et al. [2008] demonstrated that bar instability can occur in channels with ratios as low as 3.8, far lower than previously suggested. Wilkinson et al. [2008] also measured bed scour at channel constrictions within a straight flume that influenced downstream bar amplitude. To summarize these findings, alternate pool-bar structures may be formed even in channels that have low width-depth ratios due to vegetative narrowing, and exposed rootwads that create scour pools and change local width may influence bedform development downstream (**Figure 1.1**). If we also consider that riparian trees create patches of increased bank stability, migration patterns triggered by alternate bars may be further complicated, supporting the idea that effects of hardwood riparian vegetation can modify both planform and topographic morphology. Although each of these processes may be functioning at varying degrees, the collective understanding of vegetative controls on streams has much to be improved upon.

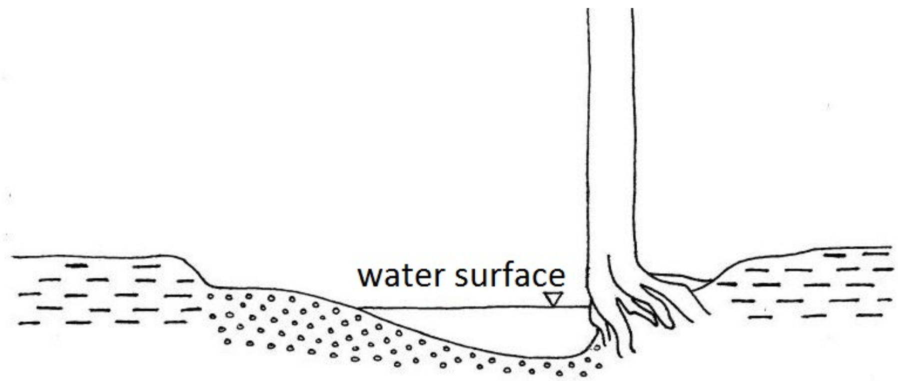

Figure 1.1: Schematic of a channel cross section with a rootwad pool formed as result of increased turbulence by submerged root mass.

To our knowledge, no studies have aimed to systematically characterize the distinction between stream channels whose forms are dominated by effects of vegetation and those whose forms are dominated by alluvial processes. As no theory currently exists to describe riparian rootwad influence on streams at varying sizes, we approach this problem in an exploratory manner. The importance of relative size between riparian trees and the stream channels is qualitatively and quantitatively analyzed using detailed surveys of stream geometry, tree location and vegetation density. As stated by Furbish [1998], it is expected that lower-order, steeper streams will be more highly affected by flow deflections from disturbances (such as trees) while bar instability will be responsible for pool-bar sequences in higher-order channels. We investigate the presence of a biological-fluvial "transition zone" in which trees become progressively less influential on channel morphology as river discharge and order increase. In addition to using parameters such as width-to-depth ratios, measured values of tree diameter compared to channel width represent geometric scaling between the stream and surrounding vegetation. Metrics collected in the field are used to inform a series of stream table experiments that examine the effects of rootwad size and tree spacing on bedform genesis and maintenance.

Chapter 2

Conceptual Model

2.1 Rootwad Effects on Pool Formation

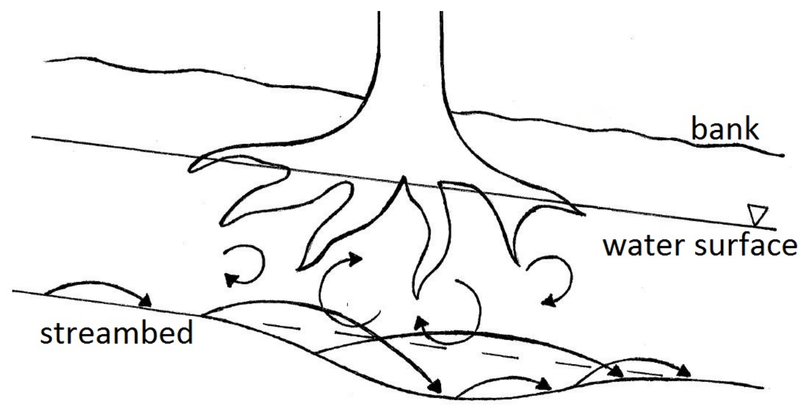

Figure 2.1: Schematic of pool scour due to rootwad-induced turbulence. Particle hop distances are increased, thus entrainment rates exceed deposition rates at rootwad locations.

Consider an alluvial stream in a temperate forested floodplain. The transport of sediment on the streambed must satisfy conservation of mass. We assume a steady-state condition wherein sediment inputs to the system are equal to the sediment outputs. In a case where this condition is not satisfied, the bed experiences a change in sediment storage, manifest as a pool or bar. To describe changes in bed storage, we use the entrainment form of the Exner equation,

$$c_\eta \frac{\partial \eta}{\partial t} = -E + D, \tag{2.1}$$

where $\partial \eta / \partial t$ is the rate of change in bed elevation with respect to time [L T^{-1}], $c_\eta = 1 - \phi$ is the volumetric concentration of bed material, where ϕ is the porosity of the bed material, E is the volumetric particle entrainment rate [L T^{-1}] and D is the volumetric particle disentrainment rate [L T^{-1}] [*Tsujimoto*, 1978]. When $\partial \eta / \partial t = 0$, the bed experiences no change in elevation, which means that entrainment and deposition are equal and the bed fulfills the steady state condition.

When flow encounters an obstruction, such as a riparian rootwad, the interference acts as a constriction that results in a higher pressure on the upstream side of the hindrance. The increase in pressure causes the fluid within close proximity to the obstruction to accelerate, thus increasing the local entrainment rate. As **equation 2.1** states, this results in a decrease in sediment storage at the bed.

Obstructions within natural channels contribute a considerable amount of turbulence to the overall flow field [*Hassan and Woodsmith,* 2004], and such alterations in the flow provided by riparian vegetation have been observed specifically at stream banks [*Thorne and Furbish,* 1995; *Bennett et al.*, 2002]. When complex vegetation patches (i.e. rootwads) obstruct streamwise flow, turbulence generated by the obstruction decreases the disentrainment of particles, decreasing the amount of deposition adjacent to the vegetation and allowing sediment to be advected further downstream [*Yager and Schmeeckle,* 2013]. Meanwhile, sediment is continually entrained from locations of decreased deposition, causing $\partial\eta/\partial t$ to be negative, yielding a depression at the bed (**Figure 2.1**). The pool will be formed slightly downstream of the rootwad due to the turbulence being advected in the streamwise direction.

When the bed elevation reaches a critical depth below the rootwad, the increased flow velocity and turbulence induced by the rootwad is insufficient to affect settling rates of sediment, and the disentrainment rate is equal to the entrainment rate from the pool. At this depth, a steady state condition is achieved and the change in sediment storage at the bed is zero, generating a persistent pool.

2.2 Rootwad Influences on Streams of Varying Size

To understand the effect that vegetation has on stream morphology, we must consider the effects associated with scaling between the channel and vegetation sizes. The influences of vegetation on the stream are more pronounced on smaller channels, but the processes by which they modulate the geometry do not go unchanged as channel size and order are increased.

Consider a large single-thread alluvial channel with cohesive, yet erodible banks. Assume that the channel width is much larger than any vegetative obstruction that may occur on the banks or within the channel, and roots of riparian trees do not extend to the stream bed. If this channel exhibits a typical width-depth ratio for natural rivers, it can be assumed that the stream will take on a classic alluvial form where pools and bars occur as a result of alternate bar dynamics. Thus, in a large, purely alluvial stream, vegetation may apply a local influence on the bed topography and bank stability, but overall bedforms and planform curvature will be a product of alternate pool-bar sequences with fixed pools and bars at sites of finite curvature [*Biedenharn et al.,* 1997].

Consider an alluvial stream of lower order, where the channel width is slightly larger than any riparian obstruction. In such a stream, some roots from large riparian trees may extend from the bank to the channel bed. The larger root masses may stabilize the bank [*Montgomery and Buffington,* 1997] and cause bed scour, which is a consequence of increased turbulence from flow around the rootwad. The vegetatively forced depressions act as temporarily fixed, or "forced," pools, and associated alluvial bars are deposited downstream of the scour pools. Since the pools and bars are forced by randomly spaced trees, the behavior and spatial frequency of the pool-bar system do not adhere to the same patterns as larger, purely alluvial streams. If the forced pools and bars persist through an abundance of high-flow events, the bedforms may initiate channel curvature. Conversely, the rootwads may also stabilize the banks enough to inhibit erosion and ensuing channel migration (**Figure 2.2**).

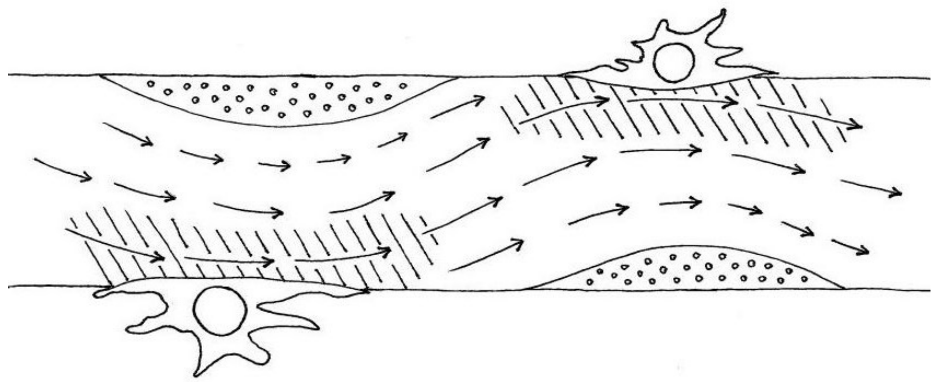

Figure 2.2: Planform schematic of a stream with rootwad pools (hatched lines) and associated sediment bars (stippled regions). Vegetative influence on flow is sufficient to affect bedform topography, but may not be great enough to modulate planform curvature or bank migration.

In headwater streams of the lowest orders, channels are narrow and have much lower discharges than the streams previously discussed. Riparian obstructions may be equal to or greater in size than the channel width, and the rootwads may extend into the stream bed and stretch more than one channel width along the bank in the streamwise direction. These rootwads create large scour pools relative to the size of the channel and "attract" the thalweg towards the bank. The rootwads adequately stabilize the bank to attenuate erosion at the bank adjacent to the pool (**Figure 2.3**). Due to the low discharges, the roots act as immovable walls that deflect the flow into different directions downstream. In addition to pool scour and flow forcing, the rootwad pools may act as anchors that prevent channel migration from zones immediately surrounding riparian trees. This is of particular importance when considering the lifespans and decay rates of riparian trees, for pools should only persist as long as a coherent root mass is present. After the rootwad degrades, the stream at that location is then free to migrate until a new tree is encountered. This implies that pool frequency and planform geometry of streams are dependent on the spatial density of trees, and that channel migration rates are controlled by rates of tree growth and decay.

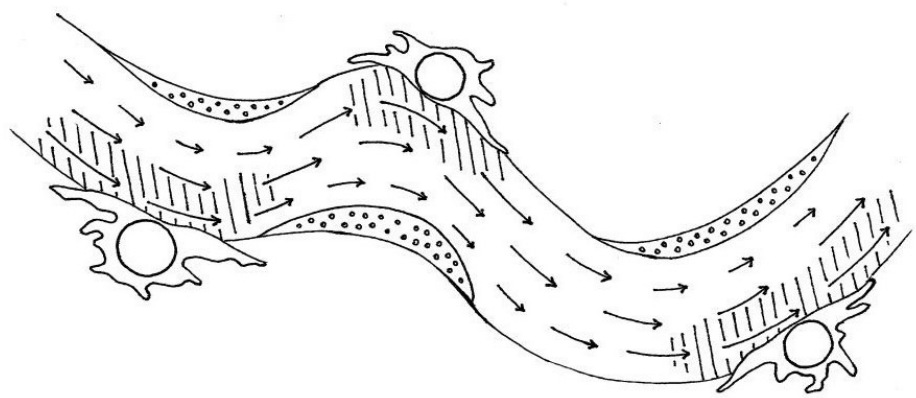

Figure 2.3: Planform schematic of stream with rootwad pools (hatched lines) and associated sediment bars (stippled regions). Vegetative influence on the flow strong enough to affect both bedform topography and planform geometry by means of thalweg forcing and bank stabilization.

Chapter 3

Field Studies

3.1 Land Between the Lakes and Barrett Creek

Land Between the Lakes National Recreation Area (LBL) is located in northwestern Tennessee and southwest Kentucky between Lake Barkley to the west and Kentucky Lake to the east, both of which are reservoirs. The inland peninsula hosts nearly 700 km^2 of forest and open land, all of which is managed under jurisdiction of the United States Department of Agriculture Forest Service.

The Tennessee Valley Authority began construction of Kentucky Dam in 1938 to control flow from the Tennessee River into the Ohio and Mississippi rivers during flood events. Kentucky Lake began to fill in 1944, and now is the largest manmade lake in the United States [*Lake Productions LLC*, 2016]. Construction of the Barkley Lock and Dam was completed by the United States Army Corps of Engineers in 1966, impounding the Cumberland River to create Lake Barkley. At average levels, Lake Barkley covers 234 square kilometers and has over 1600 km of shoreline [*Lake Barkley Tourism*, 2016]. Reservoir filling has caused an increase in base level for the streams at LBL, but effects of damming on the drainage systems appear to have changed the surface hydrology of only the lowest reaches of the streams.

The bedrock geology of LBL consists primarily of calcareous Mississippian rocks, although the stratigraphic column includes marine and fluvial clastic rocks ranging from Devonian to Quaternary ages [*Marcher*, 1962]. Units of particular prevalence in the area are the Fort Payne Chert, Warsaw Limestone, and St. Louis Limestone, which cover more than 90% of the Tennessee portion of LBL and all exceed 60 meters in thickness. Cretaceous clays, sands, and gravels cap some of the higher ridgetops atop the Barkley-Kentucky watershed divide.

Structurally, LBL has a major eastward-plunging syncline surrounded by numerous high-angle normal faults oriented northeast-southwest [*Marcher*, 1962]. Marcher [1962] suggests that other small anticlines and synclines that occur near faults likely folded as a result of deformation during the faulting process. The effects of deformation on local hydrology have not been quantified, but movement along the faults expose different bedrock units which may exhibit different hydraulic conductivities and weathering rates.

The drainage networks at LBL assume dendritic patterns. The watershed divide between Lake Barkley and Kentucky Lake runs parallel to the shorelines, providing approximately equal drainage area on each side of the peninsula. Broad floodplains occupy the valleys and are often used for agriculture.

Regulation and management by the USDA Forest Service makes LBL an ideal location for eco-geomorphological research. The Programmatic Agreement among the USDA Forest Service, Land Between the Lakes National Recreation area and many other preservation organizations states that undertakings within LBL limits must follow specific guidelines and require permissions before any alterations of the land can take place [*United States A.C.H.P*, 2014]. Of particular importance is that any agricultural practices must qualify as non-ground disturbing broadcast seeding and/or no-till seeding. The purpose of this policy is to limit the amount of human induced erosion from the floodplain and prevent any excessive sediment loading into the stream systems. Limiting the amount of anthropogenic inputs of sediment into the stream allows for examination of natural riverine processes. This implies that nearly all sediment within the streams is being supplied naturally by the hillslopes in the first-order streams, and that the channels at LBL are representative of natural geomorphological processes.

The Barrett Creek Watershed is located in the southeastern section of LBL, and the main branch flows eastward into Bard's Lake before draining into Lake Barkley. Barrett Creek is a fourth order stream system with a watershed of roughly 12 square kilometers and total relief of 80 meters. The drainage pattern is dendritic and fairly symmetrical about the confluence of the third order channels. The bedrock in the lowest portion of the watershed is Warsaw Limestone, which is typically fossiliferous, locally silty, and cross-bedded. Most of the rest of the watershed is St. Louis Limestone, which is also silty/sandy limestone, but is characterized by residual chert nodules several centimeters to decimeters in diameter. Both the Warsaw and St. Louis Limestones are overlain by reddish-yellowish sandy clay soils. Quaternary, Tertiary and Cretaceous sands and gravels can be found at the highest elevations of the watershed, most notably at the western catchment boundary [*Marcher et al.*, 1967].

Sediment within the channels is composed of gravel made of porous limestone and chert nodules several centimeters in diameter. The size, shape and color of the nodules are consistent with those described in the bedrock geology, suggesting that clastic sediments are sourced directly from the hillslopes within the drainage basin

Barrett Creek hosts reaches of several different orders within a small area. Second, third, and fourth order reaches can be found within a downstream distance of less than 1.5 kilometers. Aside from accessibility, the close proximity of streams of different order within the same drainage system reduces the variability in local hydrology, soil types, geologic units, sediment sourcing and vegetation.

All of the selected reaches satisfy the same requirements for a proper investigation of the idea of hardwood vegetative influence. Each studied stream at Barrett Creek is a single-thread gravel bedded channel with cohesive silt-clay banks. These characteristics are important in relating the conceptual model to field evidence because we are interested in both alluvial bed dynamics and bank maintenance. Consistency in the bed and bank material allows for reliable comparison between streams and discharges of different sizes. The vegetation surrounding selected streams also exhibits a variety of hardwood species at various stages of growth. Tree and rootwad size can indicate the tree's age which may suggest how long a stream has been present at that specific location, and smaller trees may illustrate the genesis of rootwad-induced modification on channel curvature and bedforms.

3.2 Overview of Selected Reaches

3.2.1 Second Order

The second order stream is located just north of Tharpe Road (Rt 221) and flows from northeast to southwest. The catchment of this reach is less than one square kilometer, and like the other selected streams, is dry for most of the year. A cornfield lies on the western end of the floodplain, and the eastern side of the stream is a forested floodplain that increases in slope roughly 50 meters from the left bank.

The channel is characterized by frequent segments with high-amplitude curvature, often involving the presence of trees. The width of the channel varies between two and six meters. In the narrowest sections of the stream, the channel is deep with well-defined banks. The widest sections often have shallow, poorly-defined banks that slope at angles of around 45° and often host small trees (diameter <45cm) within the channel itself.

There is a visible influence of hardwood vegetation on both topographic and planform geometry of the channel. In the absence of sufficiently large trees, the channel is relatively straight and wide, decreasing the average depth across the stream. Channel curvature usually coincides with the presence of trees either in the channel, on the outside bank or on the floodplain, close enough to the stream where roots may be exposed on the channel wall. In cases where large portions of rootwads are exposed within the channel, the stream narrows and deepens beneath and slightly downstream of the rootwad.

Several areas within the stream display evidence of channel avulsions in varying stages of development. In most of these cases, the modern channel is bound by trees (sometimes quite small), suggesting that the stream is preferentially flowing towards areas where agents of stabilization and narrowing are present. Older avulsions are covered with several years worth of leaves and other organic material, and no granular sediment is visible. In most cases, the upstream end of the avulsion occurs in close proximity to trees.

Large trees and roots that cross the channel bed occasionally act as traps for leaves, twigs and other woody debris, creating small log-jams that add complexity to the pool and bar forming processes. Some of the smallest trees accumulate large amounts of organic debris which augment the obstructive effects of the rootwads.

The undisturbed floodplain (namely to the east) displays topographic variability similar to that of an alluvial fan. Abandoned channels discontinuously snake across the floodplain, and some of them still appear to carry flow in high-discharge events. These channels exhibit different stages of structural degradation, indicating they are of different age. The well-defined structures of some of the abandoned channels may indicate that stream avulsions occur at geomorphically rapid timescales. **Figure 3.1** displays a map of the second order channel.

3.2.2 Third Order

The surveyed and mapped section of the third order stream begins 450 meters downstream of the second order section. The upper part of this reach flows parallel to Tharpe road, mostly in the southeastern direction. The watershed covers an area just shy of three square kilometers. There exists a forested hillslope northeast of the upstream section of the channel. The lower section of the reach flows southward and is surrounded by farmland on both the east and west. Like all streams at LBL, a forested buffer between 20 and 40 meters wide lies between the stream's bank and the agricultural land.

At the upstream end of the third order channel, the right bank sits much lower than the left and appears to be part of the contiguous floodplain that extends throughout the farming area. The left bank is higher and is bound by the hillslope to the northeast. Tharpe Road lies atop the left bank, but sits at least eight meters from the stream bed, and no resulting anthropogenic influences regarding structures or sediment input appear to affect the stream's morphology. This section is characterized by high banks (1.5m) and has an average width of about seven meters. The downstream end of the third order reach has low sinuosity, and bank height decreases while width increases to around eight meters.

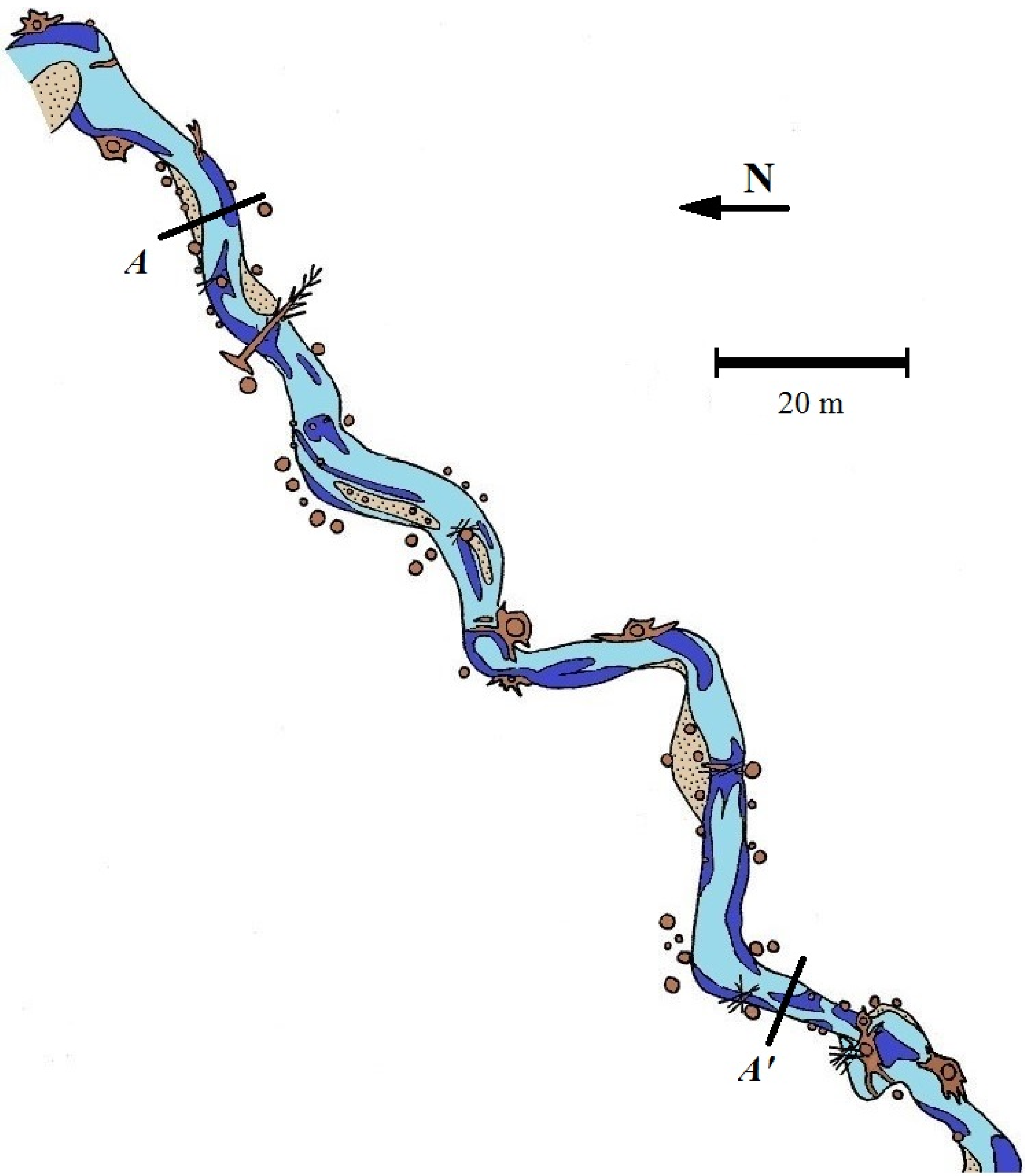

Figure 3.1: Map of second order section of Barrett Creek. Flow is oriented from northeast to southwest. Areas of dark blue represent pools, tan areas represent bars, and brown circles represent standing riparian trees. Cross-sections were measured between *A* and *A'*.

Since the channel is rather straight and incised, it does not appear that this stream has experienced any recent migration. The only surface roughness on the floodplain is contributed by treethrow. Tree density is high, with most of the trees between one half and two meters in circumference. Many of the larger trees sit atop the stream's banks with roots visible at the channel wall, but few have roots that extend downward to the bed, especially where bank heights are greatest.

There is a large log jam where large woody debris has caused considerable pool scour beneath and around several large logs. Several meters downstream, a small fallen tree crosses the channel, but there does not appear to be any evidence of flow interference that would influence channel geometry. A map of the third order channel is shown in **Figure 3.2**.

3.2.3 Fourth Order

The fourth order reach of Barrett Creek flows from west to east as the third order branches converge from the north and south. Unlike the third order stream, this channel exhibits several high-amplitude bends that constrain over 300 meters of stream into an area of approximately 12,000 square meters. Approximately 200 meters downstream of the confluence, several terraces bind the stream on the left bank.

There is a large channel avulsion that occurs approximately 260 meters downstream of the confluence. The lack of large plants within the channel of the avulsion and the presence of a log jam in the modern channel both suggest that the old channel still accommodates flow during very high discharge events. This section of the stream was not surveyed due to uncertainty of flow conditions, poorly defined banks and lack of hardwood riparian vegetation.

The fourth order stream displays a series of fixed point bars and cutbank pools at zones of high curvature. In most of these sections, the amount of bed relief between the point bar and the cutbank pool exceeds one meter. The steep channel walls of the outside banks

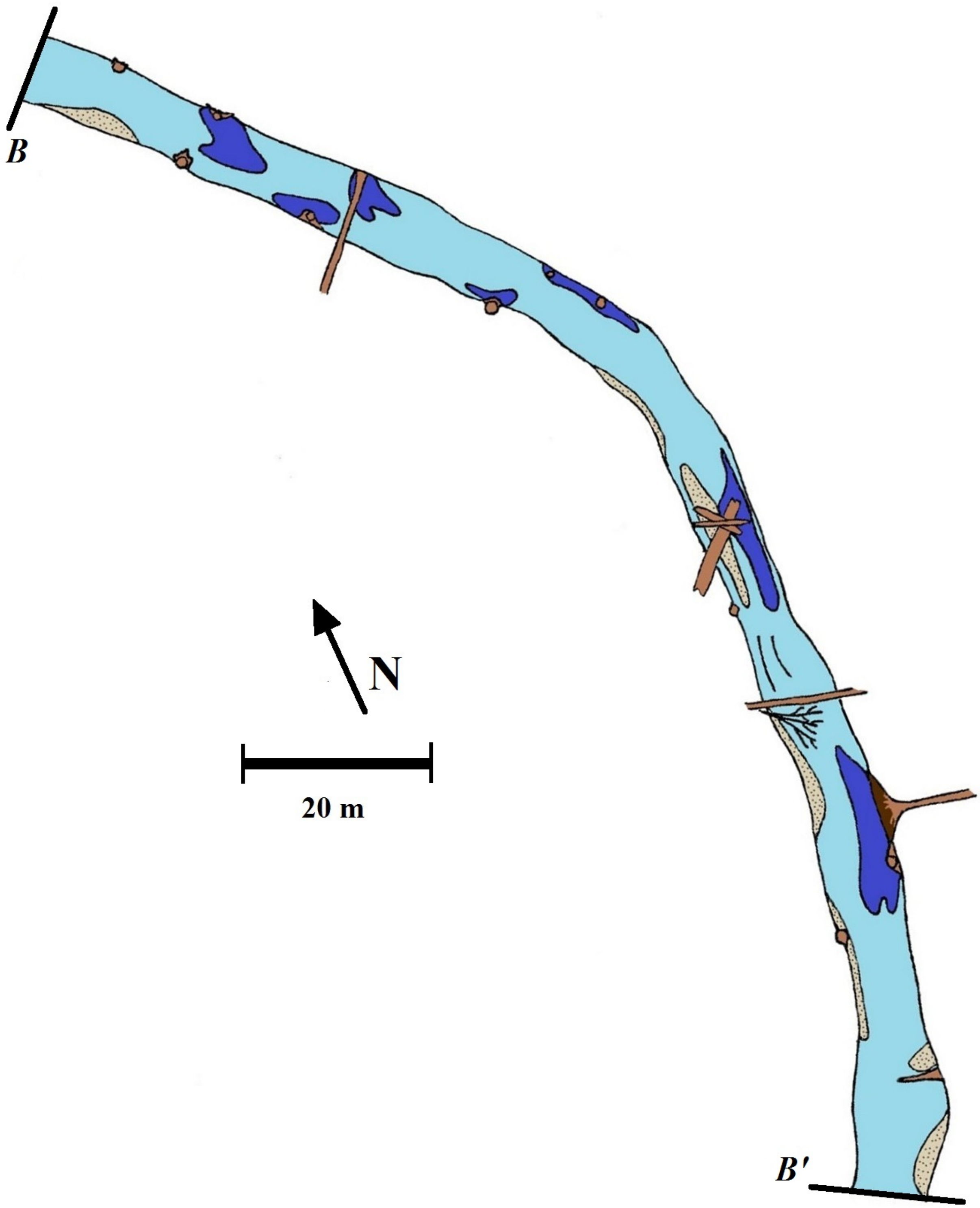

Figure 3.2: Map of third order section of Barrett Creek. Flow is oriented from north to south. Areas of dark blue represent pools, tan areas represent bars, and brown circles represent standing riparian trees. Cross-sections were measured between *B* and *B'*.

leave riparian vegetation high above much of the flow. Locally, some pool deepening occurs immediately below overhanging rootwads. In most cases, the high-rooted riparian trees are undercut by erosive processes, which may cause the trees to fall into the stream as large woody debris, further amplifying pre-existing pool scour processes.

Approximately 100 meters from the upstream confluence, a large sycamore tree sits near the center of the channel, towards the right bank. The tree is 1.3 meters in diameter and has exposed roots along the bed surface that extend radially from the trunk. The resulting scour pool is the only large riparian pool in the surveyed reach that exists in the center of the channel. Other midchannel scour pools are present in the downstream section of the reach, but these pools are small and rarely persist for more than one channel width downstream. A map of the fourth order channel is shown in **Figure 3.3**.

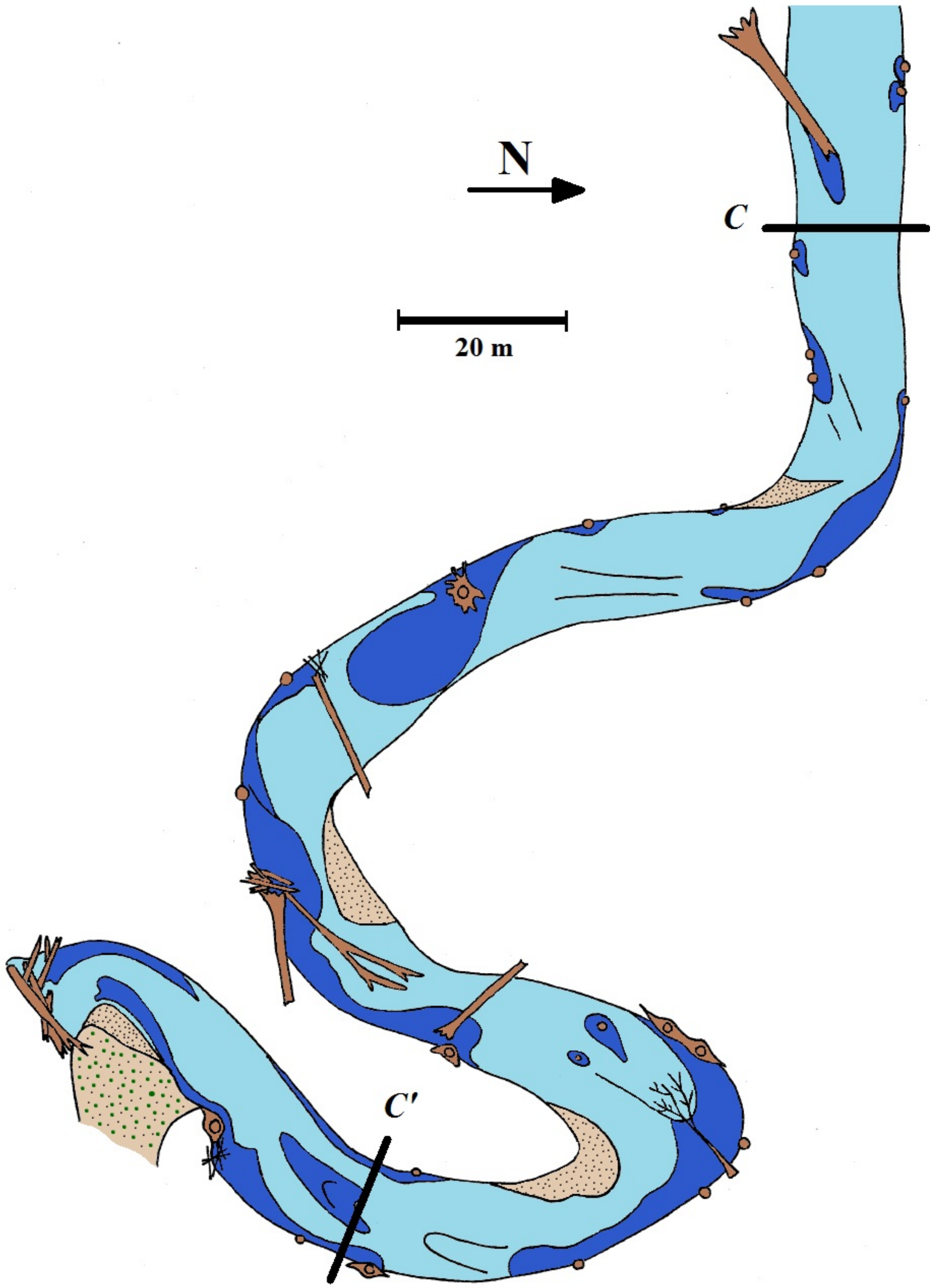

Figure 3.3: Map of fourth order section of Barrett Creek. Flow is oriented from west to east. Areas of dark blue represent pools, tan areas represent bars, and brown circles represent standing riparian trees. Cross-sections were measured between *C* and *C'*.

3.3 Field Methods

3.3.1 Topographic Surveys of Channels

A series of cross-channel topographic surveys were conducted for each streambed to characterize two-dimensional morphology. Effective stream surveys require that data are collected at sufficiently high resolution to illustrate small-scale details in cross-sectional geometry, while also covering a long enough section of the stream to represent the large-scale channel properties. To satisfy these requirements, at least 35 topographic cross-sections were sampled at downstream intervals between one half and one channel width at each stream. Cross-sections were measured at regularly spaced intervals to avoid any biased sampling of bed topography, tree presence, or curvature. At this sampling resolution, topographic persistence of bedforms between sections can clearly be detected. This also provides a surveyed stream length greater than 15 channel widths, which we assume provides an ample scope for describing a stream's overall properties.

Measurements were made using a Sokkia auto level and stadia rod. Specific points along each cross section were measured at changes in bed elevation or profile shape, but points were collected relatively uniformly across the channel to avoid topographic biasing. Each cross-section consisted of approximately 10 to 15 measurements including elevations from each of the banks. Measurements of channel walls were also recorded where the walls displayed irregular shapes. All measured points were labeled for their location on the bed, wall or banks for proper arrangement and categorization of data for future analyses. All downstream distances were measured from a graded tape stretched down the channel centerline. Orientations of cross-sections were measured with a Brunton compass.

Each of the three reaches were measured at different downstream intervals based on the size of their features. The third and fourth order streams were measured at four and six meter intervals, respectively. These intervals were used because they represent approximately half of the average channel width, and they provided ample resolution of the bed while allowing for satisfactory downstream coverage. The second order stream was measured at a downstream interval of three meters, which exceeds the average half-width of the channel. This interval was chosen to extend the downstream survey to capture more zones of curvature and types of vegetative influence, and persistence of bedforms and channel orientations were not obscured at this resolution.

3.3.2 Forest Density and “Significant Trees”

If in fact the channel morphology depends on locations and sizes of trees, the spatial density within the forested floodplain must be quantified. Tree species is of great importance as well, for different species exhibit differing growth rates, root structures, tolerances to water, sunlight and other factors. A sampling area of 400 square meters was used for all three floodplains about the second, third, and fourth order streams. Tree species were identified using the National Audubon Society Field Guide to Trees handbook. Tree circumference was measured at breast-height (1.5 meters above ground) for each tree in the sampling area. Trees with circumferences less than 45 centimeters were not recorded due to their size, which is likely too small to have any appreciable effects on channel geometry from the floodplain.

Since not all riparian trees have visible influence on the bed or bank structures, only “significant trees” were reported during field observations. In this study, significant trees are defined as those close to or within the channel that have either their trunk or roots affecting flow processes, bank location and/or stability. All significant trees were measured and identified under the same guidelines as forest density, but the minimum circumference was neglected, for even small trees are capable of influencing channel morphology within the flow. Details of cross-stream location, root exposure, surrounding features and consequential morphology were recorded for each significant tree.

3.3.3 Sediment Size Distributions

Sediments were measured using the Wolman pebble count method, in which sediment clasts are blindly selected from the bed and measured along the b-axis. Sample sizes exceed 200 to properly characterize the distribution of grains. Sediment diameters are reported in millimeters.

3.4 Field Results

3.4.1 Basic Stream Parameters

Table 3.1 below shows calculated parameters from each of the three surveyed streams. Values involving channel width all are calculated by using the bed width rather than total channel width. We used the bed width to eliminate uncertainties in geomorphically ambiguous areas, such as locations of recent avulsions or zones with poorly defined banks. Significant tree density is defined as the number of significant trees present for every downstream meter of the channel.

Grain size distributions for bed material of the three reaches are displayed in **figure 3.4**. Each of the streams display log-normal distributions, which is typical for streams with clastic sediment [*Spencer,* 1963]. We would expect mean grain size to decrease with increasing stream size, but our data indicate otherwise. It should be noted that as order is increased, the proportion of small particles (smaller than 20mm) increases. The increase in larger clasts may be a factor of the sediment that the other non-surveyed tributaries are delivering to the channel.

Parameter	Second Order	Third Order	Fourth Order
Surveyed Length (m)	120	160	210
Channel Slope	0.0112	0.0059	0.0047
Mean Bed Width (m)	4.26	4.89	10.88
St. Dev. Bed Width (m)	1.19	0.75	1.97
Mean Bank Height (m)	0.32	1.15	1.05
Width : Depth Ratio	13.27	4.27	10.41

Table 3.1: Table of measured parameters for each stream and associated environment. all values related to width are calculated using bed width as opposed to channel width.

3.4.2 Tree Density and Significant Trees

General metrics of tree data are displayed in **tables 3.2** and **3.3**, and both tree species and diameter for floodplain and significant trees of each surveyed reach are reported in

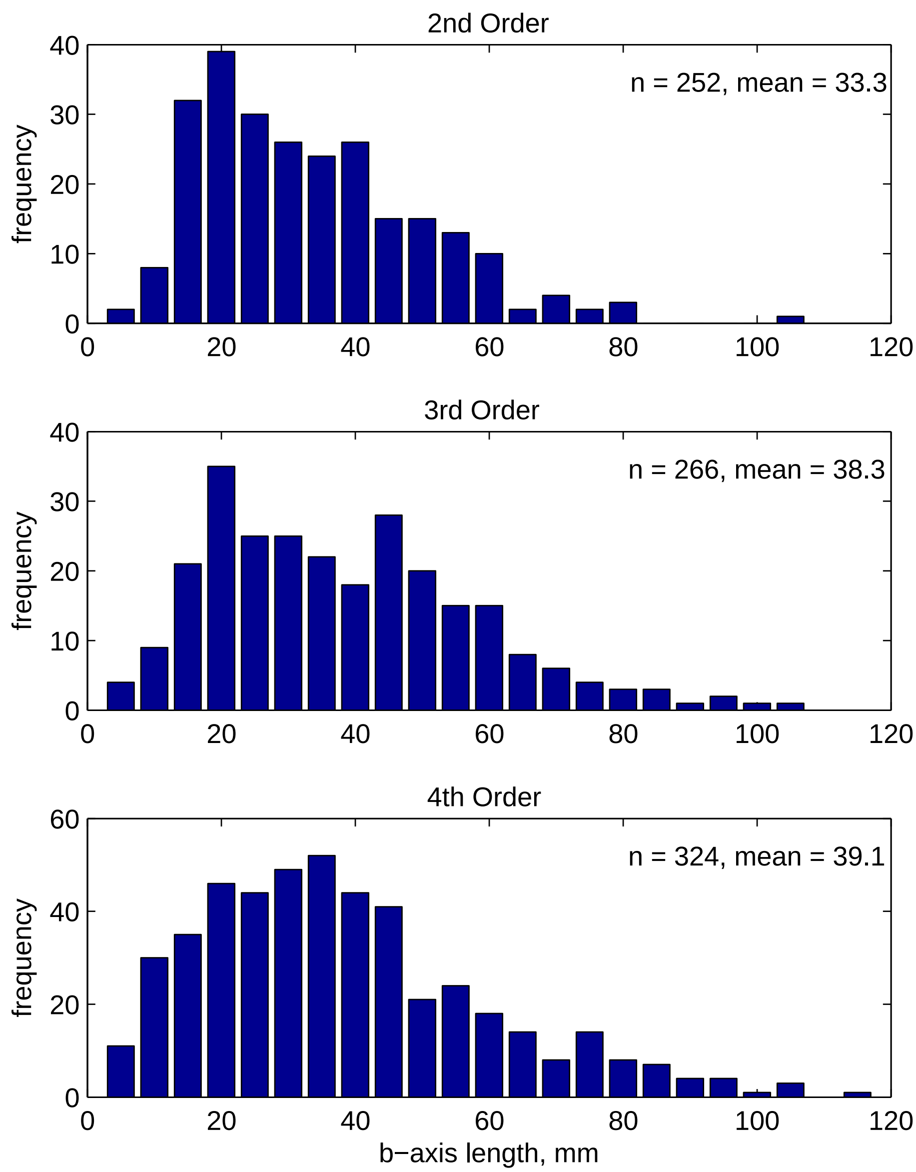

Figure 3.4: Grain size distributions for bed material of all surveyed reaches at Barrett Creek

tables 3.4 through **3.9**. The second order floodplain exhibits the lowest measured tree density of all the selected streams. The floodplain is populated with many saplings of varying species, but they are not of sufficient diameter to be measured in this study. Of measured trees, the mean diameter of the trunks at breast-height is 29.3 centimeters. There is no observable dominant species in the surveyed area. Despite the fact that this channel has the lowest floodplain tree density, the significant tree density is the greatest of the three channels. The dominant species for significant trees is maple, followed by oak and hickory. The mean diameter for significant trees is 0.33 meters, with the largest at 1.27 meters.

The third order floodplain exhibited the highest floodplain tree density at one tree per 9.76 square meters. This floodplain is dominated by sweetgum, which makes up more than 60% of the trees in the surveyed area. Since most of the trees are of similar diameter, it suggests that many of them are the same age, indicating that there may have been a felling event that effectively reset the floodplain forestry. The presence of significant trees in the third order channel is small relative to the high floodplain density. In the 160 meters of surveyed stream, only 11 standing trees were identified as having morphological effects on bed topography. Sweetgum trees accounted for nearly half of those, indicating a correlation between floodplain and riparian speciation.

The fourth order stream displayed medium values for both floodplain and significant tree density. Unlike in the third order channel, the fourth order stream displays a high width:depth value, allowing for a broader, more shallow bed on which midchannel trees can grow during inter-flow periods. Many of the significant trees identified in this order grow out either from the channel walls or the bed itself.

The presence of significant trees may be mostly affected by bank height or width:depth ratios. As bank height is increased, the distance between riparian roots and the bed also increases, which prevents much of the tree's root mass from growing towards the bed and creating local scour. The third order channel displays the highest floodplain forest density, but a much lower significant tree density than the two other surveyed streams, which suggests that the presence of trees in the general proximity of the channel does not guarantee a high frequency of vegetative influences on bed topography.

Stream	$\bar{d}$, cm	Tree Count	Floodplain Density, Tr/m^2
2nd Order	29.3	8	0.02
3rd Order	23.4	41	0.10
4th Order	34.6	14	0.04

Table 3.2: Floodplain tree data for each surveyed channel

Stream	$\bar{d}$, cm	$\bar{d} : 2\bar{b}$	Tree Count	Sig. Tree Density, Tr/m
2nd Order	32.6	0.077	29	0.242
3rd Order	59.4	0.121	11	0.069
4th Order	51.5	0.048	22	0.105

Table 3.3: Significant tree data for each surveyed channel

Tree Species	Diameter, cm
ash	26.7
sweetgum	33.4
butternut	33.1
sweetgum	42.0
sycamore	19.1
cherry	43.3
maple	20.7
elm	16.2

Table 3.4: Table of floodplain trees, second order channel

Tree Species	Diameter, cm
oak	60.5
hackberry	14.6
maple	39.8
unknown	50.9
elm	9.5
maple	8.0
elm	12.7
dead	19.1
maple	19.1
sweetgum	50.9
hickory	36.6
hickory	31.8
maple	44.6
maple	14.3
maple	127.3
oak	54.1
maple	52.5
oak	35.0
maple	17.5
maple	12.7
oak	50.9
hickory	20.7
maple	14.3
hickory	20.7
sweetgum	28.6
oak	47.7
dead	27.1
elm	30.2
sweetgum	12.7

Table 3.5: Table of significant trees, second order channel

Tree Species	Diameter, cm
cedar	21.6
elm	13.4
sweetgum	21.3
hickory	21.3
elm	14.3
sweetgum	20.1
sweetgum	22.9
sweetgum	24.5
sweetgum	27.1
sweetgum	24.5
elm	30.6
sweetgum	14.6
elm	16.9
sweetgum	14.7
oak	54.1
elm	17.2
sweetgum	20.4
sweetgum	16.2
sweetgum	25.5
sweetgum	24.8
sweetgum	30.7
sweetgum	30.2
sweetgum	21.6
sweetgum	15.3
sweetgum	22.0
hickory	23.2
sweetgum	27.1
sweetgum	18.46
elm	17.5
sweetgum	20.7
sweetgum	16.6
sassafras	15.3
elm	18.1
cherry	15.0
sweetgum	31.8
hickory	31.2
sweetgum	28.3
elm	19.73
sweetgum	43.9
elm	17.5
sweetgum	17.5

Table 3.6: Table of floodplain trees, third order channel

Tree Species	Diameter, cm
sweetgum	39.8
hickory	63.7
hickory	27.1
sweetgum	47.7
dead	41.4
sweetgum	100.3
maple	17.5
sycamore	33.4
dead	39.8
oak	38.2
sweetgum	82.8

Table 3.7: Table of significant trees, third order channel

Tree Species	Diameter, cm
elm	24.2
ash	34.4
elm	18.5
sweetgum	41.4
elm	19.4
oak	55.4
oak	49.7
maple	23.6
hickory	29.3
sweetgum	46.5
hickory	18.1
cedar	38.2
sweetgum	41.38
sweetgum	44.6

Table 3.8: Table of floodplain trees, fourth order channel

Tree Species	Diameter, cm
maple	39.8
sycamore	73.2
maple	74.8
hickory	60.5
oak	-
hickory	41.4
sycamore	47.7
sycamore	130.5
oak	55.7
hickory	50.9
oak	55.0
hickory	20.7
hickory	38.2
birch	47.7
sycamore	9.5
hickory	73.2
ash	55.7
maple	57.3
sycamore	31.8
elm	30.2
elm	28.6
elm	38.2

Table 3.9: Table of significant trees, fourth order channel

3.4.3 Calculating Physical Metrics of Stream Geometry

To understand the influence that vegetation has on bedforms in different sized streams, we analyze the way geometric features are organized in each of the channels. One of the most important metrics is the total amount of topographic bedform relief in each channel cross section. In this study, relief is characterized as the lowest elevation at a cross section subtracted from the highest elevation on the opposite side of the channel centerline. The sign of the relief value denotes the cross-stream orientation of the bed. We use the equations

$$r = (z_{min}^{left} - z_{max}^{right}) \tag{3.1}$$

and/or

$$r = (z_{max}^{left} - z_{min}^{right}) \tag{3.2}$$

where r is relief, and z is bed elevation, noted as being either a maximum or minimum on the left or right side of the channel centerline. If $r < 0$, the bed slopes toward the left bank, and if $r > 0$, the bed slopes toward the right.

The cross-stream location of the thalweg must also be evaluated. Since it was not possible to collect downstream flow velocities across the channel, we rely on the bed topography to denote where the highest flow velocities would be in high discharge events. In large river systems, the thalweg is often correlated with the local minimum elevation of the stream, which is inherently related to the cross-sectional relief as described above. But determining the thalweg location, especially in small channels, requires a two dimensional spatial context, wherein the thalweg must be relatively continuous in the downstream and cross stream directions. Local minima may be produced as a result of randomly-placed vegetation, but scour patches do not necessarily host the areas of highest flow rate across the entire stream width. The location of the thalweg is measured as the distance from the left edge of the stream bed. We calculate a normalized thalweg location relative to bed width by

$$T_{loc} = \frac{y_{left} - y_{center}}{b_{bed}} \tag{3.3}$$

where T_{loc} is the normalized thalweg location, y_{left} is the distance of the thalweg from the left edge of the bed, y_{center} is the distance of the channel centerline from the left edge of the bed, and b_{bed} is the half-width of the bed. All values for T_{loc} are between -1 and 1. If $T_{loc} < 0$, the thalweg is on the left side of the stream, and if $T_{loc} > 0$, the thalweg is on the right side of the stream, which follows the same conventions as bedform relief.

From the measured orientations of the channel centerline, we calculate the change in orientation for each downstream cross section as

$$\Delta orient_x = orient_x - orient_{x-1}, \tag{3.4}$$

where $\Delta orient_x$ is the change in orientation from downstream position $x-1$ to x, $orient_x$ is the stream orientation at position x, and $orient_{x-1}$ is the orientation of the stream at one sampling point upstream of $orient_x$. This value provides the magnitude of the orientation change, and the sign on the value denotes the direction of the orientation. With this, we calculate channel curvature [L^{-1}] by

$$curvature = \frac{\Delta orient_x}{dx}, \tag{3.5}$$

where dx is the downstream distance between orientation measurements.

According to our conceptual model, bedform relief in larger channels will be dominated by alluvial processes, such as outside bank erosion and point bar deposition, and small channels will have geometries that are influenced mostly by vegetative obstructions. To test this concept, we can calculate a correlation between relief and curvature. Plots of relief and curvature are displayed in **figures 3.5**, **3.6**, and **3.7**, and correlation coefficients between relief and channel curvature are displayed in **table 3.7**.

The surveyed section of the third order stream contains little curvature, which indicates

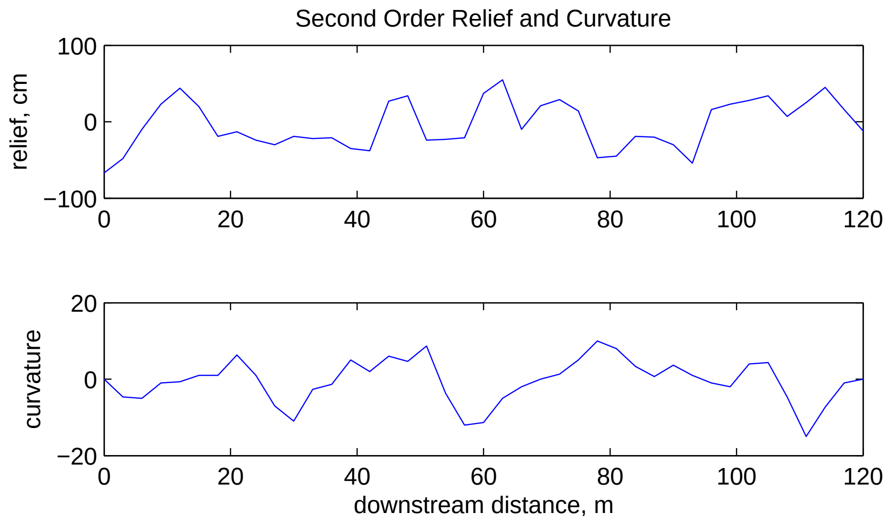

Figure 3.5: Cross section relief and channel curvature for second order channel

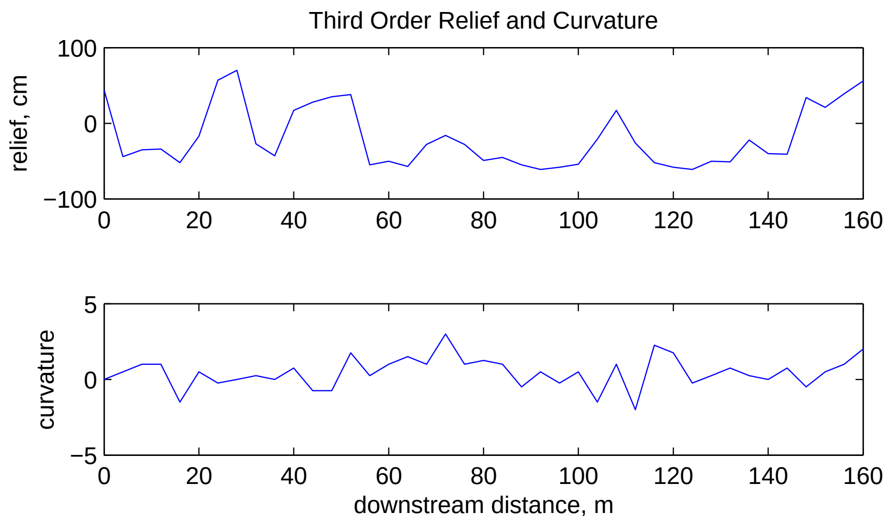

Figure 3.6: Cross section relief and channel curvature for third order channel

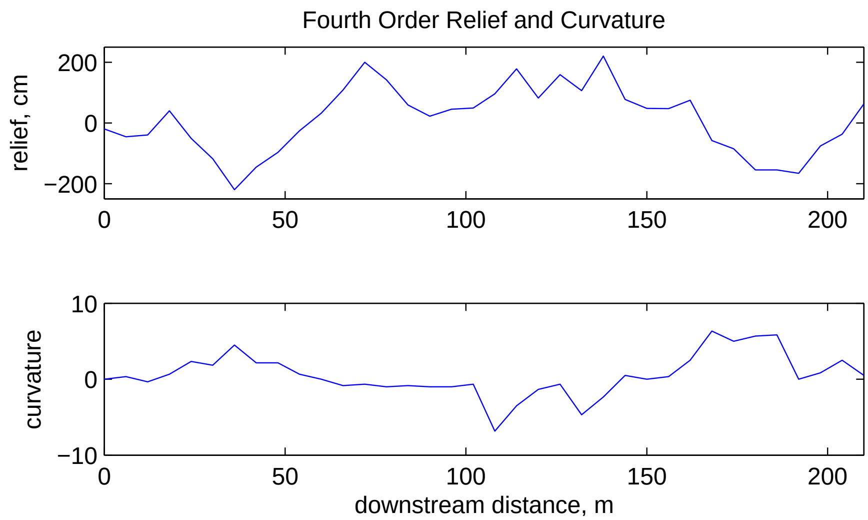

Figure 3.7: Cross section relief and channel curvature for fourth order channel

that the topographic variation in this channel is generated independently from planform geometry. To investigate the relationship between curvature and topography, we focus on the second and fourth order channels which display several high-amplitude bends. The fourth order channel displays the highest correlation between relief and channel curvature (-0.702), while the second order channel shows poor correlation (-0.204). The high correlation coefficient in the fourth order stream implies that the bedform topography is a result of planform curvature, where the outside bends experience bed scour and the inside bends experience point bar deposition. In this stream, riparian vegetation is capable of affecting the local bed topography, as observed in field observations, but the alluvial signal dominates the overall geometry. In the second order channel, the relief is poorly correlated with curvature, which suggests that much of the bedform variation occurs independently of stream curvature. This may indicate that unlike the fourth order channel, the bed of the second order stream is more strongly affected by randomly spaced vegetative disturbances, and the alluvial influence on bedform relief is weaker. This supports the conceptual model, wherein smaller streams are more greatly affected by riparian influences and larger streams assume alluvial patterns that are pocked by vegetative disturbances.

Stream	Correlation Coefficient
2nd Order	-0.204
3rd Order	-0.045
4th Order	-0.702

Table 3.10: Table of correlation coefficients between bedform relief and channel curvature

Since each of the selected reaches differ in flow conditions, geometric properties, and tree density, the physical characteristics of the bed should reflect the differences in morphological agents that create topographic diversity. At the lowest order, there is a strong influence of vegetation on both planform and bed geometry, and the effect of trees diminishes as stream order and size increase. Areas with greater vegetative disturbance tend to exhibit more randomness in bed topography, and streams dominated by alluvial processes show more regular and periodic relief patterns. Computer-generated interpolation grids for each stream based on surveyed bed topography illustrate these distinctive patterns for pool and bar spacing for the second, third and fourth order streams. Grids are displayed in **figures 3.9**, **3.10** and **3.11**.

We expect that the amount of topographic relief at the bed increases with stream order, where greater flow depths and velocities result in higher bed shear stresses. Bed shear stress is calculated by the equation

$$\tau_0 = \rho g H S, \tag{3.6}$$

where τ_0 is shear stress at the bed [M $L^{-1}T^{-2}$], ρ is the density of the fluid [M L^{-3}], g is acceleration due to gravity [L T^{-2}], H is flow depth [L] and S is bed slope. The fluid density and gravitational acceleration remain constant, and for the three surveyed streams, channel slope varies only slightly. Flow depth is the most variable and influential factor in determining the bed shear stress between each of the different stream orders. Average values of cross sectional relief are displayed in **table 3.11**.

The relationship between stream order and topographic variation is intuitive: As stream order increases, flow depth, and thus bed shear stress, also increases, causing a greater

Stream	$\bar{r}$, cm	R_N
2nd Order	29.0	0.0303
3rd Order	42.4	0.0361
4th Order	94.6	0.0351

Table 3.11: Mean relief and nondimensional roughness values for each surveyed stream

amount of work to be applied to the alluvial bed. But this generalization does not allow us to quantitatively compare the total variation in bed morphology at different stream sizes. Since the effectiveness of morphological agents that influence bed topography (i.e. vegetative interference, alluvial processes) varies with stream size, we expect that the resulting bed topographies will also vary at different geometric scales.

To compare bedform organization of differently sized streams, we normalize our values of topographic variation by average bed width to examine non-dimensional roughness measurements. The non-dimensional roughness number for a stream is calculated by

$$R_N = \frac{\sigma_{\bar{x}}}{2\bar{b}_{bed}} \tag{3.7}$$

where R_N is nondimensional roughness, $\sigma_{\bar{x}}$ is the standard deviation of the detrended surveyed bed elevation points, and $\bar{b}_{bed}$ is the average bed half-width.

Calculated values of R_N between the three streams show similar values with no trend relative to stream order, which suggests that despite varying morphological catalysts, the bed relief roughly scales with channel width. Each channel exhibits different curvature patterns and near-stream vegetation densities which appear to influence local morphology, but the overall bed roughness is similar between the channels. Values of R_N are reported in **table 3.11**.

Histograms of surveyed bed topographies were created to illustrate the relative distribution of elevations in each channel. Considering that the R_N values for each stream are similar, we must explore whether the distributions of the bed elevations are also consistent between stream scales. Values of bed elevation normalized by channel width are visible in

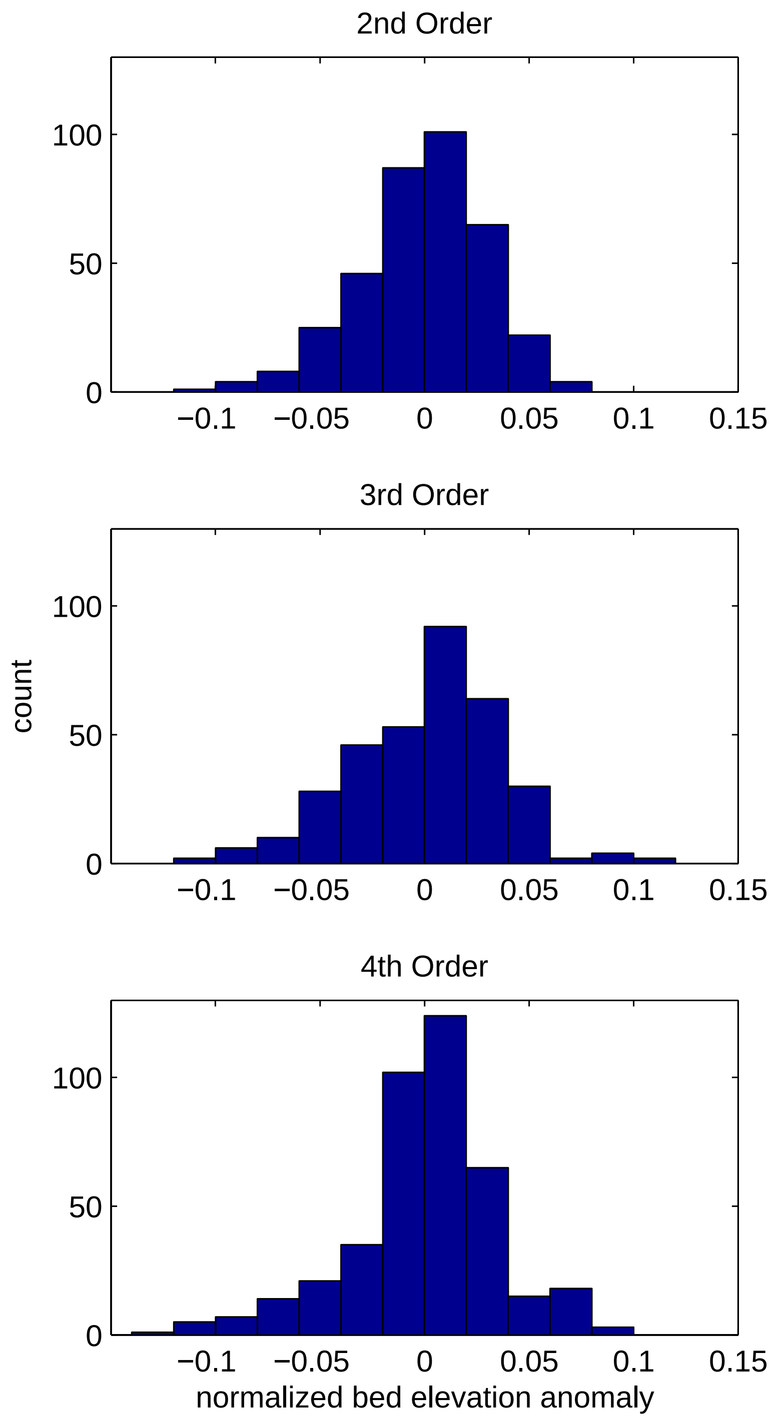

Figure 3.8: Histograms of bed topographies, normalized to channel width

figure 3.8.

Each surveyed stream displays a quasi-normal distribution about the mean elevation, 0, with the mode of the surveyed values slightly greater than zero, indicating that there is more area on the bed that is at a higher elevation than the mean. There is a skew in the negative direction, which is attributed to the development of pools and thalweg at the bed.

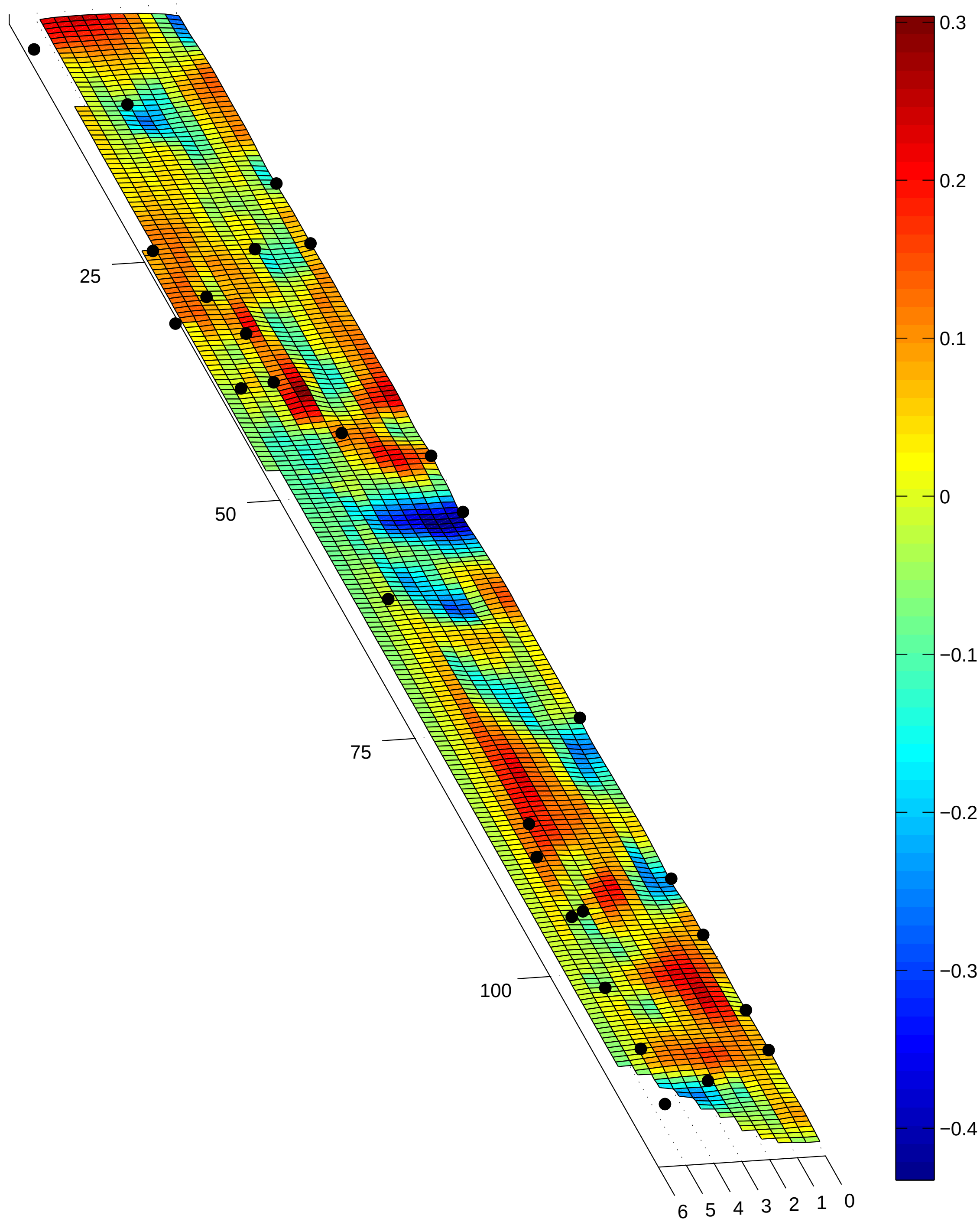

Figure 3.9: Curvilinear interpolation grid of second order stream bed. Flow is oriented from the top left to the bottom right of the figure. Black circles represent locations of documented significant trees. All values are displayed in meters.

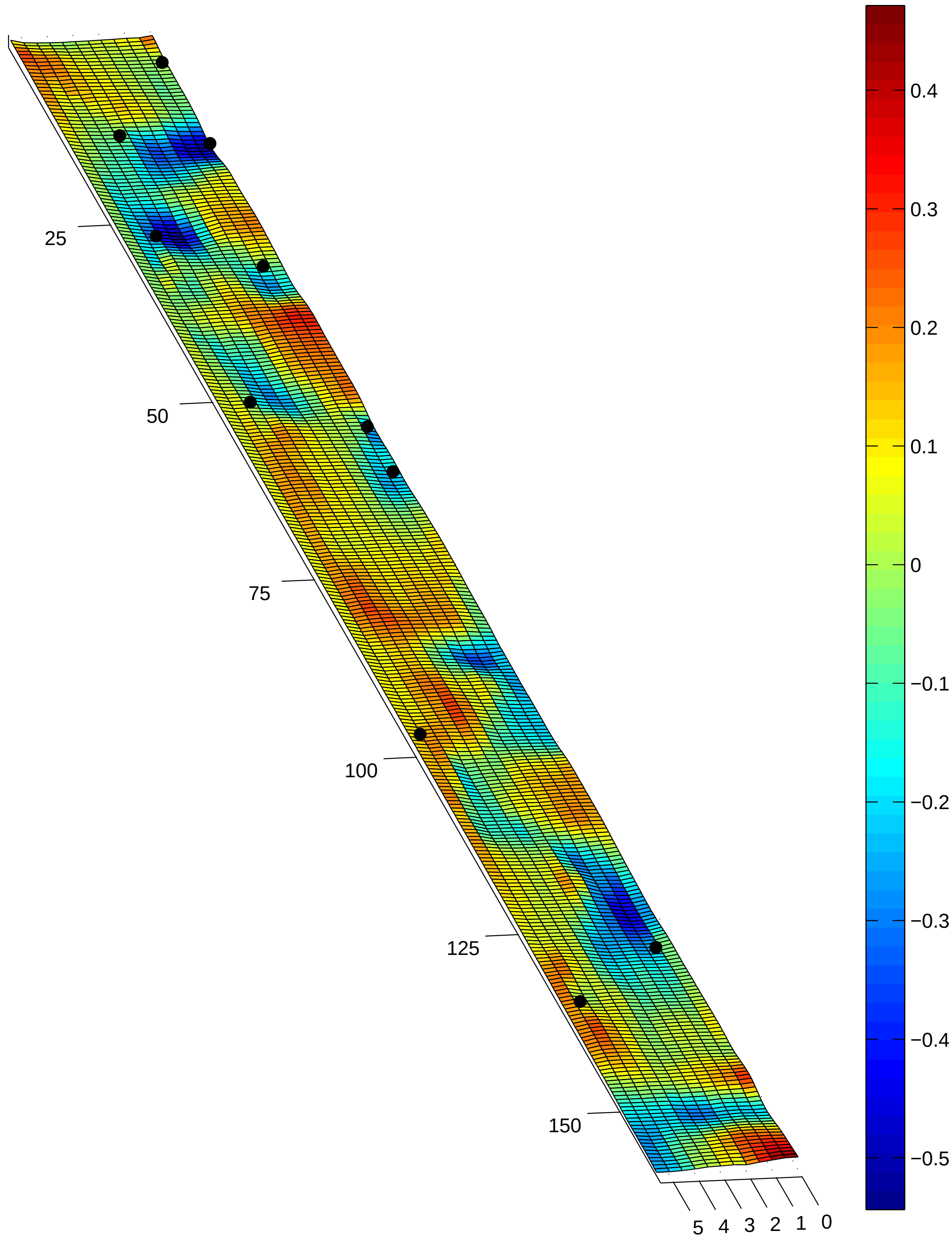

Figure 3.10: Curvilinear interpolation grid of third order stream bed. Flow is oriented from the top left to the bottom right of the figure. Black circles represent locations of documented significant trees. All values are displayed in meters.

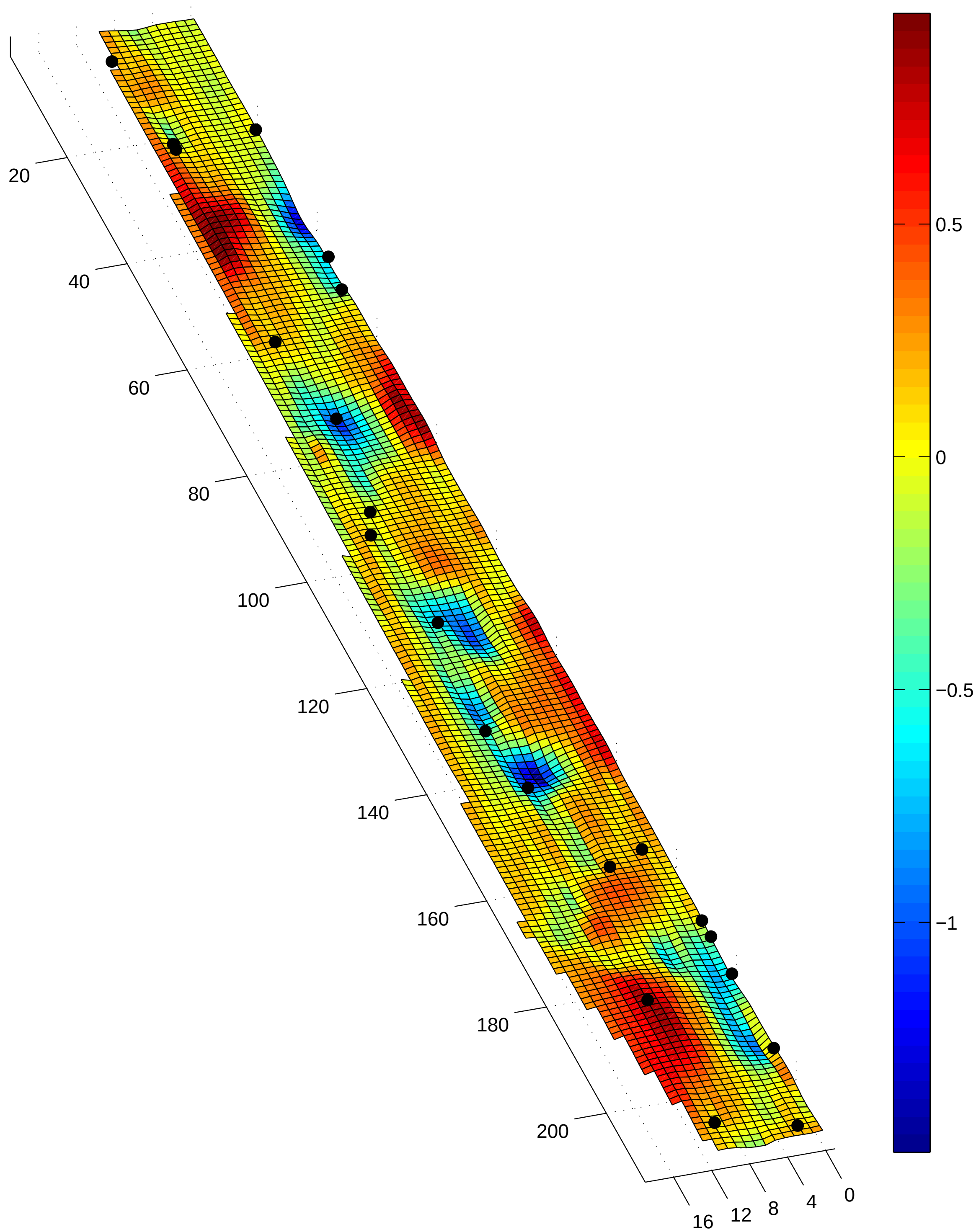

Figure 3.11: Curvilinear interpolation grid of fourth order stream bed. Flow is oriented from the top left to the bottom right of the figure. Black circles represent locations of documented significant trees. All values are displayed in meters.

Chapter 4

Laboratory Experiments

There is an inescapable amount of irregularity in natural field environments, and this irregularity can often disrupt or mask the patterns that we wish to characterize. Flume experiments have been a prominent technique in the fields of fluid mechanics for decades for their simplicity and usefulness [*Ikeda*, 1984; *Fujita and Muramoto*, 1985; *Tal and Paola*, 2010; *Wilkinson et al.*, 2008]. In experimental design, the primary goal is to create a useful model of a natural system that eliminates physical variability that may obscure or complicate results. In this study, we use a stream table to observe the specific effects that riparian obstructions have on bedforms in a straight, alluvially-bedded channel.

In the first experiment, we seek to characterize the influences of riparian vegetation of different size under consistent flow conditions. As our conceptual model states, we expect that when riparian rootwads are large compared to the channel width, they impart more pronounced effects on bedform creation than do smaller rootwads.

Our second experiment is focused on how multiple trees within a section of stream work together to create morphological patterns within the channel. This project is concerned with natural, forested environments with an abundance of trees in close proximity to the channels, so it is important that we understand the effects that the spatial distribution of trees have on alluvial streams.

4.1 General Methods

A stream table was constructed on campus at Vanderbilt University in Nashville, TN. The experimental channel is two meters by 15 centimeters and is filled with roughly seven centimeters of medium-grained sand. The flume is assembled on a plywood bed and the channel walls are placed 15 centimeters apart. A plastic sheet is wrapped on the outer side of the channel walls to prevent water and sediment seepage through the bottom of the flume walls, and sand was piled up on the outer side of each board to stabilize the channel walls. The channel is blocked at the downstream end with a rectangular piece of plywood that serves as a static base level and sediment stabilizer.

The upstream section of the stream table acts as a reservoir that is fed by one hose. The reservoir is filled with pebbles and cobbles to disrupt any jets of water resulting from high flow out of the hose. The water in the reservoir flows through a coarse plastic mesh to induce additional turbulence and homogenize flow conditions across the channel before flowing over the sand bed. The stream table is set at a slope of 0.0095 to represent a gradient that is within those measured in the three surveyed channels at LBL.

The sand bed is set to a planar initial condition before each run. Bed topographies were measured using a wooden dowel wedged between graded blocks placed across the channel. Surveys were conducted at a downstream interval of 5 centimeters and at a cross-stream interval of 1.5 centimeters. For each cross section, the graded block was laid across the tops of the channel walls and the wooden dowel was placed vertically on the bed at each marked cross-stream distance. The height of the remaining end of the dowel above the graded block was measured with a ruler to 0.5mm resolution.

Creating to-scale models requires that some parameters must be neglected in the scaling process. Constructing an experimental stream at a 1:50 scale is of little difficulty, but proper flow conditions cannot be scaled proportionally in a small laboratory model. Following methods used in a similar flume experiment by Wallerstein et al. [2001], we use Froude numbers as a scaling reference in stream experiments. Froude numbers are calculated by

$$Fr = \frac{U}{\sqrt{(gH)}}, \tag{4.1}$$

where U is the average flow velocity, g is acceleration due to gravity, and H is the flow depth.

Froude numbers for each run were calculated by measuring discharge and flow depth. We divide the flow discharge by the cross-sectional area to obtain a distance per time, which serves as the width averaged velocity, U, that can be plugged into **equation 4.1**.

4.2 Experiment 1: Effects of Rootwad Size

4.2.1 Laboratory Methods

To test whether development of pools, bars and thalweg is dependent on geometric scaling between the rootwad and channel, we conducted several experiments under the same flow conditions to observe bed topographies resulting from riparian obstructions of different diameters in a straight, alluvially-bedded channel. Our conceptual model states that when riparian trees are small compared to channel width, the resulting changes to bed topography will be minimal. Conversely, when trees increase in size compared to channel width, their morphological effects will be more pronounced. To simulate changes in relative sizes between riparian trees and streams, model trees with diameters of 1.0, 1.5, and 2.0 centimeters were placed into the channel. The selected diameters of trees represent values of $\overline{d}:\overline{2b}$ ratios within the ranges of those observed in the fourth, third, and second order channels, respectively. Riparian trees were replicated using cylinders of aluminum foil. Since field observations showed that rootwads take on a variety of shapes, cylindrical obstructions provide the most simple model of riparian influence.

In each run, the cylinders were fastened directly to the left bank and placed two millimeters into the sand bed. Each experiment was run at a known flow condition in excess of 20 minutes. Flow conditions for each run are displayed in **table 4.1**. Surveys of the bed were conducted once the bed was no longer saturated with water.

d, cm	Q, cm^3/s	h, cm	S	U, cm/s	Fr	t, min
no tree	503.9	1.20	0.0095	27.99	0.816	24
1.0	503.9	1.21	0.0095	27.76	0.806	22
1.5	497.9	1.20	0.0095	27.67	0.807	23
2.0	502.9	1.20	0.0095	27.93	0.815	23

Table 4.1: Table of flow conditions for each experimental run

4.2.2 Experimental Results

Surveyed bed data for Experiment 1 are displayed in **table 4.2**, and grids of topographies are displayed in **figure 4.1**. A series of migrating ripple-like bed features were formed in each of the surveyed runs, with a wavelength of five to seven centimeters. Since the features move downstream and coincide with waves and ripples on the flow surface, these bedforms are analogous to dunes. Dune orientation, amplitude, and wavelength were not consistent throughout each of the surveyed beds, so they were not systematically corrected for in the data. The inclusion of dune-induced bed topography is considered negligable in the scope of this study.

d, cm	mean relief, cm	σ_z, cm	R_N	σT_{loc}, cm
no trees	0.657	0.225	0.015	2.504
1.0	0.752	0.255	0.017	3.020
1.5	0.980	0.354	0.024	3.022
2.0	1.041	0.397	0.026	3.494

Table 4.2: Table of surveyed data for no trees, 1.0cm, 1.5cm and 2.0cm trees.

The location of the model trees are visible as depressions, or scour zones, on the left bank at 25 centimeters downstream of the beginning of the surveys. Areas of high elevation, manifest as tail bars, are formed immediately downstream of the trees on the left bank and tend to extend several channel widths downstream. The thalweg is formed either at the rootwad scour pool or within several centimeters downstream, and it also moves from the left side of the channel to the right with increasing downstream distance.

The surveyed beds reveal that in the absence of riparian influence, the bedforms do not

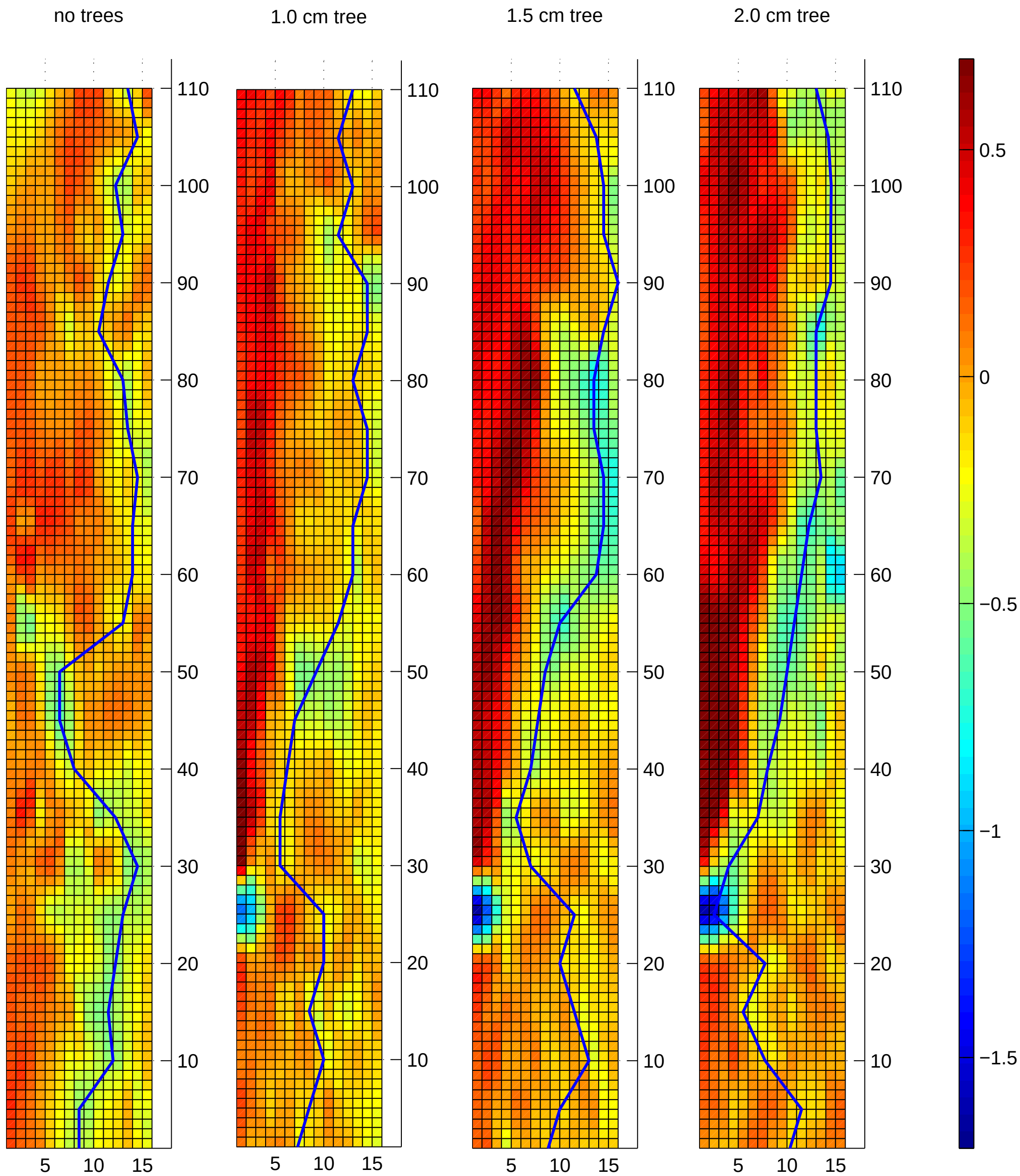

Figure 4.1: Bed topographies for no trees, 1.0cm, 1.5cm and 2.0cm trees and associated thalweg locations. Flow is directed from the bottom to the top of the page. Trees are located on the left bank at 25 centimeters.

display evidence of systematic pool and bar development. The introduction of vegetation induces proximal sediment scour, and distinct bar and thalweg features form downstream of the rootwad. As the size of the riparian obstruction is increased, the beds exhibit increasingly distinguished areas of bar deposition and thalweg scour. Mean relief for each run is calculated as the absolute value of the topographic relief at each surveyed cross section, and values increase with riparian tree diameter.

Histograms of the proportions of bed measurements at specific elevations were created to understand the contribution of topographic variation, and are displayed in **figure 4.2**. The values of the elevation are recorded as residuals about the mean bed elevation, 0. With no riparian influence, the bed topography assumes a fairly normal distribution, and the amplitudes of pools and bars are of equal topographic deviation about the mean. The introduction of the 1.0 centimeter tree yields a fairly symmetrical distribution about the mean, but the variance is increased due to the pool scour and the bar formation immediately downstream. As the vegetation is further increased in size, the variance in the bed topography is increased, with a larger proportion of the bed acting either as a topographic high or low.

To further understand the distribution of bed elevations, we calculate a non-dimensional roughness number, R_N, for each experimental run. The topographic roughness is lowest in the absence of vegetation, and in cases with riparian trees, the roughness numbers increase with tree diameter. The values displayed in **table 3.11** do not reflect R_N values calculated in field studies, but it must be considered that the scope of the survey includes only one tree as opposed to a naturally forested stream system that includes curvature-induced relief.

Topographic relief alone does not properly characterize the influence of riparian vegetation, so we must consider how vegetation affects the direction of flow in the channel. Standard deviations of the thalweg locations, σT_{loc}, were calculated to illustrate how strongly riparian vegetation influences the cross-channel location of the filament of high velocity. Larger σT_{loc} values will indicate a wider range of thalweg locations across the stream,

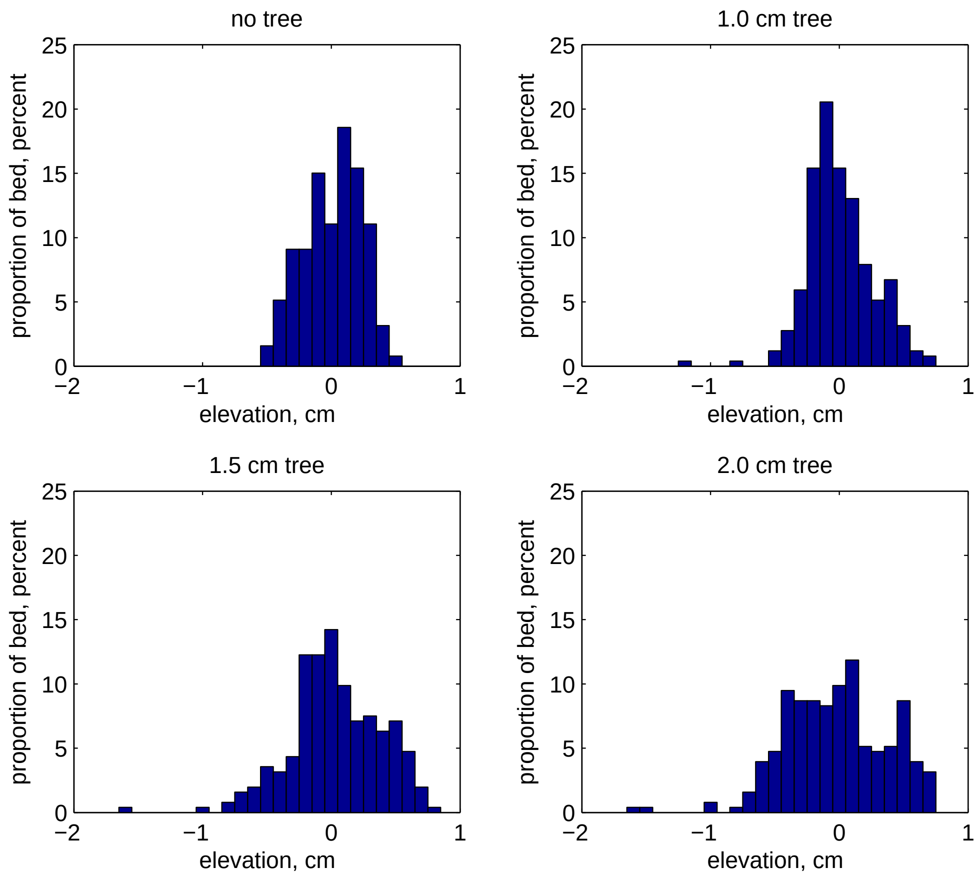

Figure 4.2: Histograms of bed elevation distribution for no obstruction and all tree sizes. Elevations are relative to the mean bed elevation for each run.

suggesting greater influence on flow direction. In the condition with no trees, the thalweg location is somewhat ambiguous, for there is no clear topographic structure or forcing agent that facilitates systematic flow patterns, and the standard deviation of the thalweg location is low. The introduction of vegetation shows that the thalweg moves from the left to the right bank downstream of the rootwads, increasing the variation of cross-stream thalweg location. The standard deviation of the thalweg locations, despite not being based on completely independent values, increases with tree size, suggesting that larger riparian rootwads are more apt to influence thalweg locations downstream. This may suggest that larger trees also are more capable of changing flow direction by "fixing" tail bars and forcing the thalweg toward the opposite bank, stimulating erosion and channel migration in systems with erodible banks.

It should be noted that despite the rootwad scour pool being the minimum elevation on the bed, it does not necessarily host the thalweg. Since the thalweg must be continuous across the stream, the upstream bed elevations and flow conditions must be considered when identifying the filament of highest flow velocity. Only in the 2.0 centimeter run does the thalweg cross through the rootwad pool, and it is likely a result of the flow immediately upstream of the tree. In the 1.0 and 1.5 centimeter runs, the thalweg bypasses the initial rootwad pool, but flows through the scour lobe several centimeters downstream of the rootwad and subsequently follows the zones of lowest elevations.

4.3 Experiment 2: Effects of Rootwad Spacing

4.3.1 Laboratory Methods

If a single riparian tree is capable of creating measurable changes to flow properties and bed topography, it must be considered that the presence of multiple trees and their relative positions will further affect how sediment at the bed will be organized. This concept is particularly important when analyzing the implications that deforestation, ecological succession, and stream restoration practices may have on channel geometry. It has been well documented that streams may develop alternate bar sequences in alluvial channels at predictable wavelengths [*Ikeda*, 1984; *Blondeaux and Seminara*, 1985], and the bars can be free or fixed by channel curvature or obstructions (such as riparian trees). If a riparian tree creates geometric complexity, presence of vegetation at different positions within the channel may amplify or diminish bedform organization. This second experiment conducted in the stream table illustrates the influence that varying downstream vegetation spacings have on bedform morphology.

The trees used in these experiments were 2.0 centimeters in diameter, the largest of the trees used in Experiment 1, to create the most prominent bed topography. The first tree was fastened to the left bank and the other set to the right bank at downstream intervals of 10 centimeters. Cross sections were measured for 65 centimeters downstream of the second tree to record a sufficient amount of the bed. The flow conditions, run times, and surveying techniques follow the same criteria as in Experiment 1. Experimental conditions for each run are displayed in **table 4.3**.

4.3.2 Experimental Results

Survey data for each run is displayed in **table 4.4**, and the surface grids are displayed in **figures 4.3** and **4.4**. Histograms of bed elevation distributions are shown in **figure 4.5**. Since each of the surveys changes in total length, the proportion of the bed upstream of the

d, cm	spacing, cm	length, cm	Q, cm^3/s	h, cm	S	U, cm/s	Fr	t, min
2.0	10	100	498.6	1.2	0.0095	27.70	0.808	24
2.0	20	110	499.9	1.19	0.0095	28.00	0.820	24
2.0	30	120	501.4	1.20	0.0095	27.85	0.812	24
2.0	40	130	497.3	1.20	0.0095	27.63	0.806	23
2.0	50	140	497.6	1.20	0.0095	27.64	0.806	23
2.0	60	150	498.6	1.20	0.0095	27.70	0.808	22
2.0	70	160	500.7	1.20	0.0095	27.81	0.811	26

Table 4.3: Table of flow conditions for each experimental run.

spacing, cm	mean relief, cm	$\sigma_{elevation}$, cm	R_N	σT_{loc}, cm
10	1.113	0.420	0.028	4.07
20	0.976	0.376	0.025	2.46
30	0.955	0.350	0.023	1.95
40	1.011	0.376	0.025	3.56
50	0.932	0.349	0.023	3.30
60	1.378	0.458	0.031	4.87
70	1.066	0.368	0.025	4.06

Table 4.4: Calculated stream table parameters for all downstream tree spacings. Displayed values omit data from the first 15 centimeters of each survey.

riparian vegetation changes between each run, which alters the amount of unaffected bed being included in the calculations. **Table 4.4** and **figure 4.5** omit the first 15 centimeters of the bed and include the cross sections at 20 centimeters and on. The bed grids include all of the cross sections to illustrate upstream flow conditions and thalweg locations.

In many of the surveys, including those in Experiment 1, there appear to be areas of high elevation that surround the rootwad depression. There is no definitive cause of the increase in elevation, but it could be due to backwater effects, flow deflections, or eddies at the boundary between the flow and the rootwad that cause sediment to deposit in close proximity to the obstruction. The high elevations next to the vegetation may inhibit the thalweg from flowing through the rootwad pools, unless the thalweg is already flowing in that direction. In the 10 centimeter spacing, the upstream tree is skipped by the thalweg altogether, and the filament of high velocity is directed into the downstream rootwad pool. The downstream tree in the 20 centimeter spacing run also displays high elevation next to the rootwad, forcing the thalweg into the center of the channel rather than allowing the scour zone to steer the thalweg against the bank. At these downstream spacings (less than two channel widths), the trees may be too close together to act as separate bedform catalysts, and the stream effectively “chooses” which rootwad will have a larger effect on the overall bed topography.

The lowest value of σT_{loc} occurs with 30 centimeters of downstream spacing between trees. The σT_{loc} value under this condition is far lower than any of the other spacings, and values of mean relief and R_N are also among the lowest observed in the experiment. Unlike in the 10 and 20 centimeter spacing conditions, there is little evidence of a coherent tail bar downstream of the second tree at the right bank. At a downstream spacing of two channel widths, the growth of the first bar at the left bank may overpower the development of the second tail bar by causing the thalweg to occupy the right bank of the channel.

Downstream tree spacings of 40 centimeters and longer begin to show more persistent thalweg alternation across the channel. The distance between the two rootwads is sufficient to allow the thalweg to occupy the scour zone from the first tree and flow across the channel into the second rootwad scour pool. This may be due to a lack of interference between rootwad scour, flow deflection, and tail bar formation. As tail bars are given space to develop in the absence of rootwad interference, the thalweg is steered toward the opposite bank into the downstream rootwad pool, inducing further sediment delivery to the scour zone that can be deposited on the downstream tail bar, resulting in another thalweg alternation. In surveys with larger downstream spacings, tail bars become increasingly coherent and well defined following the scour pools at the left and right banks. Additionally, the thalweg and cross-channel relief persist further downstream of the second rootwad.

The surface grids illustrate that in the 60 centimeter spacing, tail bars on both the left and right are of similar elevation and width. The tail bar that follows the second tree in the 70 centimeter spacing exhibits irregular features and elevation distribution. This is due to the fact that the distance between the riparian trees is long enough to allow for dune

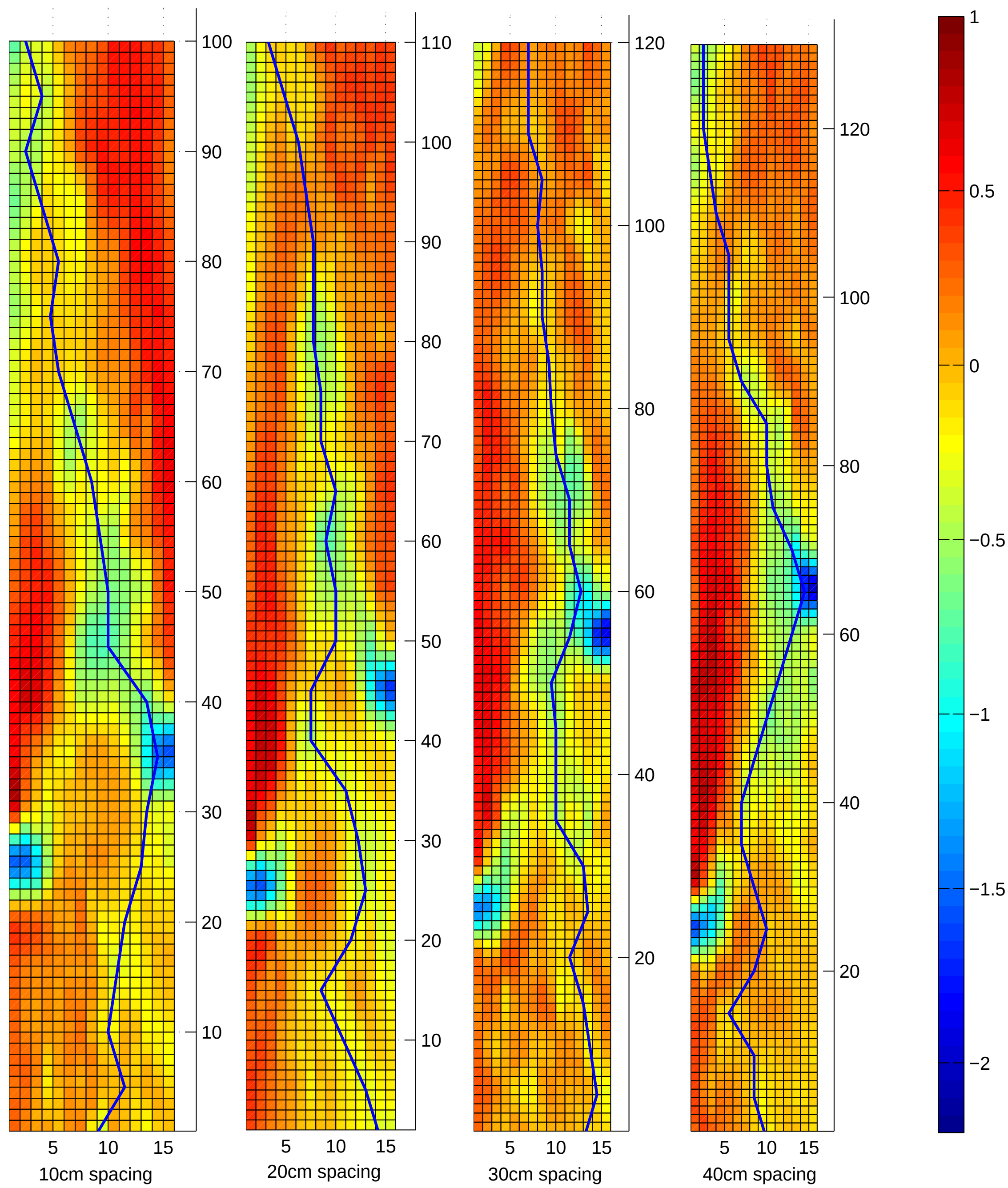

Figure 4.3: Interpolation grids for tree spacings of 10, 20, 30, and 40cm. Trees are 2.0cm in diameter. Flow is oriented from the bottom of the page to the top.

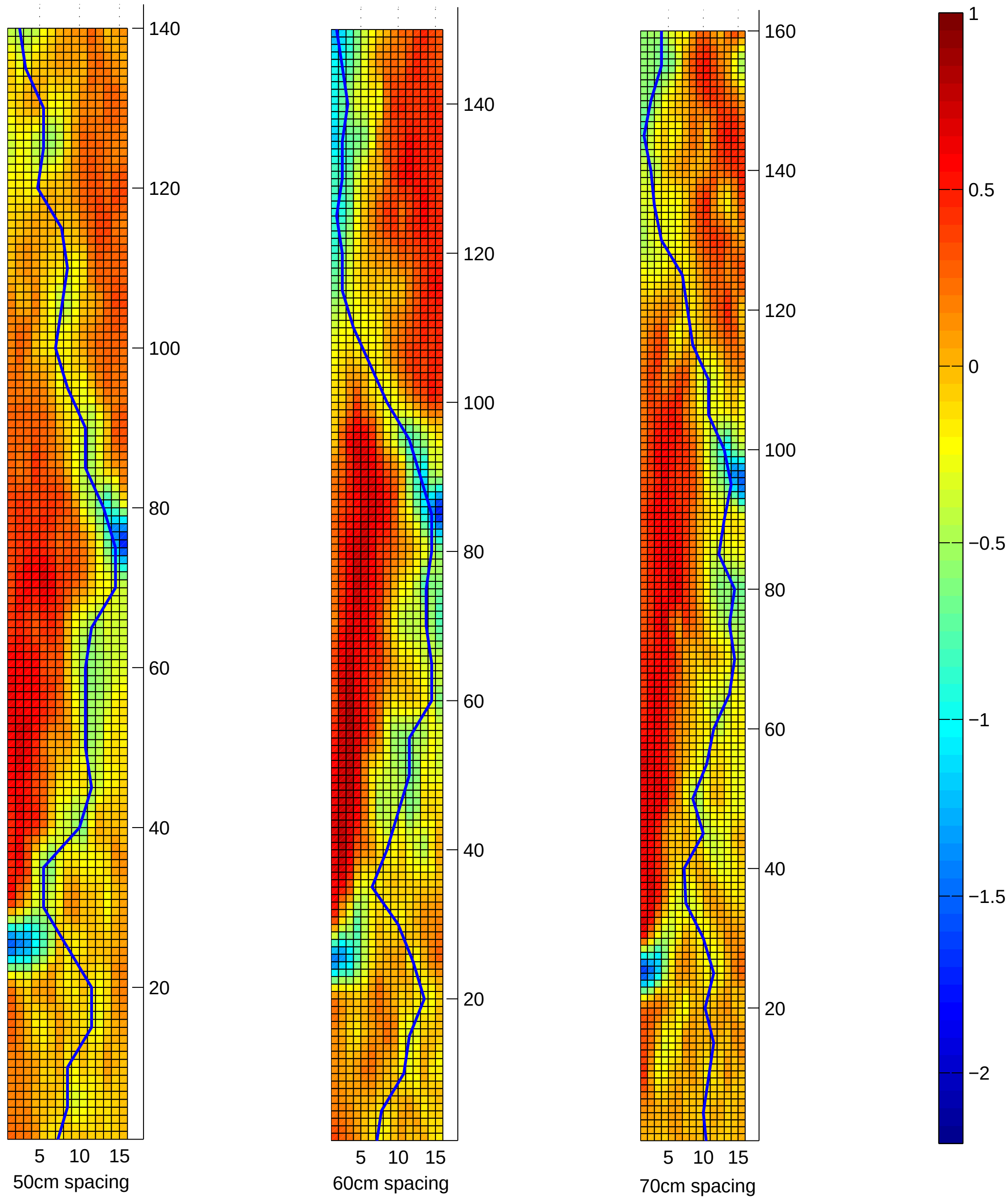

Figure 4.4: Interpolations for tree spacings of 10, 20, 30, and 40cm. Trees are 2.0cm in diameter. Flow is oriented from the bottom of the page to the top.

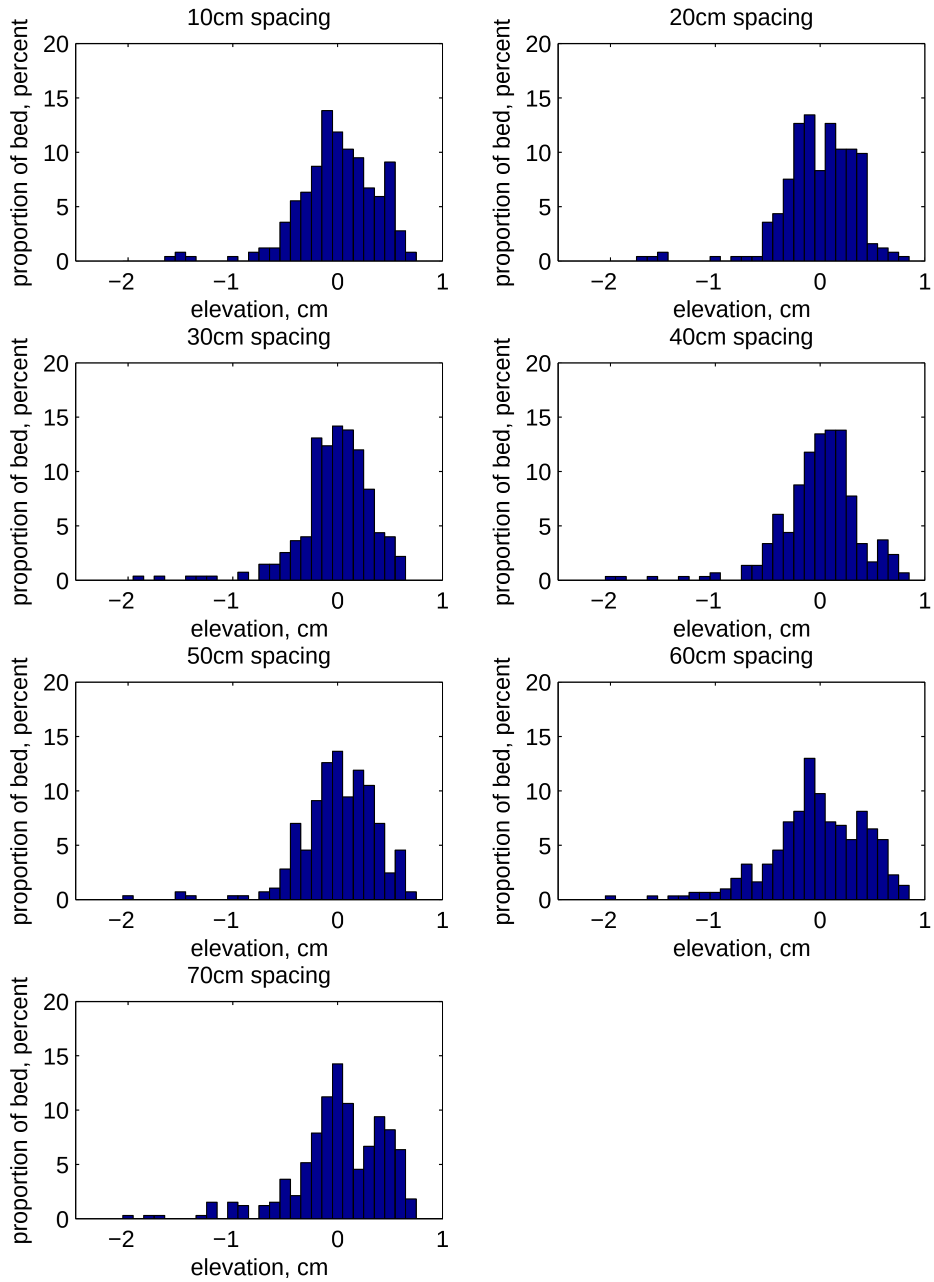

Figure 4.5: Histograms of bed elevations for all downstream spacing of trees.

development within the thalweg. As these dunes migrate into the second scour pool, they deliver pulses of sediment that get deposited onto the bars and diffuse into irregular shapes.

In addition to using σT_{loc} values as a measure of flow forcing via bedforms, autocorrelation of bed relief is calculated for all surveyed runs, and values are displayed in **figure 4.6**. Relief values do not provide a cross-stream position of the areas of lowest elevation, rather they present the value of absolute relief across the transect and denote to which side of the stream the bed is sloped. These calculations elucidate both the amount of relief that persists downstream of riparian influence and the general orientation of the cross-stream bed slope, which may indicate the location of bars and pools.

Autocorrelation figures should not be over-interpreted, but they can illustrate patterns that demonstrate effective bedform development and downstream maintenance. For spacing intervals of 20 and 30 centimeters, where the topography shows little cross-stream influence on thalweg position, autocorrelation shows low and somewhat random values, suggesting that vegetative influences of riparian vegetation are not maintained for long distances downstream. Larger spacings display greater values at long distances, indicating that the amount of downstream relief correlates highly with the upstream values. Some abrupt changes in magnitude occur in the spacings of 50 and 70 centimeters, whereas the 60 centimeter spacing displays the most consistent curve of all of the surveys.

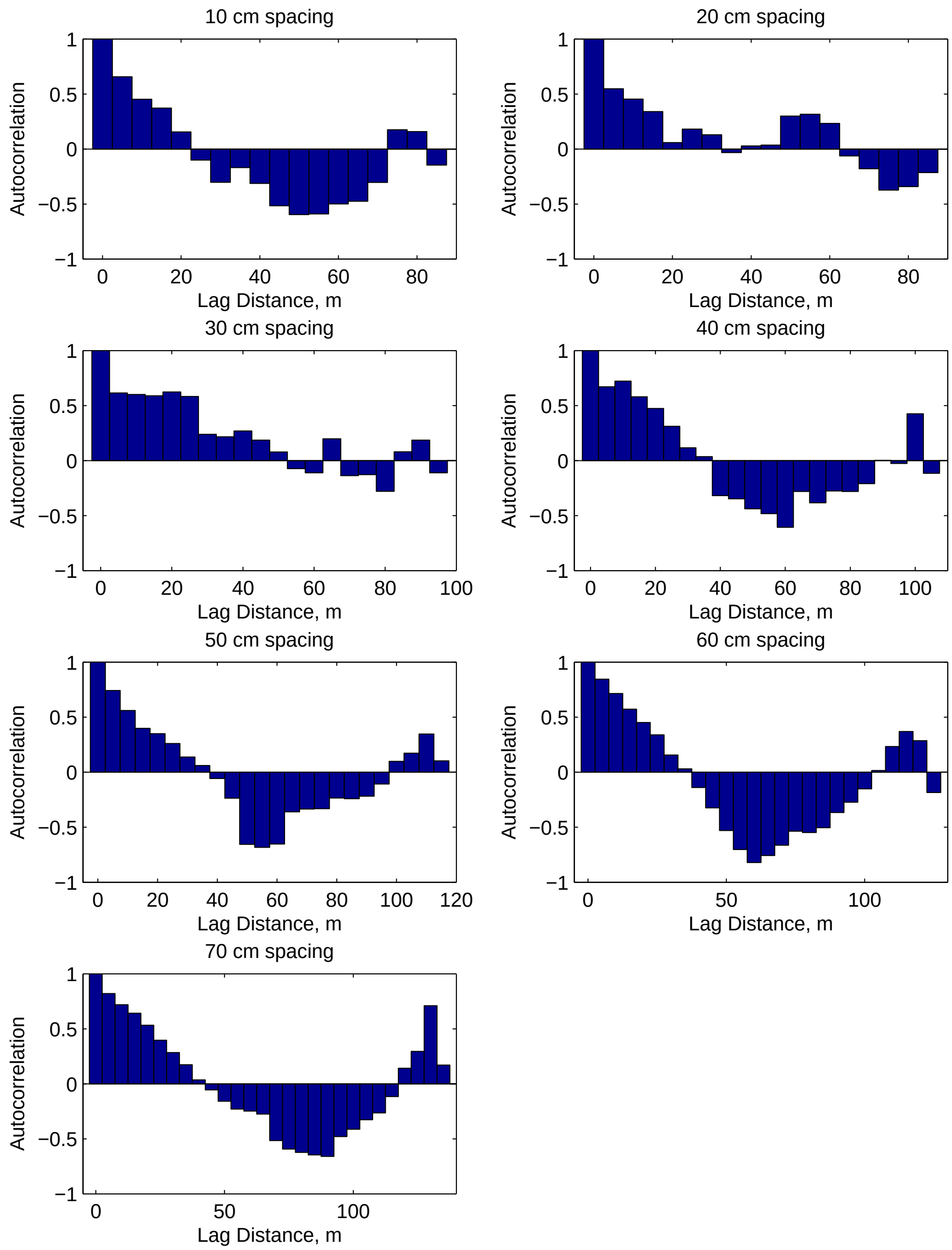

Figure 4.6: Autocorrelation of bedform relief for all tree spacings. The lag distance for each run is the total length of the analyzed survey minus one cross section.

Chapter 5

Discussion

All of the surveyed reaches of Barrett Creek display varying degrees of morphological variation at the bed as a result of hardwood presence in the flow. In many of these cases, relatively large trees create significant scour pools and/or establish thalweg locations downstream. We observe that the average diameter of significant trees increases with bank height, implying that small trees in large channels have little to no effect on bedform processes. In streams with tall banks, fewer trees have root systems that can extend down the channel walls and affect bedform conditions during high flow events. Shorter channel walls allow for small trees to extend towards the bed and influence sedimentation processes. Though not consistent at LBL, channel depth (analagous to bank height) and width often scale together, which implies that as streams increase in width, the necessary size of the trees that affect bedform processes will also increase. This suggests that as stream size increases, the effectiveness of trees to modulate bedform processes becomes limited by the size of the vegetation. Tall banks eliminate the ability of small trees to reach the bed, therefore limit vegetative influence solely as a product of geometric scaling, independent of flow or sediment conditions.

Despite the fact that vegetation and curvature contribute different amounts of topographic complexity to stream beds in channels of different size, the amount of total roughness in each of the surveyed streams is approximately proportional to the channel width. This suggests that in gravel-bedded streams, there is a stable amount of bedform variation that is produced by both vegetative and alluvial processes operating at different degrees.

Several features in the second order stream display evidence of thalweg anchoring via hardwood vegetation. The second order channel exhibits a large number of high-amplitude bends, many of which appear to be affected in some way by riparian trees. This channel also displayed the lowest floodplain forest density, but the highest number of significant trees. It must be noted that a wider range of tree sizes can be considered significant in smaller channels, including those that were too small to be measured in the floodplain forest density, but the organization of the active channel and abandoned chutes may indicate that the stream "searches" for riparian stability. As stated in the Field Observations section, the second order channel tends to widen in the absence of trees, and banks are typically not as well defined, suggesting that the stream is migrating where it is not either anchored or bound by hardwood riparian trees. If this is correct, we assume that the stream migrates across the floodplain until it encounters a tree that will create a scour pool to host the channel's thalweg. The high number of significant trees observed in this channel may be due to migration that occurs until halted by an intersection with vegetation. It was also noted that there are many abandoned channels of various age on the floodplain, and some of them flow adjacent to the oldest trees on the floodplain. This may indicate that the trees have anchored the stream in the past, and that migration and avulsion patterns occur at timescales less than or equal to hardwood tree lifespans.

We observed through experiments that in alluvially-bedded channels, the amount of bed scour and bar formation increases with relative tree size, and both processes can have direct effects on thalweg migration patterns downstream. When the thalweg is located at or near the bank as a result of riparian influence, we assume that there is a higher shear stress against the bank material, which would stimulate erosion at these locations. Since we find that the thalweg is subjected to more topographic forcing in channels with larger tree diameter:width values, the studies suggest that relatively larger trees have greater potential to influence planform geometry in addition to bed topography. Such influences may explain the apparent migration rates observed in the second order channel of Barrett Creek.

Spacing of riparian trees may have a strong influence on how bars and pools are organized within a channel, and such influences can affect planform geometry downstream. It is known that instabilities at an alluvial bed can create alternate bars within a channel that exist at predictable wavelengths [*Ikeda*, 1984; *Blondeaux and Seminara*, 1985] and that these features can be associated with incipient meandering [*Blondeaux and Seminara,* 1985; *Jaeggi,* 1984]. It should be understood that this study is not focused on alternate bar formation, but we must recognize that alluvially-bedded channels develop alternate features at wavelengths that are based on geometric scaling of physical attributes. Stream table experiments at Vanderbilt found that tree spacing of 60 centimeters produced the largest amount of topographic and thalweg-location variability. Since the trees were placed on opposite sides of the stream, the scour pools 60 centimeters apart are one-half of a downstream wavelength, which provides a total wavelength of 120 centimeters. Considering that the flume is 15 centimeters wide, the wavelength of scour pools for the most "effective" tree spacing is eight channel widths. Ikeda [1984] stated that for Froude numbers of 0.8 and greater, alternate bar formation in a stream without obstructions occurs at a wavelength of roughly 9 channel widths. The similarity in the characteristic wavelengths under similar flow conditions suggests that the effectiveness of the 60 centimeter spacing may arise from the phenomenon of "bar resonance," wherein processes of similar wavelengths augment one another [*Blondeaux and Seminara,* 1985]. Bar resonance has been identified as a process associated with bar development and meandering, but this study suggests that free-bar processes and vegetatively-forced scour pools can operate at resonant frequencies that amplify both of their effects. Since the introduction of riparian trees appears to create a coherent, interconnected pool-thalweg system, we can consider optimal spacings of vegetation to act more as a "thalweg resonance" phenomenon, where vegetation at channel-specific spatial distributions may create the most diverse bed morphologies.

The idea of resonance between natural bedform processes and vegetation distribution could have profound implications on stream restoration practices. The introduction of vegetation to streams that have undergone anthropogenic changes to their surrounding environments or general morphology is a common protocol in environmental engineering. Reeds and grasses are often introduced to channels to establish refugia and ecosystem complexity for fish and macroinvertebrates, and riparian trees are sometimes planted to stabilize bank material at outside bends to prevent rapid erosion and land losses. If stream-specific spatial distribution of hardwood vegetation is employed in stream restoration strategies, channel beds may exhibit greater topographic variation and increased connectivity of deep-water areas while using fewer trees and overall human interaction. Ideally, this would also constrain near-bank thalweg locations, those which are susceptible to erosion, to zones that are stabilized by riparian rootwads, which would prevent runaway erosion in anthropogenically affected streams. It should be noted that riparian control of channel migration could only take place in streams with small banks, as observed in the second order reach of Barrett Creek, but it would induce pool scour and bar formation in streams that may otherwise not display biologically favorable environments. Larger channels, like the higher order reaches of Barrett Creek, will likely follow more alluvial planform patterns, where bank erosion and bar deposition produces ample topographic diversity for hosting a wide variety of organisms.

Chapter 6

Conclusions

Hardwood riparian vegetation contributes significant morphological influence to natural streams in forested environments, but studies on the effects that live, standing trees have on channel geometry and morphodynamics have been insufficient in recent decades.

This study illustrates that hardwood vegetation modulates both planform curvature and bedform topography in alluvially-bedded channels. The effectiveness of the riparian influence is proportional to the size of the vegetative obstructions relative to the size of the stream. Both field and laboratory studies show that as the relative size of vegetation is increased, the riparian rootwads are more capable of inducing sediment scour, tail bar deposition, and thalweg steering. In systems where trees are large in comparison to the channel width, vegetation dominates both topographic and planform geometry. As the streams grow in size, alluvial processes override the effects of vegetative disturbance and follow geometries that coincide with classical erosional/depositional mechanisms.

The spacings between trees on forested floodplains can also have significant influence on thalweg development and maintenance downstream. Laboratory studies demonstrate that trees spaced at frequencies similar to those of alternate bar wavelengths may establish resonance that increase connectivity of deep water areas and overall bedform complexity, both of which are vital to healthy and productive stream ecosystems. Further studies on riparian tree spacing can be used to establish more ecologically and economically efficient practices in environmental engineering and restoration.

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