Mechanisms of Vegetation-Induced Channel Narrowing on an Unregulated Canyon-Bound River

Rebecca Blanche Manners
Utah State University

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MECHANISMS OF VEGETATION-INDUCED CHANNEL NARROWING
ON AN UNREGULATED CANYON-BOUND RIVER

by

Rebecca B. Manners

A dissertation submitted in partial fulfillment
of the requirements for the degree
of
DOCTOR OF PHILOSOPHY
in
Watershed Science

Approved:

John C. Schmidt
Major Advisor

Joseph M. Wheaton
Committee Member

Patrick Belmont
Committee Member

Karin M. Kettenring
Committee Member

David Rosenberg
Committee Member

Mark R. McLellan
Vice President for Research and
Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah
2013
ABSTRACT

Mechanisms of Vegetation-Induced Channel Narrowing on an Unregulated Canyon-Bound River

by

Rebecca B. Manners, Doctor of Philosophy
Utah State University, 2013

Major Professor, Dr. John C. Schmidt
Department: Watershed Sciences

The processes and interactions that determine the width of a river channel remain a fundamental area of investigation in geomorphology. An increasing appreciation of the capacity of riparian vegetation to alter fluvial processes, and thus influence channel form, has highlighted the need to include vegetation in these analyses. However, a disconnect exists between the small spatial and temporal scales over which the linkages among flow patterns, sediment, and plants are evaluated and the larger spatial and temporal scales in which river systems operate. In this dissertation, I strove to identify some of the key mechanisms by which vegetation affects channel width. I worked to reconcile the issue of scale by developing a novel tool that resolves patch-scale (sub-meter) patterns of hydraulic roughness over the reach scale. While the approach can be generalized to evaluate any vegetated floodplain, the multi-scalar model was specifically applied to stands dominated by the non-native riparian shrub, tamarisk, that invaded the riparian corridor of southwestern US rivers during the past century.

I focused my analyses on the lower Yampa River in western Colorado. Tamarisk colonized the Yampa in the absence of other environmental perturbations. As a result, adjustments to channel form may be linked to an altered vegetation community. From a careful
geomorphic and vegetation reconstruction of the Yampa, I determined that tamarisk was the driving force in channel narrowing.

Application of the multi-scalar model of vegetation resistance to the Yampa enabled me to reconstruct the changing hydraulic conditions as tamarisk established and the channel narrowed over time. This hydraulic reconstruction furthered our understanding of the interactions among vegetation recruitment patterns, the increased hydraulic resistance, and the changing flow and sediment transport field. Positive feedbacks between vegetation and geomorphic change created additional areas within the channel where tamarisk could establish, and thus accelerated the rate of channel narrowing. However, these feedbacks also changed the importance of common and large floods for vegetation establishment and sediment transport. Application of this process-based understanding to future flow regimes will help managers anticipate locations along the channel that are susceptible to vegetation encroachment and changes to channel width.

(214 pages)
PUBLIC ABSTRACT

Mechanisms of Vegetation-Induced Channel Narrowing
on an Unregulated Canyon-Bound River

Rebecca B. Manners

The accurate prediction of river channel width remains a fundamental area of investigation in the field of geomorphology. River managers and scientists are interested in understanding how a channel will respond to environmental perturbations such as altered runoff patterns from climate change, a new dam, or a pulse of sediment from a landslide. Increasingly, studies that focus on this question acknowledge the importance of accounting for the vegetation that lines the river banks. For this dissertation, I strove to identify some of the primary ways by which vegetation affects channel width.

At a fundamental level, vegetation influences the size of a channel by altering the depth and velocity of flowing water and the transport of sediment. To account for this, I developed a novel method that links small scale interactions among water, sediment, and plants to the larger scale over which channel width is evaluated. While this multi-scalar (i.e., linking multiple scales) methodology may be generalized to any type of vegetation community, I applied it specifically to stands of the non-native riparian shrub, tamarisk that invaded the rivers of the southwestern US during the past century.

I focused my analyses on the lower Yampa River in western Colorado. Tamarisk expansion along the free-flowing Yampa occurred in the absence of modifications to the delivery of water or sediment from upstream that often occur as a result of dams or water development. Where tamarisk established, the channel narrowed. Thus, the Yampa is a unique environmental setting. Without changes to the water and sediment, adjustments to channel form may be linked to an altered vegetation community. A careful reconstruction of the timing, style, and pattern of channel and vegetation changes that have occurred on the Yampa during the past 50 years informed us on the important processes by which the expansion of vegetation affects channel width. Specific attention was paid to the relative importance of commonly occurring vs infrequent, large floods in driving these processes.

Tamarisk establishment enhanced not only sediment deposition that leads to channel narrowing, but also to new vegetation establishment. Plants increased the friction in the channel, thus decreasing water velocity close to plants. Low velocity areas became susceptible to further vegetation encroachment, particularly if they did not have high velocities for a series of ~4 or more years. As vegetation encroached and changed the shape of the channel, the importance of common and large floods, for vegetation establishment and sediment transport, changed. Application of this process-based understanding to future flow regimes will help managers anticipate locations along the channel that are susceptible to vegetation encroachment and changes to channel width.
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First and foremost, I would like to thank my mentor and friend Jack Schmidt. Jack’s long-term dedication to the study and protection of the rivers of Dinosaur National Monument and the Colorado River basin has been an inspiration for me. Jack provided me with numerous opportunities to grow as a scientist, supported my academic inquiries, and pushed me to think critically. I valued the time spent in the field with Jack. He taught me to be a good field scientist and boatman. I would also like to thank my committee members, Drs. Joe Wheaton, Patrick Belmont, Karin Kettenring, and David Rosenberg. I am appreciative of their feedback and guidance.

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Rebecca B. Manners
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CHAPTER 1
INTRODUCTION

Channel width scales with discharge [Lacey, 1930; Leopold and Maddock, 1953; Lane, 1955], but the processes and interactions by which channel width is maintained are still poorly understood. Geomorphologists have, for many years, acknowledged that vegetation impacts the size and shape of the channel [e.g., Zimmerman et al., 1967; Graf, 1978]. However, recent laboratory experiments [Jarvela, 2004; Nepf and Ghisalberti, 2008], numerical models [Griffin et al., 2005; Crosato and Saleh, 2011], and physical models using scaled vegetation [Tal and Paola, 2007; Braudrick et al., 2009] have increased our appreciation of the fundamental role riparian vegetation plays in determining channel form.

A thorough understanding of the mechanisms by which vegetation affects channel width is challenging because the interaction among vegetation, water, and sediment results in highly non-linear adjustments [Corenblit et al., 2007]. One-way interactions among vegetation, water, and sediment are relatively well studied. Great progress has been made in isolating the impact of single stems, or small patches, on the flow and sediment transport field [e.g., Bennett et al., 2002; Jarvela, 2002]. Similarly, we know a good deal about the influence of stream flow patterns and fine sediment availability on the establishment and success of vegetation [Auble et al., 1994; Scott et al., 1996, 1997; Mahoney and Rood, 1998]. However, in a natural river, a single plant or patch of vegetation is situated within a larger setting. Interactions characterized in a laboratory may only be applicable for a short time period and for a limited spatial extent. As the flow regime, channel morphology, or vegetation stand composition or structure (e.g., height) changes along a river corridor, or over multiple decades, simple one-way interactions give way to complex feedbacks [Heffernan, 2008; Dean and Schmidt, 2011].

Field studies provide critical commentary on these interactions, particularly over the larger spatial and temporal scales in which river systems operate. Important processes responsible
for vegetation establishment and the erosion or deposition of channel and floodplain sediment continuously occur. Where the riparian vegetation community has expanded and the channel narrowed within the modern record, these processes are often preserved within newly constructed floodplains and stands of vegetation [Schumm and Lichty, 1963; Friedman et al., 1996; Allred and Schmidt, 1999; Birken and Cooper, 2006]. Many narrowing river channels, however, do so in response to multiple, and often simultaneous, changes to environmental conditions (e.g., dam closure and the expansion of invasive, non-native vegetation). In such field studies, it is difficult to isolate the driving mechanisms of channel changes, particularly the role of vegetation relative to reductions in flow.

This dissertation focuses on the lower Yampa River in Dinosaur National Monument, western Colorado, where human modifications to the flow regime and presumably sediment supply have not occurred within the modern record (~ 90 years) [Elliott and Anders, 2004]. However, the non-native riparian shrub tamarisk (Tamarix spp.) has invaded the riparian corridor. Where tamarisk has established, the channel has narrowed [Larson, 2004]. Thus, the Yampa River has qualities of a laboratory experiment wherein most environmental conditions have been controlled, and of a field study, where the processes that have created today’s narrower channel have continuously occurred for the past century. I take advantage of this natural, field-scale, experiment to identify the mechanisms by which vegetation alters fluvial processes to create a narrower channel. I ask the questions, “how is channel width influenced by vegetation,” and more importantly “what are the mechanisms by which vegetation alters fluvial processes in order to create a narrower channel and simplified planform?”

I work at multiple scales, from the individual plant to the reach, to identify and describe the geomorphic and vegetation history of the Yampa River. These histories provide new insight on the channel processes and resulting morphologies that dominated an unregulated, large southwestern river within the last century. These histories also illustrate the process by which an invasive riparian plant species colonizes the riparian corridor of a wild river and change the cross-
section. For the various scales I develop a unique suite of observation- and process-based modeling tools. These tools allow me to look at the long-term impacts of vegetation on channel form at the meaningful scale of a channel reach. In the following chapters I present the range of insights gained from the field and modeling analyses I completed on the Yampa River. This dissertation is one of the first to build a process-based understanding of the vegetation-geomorphic linkage at the field scale.

Chapter 2 presents an innovative multi-scalar model that resolves patch-scale patterns of hydraulic roughness over the reach scale caused by stands of shrubby riparian vegetation. While the concept of upscaling detailed patch-scale information was inspired by Hodge et al. [2007], the multiscalar analysis presented in Chapter 2 is the first to mechanistically account for shrubby riparian vegetation stand structure, and associated hydraulic roughness at the reach scale. I relied on this model of vegetative resistance in Chapters 3 and 4.

At a fundamental level, the processes that cause channel narrowing result from the small-scale interaction of stems, stream flow, and transported sediment [Schnauder and Moggridge, 2009]. However, the geomorphic implications for these small-scale processes are typically observed and investigated at larger spatial scales, such as that of a reach (10-20 channel widths). While some progress has been made in quantifying vegetation resistance patterns over large spatial scales [Mason et al., 2003; Stoesser et al., 2003; Griffin et al., 2005], these studies make many assumptions about the stand structure and corresponding hydraulic resistance. This chapter is therefore motivated by the need to link small-scale processes with the larger pattern of vegetation in order to evaluate the impact of vegetation on the larger-scale flow and sediment transport field.

Detailed terrestrial laser scan (TLS) data, collected for 12 patches of tamarisk and willow on the Yampa and Green Rivers in Dinosaur National Monument, characterized the stand structure. Two-dimensional, patch-scale, hydraulic models were used to parameterize the stage dependence of hydraulic roughness for each patch. Taking advantage of the overlap in coverage
of less detailed, yet more spatially extensive airborne LiDAR (ALS), we extrapolated the patch-scale relationships to the entire floodplain of the two study areas. Results from this model were applied to a 2D reach-scale model of the Laddie Park site on the Yampa River. We compared model runs that included our vegetation roughness model to those with spatially uniform roughness. Our results highlight the importance of explicitly accounting for riparian vegetation and its hydraulic roughness in determining geomorphically relevant patterns (i.e., areas of high and low shear stress).

Chapter 3 presents the history of channel form and tamarisk coverage as they mutually adjusted on Yampa River in Yampa Canyon, Dinosaur National Monument during the past 50 years. In this chapter, I describe an integrated story of the rate and style of geomorphic change and the timing and pattern of tamarisk encroachment. Evidence comes from extensive field campaigns, analysis of remotely sensed data, and hydraulic models. Chapter 3 stands on the shoulders of other studies in the Colorado River basin [Graf, 1978; Hereford, 1984; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Birken and Cooper, 2006] and elsewhere [Dean and Schmidt, 2011] that integrate vegetation and geomorphic histories to understand how modifications to boundary conditions impacted the trajectory of changes in channel form that has led to narrower channels and a simplified planform. These histories inform us on the condition of the rivers of the Southwestern United States as humans altered flows and the climate changed and therefore, help us determine what the future condition of these rivers will be. With its relatively unregulated hydrology, the environmental history of the Yampa River provides a critical piece of this larger story.

As mentioned above, the Yampa River also represents a unique situation, where non-native vegetation established on an otherwise unregulated river. Thus, the geomorphic and vegetation history provides a key field study on how channel width is influenced by vegetation. A precise evaluation of the spatial and temporal trends in the mutual adjustment of vegetation cover and the cross section isolates the role vegetation. With specific attention to the interactions and
feedbacks among hydrology, tamarisk, and sediment, I identify the likely mechanisms by which vegetation alters fluvial processes to change channel form.

Chapter 4 extends our process-based understanding of the mechanisms of vegetation-induced narrowing. This chapter predominately focuses on the multi-thread planform of Laddie Park. Laddie Park has experienced significant planform simplification over the past 50 years, as tamarisk invaded and the channel narrowed. Multi-thread planform settings, while relatively rare in the Colorado River basin, provide critical habitat for the endemic, endangered fish species [Tyus and Karp, 1989]. Such reaches are relatively wide, support multiple channels and are the first to respond to changes in stream flow [Van Steeter and Pitlick, 1998; Allred and Schmidt, 1999]. A growing literature has begun to identify variables that promote the stability, or instability, of the multi-thread planform, predominately in braided rivers or experimental settings [e.g., Federici and Paola, 2003; Burge, 2006; Bertoldi, 2012]. However, the driving forces that maintain this type of planform in rivers of the basin that have high suspended sediment loads are poorly understood.

To define these driving forces, I take advantage of the robust historical and contemporary datasets that I collected for the Laddie Park site. With the development of an observation-based model of topographic change [Perona et al., 2009], I evaluate the patterns of erosion and deposition for the flood regime. This simple tool allows me to identify those floods that prevent the accumulation of fine sediment and, therefore, allows me to identify those floods that maintain channel form. I apply the observation-based model to present conditions as well at two periods of time in the past 50 years that represent stages in the transition of a multi-thread planform towards a simplified single-thread channel. A process-based historical perspective helps to identify the relationship among floods, geomorphic change, and vegetation. From this analysis, I test the hypotheses formulated with the stratigraphic and dendrogeomorphic results presented in Chapter 3.
Threats to develop the water resources of the Yampa River provided additional motivation to understand the maintenance of multi-thread settings, especially the role of different flood sizes. I took a novel approach to defining geomorphically relevant environmental flows (i.e., channel maintenance flows). Many studies identify the dominant discharge that is responsible for transporting most of the sediment [Andrews and Nankervis, 1995; Pitlick and Van Steeter, 1998], or the critical discharge that initiates movement of gravel [Reiser et al., 1989; Kondolf and Wilcock, 1996]. Instead, I define channel maintenance flows as those that preserve a critical aspect of channel form, the multi-thread planform. I apply the observation-based predictive model to future flood regimes based on different water removal scenarios and identify floods critical for the maintenance of channel form. This approach accounts for the whole flood regime, and therefore represents a significant step towards incorporating the complexity of geomorphic processes in a management recommendation [Ligon et al., 1995].

Chapter 5 summarizes the findings from the previous chapters. Additionally, this chapter synthesizes the insights gained from the natural field experiment on the Yampa River and discusses the future condition of the river.

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CHAPTER 2
MULTI-SCALAR MODEL FOR THE DETERMINATION OF SPATIALLY EXPLICIT RIPARIAN VEGETATION ROUGHNESS

Abstract

Improved understanding of the connection between riparian vegetation and channel change requires evaluating how fine-scale interactions among stems, water, and sediment affect larger-scale flow and sediment transport fields. We propose a spatially explicit model that resolves patch-scale (sub-meter) patterns of hydraulic roughness over the reach scale caused by stands of shrubby riparian vegetation. We worked in tamarisk-dominated stands on the Yampa and Green Rivers in Dinosaur National Monument, northwestern Colorado, USA, where questions remain regarding the role of vegetation in inducing or exacerbating documented channel changes. Hydraulic roughness patterns were derived from patch-scale measurements made with detailed terrestrial laser scan (TLS) data that were extrapolated to reach scales based on correlation with LiDAR (ALS) data. Two-dimensional, patch-scale, hydraulic models were used to parameterize the stage dependence of hydraulic roughness of typical patch types (i.e., sparse, moderate, and dense patches). We illustrate the value of using this approach to characterize vegetation roughness by applying our results to a 2D hydraulic model of flow for one of our study sites. Results from this work predict that the roughness of vegetated floodplains increases with flow depth and is dependent on patch-scale stem organization. Geomorphically-relevant patterns (i.e., areas of low or high shear stress that are likely to scour or fill during high flows) become apparent with the detail introduced by spatially explicit, depth-dependent roughness. To our knowledge, the multi-scalar analysis presented here is the first to mechanistically account for shrubby riparian vegetation stand structure, and associated hydraulic roughness of vegetation patches, at the reach-scale.
1. Introduction

Riparian vegetation encroachment onto active alluvial surfaces can significantly modify channel form, resulting in narrowing and simplification of planform [Tal and Paola, 2007; Corenblit et al., 2009]. An improved understanding of the processes that link vegetation and geomorphic form is especially important in light of major shifts in riparian communities caused by water development [Rood and Mahoney, 1990; Auble et al., 1994; Merritt and Wohl, 2006], climate change [Meyer et al., 1999; Gibson et al., 2005], and the invasion of non-native species [Friedman et al., 2005].

At a fundamental level, vegetation-induced channel change results from the interaction of stems, stream flow, and transported sediment [Schnauder and Moggridge, 2009]. Stems perturb the flow field, modifying the distribution of velocity and shear stress, and, as a result, patterns of sediment entrainment and transport [Nepf et al., 1997; Bennett et al., 2002; Zong and Nepf, 2010]. Over time, these patterns may cause net erosion and deposition, which are the mechanisms that alter the channel cross-section and/or planform.

Although the processes that cause channel narrowing occur at small spatial scales, the geomorphic implications of these processes are typically observed and investigated at larger spatial scales, such as that of a reach (10 to 20 channel widths). There has been limited progress in applying the insights gained from stem-scale studies to the reach-scale changes that are of geomorphic significance [Forzieri et al., 2012]. One approach to applying small-scale insights to larger scale processes involves development of techniques and classification schemes that empirically link coarsely measured vegetation attributes, such as vegetation height [Cobby et al., 2001; Mason et al., 2003], crown characteristics [Antonarakis et al., 2008; Forzieri et al., 2011], species [Stoesser et al., 2003], or vegetation “type” (i.e., shrub vs. grass, flexible vs. rigid) [Darby, 1999; Brookes et al., 2000] to the hydraulic resistance of vegetation. Application of these techniques and classification schemes requires assumptions about stand structure, either applied
as typical attributes [e.g., Griffin et al., 2005], or through inferred relationships linked to a single variable (i.e., vegetation height) [e.g., Mason et al., 2003]. However, riparian vegetation communities often have species assemblages and stand ages that result in variable stand structure. In these cases, techniques based on coarsely measured variables oversimplify the hydraulic effects of vegetation. Additionally, many riparian corridors are dominated by shrubby species [Friedman et al., 2005] whose stand structure is complex and cannot be characterized based on canopy structure.

The ability to control environmental conditions in a laboratory setting has resulted in improved methods to quantify the stem-scale impact of vegetation on the flow field. Such approaches are capable of accounting for specific attributes of vegetation structure, including stem density, stem spacing, flexibility, and relative submergence [Petryk and Bosmajian, 1975; Bennett et al., 2002; Jarvela, 2004; Liu et al., 2008]. These physically meaningful results are limited in spatial extent, suffer from issues of how to apply the results to larger scales, and are generally restricted to idealizations of vegetation, rather than actual plants. Little progress has yet been made on how to apply the ever-improving insights gained from small-scale studies in laboratories to the field scale.

In this study, we linked detailed measurements of stand structure derived from terrestrial laser scanning (TLS; also called ground-based LiDAR) to reach-scale riparian vegetation patterns derived from airborne LiDAR (also referred to as airborne laser scanning; ALS). Acknowledging that fine-scale interactions among stems, water, and sediment may be critical in the accurate identification of the role of riparian vegetation, we developed a method that merges small-scale, high resolution, TLS data and broader-extent ALS data. We related TLS data collected at the patch scale ($10^0-10^1$ m) to the reach scale ($10^2-10^3$ m) using a scaling methodology. This methodology does not necessitate a “brute force” approach where high resolution TLS data are collected for an entire reach. Our method is inspired by the fact that TLS is not practical to deploy over large areas or in thick vegetation. We describe a methodology to extrapolate detailed TLS
data to the reach scale. We quantify the patch-scale stand structure of shrubby riparian vegetation using TLS data; relate physically based, depth-dependent roughness to stand structure; upscale these relationships from patch scale to reach scale using ALS data; and, describe the response of reach-scale flow hydraulics to the patch-scale distribution and structure of riparian vegetation. We conclude by discussing the implications of riparian vegetation invasion on channel hydraulics by using our method to model the bed shear stress distribution in the absence and presence of riparian vegetation. Although we present only limited field verification of our model, the methodology described here represents a novel effort to account for variable stand structure and its effects on reach-scale hydraulics.

2. Tamarisk in the Colorado River Basin

We focused on the invasive non-native riparian shrub tamarisk (*Tamarix spp.*). During the past century, tamarisk has densely colonized alluvial valleys of most of the Colorado River system. A general trend in these valleys has been towards denser vegetation encroaching along the margins of the active channel and greater dominance by tamarisk and native willow species (*Salix spp.*). A decline of bare, dynamic, sand bars has generally led to the simplification of channel planform [Turner and Karpiscak, 1980; Webb et al., 2007].

Tamarisk’s spread through the basin was concurrent with other environmental shifts, including the closure of large dams and 20th century climate change [Graf, 1978; Allred and Schmidt, 1999; Birken and Cooper, 2006]. As a response to the changes in these environmental drivers, channel narrowing has been ubiquitous [e.g., Hereford, 1984; Grams and Schmidt, 2002]. There is extensive documentation of channel narrowing by inset floodplain formation in many parts of the Colorado River basin [e.g., Graf, 1978; Hereford, 1984; Grams and Schmidt, 2002]. These studies implicate either of two causes of narrowing. One potential cause is the invasion of riparian vegetation that results in increased bank stabilization and roughness that induces sediment deposition [Graf, 1978; Birken and Cooper, 2006; Dean and Schmidt, 2011]. The other
potential cause is decreased flood flows due to water development. Decreased flows may result in sediment mass balance surplus, leading to the development of inset floodplains, regardless of whether or not invasive riparian vegetation is present [Everitt, 1993; Allred and Schmidt, 1999]. Improved understanding of the mechanisms by which riparian vegetation affects the local hydraulics through tamarisk stands and, in turn, larger-scale flow patterns is essential for understanding the relative role of these two causes of narrowing [Schnauder and Moggridge, 2009].

3. Study area

Our study was comprised of two sites in Dinosaur National Monument (Figure 2.1), located in the middle Rocky Mountains in eastern Utah and western Colorado: Laddie Park in Yampa Canyon on the Yampa River, and Seacliff in Whirlpool Canyon on the middle Green River downstream from the Yampa. The channels at both of these sites have progressively narrowed during the 20th century [Grams and Schmidt, 2002]. The oldest surviving tamarisk individual recovered to date in this area germinated in 1938 [Cooper et al., 2003]. We analyzed extensive geomorphic, hydrologic, and vegetative data obtained from ongoing data collection efforts at the two sites [Manners et al., 2011]. Additionally, ALS data were obtained from a flight over the study sites in October 2008, and 3-band multispectral imagery was obtained from a flight in June 2010.

The two study sites are both 0.6-km long (Figure 2.2). Laddie Park is in the downstream part of Yampa Canyon where the Yampa River has established a series of incised meanders. The average channel slope is 0.0009, and the average channel width is 106 m [Larson, 2004]. In contrast, the Green River in Whirlpool Canyon has a steeper slope (0.002) and narrower channel width (64 m) [Grams and Schmidt, 2002]. Whirlpool Canyon is a debris-fan affected canyon. In such a canyon, fan-eddy complexes occur wherever debris fans partly constrict the channel, thereby creating backwaters upstream from the debris fan and lateral separation eddies and
expansion gravel bars downstream [Schmidt and Rubin, 1995]. The flow regime of the Yampa River is relatively unregulated, but the flow regime of the middle Green River reflects the combined influences of the Yampa River and the flow regulation by Flaming Gorge Dam on the upper Green River [Grams and Schmidt, 2002].

Laddie Park is in a relatively wide part of Yampa Canyon where there are discontinuous floodplains, an island that splits the channel, and mid-channel bars. Laddie Park is upstream from a pronounced bedrock bend in the river whose radius of curvature is small. At flood stage, flow is backwatered upstream from this bend. The island and parts of the floodplain in Laddie Park have been progressively colonized during the past 70 years with tamarisk, sandbar willow (Salix exigua), and to a lesser extent, box elder (Acer negundo). Today, the woody riparian vegetation community of the Laddie Park reach is 86% tamarisk, 11% sandbar willow, and 3% box elder.

The Seacliff site consists of a series of small debris fans and eddy bars on river left. We focus on the eddy bars that have been progressively colonized by tamarisk during the past 60 years. Today, the woody riparian vegetation community of these bars in the Seacliff reach is composed of 62% tamarisk and 38% box elder.

4. Characterization of patch-scale stand structure and depth-dependent roughness

Extrapolation of the results of small-scale processes to large areas can be accomplished in a spatially explicit manner by appropriate parameterization. For example, Hodge et al. [2007] used a discrete element model of the entrainment and transport of individual grains at the patch scale to develop basic transport relations, which were upscaled and used to parameterize a much broader reach-scale, reduced complexity, morphodynamic model. In the case of scaling roughness caused by vegetation, parameterization must account for the differences in growth and distribution of riparian vegetation that cause complex and highly variable interactions among individual plants. Therefore, spatially explicit characterization of vegetation’s role in perturbing
the flow field should account for the patterns of riparian vegetation growth and density and how these characteristics change with height above the ground surface.

Our multi-scalar analysis began at the patch scale. We defined a patch to be a cluster of similarly sized, spaced, and aged individual plants with similar stand structure (i.e., height, dominant stem size, stem spacing). High-density TLS point clouds (i.e., >200 pts/m²) were used to characterize the patch-scale stand structure, which we defined as the height dependent stem density and vertical projected area. We used the detailed TLS data to parameterize the patch-scale roughness.

4.1. Methodology: Deriving Stand Structure from Terrestrial Laser Scan Data

4.1.1 TLS Data Collection

We positioned a Leica Scan Station 2 upstream from 12 patches to acquire a high resolution (0.005-m point spacing) point cloud (Figure 2.3; Table 2.1). Data were acquired in July 2010 during base flows when the patches were not inundated. The ground topography of each patch was relatively flat. Tree ages, as determined by the germination year of a sample of tamarisk stems within or close to a patch, ranged between 10 and 60 years. The substrate in these patches was either sand or gravel. Individual plants in some patches had been buried after germination by as much as 3.5 m of sand and mud, as observed in floodplain trenches [Manners et al., 2011]. The bed-parallel area of each patch varied between 10¹ and 10² m²; patches with denser vegetation were of smaller size.

In the field, the scanner was positioned to collect data from the perspective of the predominant direction of overbank flows. One scan per patch was collected. We assumed that the flow direction on the floodplain is approximately the same at all flows. As such, our single-scan perspective was a reasonable characterization of how vegetation interacts with the flow. We also assumed that the maximum streamwise patch length of 3-9 m prevented significant occlusion, or shadowing, of stems since TLS measurements are line of sight [Warmink, 2007]. We occupied
several control points throughout the two field sites in order to register the scans to each other and convert scan data to UTM coordinates. Each scanner setup lasted between 1 to 4 hours and acquired a total of $10^5$ to $10^7$ points per patch.

4.1.2 Scan Data Analyses

We calculated the stand structure of different horizontal slices of the patch above the ground surface using the method of Straatsma et al. [2008]. A series of models and Python scripts were created in ESRI’s ArcGIS ModelBuilder to convert raw point cloud data into metrics, such as vegetation density and vertical projected area. While the majority of vegetation studies using TLS data have quantified vegetation density by identifying individual stems [e.g., Thies et al., 2004], Straatsma et al. [2008] adopted MacArthur and Horn’s [1969] gap fraction method and quantified vegetation density as the ratio of laser pulses emitted to those not intercepted. Such a methodology treats TLS returns as a proxy for density, which is appropriate for tamarisk and other shrubby riparian species with complicated branching patterns (Figure 2.4).

We created a grid of 3D cells, or voxels, based on a cylindrical polar coordinate system in ArcGIS (Figure 3). The vertical height of each cell ($z$) was 0.20-m; thus the grid was composed of a series of 0.20-m thick adjoining layers that spanned the vertical distance from the ground surface to the top of the tamarisk stand. The depth of each voxel along the radial distance from the scanner ($\alpha$) was 0.10 m. Therefore, the number of voxels in the radius from the scanner depended on the depth to which the laser pulses penetrated the patch, as explained below. The third dimension of each voxel, the angular distance ($\varphi$) was held constant at 2°. As such, the length of this dimension varied based on the distance of the cell to the scanner-parallel plane defined by $\alpha \varphi$. After manually removing ground points in Leica’s Cyclone Software, we then used this polar cylindrical grid to quantify vegetation density ($D_v$) from the point cloud. For each grid cell, vegetation density, $D_{v,ij}$, was approximated as:

$$D_{v,ij} = \frac{1}{\alpha} \ln \left( \frac{T_{ij} - B_{ij}}{T_{ij} - B_{ij} - G_{ij}} \right)$$  \[1\]
where $T_{ij}$ is the total number of emitted laser pulses that would have passed through the distal boundary of the cell if no obstructions were present, $B_{ij}$ is the number of pulses intercepted between the scanner and the cell, and $G_{ij}$ is the number of points intercepted within the cell. As vegetation density is defined as the vertical projected area per unit volume, the vertical projected area of the stems in the cell, $A_{P,vert,ij}$ ($m^2$) was then calculated as:

$$A_{P,vert,ij} = D_{ij} \times A_{ij} \times 0.2 \quad [2]$$

where $A_{ij}$ is the basal area of the individual voxel parallel the plane defined by $\alpha\phi$. Vertical projected area ($A_{P,vert}$), defined as the area of the vegetation projected normal to the flow, was summed over the patch to get a single value of $A_{P,vert}$ for each 0.20-m horizontal slice. We divided $A_{P,vert}$ by the bed-parallel, basal area of a given patch ($A$) to get a normalized vertical projected area ($A_{P,vert(n)}$) to account for the variability in patch size. Both vertical projected area and cumulative vertical projected area curves were obtained by this method and used to evaluate the structure of tamarisk stands (Figure 2.3).

4.2 Methodology: Quantification of Stage-Dependent Roughness

We created 2D hydraulic models of flow in each patch to link stand structure to the patch’s hydraulic roughness (Figure 2.5). Scan data were converted into 2D stem maps that described the vertical projected area and spatial organization of each patch. These maps used the cumulative $A_{P,vert}$ value for each voxel to define the size and position of vertical cylinders. Due to the vertical averaging implicit in a 2D representation of vegetation, we created a unique stem map for each 0.20-m thick increment to depict the vertically changing spatial configuration of the cumulative $A_{P,vert}$. In reality, not all stems line up with the voxels. A clustering of high $A_{P,vert}$ voxels is likely a product of a stem whose diameter exceeds the angular distance of the voxel (Figure 2.3). We accounted for this by merging adjacent cylinders that intersect. This new merged cylinder was then moved along the $\alpha\phi$ plane so that its center matched the center of those voxels.
used to define it (Figure 2.5). We acknowledge that vertical, cylindrically shaped, “stems” are an oversimplification of the complex 3D branching pattern.

We used River2D to develop the stem map mesh and run the various flow scenarios. We chose River2D as it uses a TIN-based unstructured mesh, which is suitable for varying the resolution to adequately capture the 2D stem maps. River2D uses a finite element method to solve the basic equations of vertically averaged 2D flow [Steffler and Blackburn, 2002]. Mass and momentum are conserved in the two horizontal dimensions, solving for bed and bank shear stresses with the Manning equation and a Boussinesq type eddy viscosity, respectively. Since the fundamental goal of the 2D patch model was to resolve the flow field through individual “stems”, we assigned high node spacing at the edges of the stems (0.0003-0.0004 m), represented as no flow boundaries. Elsewhere, node densities were relaxed. Steffler and Blackburn [2002] suggest that a minimum of four nodes along an obstruction in each of the four horizontal directions (i.e., positive and negative stream-wise direction and positive and negative cross-stream direction) are necessary to reliably resolve a feature in the flow field. Thus, in the coarsest sense, our meshes accounted for stems with 0.001-m diameters, while the majority of the stems in our stem maps had diameters greater than 0.005-m. This is important as it means the computational mesh can be constructed to allow us to adequately represent the impact of the obstructions on the flow field and back out the effective drag from the solution.

The model domain extended beyond the defined patch to assure unobstructed flow conditions in the upstream and lateral directions (Figure 2.5). Node spacing through the patch, outside of the stems, was set to 1 m. A unique numerical mesh was created for each stem map. We created meshes with the intent of making depth-averaged predictions from the bed, for 0.20-m flow depth increments, to evaluate changes in roughness and hydraulics. To assure that flow depth within the patch was less than the upper boundary of the 0.20-m increment, we assigned the flow depth at the downstream boundary as 0.05 m less than the upper boundary of the cumulative
A $A_{P,\text{vert}}$ profile. For example, for a stem map created for the cumulative $A_{P,\text{vert}}$ profile whose upper limit was 0.80 m above the bed, the assigned downstream flow depth was 0.75 m.

Each mesh was assigned a bed roughness height ($k$) consistent with the dominant bed material type for a given patch; gravel ($k_s = 0.4$ m) or sand ($k_s = 0.1$ m). Bed roughness heights were assumed constant for all flow depths within a given patch [Whiting and Dietrich, 1990]. In order to simplify our approach and focus on vegetative roughness, we did not account for bed form roughness, although we recognize that parts of the bed surface in the patches could support ripples at some flows. We converted bed roughness height into roughness coefficients (Manning’s $n$), in order to solve for total patch roughness (see below), and as such, bed roughness became depth-dependent based on the following equation

$$n = \frac{y^{3/6}}{2.5\sqrt{g}m(\frac{k_s}{k_s})}$$  \hspace{1cm} [3]$$

where $g$ is the acceleration from gravity and $y$ is flow depth.

Flow rates for individual model runs were chosen so as to maintain constant water surface slope (~ 0.001) through the patches. All flows filled the extent of the model domain and as such the model did not need to account for the wetting and drying of elements. Results were iteratively solved for depth and velocity at each node by River2D until the model reached a steady state.

Total patch roughness, $n_{\text{patch}}$, was partitioned into roughness caused by the bed, $n_{\text{bed}}$, and roughness caused by vegetation, $n_{\text{vegetation}}$, based on

$$n_{\text{patch}} = n_{\text{bed}} + n_{\text{vegetation}}$$  \hspace{1cm} [4]$$

where bed roughness was derived from the bed roughness height ($k_s$) specified for each patch type. For vegetation roughness, we adopted an approach first proposed by Petryk and Bosmajian [1975] and subsequently used by many researchers [e.g., FathiMaghadam and Kouwen, 1997; Jarvela, 2004; Musleh and Cruise, 2006] that relates a roughness coefficient to the energy extracted by vegetative elements
\[ n_{\text{vegetation}} = \sqrt{\frac{4C_D}{A}} \left( \frac{A_{P,\text{vert}}}{A} \right)^{\frac{1}{3}} \sqrt{\frac{\rho y}{8g}}. \]  

where \( C_D \) is the vegetative drag coefficient, \( A_{P,\text{vert}} \) is the cumulative vertical projected area of the vegetation, and \( A \) is the bed-parallel, basal area of the patch. While \( C_D \) values may be derived from the literature [e.g., Nepf, 1999], our goal was to link the specific stand structure of tamarisk patches to their effects on channel hydraulics. Consequently, we back-calculated \( C_D \) for each 2D patch model from the drag force equation

\[ F_{D,\text{veg}} = \frac{1}{2} \rho C_D U_r^2 A_{P,\text{vert}} \]  

where \( F_{D,\text{veg}} \) is the bulk-streamwise drag force on the stems, \( \rho \) is the density of water, and \( U_r \) is the upstream reference velocity taken as the average velocity across the upstream boundary of the control volume.

To quantify \( F_{D,\text{veg}} \), we calculated the momentum extracted through the control volume surrounding each patch (Figure 2.5) [Shields and Gippel, 1995; Manners et al., 2007]. The lateral boundaries of the control volume were delineated based on the extent of the patch-influenced flow field defined as the transition from flow vectors with a cross-stream component to those with no cross-stream component. We consistently defined the boundaries in this manner and did not evaluate the sensitivity of the drag calculation as a result of the location of the control volume boundary. The net external force on a system (\( F_{\text{external}} \)) is equal to the change of momentum through the control volume (\( F_{\text{downstream}} - F_{\text{upstream}} \))

\[ F_{\text{external}} = F_{\text{downstream}} - F_{\text{upstream}} \]  

Assuming steady flow and defining the two external forces within each patch model that change the momentum through the system as the shear stress exerted by the bed (\( F_{\text{bed}} \)) and the forces exerted by the stems (\( F_{D,\text{veg}} \)), we relate these external forces to the forces across the upstream and downstream control volume boundary

\[ F_{D,\text{veg}} + F_{\text{bed}} = (F_{\text{static}} + F_{\text{dynamic}})_{\text{downstream}} - (F_{\text{static}} + F_{\text{dynamic}})_{\text{upstream}} \]
where, $F_{\text{static}}$ is a pressure force that is equal to the hydrostatic pressure, $p$, of the water normal to flow

$$F_{\text{static}} = \int p dA_{\text{vert}} \quad [9]$$

and $F_{\text{dynamic}}$ is the momentum flux across the control volume boundary (either upstream or downstream),

$$F_{\text{dynamic}} = \int \rho U^2 dA_{\text{vert}}. \quad [10]$$

In equations [9] and [10], $U$ is the depth-averaged velocity at a point across the boundary and $A_{\text{vert}}$ is the area vector that has the magnitude of the area and is directed normal to the control volume boundary in question. The force exerted by the bed is defined as

$$F_{\text{bed}} = \int \tau_b dA \quad [11]$$

where $\tau_b$ is the near bed shear stress obtained as model output and $A$ is the area parallel to the bed within the control volume. Rearranging [8] to solve for the bulk, streamwise force on the stems, and substituting equations [9-11],

$$F_{\text{D,veg}} = (F_{\text{static}} + F_{\text{dynamic}})_{\text{downstream}} - (F_{\text{static}} + F_{\text{dynamic}})_{\text{upstream}} - F_{\text{bed}} \quad [12]$$

$$= [\int (p + \rho U^2) dA_{\text{vert}}]_{\text{downstream}} - [\int (p + \rho U^2) dA_{\text{vert}}]_{\text{upstream}} - \int \tau_b dA$$

We also accounted for stem flexibility of tamarisk patches as the patches become submerged. As flows increase, the force of the water on the stems pushes the stems downstream, and the effective stem height (i.e., the height interacting with the flow in the vertical) decreases. We took a simplified approach to quantifying the deflected height of stems. With a known $U$ and $C_D$, we adopted a version of the beam elasticity equation applied to the mid-point of the stems to quantify the deflection of a single representative stem [Kubrak et al., 2008; Velasco et al., 2008], or displacement of the stem axis in the water flow direction $\delta(x)$,

$$\delta(x) = \frac{1/2\rho C_D U^2 d}{EI} \quad [13]$$

where $d$ is the average stem diameter, $E$ is the stiffness modulus of which a constant value experimentally determined for tamarisk of $13.1 \times 10^8$ N/m$^2$ was used [Freeman et al., 2000], and $I$
is the cross-area inertial modulus calculated from the average stem diameter. In [13], the numerator represents the force, or hydrodynamic thrust, on the mid-point of the modeled stem, and the denominator is a mechanical property of the stem.

To account for submergence and deflection, we decreased $A_{P,\text{vert}}/A$ in [5] based on the ratio of the flow depth that interacts with the vegetation to the portion of flow depth that does not. For example, based on the elasticity of a typical tamarisk stem, a flow depth of 2.4 m interacting with a 2.2-m tall patch of tamarisk, deflects the mid-point of the average stem in the streamwise direction ($\delta(x)$) by 0.09 m, thereby reducing the effective height (i.e., the total amount of the flow column interacting with the stem) to 2.07 m. As such, 0.33 m (or 8%) of the water profile is not directly obstructed by the vegetation. $A_{P,\text{vert}}/A$ was reduced by 8% and [5] was then solved for the new vegetation roughness value.

We acknowledge that this approach has limitations. Bending of stems in the flow and the submergence of vegetation is fundamentally a 3D problem [Stephan and Gutknecht, 2002]. By using a depth-averaged velocity, we likely underestimate velocities, and as a result, the degree of stem deflection. Additionally, we do not update $C_D$ values in equation [6], which were calculated for stiff stems. This simplification along with our representation of complex tamarisk patches as single stems by using the patch-average stem diameter in equation [13] introduces additional uncertainty.

4.3 Results: Vegetation Profiles and Hydraulic Influence

The 12 cumulative, normalized, vertical projected area ($A_{P,\text{vert}(n)}$) profiles of the tamarisk-dominated patches were classified into three groups (Figure 2.6). An analysis of variance among the three groups indicates that their $A_{P,\text{vert}(n)}$ values are statistically different ($p<0.001$). Relatively young (<20 yrs old) patches whose stand height was short (< 3 m) made up one group (Table 2.1). Hereafter, we refer to this group of patches as the “sparse group.” These patches occur on low elevation gravel bars that are inundated by common floods. This hydraulically stressful
environment presumably causes the short stature and sparse plant density. Cumulative $A_{P,vert(n)}$ values for this group range from a minimum of 0.01 to 0.18 m$^2$/m$^2$. Patches of the other two groups grow in fine sediment. Maximum height of these patches was similar and ranged between 3.0 and 5.9 m and in age from <10 to 60 years old (Figure 2.6). One of these group’s cumulative $A_{P,vert(n)}$ values ranged between 0.03 and 0.61 m$^2$/m$^2$, and we refer to these patches as the “moderate group.” The other group’s cumulative $A_{P,vert(n)}$ values ranged between 0.07 to 1.10 m$^2$/m$^2$, and we refer to these patches as the “dense group.” We used this profile classification scheme to extrapolate the characteristics of tamarisk to the reach scale.

Drag coefficients calculated for hydraulic model runs for each patch and for different stages ranged from 0.1 to 1.9. We used an analysis of variance to evaluate differences in $C_D$ among the three vertical projected-area profile groups (sparse, moderate, dense). For flow depths 1m and less, $C_D$ was not statistically different among the three groups (mean =1.0, sd= 0.3). However, $C_D$ was different among groups for flow depths greater than 1m (p<0.001). Drag coefficients were greatest for the dense patches (mean=1.5, sd=0.2) and smallest for moderate patches (mean=1.1, sd=0.1); sparse patches had intermediate values (mean=1.3, sd= 0.1). We explore the potential cause of the observed trend in $C_D$ values for the different density patches in section 6.2.

Patch roughness caused by flow through vegetation generally increases with increasing flow depth to the point where the vegetation is completely submerged; thereafter, roughness decreases (Figure 2.7). Roughness increases with depth because cumulative vertical projected area also increases with depth. However, the relationship between projected area and roughness is not linear. This is especially apparent for flow depths less than 1.2 m. As expected, we also find that $A_{p,vert(n)}$ for the moderate group is greater than for the sparse group. However, the vegetation and total patch roughness for the sparse group are slightly greater than those for the moderate group (Figure 2.7). We attribute some of the greater patch roughness values of the sparse group at low flows to the gravel substrate. For flow depths less than 0.6 m in the sparse group patches, the
bed contributes greater roughness than do the stems (Figure 2.7). However, this difference may also be attributed to a slightly higher \( C_D \) value in the sparse group than the moderate group.

Where flow depth exceeds 1.2 m, roughness values for moderate density patches increase at a greater rate than do the values for sparse patches. A maximum \( n \) value of 0.178 occurs at flow depths between 2.8 and 3.0 m in moderate patches. Sparse patches become fully submerged when the local flow depth exceeds 2.2 m. From 2.2 to 3.0 m, the vegetation roughness of sparse patches decreases from 0.106 to 0.099. Stage dependent vegetation roughness values are greatest for dense patches and range from 0.045 at a flow depth of 0.20 m to 0.293 at a flow depth of 3.0 m.

5. Upscaling from the patch scale

5.1 Methodology

Patch-scale data are insufficient to describe reach-scale riparian vegetation patterns, because patch data alone do not inform how those data can be extrapolated to the reach scale. We took advantage of the overlap in coverage of TLS and ALS data in the study areas to extrapolate patch-scale field measurements to the reach scale by creating a relation between stand structure and the corresponding hydraulic roughness. Thus, we leveraged the precision of the detailed TLS data against the spatially extensive, yet coarser, ALS dataset. First, we created a model that related ALS to TLS data using the 12 patches and then extended this model to the entire study area. While the scales over which we attempted to match these data were variable, two aspects of our methodology allowed us to create a scale-independent relationship. We took a probabilistic approach to the likelihood of ALS data intercepting a branch or stem for discrete vertical slices, because ALS data are significantly more sparse than TLS data -- on the order of \( 10^1 \) ALS points per tamarisk patch versus \( 10^6 \) TLS points per patch. Stand structure values (i.e., vertical projected area) were summed and normalized by bed-parallel area of the patch. Hereafter, the term “patch” is used to describe the scale over which TLS data were collected and analyzed. Model development was based on observations made from the TLS patches (section 5.1.2). The term
“window” is used to describe the scale over which the model was applied at the reach scale (section 5.1.3).

5.1.1 ALS Probability Maps

Using a series of morphological filters, developed in part using the methodology of Zhang et al. [2003], the ALS data were classified as either bare ground or vegetation. Averaging 1.5 pts/m², we used the bare ground points to create a 0.5-m resolution, bare-earth digital elevation model (DEM) of the study areas. A 0.5-m DEM assured sufficient topographic detail of the smallest patch (SC2, 6.5 m²). The height above the bare ground of each vegetation point was determined as the difference between the elevation of each vegetation point and that of the ground surface. We took 0.20-m thick horizontal slices of the ALS vegetation point cloud, corresponding to the 0.20-m horizontal slices used in the analysis of TLS data (section 4.1.2). Probability maps (0.5-m resolution) of the incidences of ALS points for each of the 0.20-m horizontal slices were created using indicator kriging [Todd et al., 2003]. To construct probability maps, we used all LiDAR returns (i.e., ground and vegetation points) within the tamarisk-dominated floodplains and transformed them into indicator variables. For a given horizontal slice, those returns that were within the 0.20-m limits (e.g., between 2.0 and 2.2 m above the ground surface) were assigned a value of 1, while all other values for vegetation returns outside of the horizontal slice range and ground points were assigned a value of 0. As a result, each probability map provides a measure of the probability of a LiDAR pulse (ALS) being returned from vegetation at the associated height.

5.1.2 Creation of a Model to Link ALS to TLS

We assumed that all the tamarisk-dominated stands in the two study reaches belonged to one of the three vertical projected area profile groups: sparse, moderate, or dense. For each of the three profile groups, we developed relations between height above the bed ($H$) and cumulative
Each of these relations was defined as a band with upper and lower bounds based on the cumulative \( A_{P,\text{vert}(n)} \) curves of the twelve patches. Assignment of a patch into one of these three bands, and therefore as one of the three types of vertical projected area profiles (sparse, moderate, or dense), required knowledge of at least one height-dependent cumulative \( A_{P,\text{vert}(n)} \) value. With the expressed goal of upscaling patch-scale observations using spatially robust ALS datasets, the height-dependent cumulative \( A_{P,\text{vert}(n)} \) value must ultimately be derived from the vertical structure of the ALS data.

ALS probability maps only provided us with an estimate of the likelihood that a branch or stem exists at a point on the floodplain. These maps did not provide us with a direct measure of the vertical projected area of tamarisk stands. To relate ALS probability maps to vertical projected area profiles derived from TLS scan data, we extracted the probability value from the ALS probability maps for every 0.20-m horizontal slice and applied those data to the centroid of each grid cell (section 4.1.2). Summed over the area of the whole patch, we quantified a vertical distribution of “blockage” \((\text{m}^2/\text{m}^2)\), defined as a measure of vegetation density from the top-down perspective, for each patch,

\[
Bk_{ALS} = \frac{\sum P(ALS)_{ij} \times A_{ij}}{A}
\]

where \( P(ALS)_{ij} \) is the probability extracted from the ALS probability map at the centroid of each polar grid cell, \( A_{ij} \) is the bed-parallel area of the cell, and \( A \) is the bed-parallel area of the TLS patch. From the vertical distribution of blockage, we constructed cumulative distribution curves of blockage from the ground to the maximum height of the vegetation in the patch. Both the cumulative \( Bk_{ALS} \) curves and cumulative \( A_{P,\text{vert}(n)} \) curves were converted into cumulative frequency curves (Figure 2.9). We quantified \( A_{P,\text{vert}(n)} \) and \( Bk_{ALS} \) quantiles from these cumulative frequency curves.

For each patch, we calculated two \( H\)- \( A_{P,\text{vert}(n)} \) values, the maximum and the median points (Table 2.2). The maximum value was the largest cumulative \( A_{P,\text{vert}(n)} \) value \( (A_{P,\text{vert}(n)}(\text{max})) \).
value necessarily occurs at the top of the vegetation canopy. The median value (\(A_{P,\text{vert}(n)(50)}\)) was identified as the 50th percentile of the cumulative \(A_{P,\text{vert}(n)}\) distribution (Figure 2.9). The height at which the \(A_{P(n)(50)}\) occurred was dependent on the profile shape, and was not immediately apparent from the ALS data.

To quantify these two points from ALS data, we determined the maximum height from the ALS data (\(H_{\text{ALS(max)}}\)) and calculated the maximum cumulative blockage (\(Bk_{\text{ALS(max)}}\)) (Figure 2.9). The relationship that we established between \(Bk_{\text{ALS(max)}}\) and \(A_{P,\text{vert}(n)\text{max}}\) was based on 11 of the 12 patches. We excluded patch LP2, where we determined that the canopy density was too thick to characterize the rest of the profile (\(Bk_{\text{ALS}=1.8}\)). We assumed that patches whose \(Bk_{\text{ALS(max)}}\) values exceeded 1.5 m²/m² belonged to the dense group. Based on the remaining eleven patches for \(Bk_{\text{ALS(max)}} < 0.50\) m²/m², a positive power-law relationship exists between \(Bk_{\text{ALS(max)}}\) and \(A_{P,\text{vert}(n)\text{max}}\) (\(a=6.75, b=1.92, R^2=0.76\)) while for \(0.5 < Bk_{\text{ALS(max)}} < 1.5\) m²/m², a negative relationship exists (\(a=2.24, b=-1.07, R^2=0.77\)). The presence of a threshold at 0.5 m²/m² indicates that the canopy begins to filter out points greater than this value and that the lower portion of the plant is hidden from the ALS data acquisition process. Similar relationships were established between the maximum blockage (\(Bk_{\text{ALS(max)}}\)) and the median \(A_{P,\text{vert}(n)}\) value (\(A_{P,\text{vert}(n)(50)}\)) for values of \(Bk_{\text{ALS(max)}} < 0.50\) m²/m² (\(a=13.5, b=1.92, R^2=0.76\)) and \(Bk_{\text{ALS(max)}} > 1.5\) m²/m² (\(a=2.98, b=-1.07, R^2=0.77\)). These relationships allowed us to calculate both \(A_{P,\text{vert}(n)\text{max}}\) and \(A_{P,\text{vert}(n)(50)}\) from \(Bk_{\text{ALS(max)}}\), a value derived from ALS data alone. Error between the quantified \(A_{P,\text{vert}(n)(50)}\) (\(A_{P,\text{vert}(n)\text{imax}}\)) and the predicted \(A_{P,\text{vert}(n)\text{imax}}\) (\(A_{P,\text{vert}(n)\text{max}}\)) using these relationships was approximately 20%. Additional relationships were established for \(A_{P,\text{vert}(n)(25)}\) and \(A_{P,\text{vert}(n)(75)}\) as a means of evaluating the shape of the \(A_{P,\text{vert}(n)}\) profile, as explained below.

To determine the height of \(A_{P,\text{vert}(n)(50)}\), we identified a pattern in the relationship between the cumulative distribution of blockage and the cumulative distribution of \(A_{P,\text{vert}(n)}\) for a given patch. These relationships reflect differences in the perspective from which the ALS and TLS datasets were collected; ALS data are collected from directly above (i.e., airborne) each area of
vegetation, and TLS data are collected from a low-oblique perspective (i.e., a tripod). For patches whose maximum tree heights were greater than or equal to 5 m, $Bk_{ALS(50)}$ occurred 2.3 m (sd=0.02) higher in the profile than $A_{P,vert(n)(50)}$. For patches whose maximum heights were between 4 and 5 m, the difference was 1.4 m (sd=0.2). For patches whose maximum height was less than 4 m, the difference was 0.2 m (sd=0.2) (Table 2.2).

Accounting for the 20% uncertainty in quantified and predicted $A_P(n)$ values (horizontal error bars), and a 6% difference in the maximum height of the vegetation (Table 2.2) within a patch between TLS and ALS (vertical error bars), we predicted the correct $A_{P,vert(n)}$ profile group (i.e., sparse, moderate, or dense) for 9 of the 11 patches using the $H_{50}-A_{P,vert(n)(50)}$ values and 6 of the 11 patches using the $H_{max}-A_{P,vert(n)(max)}$ values (Figure 2.8). On average, the $A_{P,vert(n)(50)}$ was over predicted by 0.22 m²/m², while the $A_{P,vert(n)(max)}$ was under predicted by 0.28 m²/m².

The discrepancy between data collected from a top down perspective and that collected parallel to the flow is greatest for dense canopies. $A_{P,vert(n)}$ values for SC2 and SC3 were significantly underpredicted by the model. We attribute this divergence in model success to an extremely dense canopy, where the ratio between $Bk_{ALS(75)}/Bk_{ALS(25)}$ is relatively large. For SC2 and SC3, this ratio was greater than 7, while for the remaining 9 patches, the ratio was on average 2. In patches such as SC2 and SC3, the density of the top of the canopy essentially shadows the lower portion of the profile, thereby altering the cumulative blockage curve. We determined that an adjustment of 50% from the predicted value was appropriate to correct for the canopy blockage.

5.1.3 Application of the Model

With these relationships established, we extended the patch-scale observations to the entire study area. To do this, we used a 2-m, 3-m, and 4-m circular moving window. Within each moving window, we summed the blockage values derived from the ALS probability maps. The window was used as a proxy for the patch. We used various window sizes to determine the best scale over which to apply the ALS-TLS model. Both the maximum and median $H_{ALS}-A_{P,vert(n)}$
values were calculated in order to provide the best gage for the patch type to which each discrete window belonged. The 50% correction was applied to those profiles that had a predicted ratio of $Bk_{ALS(75)}/Bk_{ALS(25)}$ greater than 7.

A 2-m grid overlaying the study area extracted the summed probabilities at the center of each grid cell. We applied the same methodology as described in section 5.1.2 to extract maximum height, maximum blockage, and the height and value of the quartile values of blockage over the window. We classified the two reaches by the type of vertical projected-area profile and therefore the type of depth-dependent roughness profile, based on these values and the empirical models that link $Bk_{ALS(max)}$ to $A_{P,vert(n)(max)}$ and $A_{P,vert(n)(50)}$. We estimated the various metrics for modern alluvial deposits that were dominated by tamarisk and did not apply the model to areas of vegetation dominated by other species, such as box elder.

Thus, we applied our TLS relations to the two study reaches, based on the ALS data, the result of which was a map of vegetation density (i.e., classified into the three profile groups: sparse, moderate, or dense) present within each map cell (Figure 2.10). We evaluated the model, and the size of the moving window, by comparing the model predictions of conditions in the 12 patches to those estimated from the ALS data (Figure 2.10, Table 2.3). Since individual patches are larger than the scale of the grid (4 m$^2$), the roughness map consisted of multiple grid-cells within each patch. We acknowledge that the discrepancy in scale, both between patch and window sizes as well as between patches and the grid over which we validated the model, inevitably resulted in differences in model prediction. For example, if a 50-m$^2$ patch is evaluated using a 2-m circular window (12.5 m$^2$), the stand structure of sections of this patch, while characterized as one group in the development of the model, may belong to two or more groups. Variability in density existed within a given patch. While averaging during model development masked density differences, this patch-scale variability was highlighted during model application, especially when using different window sizes.
5.2 Upscaling Results and Interpretation

The moderate and dense patches were best captured with a moving window of 3 m (Table 2.3). The model correctly classified 84% and 70% of the cells within the three moderate and five dense patches, respectively. In contrast, the sparse patches performed the best when the moving window was 4 m; the success rate in this case was 42%. However, the difference in performance for the sparse patches did not vary greatly for the different window sizes (36% and 35% for a 2-m and 3-m moving window, respectively). The sparse patches had the lowest success in application of the ALS-TLS model. Based on the above findings, we considered that the 3-m window was best applied to these study reaches.

Classified maps of the Laddie Park and Seacliff reaches qualitatively showed good agreement with field observations (Figure 2.10). Generally, the sparse group was restricted to low-elevation gravel bars. These stands only occur in the Laddie Park reach. The tamarisk stands in the Seacliff reach were predominately established on eddy bars and are denser. Many individuals in these groups are buried by > 1 m of fine sediment. Moderate and dense stands also occur in the Laddie Park reach on higher topographic surfaces. Thick deposits in the central parts of the islands support relatively dense tamarisk stands.

The discrepancy in scale, both between TLS patch and moving window ALS model sizes as well as between patches and the grid over which we validated the model, inevitably contributed to differences in model prediction of stand type within the 12 TLS patches, especially for the sparse patches. Spatial variability exists within a TLS patch, and, therefore, the larger the size of the patch, the greater the expected variability in predicted $A_{P,\text{vert}(n)}$ groups within that patch. We expect there to be the greatest within-patch variability in the sparse-group patches. Extraction of $A_{P,\text{vert}(n)}$ profiles from the TLS scan data over the same scale of TLS-ALS model application (i.e., the 3-m window) increased the match in $A_{P,\text{vert}(n)}$ group type for the sparse groups from 35% to 65% (Table 2.3). Additionally, cells located closest to the scanner had greater success, highlighting the difficulty in capturing large areas with TLS.
Future work might be able to fine-tune these upscaling relationships and/or more robustly validate their application at particular sites and/or their transferability to other fluvial settings. While the methodology could be developed using a smaller TLS patch size, and potentially a greater number of patches, one must be cognizant of the impact of patch size on identification of the within-patch processes (e.g., routing of flow around individual stems that influence the larger, reach-scale flow field) (discussed further in section 6.2). Additionally, greater spatial congruity between patch and moving window size would likely result in increased predictive success. However, an increase in the size of the window to more closely match patch size would result in unreasonable averaging across vegetated/unvegetated areas and the locations of high variability in vegetation density.

6. Discussion

6.1 Verification and Uncertainty of Patch-Scale Values

To verify the vertical projected areas we determined from our TLS measurements, we compared our values with direct field measurement of tamarisk and willow in other studies. The majority of studies that report vegetation densities do so at the reach scale as stem densities (e.g., # stems/ha) [e.g., Stromberg et al., 1993; Beauchamp and Stromberg, 2007]. These bulk values mask the fine spatial resolution that we captured in our study. However, a few studies report values collected over spatial scales comparable to the patch scale. Griffin et al. [2005] found that tamarisk stems > 0.01 m in diameter on the Rio Puerco in New Mexico were spaced 0.20-m apart, and therefore, have an \( A_{P, \text{vert}(n)} \) value of 0.25 m\(^2\)/m\(^2\) at a height of 1 m. Detailed stem measurements of young sandbar willow (< 10 years) growing on a gravel bar on the upper Colorado River had \( A_{P, \text{vert}(n)} \) values that ranged between 0.06 and 0.14 m\(^2\)/m\(^2\) at a height of 1 m [Logan, 2000]. Values for sandbar willow on tributaries of the South Platte River, Colorado, ranged between 0.08 and 0.93 m\(^2\)/m\(^2\) at a height of 1 m [Griffin and Smith, 2004]. Generally, the
range of values from these studies fits within the range of $A_{P,vert(n)}$ values quantified for the 12 patches of this study (0.06 to 0.37 m$^2$/m$^2$ at a height of 1 m).

Without independent, non-TLS, field measurements of stand structure, we cannot assign a degree of uncertainty or estimate of error to the vegetation densities calculated in this paper. Nevertheless, prior studies provide information on the potential accuracy of the approach used in our investigation. In the development of the methodology employed here, Straatsma et al. [2008] measured stem densities for 23 plots. They determined that their modeling efficiency was 63%. Errors were attributed to (1) the assumption of randomly distributed stems in the development of the methodology, (2) the presence of leaves at the single elevation measured, and (3) the relatively low resolution of their scans. However, differences exist between our study and Straatsma et al.’s [2008], which preclude direct extension of their reported uncertainties to our work. For one, the types of vegetation analyzed in the two studies differ greatly, from a sparse stand of straight-stemmed willow ($Salix alba$) [Straatsma et al., 2008] to a densely vegetated stand of tamarisk with randomly oriented stems (this study). As such, the assumption of randomly distributed stems might introduce less error to our study, especially for the moderate to dense stands. We acknowledge that measurement of structure of tamarisk stands during the growing season adds some error to the measurements due to the presence of leaves. However, the stem area to leaf area ratio for tamarisk is relatively high and unlikely to exert a major influence. Finally, the resolution at which Straatsma et al. [2008] scanned was much coarser than ours; 238-1104 pulses per angular degree [Warmink, 2007] vs. 1005-3016 pulses per angular degree. This increased density of points has a greater likelihood of capturing all stems. Additionally, we limited our scanned patches to relatively small footprints, thereby limiting shadowing of stems. It should be emphasized that our goal with this research was not to build a highly precise model of vegetation density, but rather to find a reasonable proxy for vegetation density that can be used to estimate its effect on floodplain hydraulics.
We back-calculated the drag coefficient \((C_D)\) from the drag force equation as a way to relate stand structure (vertical projected area profiles) to roughness. For vertical cylinders, a \(C_D\) value between 1.0-1.2 is regularly cited as the most reasonable value for the range of flow conditions used in experimental work [e.g., Jarvela, 2004]. A large literature exists that explores ways in which these values may be predicted or adjusted given the range of variability of natural conditions. Nepf [1999] found that for an increase in density of cylindrical “stems,” the bulk \(C_D\) decreased from 1.2 to less than 0.4. In a series of flume experiments using willow, Jarvela [2002] calculated \(C_D\) values that averaged between 1.6 and 1.4 depending on the spacing and distribution of the willow. Other studies using real stems [James et al., 2004] or measuring drag in a non-controlled, field-based setting [Hygelund and Manga, 2003; Manners et al., 2007] have reported a much larger range and maximum values, as high as 20. Average \(C_D\) values in our study (1.0 for all groups when flow depth < 1.0-m and 1.3, 1.1 and 1.5 for the sparse, moderate, and dense groups, respectively for flow depths ≥ 1.0-m) fall well within this range of experimentally determined drag coefficients.

6.2 Hydraulic Roughness of Tamarisk

The increase in hydraulic roughness associated with colonization of bare alluvial deposits by tamarisk has been suggested as an important cause of channel narrowing of the Colorado River and its tributaries [Graf, 1978; Birkeland, 2002]. However, few studies have quantified the change in hydraulic roughness.

In this study, we estimated the large-scale distribution of roughness of tamarisk patches. Patch-scale Manning’s \(n\) values ranged from 0.057 to 0.319. The higher end of these values are greater than those generally reported for vegetated floodplains (upwards of 0.25) that are often calculated from the hydraulic conditions (water surface slope and depth) for small reaches or whole floodplain surfaces [Barnes, 1967; Arcement and Schneider, 1989; Sandercock and Hooke, 2010]. Averaging conditions over these areas inevitably accounts for spatial variability in
roughness values. In contrast, we calculated roughness values over smaller spatial scales. Our values are therefore representative of the local resistance of vegetation and are solely applicable to the patch scale.

When we compare our predicted patch-scale Manning’s $n$ values to those determined experimentally for tamarisk stands, we find good agreement. The sparse group best represents the types of plants used in experimental studies. Our predicted values (0.076-0.141) fall within the range of experimentally determined values (0.055-0.180) [Freeman et al., 2000; Fathi-Maghadam et al., 2011]. Specifically, we identified the experimental conditions in Freeman et al. [2000] that most closely match our 2D models and found excellent agreement (Figure 2.7).

We found that roughness increases with flow depth, generally scaling with the vertical projected area of vegetation patches. This finding is consistent with experimental work [Fathi-Maghadam and Kouwen, 1997; Musleh and Cruise, 2006]. Musleh and Cruise [2006] reported that roughness through a patch of partly submerged rigid cylindrical rods increases linearly with flow depth from 0.06 to 0.24. However, while other studies documented a linear increase in roughness with depth, we found that roughness increases in proportion to changes in the vertical projected area. As expected, roughness decreases as patches become submerged (Figure 2.7). For sparse density stands, total patch roughness decreased after a stand was completely submerged.

Often, hydraulic models assume that roughness decreases as flow depth increases [Arcement and Schneider, 1989]. This assumption is applicable for in-channel conditions either where no vegetation exists or where vegetation becomes fully submerged. The declining contribution of bed roughness to total patch roughness with increasing flow depths supports the applicability of the above assumption (Figure 2.7). However, for floodplain flows through stands of tamarisk and willow, and likely other types of shrubby riparian vegetation, our results predict that total patch roughness increases with increasing flow depth because cumulative vertical projected area also increases with increasing flow depth.
Group-average normalized vertical projected area profiles (Figure 2.11) indicate that the profile shapes for moderate and dense patches are similar, although the magnitude of projected area is greatest for dense patches. Both have maximum values around 2 m above the ground surface. However, the profiles differ within 0.5 m of the ground surface. Here, there is a second maximum $A_{P, vert(n)}$ value in densely vegetated patches, on average three times greater than that of the moderate patch. We hypothesize that this difference may be attributed to patch-scale organization (Figure 2.12).

Densely vegetated patches may promote more well-defined flow pathways and channels that occur between clumps of dense vegetation. A feedback between dense clumps of stems close to the ground surface and strong flow paths likely exists [Corenblit et al., 2007]. Dense clumps redirect and channelize flow, scouring out new vegetation and maintaining flow paths. Higher velocities in these flow paths have the potential to shear low-lying stems. When tamarisk stems break, a greater number of stems regrow, thereby creating greater stem density. Additionally, because these flow paths are more well-defined, have a larger proportion of the flow, and therefore faster velocities, they are capable of transporting woody debris, some of which may become trapped by stems. Field observations of woody debris in and around dense group patches support this notion. All of these factors contribute to high stem density close to the ground (Figure 2.12).

Similarly, the sparse group profile shows the same characteristic secondary peak close to the ground. These patches grow on gravel bars along the edge of, or even within, high-flow side channels. High velocities often shear stems here and deliver woody debris. As such, similar processes may be attributed to determining the shape of the profile. However, the magnitude of these processes and location within the channel prevents the sparse group from growing to the same density.

The fact that the moderate density patches are generally composed of evenly spaced stems, while dense (and sparse) patches tend to have clumps of stems between larger open areas
has a direct impact on the hydraulic effectiveness of these two patch types. An extensive literature exists on the hydraulic impact of stem spacing [e.g., Nepf, 1999; Stone and Shen, 2002; Liu et al., 2008]. Generally, closer spacing among stems reduces the bulk drag coefficient due to the downstream “sheltering” effect [Raupach, 1992]. We might attribute the lower average $C_D$ value for moderate patches (1.1 as compared to 1.5 for dense patches and 1.3 for sparse patches) to this effect, whereby the arrangement of stems in a moderate patch (Figure 2.12) increases the wake interference.

We do not know if tamarisk patches get denser or sparser as they age, but we have observed changes to tamarisk patches as a result of the aggradation of fine sediment. Tamarisk on gravel bars remain short and sparse as the stands age, presumably because of the harsh hydraulic environment. However, we have observed that tamarisk stands that established on gravel bars, but are now buried by as much as 3 m of fine sediment, have moderate or dense vertical-projected area profiles. Fine-sediment deposition on gravel bars may be a result of an increase in the local hydraulic roughness, an indication of an alteration to the flow field, or of a change in the hydrology and/or sediment load that has resulted in sediment surplus. In the study reaches, we find fine-grained caps on gravel bars in areas whose hydraulic setting (e.g., upstream from tight bedrock bends) promotes deposition. However, these caps were not as spatially extensive prior to the establishment of tamarisk and willow. The caps have been increasing in size with the expansion of riparian vegetation. This observation suggests that within certain hydro-geomorphic environments, establishment of vegetation increases hydraulic resistance and promotes deposition of fine sediment. Fine-grained alluvial deposits provide additional surfaces for the colonization of new plants. Additionally, field observations from floodplain trenches indicate that fine sediment deposition increases the density of tamarisk stands. Greater coverage and density of tamarisk further increases vegetative hydraulic resistance, altering flow fields, and promoting deposition of fine sediment. As such, feedbacks exist among flow, sediment, and tamarisk growth. It is these feedbacks that control the spatial pattern of vegetation hydraulic roughness.
6.3 Upscaling the Hydraulic Roughness of Patch-Scale Observations

As an illustration of how a reach-scale evaluation of the impact of vegetation on the flow field might be pursued, we applied the methodology described in this paper to a 2D hydraulic model evaluated over the entire Laddie Park site. Our goal was to illustrate the importance of incorporating a spatially variable representation of vegetation roughness. We applied the stage-dependent roughness curves established for the study sites (Figure 2.7) to the 2D hydraulic model River2D.

A combination of LiDAR-derived topography, acquired in 2008, and RTK-GPS-based bathymetric surveys, acquired in 2010, were used to create a DEM that was sampled onto a triangular finite element mesh with 2-m node spacing around the tamarisk-dominated floodplains and 10-m node spacing elsewhere. A constant discharge upstream boundary condition was established for two flood discharges, 450 and 935 m$^3$/s, and a constant downstream water surface elevation was specified. Because a rating relation was not available to use for specifying flow boundary conditions, downstream water surface elevations were derived from a 1D HEC-RAS [U.S. Army Corps of Engineers, 2008] model run under steady, subcritical flow conditions with a normal depth boundary condition (water surface slope of 0.001). For context, baseflows are approximately 15 m$^3$/s; a 450 m$^3$/s flood has a recurrence of approximately 5 years, and a 935 m$^3$/s flood is the flood of record whose recurrence is >100-years [Elliott and Anders, 2004].

Roughness in the model is provided in terms of a roughness height ($k_s$). While the roughness height of the bed does not change with flow depth [Whiting and Dietrich, 1990], we determined in section 4 that the roughness, as measured by Manning’s $n$, of a patch of tamarisk changes with flow depth. To account for the changing roughness over the flow depth, we converted group-specific roughness profiles into $k_s$ values based on equation [3].

We ran two scenarios for each of the two discharges:

1. Constant roughness for the entire reach ($k_s$=0.1 m)
2. Assignment of stage-dependent, spatially variable roughness as determined for vegetated areas using the ALS-TLS model. We used the relationships established between $Bk_{ALS(max)}$ to $A_{P,vert(n)(max)}$ and the stand height to determine the vegetation density (Figures 8 and 9). The classified map is shown in Figure 10. With a known vegetation density group, we assigned the corresponding roughness profile (Figure 2.7). Unvegetated areas were assigned values of $k_s=0.4 \text{ m}$ for gravel and $k_s=0.1 \text{ m}$ for pools/bare sand bars. Unvegetated areas were delineated based on aerial photographs and ground surveys.

Model validation was based on a few field measurements made at 450 m$^3$/s in spring 2011. We took discharge measurements with a Teledyne RD Instruments RiverRay ADCP (acoustic Doppler current profiler) in the side channel (river left) of the study site at 450 m$^3$/s. These measurements are in good agreement with model output (4% difference from the total discharge of scenario 2).

The extent of floodplain inundation was slightly sensitive to the addition of spatially variable depth-dependent roughness at 450 m$^3$/s (Figure 2.13). The average water depth through the reach differed by less than 0.30 m for both discharges. However, the various model runs using different scenarios show that prediction of the distribution of bed shear stress differs in important ways (Figure 13). Characterization of the spatial distribution of shear stress is a critical component in the prediction of the divergence of the sediment transport field and to the prediction of the distribution of scour and fill that causes channel narrowing or widening. The shear stress predicted by River2D is the total boundary shear stress, $\tau_o$, and is the sum of the stress exerted on the vegetation, $\tau_{veg}$, (i.e., form drag) and the stress exerted on the bed and banks, $\tau_b$, (i.e., skin friction) [Buffington and Montgomery, 1999; Smith, 2004]. We are interested in extracting the latter component, $\tau_b$, because of its geomorphic importance in sediment transport.

The proportion of $\tau_o$ from $\tau_{veg}$ and $\tau_b$ may be assigned based on the forces exerted on the stems and on the bed, respectively, in the 2D patch model. In the process of quantifying the vegetative
and whole patch roughness in section 4.2, we quantified the force exerted on the bed, $F_{bed}$, and the force exerted on the stems, $F_{D,veg}$. We determined $F_{D,veg}/F_{bed}$ as a function of flow depth for each of the three vertical projected area profile groups (i.e., sparse, moderate, and dense) (Figure 2.14). As stress is the force per unit area, the force ratios for each vegetation group also specify corresponding $\tau_{veg}/\tau_{b}$ ratios. We draped the density classification for vegetation patches, as determined by the TLS-ALS model (Figure 2.10), over River2D $\tau_o$ output and applied the $\tau_{veg}/\tau_{b}$ ratio, unique to each group, to quantify the near-bed shear stress (Figure 2.13).

The general patterns of vegetative roughness and the resulting near-bed shear stress values predicted through the application of the methodology developed in this paper appear reasonable based on field observations, aerial photograph analyses, and an intimate knowledge of the site [Manners et al., 2011]. Incorporation of a spatially variable representation of vegetation roughness exposes regions of very low near-bed shear stresses (Figure 2.13) that correlate with thick deposits of fine-grained alluvium. Differences in the pattern of near-bed shear stress between the spatially uniform and spatially variable roughness are more pronounced for the higher discharge (935 m$^3$/s), because the water accesses the vegetated floodplain. This example of the Laddie Park site is a proof-of-concept that we can use the fusion of TLS and ALS data across multiple scales. Such a multi-scalar analysis provides a platform to more robustly explore the mechanisms and feedbacks between vegetative encroachment into active alluvial surfaces and the geomorphic responses.

7. Summary and Conclusions

The methodology described here demonstrates the feasibility of incorporating small-scale interactions between water and stems into a larger-scale process-based evaluation of the role of riparian vegetation on the flow field. To our knowledge, the multi-scalar analysis presented here is the first to mechanistically account for shrubby riparian vegetation stand structure, and associated hydraulic roughness of vegetation patches, at the reach scale. Vegetation metrics that
have been repeatedly shown to affect the flow field, including stem density and spacing [e.g., Nepf, 1999; Bennett et al., 2002; Jarvela, 2002] were implicitly incorporated in a spatially explicit way into the larger-scale parameterization of vegetation. Although we applied this parameterization to a reach, the ALS data we used could have been applied to the entire Yampa and Green River corridors within Dinosaur National Monument. By incorporating this finer-scale detail derived from the TLS data, we believe that the methodology presented here has the potential to capture the impact of riparian vegetation on the flow field in a detailed and spatially explicit way at a large scale.

Our study formulated a methodology that takes advantage of the increasing availability of spatially extensive datasets, such as ALS, as well as the accessibility of high resolution point clouds from TLS. We present one possible way to relate the stand structure of discrete patches of vegetation derived from high resolution measurements to the much coarser signature of stand structure derived from airborne data. As such, the goal of this methodological development has been to capture the detailed structure of riparian vegetation and extrapolate those influences out over large areas. Adoption of the specific relationships formulated here may not necessarily apply to other vegetation communities, however, the methodology presented here probably transcends geographic location and vegetation community composition.

Results from this work predict that the roughness of forested floodplains increases with flow depth. With rising stage, the hydraulic resistance of the floodplain increases until the vegetation is fully submerged; thereafter, roughness declines. This prediction supports experimental observations and implies that reach-scale dynamics over a flood event are continually being altered by the interaction of water and vegetation.

Although there are a variety of other approaches that can be used for modeling the hydraulic impact of vegetation [e.g., Nepf, 1999; Kean and Smith, 2004], a key contribution of this study is the description of a multi-scalar model. Application of our TLS-ALS model to a 2D hydraulic model of Laddie Park highlights the fact that assigning spatially explicit, stage-
dependent hydraulic roughness values have the potential to reveal geomorphically-relevant hydraulic patterns at the reach scale that would not be apparent with more simple characterizations of channel or vegetation roughness. Ultimately, detection of geomorphically-relevant patterns at these scales provides a first step in the identification and prediction of vegetation on both inducing and exacerbating channel change.

The role of riparian vegetation in causing channel change is an enduring and pervasive question in river management. For example, the Colorado River basin has been plagued by the invasion of tamarisk. The rapid establishment and dominance of this species has contributed to profound channel narrowing and cross-section simplification to the detriment of in-channel habitat critical to the survival of some native fish species [Olden et al., 2006]. The 2D hydraulic floodplain models developed with spatially variable, stage-dependent roughness described here have the potential to reveal areas sensitive to further channel change and ultimately in building predictive morphodynamic models of channel evolution.

Notation

\( A \): bed-parallel area, \( m^2 \).
\( A_{ij} \): bed-parallel area of a cell, \( m^2 \).
\( A_{P,\text{vert}} \): flow-perpendicular projected area, \( m^2 \).
\( A_{P,\text{vert},ij} \): flow-perpendicular projected area of a cell, \( m^2 \).
\( A_{P,\text{vert}(n)} \): maximum, cumulative, flow-perpendicular, normalized projected area, [-]
\( \alpha \): depth of the cell along the radial distance from the scanner, m.
\( B_{ij} \): number of points intercepted between the scanner and the cell, [-].
\( B_{k_{ALS}} \): ALS blockage, [-].
\( C_D \): drag coefficient, [-].
\( \delta(x) \): stem deflection in the streamwise direction, m.
\( d \): stem diameter, m.
\( D_v \)  
vegetation density, m\(^{-1}\).

\( D_{v,ij} \)  
vegetation density of a cell, m\(^{-1}\).

\( E \)  
stiffness modulus, N/m\(^2\).

\( F \)  
external or internal forces, N

\( F_{D,\text{veg}} \)  
vegetative drag force, N.

\( G_{ij} \)  
number of points intercepted within a cell, [-].

\( g \)  
gravitational acceleration, m/s\(^2\).

\( H \)  
tamarisk height above the bed, m.

\( H_{\text{ALS}} \)  
tamarisk height measured from ALS data, m.

\( H_{\text{TLS}} \)  
tamarisk height measured from TLS data, m.

\( I \)  
cross-area inertial modulus, m\(^4\).

\( k_s \)  
effective roughness height, m.

\( n \)  
Manning’s roughness value, [-].

\( n_{\text{bed}} \)  
Manning’s bed roughness value, [-].

\( n_{\text{patch}} \)  
Manning’s patch roughness value, [-].

\( n_{\text{vegetation}} \)  
Manning’s vegetation roughness value, [-].

\( p \)  
hydrostatic pressure, Pa.

\( \rho \)  
density of water, kg/m\(^3\).

\( \varphi \)  
angular distance, degrees.

\( T_{ij} \)  
total number of emitted laser pulses that passed through the distal boundary.

\( \tau_0 \)  
total boundary shear stress, N/m\(^2\).

\( \tau_b \)  
shear stress on bed, N/m\(^2\).

\( \tau_{\text{veg}} \)  
shear stress on vegetation, N/m\(^2\).

\( U \)  
depth-averaged velocity, m/s.

\( U_r \)  
depth-averaged reference velocity, m/s.

\( y \)  
flow depth, m.
vertical height of the cell, m.

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Sandercock, P. J., and J. M. Hooke (2010), Assessment of vegetation effects on hydraulics and of feedbacks on plant survival and zonation in ephemeral channels, *Hydrol Process*, 24(6), 695-713.


Table 2.1. Attributes of the 12 tamarisk patches whose stand structure was characterized by terrestrial laser scans

<table>
<thead>
<tr>
<th></th>
<th>Patch Size (m²)</th>
<th>Age** (years)</th>
<th>Substrate***</th>
<th>Depositional History**** (cm)</th>
<th>Profile Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 LP1</td>
<td>28.9</td>
<td>20</td>
<td>s</td>
<td>160</td>
<td>moderate</td>
</tr>
<tr>
<td>2 LP2</td>
<td>18.7</td>
<td>55-60</td>
<td>s</td>
<td>190</td>
<td>dense</td>
</tr>
<tr>
<td>3 LP3</td>
<td>10.3</td>
<td>50-55</td>
<td>s</td>
<td>85</td>
<td>dense</td>
</tr>
<tr>
<td>4 LP4</td>
<td>21.2</td>
<td>60</td>
<td>s</td>
<td>125</td>
<td>moderate</td>
</tr>
<tr>
<td>5 LP5</td>
<td>29.2</td>
<td>45</td>
<td>s</td>
<td>300</td>
<td>moderate</td>
</tr>
<tr>
<td>6 LP6</td>
<td>136.5</td>
<td>20</td>
<td>g</td>
<td>0</td>
<td>sparse</td>
</tr>
<tr>
<td>7 LP7</td>
<td>11.9</td>
<td>&lt;10</td>
<td>s</td>
<td>50</td>
<td>moderate</td>
</tr>
<tr>
<td>8 LP8</td>
<td>37</td>
<td>20</td>
<td>g</td>
<td>0</td>
<td>sparse</td>
</tr>
<tr>
<td>9 LP9</td>
<td>9.77</td>
<td>20</td>
<td>g</td>
<td>0</td>
<td>sparse</td>
</tr>
<tr>
<td>10 SC1</td>
<td>12.8</td>
<td>15</td>
<td>s</td>
<td>110</td>
<td>dense</td>
</tr>
<tr>
<td>11 SC2</td>
<td>6.5</td>
<td>50</td>
<td>s</td>
<td>140</td>
<td>dense</td>
</tr>
<tr>
<td>12 SC3</td>
<td>9.8</td>
<td>15</td>
<td>s</td>
<td>35</td>
<td>dense</td>
</tr>
</tbody>
</table>

*LP denotes patches located at the Laddie Park study site on the Yampa River and SC denotes patches located at the Seacliff site on the Green River

**Age was determined by identification of the germination year of a sample of tamarisk located either within or close to each patch.

*** s = sand and g = gravel

****Depositional history refers to the amount of fine-sediment that has been deposited around those individuals recovered for aging. We measured the amount of deposition as the total accumulation of sediment above the germination point.
Table 2. Measured and predicted tamarisk height ($H$), ALS blockage ($B_{ALS}$), and normalized vertical projected area ($A_{P,\text{vert}(n)}$) values for 12 vegetation patches used in the development of the ALS-TLS model.

<table>
<thead>
<tr>
<th>Patch</th>
<th>$H_{\text{TLS(max)}}$</th>
<th>$A_{P,\text{vert(max)}}$</th>
<th>$B_{\text{ALS(max)}}$</th>
<th>$H_{\text{TLS(50)}}$</th>
<th>$A_{P,\text{vert(50)}}$</th>
<th>$H_{\text{ALS(50)}}$</th>
<th>$A_{P,\text{vert(50)}}$</th>
<th>$B_{\text{ALS(50)}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP1</td>
<td>4.4 m</td>
<td>1.88 m$^2$/m$^2$</td>
<td>4.4 m</td>
<td>1.5 m</td>
<td>0.94 m$^2$/m$^2$</td>
<td>3.10 m</td>
<td>1.60 m$^2$/m$^2$</td>
<td>1.70 m</td>
</tr>
<tr>
<td>LP2</td>
<td>5.9 m</td>
<td>5.13 m$^2$/m$^2$</td>
<td>5.7 m</td>
<td>2.0 m</td>
<td>2.57 m$^2$/m$^2$</td>
<td>4.25 m</td>
<td>3.05 m$^2$/m$^2$</td>
<td>1.40 m</td>
</tr>
<tr>
<td>LP3</td>
<td>4.4 m</td>
<td>4.20 m$^2$/m$^2$</td>
<td>4.8 m</td>
<td>1.5 m</td>
<td>2.10 m$^2$/m$^2$</td>
<td>2.80 m</td>
<td>2.55 m$^2$/m$^2$</td>
<td>1.84 m</td>
</tr>
<tr>
<td>LP4</td>
<td>5.8 m</td>
<td>2.54 m$^2$/m$^2$</td>
<td>5.8 m</td>
<td>1.8 m</td>
<td>1.27 m$^2$/m$^2$</td>
<td>4.14 m</td>
<td>1.93 m$^2$/m$^2$</td>
<td>2.05 m</td>
</tr>
<tr>
<td>LP5</td>
<td>5.0 m</td>
<td>3.06 m$^2$/m$^2$</td>
<td>5.2 m</td>
<td>2.3 m</td>
<td>1.53 m$^2$/m$^2$</td>
<td>4.35 m</td>
<td>0.35 m$^2$/m$^2$</td>
<td>1.09 m</td>
</tr>
<tr>
<td>LP6</td>
<td>2.6 m</td>
<td>0.67 m$^2$/m$^2$</td>
<td>2.6 m</td>
<td>1.2 m</td>
<td>0.34 m$^2$/m$^2$</td>
<td>1.25 m</td>
<td>1.46 m$^2$/m$^2$</td>
<td>1.37 m</td>
</tr>
<tr>
<td>LP7</td>
<td>3.2 m</td>
<td>1.94 m$^2$/m$^2$</td>
<td>3.4 m</td>
<td>1.4 m</td>
<td>0.97 m$^2$/m$^2$</td>
<td>1.53 m</td>
<td>0.51 m$^2$/m$^2$</td>
<td>1.32 m</td>
</tr>
<tr>
<td>LP8</td>
<td>2.8 m</td>
<td>0.75 m$^2$/m$^2$</td>
<td>2.8 m</td>
<td>1.2 m</td>
<td>0.38 m$^2$/m$^2$</td>
<td>1.48 m</td>
<td>0.32 m$^2$/m$^2$</td>
<td>0.99 m</td>
</tr>
<tr>
<td>LP9</td>
<td>2.2 m</td>
<td>0.74 m$^2$/m$^2$</td>
<td>2.2 m</td>
<td>1.1 m</td>
<td>0.37 m$^2$/m$^2$</td>
<td>1.15 m</td>
<td>3.84 m$^2$/m$^2$</td>
<td>1.30 m</td>
</tr>
<tr>
<td>SC1</td>
<td>4.2 m</td>
<td>5.40 m$^2$/m$^2$</td>
<td>3.0 m</td>
<td>1.4 m</td>
<td>2.70 m$^2$/m$^2$</td>
<td>2.70 m</td>
<td>3.82 m$^2$/m$^2$</td>
<td>1.52 m</td>
</tr>
<tr>
<td>SC2</td>
<td>3.8 m</td>
<td>3.11 m$^2$/m$^2$</td>
<td>3.2 m</td>
<td>1.2 m</td>
<td>1.56 m$^2$/m$^2$</td>
<td>1.75 m</td>
<td>3.48 m$^2$/m$^2$</td>
<td>0.30 m</td>
</tr>
<tr>
<td>SC3</td>
<td>4.2 m</td>
<td>4.17 m$^2$/m$^2$</td>
<td>3.8 m</td>
<td>1.9 m</td>
<td>2.09 m$^2$/m$^2$</td>
<td>1.70 m</td>
<td>3.48 m$^2$/m$^2$</td>
<td>0.30 m</td>
</tr>
</tbody>
</table>

*B_{ALS(75)} / B_{ALS(25)} > 7 indicates high canopy blockage, predicted value increased by 50%.
Table 2.3 Percentage of 2 m cells within the 12 TLS patches that match the TLS profile group in the application of the TLS-ALS model using a 2-m, 3-m, and 4-m moving window.

<table>
<thead>
<tr>
<th>Profile Group</th>
<th>2-m Moving Window</th>
<th>3-m Moving Window</th>
<th>4-m Moving Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sparse</td>
<td>36%</td>
<td>35%*</td>
<td>42%</td>
</tr>
<tr>
<td>2. Moderate</td>
<td>46%</td>
<td>84%</td>
<td>58%</td>
</tr>
<tr>
<td>3. Dense</td>
<td>52%</td>
<td>70%</td>
<td>60%</td>
</tr>
</tbody>
</table>

*Within-patch spatial variability of $A_{P, \text{vert}(0)}$ profiles, analyzed at the same 3-m moving window scale as the TLS-ALS model application, increases model prediction to 65%.
Figure 2.1. Study areas in Dinosaur National Monument, Colorado.
Figure 2.2. Twelve patches captured with the terrestrial laser scanner. These patches are located at two ongoing study reaches, A) Laddie Park on the Yampa River and B) Seacliff on the Green River. Dashed lines delineate tamarisk-dominated floodplain areas that the multi-scalar model was applied to.
Figure 2.3. Schematic of the procedure used to quantify vertical projected area profiles from a 3D point cloud. We established a cylindrical polar grid, composed of 3d cells or voxels, for each patch centered on the scanner location. Each cell’s vertical height (z) was 0.20 m. The depth along the radial distance from the scanner (α) was 0.10 m. The third dimension was defined by the angular distance (ϕ) that was set to 2°. As such, the length of this dimension varied based on the distance of the cell to the scanner along the plane defined by αϕ. For illustrative purposes, we only show a single 0.20-m horizontal slice, composed of grid cells all located at the same height above the ground surface. Vertical projected area \( A_{P,vert} \) was first calculated within each cell and then summed over the patch at each 0.20-m interval. Patch-total \( A_{P,vert} \) values were normalized by the bed-parallel area of the patch, resulting in normalized vertical projected area values \( A_{P,vert(n)} \). We use two types of curves from this analysis: a vertical projected area curve that is representative of the vertical distribution of stems through the profile, and the cumulative vertical projected area curve that represents the sum of all stems through the profile and is closer to what the flow field encounters.
Figure 2.4. Example of a patch of *Tamarix ramosissima*, (tamarisk) at Laddie Park. Flow is from left to right in photo.
Figure 2.5. Example of a single 2D patch model run for patch LP2. “Tamarisk stems” are depicted here as a series of vertical cylinders (red circles) representative of the cumulative vertical projected area and spatial organization of a patch at a given height. The River2D depth (contours) and velocity (vectors) solutions are shown. See text for further explanation of the modeling procedures.
Figure 2.6. Cumulative normalized vertical projected area ($A_{P_{vert}(n)}$) curves for the twelve patches, classified into three vegetation density groups: sparse, moderate, and dense.
Figure 2.7. Average roughness profiles for the three vegetation density groups. (A) Total patch roughness \( n_{\text{patch}} = n_{\text{veg}} + n_{\text{bed}} \) for the dense group (squares), moderate group (circles), and sparse group (diamonds). (B) Profiles of \( n_{\text{veg}} \) (black) and \( n_{\text{bed}} \) (gray) for the three groups. The moderate and dense groups have the same \( n_{\text{bed}} \) values. Total patch roughness, vegetation roughness, and bed roughness are shown separately to illustrate the significant contribution of vegetation to total roughness. \( A_{P,\text{vert}}/A \) (same value as \( A_{P,\text{vert}(n)} \)) used to quantify \( n_{\text{veg}} \) (from equations 5 and 14) are averages of all patches within that group. Error bars were calculated from standard deviation of back-calculated \( C_D \) values from 2D patch models. In general, vegetation roughness and total patch roughness increase with increasing depth. The exception is the sparse group. When the sparse group is overtopped at a flow depth of 2.4 m, roughness begins to decrease. The “x” shown in (A) is a data-point taken from the experimental work of Freeman et al. [2000] and shows good agreement with our results.
Figure 2.8. Space defined by height above the bed and normalized vertical projected area for the three projected-area profile groups (sparse, moderate, and dense) and the predicted positions of the maximum and median $A_{\text{vert}}$ of those TLS patches used to create the TLS-ALS model (Table 2). Bands were defined by the range in values measured from the eleven TLS patches (LP2 was not included, see text for explanation). This space was used to classify values extracted from the ALS data in the moving-window analysis. Horizontal error bars correlate to the 20% error in the predictive model and vertical error bars to the 6% error between stand height measured from ALS and TLS. Solid error bars are associated with predicted median values. Dashed error bars are associated with predicted maximum values. The SC# and LP# labels refer to specific patches at Seacliff and Laddie Park respectively.
Figure 2.9. Cumulative curves used to relate TLS data to ALS data. Example shown for patch LP4. (A). Cumulative maximum blockage ($B_{ALS(max)}$) occurs at the maximum height from the ALS data ($H_{ALS(max)}$). (B) Cumulative frequency curve for $A_{P,vert(n)}$ (solid black line) and $B_{ALS}$ (dashed gray line). The median values of $A_{P(n)}$ and $B_{ALS}$ were used to define the median heights for the $H_{TLS(50)}$ and $H_{ALS(50)}$ from the cumulative frequency curves, respectively. A relationship between the heights at which the median values occurred at a single patch for the $A_{P(n)}$ and $B_{ALS}$ was identified that was subsequently used in the application of the TLS-ALS model to the reach-scale.
Figure 2.10. Application of the TLS-ALS model (with a 3-m moving window) to the (A) Laddie Park and (B) Seacliff reaches. The pattern of profile group recognition is generally realistic. We evaluated the model based on the correct prediction of group type for each 2-m square cell within the 12 patches.
Figure 2.11. Group-averaged normalized vertical projected area profiles.
Figure 2.12. Cartoon showing the interaction between tamarisk patch density and flow. Stem spacing influences the size and strength of flow paths around and through the patch. If stems are clumped together, the flow will be channelized, shearing low-lying stems and delivering wood. A greater number of stems will grow back after being sheared, all of which results in higher stem density and therefore greater vertical projected area in the 0.5 m above the ground surface. The density and spacing of stems also has an influence on the hydraulics of flow through a patch (i.e., on the $C_D$). These relationships suggest that feedbacks exist among flow and tamarisk growth. It is these feedbacks that control the spatial pattern of vegetation hydraulic roughness.
Figure 2.13. 2D model output at the Laddie Park reach for two discharges (Q=450 and 953 m$^3$/s) and two roughness scenarios. 1) Spatially uniform roughness: A constant $k_r$ value was assigned to the reach. When converted to $n$, these values varied slightly as a result of the depth-dependence of this relationship. 2) Spatially variable roughness: Application of the TLS-ALS model expressly accounts for stand structure in the parameterization of roughness. A constant $k_r$ value was assigned separately to pools/ sand bars and to gravel bars/riffles. When converted to $n$, these values varied slightly as a result of the depth-dependence of this relationship. Upper panel shows the resulting maps of roughness (shown here as Manning’s $n$) for the two scenarios at the two discharges. The lower panel shows the near-bed shear stress ($\tau_b$).
Figure 2.14. Depth-dependent ratio of forces on the stems to those on the bed ($F_{D,veg}/F_{bed}$) for each of the three vertical projected area profile groups (i.e., sparse, moderate, and dense). As stress is the force per unit area, we used the $F_{D,veg}/F_{bed}$ ratios to partition total boundary shear stress into the stress exerted on the vegetation, $\tau_{veg}$, (i.e., form drag) and the stress exerted on the bed and banks, $\tau_b$, (i.e., skin friction). The fitted curves had $R^2$ values of 0.91, 0.99, and 0.99 for the sparse, moderate, and dense groups, respectively.
CHAPTER 3
MECHANISMS OF VEGETATION-INDUCED CHANNEL NARROWING ON AN UNREGULATED CANYON-BOUND RIVER: RESULTS FROM A NATURAL FIELD-SCALE EXPERIMENT

1. Introduction

Alteration of the hydrologic regime and sediment supply of many rivers throughout the Colorado River system has resulted in widespread channel narrowing and simplification of planform [Van Steeter and Pitlick, 1998; Schmidt, 2008]. Changes to the timing of peak flows and reduced flood magnitudes also created favorable conditions for non-native vegetation establishment [Stromberg et al., 2007; Merritt and Poff, 2010; Mortenson and Weisberg, 2010]. Shifts in the composition and distribution of riparian vegetation have altered fluvial processes which, in turn, have changed the shape of the channel [Johnson, 1994; Tal et al., 2004]. The complex interactions among water, sediment, and vegetation created non-linear responses that exacerbated changes to both geomorphic form and the character of riparian vegetation communities [Corenblit et al., 2007]. Thus, the physical template of much of the river network has, within the past century, changed rapidly.

Climate change and persistently increasing water development pressures will further alter the flow regime and the dominant riparian vegetation species [Meyer et al., 1999], likely promoting additional channel narrowing and planform simplification. Such river channel adjustments reduce the viability of in-channel habitat for endemic endangered fish species many of which depend on particular settings, such as shallow water habitats [Tyus and Karp, 1990] and degrade other unique resources provided by the rivers of the Colorado River basin [e.g., Kearsley et al., 1994]. The effectiveness of measures designed to protect or restore these resources depends on our ability to anticipate the impact of several possible management actions on channel form (e.g., vegetation removal vs more bypass floods). It is therefore essential to understand the
interactions that occur among water, sediment, and vegetation. Specifically, we need to identify key mechanisms and feedbacks responsible for the current channel morphology and vegetation community and develop a predictive basis for determining how future changes will propagate through the system.

While it is well established that channel width scales to discharge [Lacey, 1930; Leopold and Maddock, 1953], we lack a predictive theory of channel morphodynamics that fully incorporates vegetation [Jarvela et al., 2006]. Great progress has been made on identifying the processes by which water, sediment, and vegetation interact in laboratory settings [e.g. Jarvela, 2002; Tal and Paola, 2007]. Holding nearly all environmental conditions constant, this body of work predominately focuses on one-way interactions, where for example, stem density has been shown to exert primary control over how water moves through a vegetation patch [Bennett et al., 2002]. However, in a natural river, vegetation patches are situated within a larger, more complicated setting. Interactions characterized in a laboratory may only be applicable for a short time period, limited spatial extent, and for steady flow conditions. As the flow regime, channel morphology, and/or vegetation stand composition or structure (e.g., height) changes along a river corridor, or over time for a given location, simple one-way interactions are obscured by complex feedbacks [Dean and Schmidt, 2011].

Field studies provide critical insight regarding these interactions, particularly over the larger spatial and temporal scales in which river systems operate. Key processes responsible for vegetation establishment and the erosion or deposition of channel and floodplain sediment continuously occur. Where the riparian vegetation community has recently expanded and the channel narrowed, the signature of these processes are often preserved within newly constructed floodplains and vegetation stands [Schumm and Lichty, 1963; Friedman et al., 1996; Allred and Schmidt, 1999; Birken and Cooper, 2006]. While others have previously documented systematic channel narrowing in the Colorado River basin and elsewhere [e.g., Graf, 1978; Hereford, 1984; Dean and Schmidt, 2011], in nearly all cases, the channels studied were responding to multiple,
and often simultaneous, changes to environmental conditions (e.g., dam closure and the expansion of invasive, non-native vegetation). In such field studies, it is difficult to isolate the driving mechanisms of channel changes, particularly the role of vegetation relative to reductions in flow.

The Yampa River, unlike the other large tributaries of the Colorado River, retains its natural snowmelt flood pulse. There are relatively few dams and diversions in the basin, and presumably, the sediment supply has remained relatively similar. However, even without widespread alterations to the flow regime, the non-native, invasive, riparian shrub tamarisk (Tamarix spp.) has established along portions of the river corridor during the past century [Fischer et al., 1983; Merritt and Cooper, 2000]. Where tamarisk is present the channel has narrowed [Larson, 2004].

We posit the Yampa River as the setting of a natural, field-scale experiment, established when an invasive riparian plant began to colonize an unregulated river. All else held constant, the unchanged nature of the Yampa’s flow regime should have maintained channel size and shape (i.e., channel width). Deviation from a long-term steady state condition may presumably be attributed to the only significant change in the environment, a change in the riparian vegetation community, specifically, the increase in vegetation coverage by dense stands of the shrubby plant tamarisk. Thus, the Yampa has qualities of a laboratory experiment wherein most environmental conditions have been controlled, and of a field study, where the processes that have created today’s narrower channel have occurred over a large area for the last century. We took advantage of this natural, field-scale, experiment, to identify the mechanisms by which vegetation alters fluvial processes to create a narrower channel. Using a variety of field and computational methods over different spatial and temporal scales, we report the results of this experiment and describe the timing, style, and magnitude of channel and vegetation changes on the Yampa River during the past century.
This paper builds on other studies in the Colorado River basin [Graf, 1978; Hereford, 1984; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Birken and Cooper, 2006] and elsewhere [Dean and Schmidt, 2011] that integrate vegetation and geomorphic histories to understand how modifications to the flow regime, sediment supply, and riparian vegetation impacted the trajectory of changes to channel form. These histories inform us on the current condition of the rivers of the Southwestern United States as human society continues to alter flows and the climate continues to change. With its relatively unregulated hydrology, the environmental history of the Yampa River provides a critical piece of a larger story.

2. Study Area

The Yampa River in Dinosaur National Monument flows for 74 km through a canyon in the easternmost Uinta Mountains before joining the upper Green River in Echo Park in northwestern Colorado (Figure 3). Annual discharge is similar between the Yampa River and upper Green River. Thus, the Yampa and the upper Green River are essentially co-equal headwater branches of the middle Green River that begins in Echo Park. The hydrologic regime of the Yampa is dominated by the spring snowmelt flood. Estimated annual sediment loads range between 1.85 and 2.20 million Mg/year, the majority of which (~70%) is delivered by the Little Snake River 6.6 km upstream from the park boundary. Approximately 95% of the annual load on the Yampa River is transported as suspended sediment [Andrews, 1980; Elliott and Anders, 2004]. Water and sediment flux entering the Yampa Canyon is measured at the USGS stream gage, Yampa River at Deerlodge Park (#09620050) (Figure 3.1).

Opportunities for alluvial sediment storage and riparian vegetation establishment in the study area are limited. Two dominant valley types exist within this canyon, determined by river-level geology. Interbedded sandstone, shale, and limestone comprise the Morgan formation. Where this resistant rock type dominates, the river flows within a very narrow valley, where the gradient is also steep. The alluvial valley in the less resistant Weber Sandstone is wider, and the
channel has a flatter gradient. There are a few places in the Weber Sandstone part of the Yampa Canyon where the valley is particularly wide, and multi-thread channels diverge around islands. Floodplains are most extensive in these reaches [Larson, 2004]. This study was primarily conducted in the two widest reaches of the Weber Sandstone segment of the Yampa Canyon, Harding Hole and Laddie Park, which cover 5.5 and 1.6 river km, respectively (Figure 3.1). Since we focused on the widest settings, our results likely represent the largest channel and vegetation changes that have occurred in Yampa Canyon. However, the processes described in this study are applicable to other places in the canyon amenable to vegetation establishment. These locations include nearly the entire lower canyon that flows through the Weber Sandstone and at the few locations in the Morgan Formation part of the canyon that have recirculating eddys upstream of debris flow constrictions.

First introduced to the lower Colorado River basin in the 1880’s, the non-native woody shrub tamarisk expanded north, entering the Yampa and Green Rivers by the early to mid 20th century [Webb et al., 2007]. Two morphologically similar species, Tamarix chinensis and Tamarix ramosissima dominated the invasion. Today most plants are a hybrid between the two [Gaskin and Schaal, 2002]. The success of tamarisk in the Colorado River basin has been attributed to its prolific seed dispersal during a long viability window in the spring and its long tap roots and morphologic properties that allow the plants to survive during prolonged dry periods [Cleverly et al., 1997; Di Tomaso, 1998; Merritt and Poff, 2010].

3. Methods

This study used multiple lines of evidence, over various spatial and temporal scales, to identify the rate, style, and timing of changes in channel width and vegetation cover. We matched spatially-limited, yet temporally rich, stratigraphic and dendrogeomorphic analyses from floodplain trenches and pits with spatially-rich, yet temporally limited, historical aerial photographs to identify long-term trends in channel form. Tamarisk cohort maps portrayed the
large-scale distribution and timing of non-native vegetation encroachment, and detailed germination and geomorphic histories of individual tamarisk were interpreted to provide information on the interactions and feedbacks among floods, tamarisk, and geomorphic processes. All data were linked to RTK-GPS survey data and LiDAR datasets to identify geomorphic and vegetation patterns in a spatially-explicit way. We developed a 1-D hydraulic model of the study reaches, to estimate stage and inundation patterns for the historical range of flows.

3.1 Hydrology

We analyzed components of the flow regime important to both geomorphic processes and vegetation recruitment. Entrainment and transport of sediment are often linked to flood magnitude, duration, and frequency [Haschenburger and Wilcock, 2003], while the quantity of water and the timing of flood peak and its rate of recession control the germination of riparian vegetation in semi-arid systems [Hupp and Osterkamp, 1996]. Instantaneous peak flow was measured at the Deerlodge Park gage between 1983 to 2011. To extend the record, we estimated peak flow magnitude at Deerlodge Park by adding two upstream USGS gages; one on the Yampa River (Maybell) above the confluence with Little Snake River and the other on the Little Snake River (Lily) (Figure 3.1). For 1923 to 1982, we estimated instantaneous peak flow by taking the larger of the two values: 1) instantaneous peak from the Maybell gage and the daily average flow from the Lily Park gage for the corresponding day, or 2) instantaneous peak from the Lily Park gage and the daily average flow from the Maybell gage for the corresponding day. Similarly, daily average flows for the Maybell and Lily Park gages were added together to reconstruct the annual hydrograph prior to 1983.

We distinguished years with large floods (recurrence > 10 years) and small floods (recurrence < 2 years) based on the long-term flood frequency (Log Pearson III) analysis of the instantaneous annual maximum series for the 89-year record. We also distinguished years that were wet (annual runoff > 75th percentile of the long-term average) and dry (annual runoff < 25th
percentile). We characterized the typical hydrograph shape for all flow years, using mean daily discharge for the water year, as well as those that were classified as wet and those classified as dry.

Various studies show that climate change has altered runoff patterns of other large rivers in the Colorado River basin [Lettenmaier et al., 1999; Christensen et al., 2004; Barnett et al., 2008]. We analyzed the 89-year hydrologic record to identify any shifts or trends in the flow regime. Climate change is often expressed in the extremes detectable at the decadal scale [Dai et al., 1998; Easterling et al., 2000]. We calculated the 10-year standard deviation of annual runoff as a moving window. Upon detection of a shift, identified here as a large increase in the standard deviation, we re-evaluated the flood frequency analysis for the time period prior to, and following, the shift.

3.2 Hydraulics

Using the US Army Corps of Engineers Hydraulic Engineering Center (HEC)’s series of 1-D hydraulic modeling tools (HEC-RAS and HEC-GeoRAS), we built hydraulic models of the two study reaches. Channel geometries (i.e. cross-sections, channel centerline, and bank stations) were delineated in ArcGIS using a 2008 LiDAR dataset. Bathymetric surveys were conducted in 2011 using an RD Instruments River Ray Acoustic Doppler Current Profiler (ADCP). For areas not dominated by tamarisk, we matched landcover from a classified base map of vegetation and general substrate covers (i.e., sand vs gravel) [Neale, unpublished] to published look-up tables to define roughness values [Chow, 1959]. Tamarisk-dominated stands were assigned a roughness value based on a specific model of vegetative roughness (Chapter 2). In 2009, 2010, and 2011, we measured the edge of water and water surface elevations at six different discharges between 10 and 470 m$^3$/s. Four of these measurements occurred in Laddie Park, and two in Harding Hole. While survey point density varied, all six surveys characterized more than 50% of the length of the water surface profiles in its respective reach. Where the water surface survey points were
spatially co-located with HEC-RAS sections, we compared observed (surveyed) and modeled water surface elevations to evaluate model performance.

3.3 Historic Aerial Photograph Analysis

We measured active channel width in two study reaches using aerial photographs taken in 1961, 1982, 1983, 1989, 1999, 2005, 2010, and 2011 (Table 3.1). We scanned and clipped the photos that predated 2010. These photos were georeferenced in ERDAS Imagine to the 2010 image using 20 to 80 ground control points and a 2nd-order polynomial correction model [Hughes et al., 2006]. The root mean square error’s ranged from 2 to 4 m depending on the quality and scale of the photo. The 2010 and 2011 photos were already georeferenced.

On each photo, we manually digitized the boundary of the active channel (Figure 3.2). We delineated this boundary by noting differences in the elevation of geomorphic surfaces and the abundance of vegetation and relative canopy density (measure of stand maturity). Floodplain surfaces were identified predominately as those having mature vegetation, and alluvial surfaces were included in the active channel. This definition of the active channel is a geomorphic one and not based on, or sensitive to, the discharge at the time of each photograph. The floodplain is not inundated at the same discharge everywhere, but generally between the 1.5 to 2-year flood (300 and 400 m$^3$/s, respectively as determined from the HEC-RAS model). Active channel width was measured as the total active channel area divided by the reach length. Between successive air photos, a change in active channel width was calculated as the change in active channel area divided by total reach length. These changes occurred either from channel narrowing (i.e. conversion from active channel to floodplain, also referred to as floodplain construction) or channel widening (i.e. conversion from floodplain to active channel, also referred to as floodplain stripping).

Changes in channel width from one year to the next were generally small and may be within the uncertainty of air photo measurements. The accuracy of measurements made from the
series of historical aerial photographs is affected by various factors including the resolution of the photo, distortion introduced in georeferencing, the quality of the georectification, and our ability to precisely demarcate the edge of the active channel. We quantified uncertainty associated with the active channel width measured for each photo. For successive pairs of photos (i.e., from 1961 to 1982), we measured the linear difference between permanent topographic features (i.e., boulders). The resulting value, the linear digitizing error, is a measure of both the distortion in the air photos and our ability to identify features. This error averaged 3.3 m. Since we used active channel area to obtain a measure of the average active channel width, we needed to translate this linear digitizing error to active channel area in order to account for the uncertainty in the active channel width. To do this, we multiplied the linear digitizing error by the length parallel to the channel centerline of the difference polygons between successive pairs of air photos (i.e., the area that changed from floodplain to active channel), to get an error in units of m². Averaging this areal error over the two reaches, and therefore dividing by the length of the two reaches, our active channel measurements had 0.90 m uncertainty in channel width measurements from one set of photos to the next.

3.4 Stratigraphic and Dendrogeomorphic Analysis of Floodplain Deposits

We excavated five trenches through the floodplain; four in an island complex at the downstream end of Laddie Park and one in an eddy bar in the middle of Laddie Park (Figure 3.2). We focused our efforts here, because, within the 50-year air photo record, this portion of the study area had experienced significant tamarisk encroachment and channel change. Interpretation of the stratigraphy exposed in the trenches provided data on the mechanisms of floodplain building and channel narrowing.

Alluvial stratigraphy was mapped and interpreted in each trench. We marked the location of stratigraphic contacts at the rootstocks of one willow and 28 tamarisk plants. We excavated these 29 plants, determined the date and elevation of germination, and analyzed changes in tree
ring anatomy due to burial using the methods of Friedman et al. [2005]. Burial signals provided a constraining age on stratigraphic contacts and therefore allowed us to identify years in which individual stratigraphic units were deposited. An additional three trees, excavated from pits, were also analyzed for germination date and elevation to increase the sample size and extent of tamarisk individuals.

For the 31 tamarisk samples from the five trenches and three pits, we established a stage-discharge relationship using predicted water surface elevations from our HEC-RAS model. This allowed us to identify the discharge of the germination stage. We increased our sample size with germination elevations identified and surveyed by Larson (2004). Larson (2004) excavated 29 tamarisk plants in the Harding Hole Reach, identified their germination elevation, and surveyed the elevation of germination relative to baseflow. We identified the approximate location of 24 of these samples and similarly predicted a germination discharge from modeled water surface elevations.

3.5 Tamarisk Cohort Mapping

To identify the timing and distribution of tamarisk establishment, we mapped tamarisk cohorts onto a vegetation base map classified from a 2010 multi-spectral image [Neale, unpublished]. This base map captures the aerial coverage of the canopy, and therefore is not a direct measure of basal area. Tamarisk establish in cohorts of similar ages. Cohorts typically germinate as a result of floods or germinate during a period of drought [Birken and Cooper, 2006]; thus, tamarisk plants occur in clumps along elevation bands or on similar geomorphic surfaces. Cohorts were defined as similarly aged groupings of > four individual plants.

During a field campaign between July and October 2010, we identified similarly aged groups of plants, based on size and current growing elevation. Within each suspected cohort, we chose at least two individuals and determined the age of those plants by counting the number of rings near or below the ground surface, and always below where any branching stems came
together. If the field-determined ages of the two individual plants were not the same, we excavated more individuals to establish consistent cohort dominance. We did not always find the root crown that would indicate the point of germination, because the goal of this method was to identify the general timing, style, and distribution of tamarisk. Therefore, we do not report precise ages for individual tamarisk plants aged using this method. In some places, no dominant cohort existed. In these situations, we cut additional slabs to determine the distribution of ages and assigned a weighted distribution of ages based on the slabs cut. We determined the location of each individual sample using a handheld GPS unit. We also performed a more accurate interpretation of each slab in the lab. If the field and laboratory ages differed, we revised the cohort delineation to match the laboratory age. Examples of the spatial distribution of slab samples and cohort coverages are shown in Figure 3.3. We summarize the cohort maps as tamarisk aerial coverage and tamarisk width over time. Tamarisk width, similar to channel width, was calculated as the areal coverage of tamarisk at a given point in time divided by the length of the reach.

As tamarisk coverage increased, stands aged. Older plants add greater stability to the channel bank than do younger plants. To account for this in analyses of floodplain stripping, we weighted tamarisk width based on the age distribution, and herein specifically refer to this as the “weighted tamarisk width.” On average, a channel bank that has 20-year-old plants is twice as stable as one without and as one with newly established seedlings [Pollen-Bankhead and Simon, 2009]. Assuming a linear relationship of age and added stability, with a maximum of 2 times the stability for stands that established 20 or more years earlier, we accounted for the variable cohesion contributed by tamarisk by weighting tamarisk width by its age over time. For example, for a hypothetical time period in which tamarisk width was 2 m, 1 m of which established 5 years earlier and 1 m of which established 20 years earlier, the weighted tamarisk width would be 3.25 m.
4. Results

4.1 Hydrologic Analyses

Large flood years (in excess of 606 m$^3$/s) typically occur in years of large total runoff (Figure 3.4). Similarly, most small floods (less than 400 m$^3$/s), occur during years of low total runoff. Five wet periods and six dry periods occurred during the 89-year record. The period between 1978 and 1986 was particularly wet. Two very large floods, 1983 and 1984, occurred and seven of the nine years of this period had total runoff volumes greater than the 75$^{th}$ percentile. Following this wet period, a series of dry years spanned from 1988 to 1992 and include four years where the peak discharge was less than 400 m$^3$/s and the annual flow was less than the 25$^{th}$ percentile of all annual flow volumes.

Prior to the 1970’s, annual runoff and flood magnitude were less variable between years. A rise in the decadal-scale standard deviation around 1980 indicates that a shift in the distribution of floods and runoff patterns within a 10-year time period began around 1970. Average runoff volumes, however, are not statistically different (p < 0.01) between the two time periods (Figure 5). While the magnitude of large floods has increased in recent decades, those with a return period less than 10-years, which tend to exert stronger control over long-term channel form have not changed (Figure 3.5).

The shape of the Yampa River’s hydrograph is consistent from one year to the next, expanding in magnitude and duration during wet years, and contracting during dry years (Figure 3.6). Flood recession, measured as the time the hydrograph takes to go from peak discharge to 10 m$^3$/s, the baseflow for the Yampa during an average year, occurs during 61 days for dry years and 131 days for wet years, and averages 97 days for all years within the record.

4.2 Hydraulic Analyses

Modeled flows were in good agreement with measured water surface elevations (Table 3.2). Based on a minimum of seven and maximum of 44 observations, where water surface
surveys were matched to HEC-RAS cross-sections, errors ranged from an average of 0.44 m over-prediction for 300 m$^3$/s in the Harding Hole reach to a 0.04 m under-prediction for 10 m$^3$/s in Harding Hole. Water-surface observations for flows slightly greater than the 2-year flood, 410-470 m$^3$/s, indicate that our 1-D models predict the stages of larger flood flows reasonably well.

4.3 Styles of Channel Change

We identified five styles of channel change; four that contributed to channel narrowing and one to channel widening. Channel narrowing occurred as a result of one of four different floodplain construction processes: (style 1) inset development along the channel margin, (style 2) backwater or eddy in-filling, (style 3) inset floodplain development formed along the margins of a stable mid-channel bar, or (style 4) mid-channel bar stabilization (Figure 3.7). Areas along the channel margin were considered inset if the new floodplain was a bench parallel to the 1961 floodplain, while those that narrowed by backwater or eddy in-filling were located in areas that tend to pond during higher flows and whose surfaces were not necessarily parallel to the 1961 floodplain. New floodplain constructed in the middle of the channel was considered inset if it formed a bench parallel to a stable 1961 mid-channel bar, considered as such, if it had mature vegetation on it in 1961. New floodplain constructed in the middle of the channel not attached to a 1961 floodplain was classified as mid-channel bar stabilization. Removal of floodplain was a result of vertical erosion of floodplain or bank erosion, collectively referred to as floodplain stripping (style 5).

The majority change during the 50-year period occurred as floodplain construction (82% of the area that changed either as a result of narrowing or widening), predominately in the form of inset floodplains along the channel margins (style 1, 54% of channel narrowing) (Table 3.3). New floodplain area constructed within the middle of the channel contributed to 32% of the total channel narrowing (styles 3 and 4), and eddy/backwater infilling contributed to 17% (style 2). We correlated the presence of tamarisk relative to the different styles of channel change to identify
the role of tamarisk in initiating or accelerating the associated processes. While the presence of tamarisk on a narrowed surface may be indicative of its contribution to floodplain construction, absence of the plant does not necessarily identify channel narrowing in the absence of vegetation. In general, tamarisk covered 35% of the narrowed surfaces. Mid-channel surfaces converted to floodplain by 2011 had the greatest coverage of tamarisk (60%), while tamarisk covered less of the new channel-margin floodplain surfaces (17%).

4.4 Pattern of Tamarisk Encroachment

We segmented the tamarisk population into nine unique cohorts based on the hydrologic record (i.e., the clustering of wet or dry years) and the similarity of tamarisk sample ages both on a single geomorphic surface and on different surfaces through the study area. These cohorts were defined by years of establishment. Multiple stands, located along different portions of the corridor, were identified as belonging to the same cohort. Laddie Park, the wider of the two reaches with larger floodplains, had greater tamarisk coverage than Harding Hole (Figure 3.8). For the existing and known distribution of tamarisk plants, early (i.e., 1948-1974), tamarisk recruitment occurred only in Laddie Park. Beginning in the late 1970’s, both Laddie Park and Harding Hole had similar patterns of tamarisk encroachment. The maximum coverage for both reaches was associated with cohorts that established in the dry period of the late 1980’s and early 1990’s. In Laddie Park, the wet period of the early to mid- 1980’s was responsible for the second largest coverage, while the wet period of the mid- to late- 1990’s was responsible for the second largest coverage in Harding Hole. This difference can be attributed to the large flood cohort that established in the mid-1980’s almost exclusively along the topographic depressions of the large floodplain in Laddie Park. We found very few cohorts that established after 2000.

Tamarisk removal by the National Park Service (NPS) in Dinosaur National Monument in popular camping areas and critical native fish habitat during the past 15 years introduced a degree of uncertainty into our observations. Reconstruction of the distribution of targeted stands
indicates that the NPS removed what would have been 20% of the present day aerial coverage within the two reaches. The plants removed were of unknown age. The aerial coverage of removed tamarisk was a small portion of the total Laddie Park coverage (6%). Conversely, tamarisk removed in Harding Hole made up approximately 45% of the total tamarisk coverage. NPS removal efforts in Harding Hole focused on the downstream 1.3 km, commonly referred to as Cleopatra’s Couch, and the 0.3 km around the Mather’s Hole campsite. We account for the uncertainty associated with tamarisk removal by displaying the timing of tamarisk encroachment as a range of values. At a minimum, tamarisk coverage over time was defined by the present day distribution of stands of known age. The uncertainty in tamarisk coverage over time increased, such that by 2009 the range in tamarisk width represents the existing stands plus those removed by the NPS.

4.5 Timing and Style of Tamarisk Encroachment and Channel Change

During the 50-year air photo record, the Yampa River in Laddie Park and Harding Hole narrowed by 10% and 4%, respectively (Figure 3.4). Regardless of the net trend, both floodplain construction and stripping occurred through the record (Figure 3.9). Over time, stripped floodplains became less common in the record, and areas where active channel converted to floodplain became more prevalent. Two periods had greater aerial coverage of floodplain stripping than floodplain construction, thus resulting in a wider channel: the large flood of 1983 and the wet period of the late 2000’s (Figure 3.4). However, the magnitude of erosion (and deposition) was very different between these two widening periods (Figure 3.9).

The general trend in tamarisk encroachment is related to the pattern of net channel changes in the two study reaches (Figure 3.4). Tamarisk coverage increased steadily until the early 1980’s. A rapid expansion occurred in the 1980’s and into the 1990’s. In the past 20 years, however, the rate of tamarisk establishment has declined. We note that Figure 3.4 presents tamarisk coverage as an aerial coverage and as such, is partly biased towards older stands that
have larger canopies. However, in the following discussion of the results, we make reference to specifics about the individual cohorts and their relative presence along the corridor.

4.5.1 Pre-1961: Early Tamarisk Encroachment onto Stable Mid-Channel Bars

In the mid-20th century, the Yampa River had expansive bare bars (e.g., Figures 3.2 and 3.7). The earliest air photo of Laddie Park, taken in late summer 1961 at baseflow (9 m$^3$/s), shows large, recently-reworked mid-channel bars with sparse vegetation. There is a small vegetated island in the middle of the channel. Elsewhere through the study area, other evidence of recently reworked channel sediments exists and there was little in-channel vegetation (Figure 3.7). Tamarisk presence prior to the 1961 air photo was minimal through the canyon and restricted to the mid-channel, where the geometry of the valley maintained persistent and stable bars, including the surfaces where we dug trenches 2 and 3. The average width of tamarisk by 1959 was 0.4 m.

Trenches 3 and 4 represent a complete valley cross-section through the downstream end of Laddie Park (Figure 3.10). At the core of trench 3, we documented a low-lying bar. This bar is evident in the 1961 air photo. Four tamarisk plants used in the dendrogeomorphic analysis had established close to the top of the original bar. While the oldest of these tamarisk, and in fact the oldest we aged in either of the two reaches, germinated in 1948, the other three established between 1955 and 1957. Within the core of the original vegetated island, multiple flood packages are preserved, suggesting that these original tamarisk established on a relatively stable mid-channel bar. They established during, and immediately after, the first dry period (1953-1955) that occurred after tamarisk seeds reached the area (Figure 3.4). While we suspect that tamarisk germinated on much of the low-lying surfaces during this dry period, those that survived were located in an area of the channel that remained stable (i.e., not significantly erosional). Thus, the earliest tamarisk recruitment took advantage of a relatively unique geomorphic setting.
The pattern of subsequent tamarisk establishment identified in trenches 3 and 4 differed from that of the earliest plants. After the original stable bar was colonized, tamarisk established at the edges of this bar in coarse channel sediments (pea gravels, small gravels, and coarse sand). Fine sediment then began to deposit in and around these plants on top of the channel sediment.

4.5.2 1961-1982: Dynamic Channel Maintenance

Channel width was approximately maintained in the period between the 1961 and 1982 air photos. Floodplain construction slightly outpaced floodplain stripping (Figure 3.9), and as a result, channel width decreased by 1.2m (+/- 1.9m). We documented different spatial patterns of floodplain construction and floodplain stripping. Along channel margins, floodplains were stripped down to active channel deposits. In trench 1, located in an eddy bar along the channel margin, we identified a probable cutbank that dates to the 1970’s (Figure 3.11). We interpreted the abrupt truncation of the stratigraphy as a preserved erosional feature that suggests a channel widening episode and is consistent with channel changes mapped in the air photos. Conversely, floodplain construction predominately occurred in the mid-channel. Evidence of such processes exists in trench 3 (Figure 3.10). Three distinct bars were deposited inset to the original vegetated island. Dune-scale ripple drift cross-stratification and discontinuous, diffuse contacts in the lower deposits whose age is constrained between 1957 and 1968 suggest that this bar was part of the active channel in the early part of this period. The first span of relatively wet, larger flood years after 1961 (1970/71 and 1974), deposited flood packages on top of, and inset to, the original vegetated island and the active channel deposits. These vertically-accreted deposits effectively converted the active channel to floodplain.

Tamarisk areal coverage in Laddie Park increased by an order of magnitude by the 1982 air photo, while there were few tamarisk in the Harding Hole reach. The majority of the stands that established in Laddie Park between 1961 and 1982 established as a result of the floods of the early 1970’s. These cohorts were the first to establish on surfaces other than relatively stable mid-
channel bars. For example, a 1971-1974 cohort established in the active channel along a channel margin surface in Laddie Park, inset into the 1961 floodplain (Figure 3.4). By the late 1980’s, this surface had converted to floodplain.

4.5.3 1982-1989: Large Floods

Large floods in the mid-1980’s slightly widened the channel (Figure 3.4). Between the 1982 and 1989 air photos, channel width increased by 1.6 m (+/- 1.4 m), predominately from the 1983 flood. Air photos taken before and after the 1983 flood constrained the geomorphic changes as a result of the single large flood. Both floodplain stripping and sediment deposition occurred during the 1983 flood.

The following year’s flood, the largest on record, caused less geomorphic change. Our air photo record does not capture conditions immediately following the 1984 flood. Instead, a photo from 1989 constrains geomorphic changes after 1983. Between the 1983 and 1989 air photos, we mapped similar amounts of floodplain stripping and floodplain construction (1.1 m) (Figure 3.9). These measurements were less than the uncertainty associated with them (+/-1.6 m), suggesting that no significant reworking of floodplain sediment occurred as a result of the 1984 flood, or subsequent floods. Preservation of pre-1984 floodplain deposits in the four trenches whose floodplain surfaces existed prior to 1984 further suggests a lack of significant erosion (Figure 3.10 and 3.11). From the trenches, we note that the large flood of 1984 created thick flood deposits on some areas of the floodplains, an observation not apparent from the air photos. The largest single flood package in trench 3 dates to the 1984 flood and is as thick as 1.5 m. The 1984 flood packages in trenches 1, 2, and 5 are much smaller (Figure 3.11). Erosional contacts between the 1984 deposits and the subsequent flood packages in trenches 1, 2, and 5 suggest reworking of existing deposits after 1984.

During this wet period, tamarisk expanded at a high rate (Figure 3.4). We attribute the majority of this significant increase in coverage to the cohort that established between 1983 and
1986, predominately in the topographic depressions of the expansive floodplain along river right in Laddie Park (Figure 3.3).

The floods of the latter half of the decade were neither significantly erosional nor depositional. A gap in the depositional record exists following the 1984 flood. No sediment packages remain as a result of floods between 1985-1989 (Figures 3.10 and 3.11). The first two years (1985 and 1986) were wet with moderately sized floods (Figure 3.4). A dry period began within the last three years (1987-1989). Since widespread deposition was initiated within the dry period of the late 1980’s/early 1990’s, around 1990 (see section 4.5.4), it is likely that if sediment was deposited as a result of the floods between 1985 and 1989, it would have been preserved. We interpret the absence of a depositional record to result from two factors. First, the large sediment packages from the floods of 1983 and 1984 may have disconnected the existing bars and floodplains from the subsequent moderate floods. Second, we did not find tamarisk in either of the reaches that established in the late 1970’s and early 1980’s (and survived) (Figure 3.4), just prior to the large floods. Therefore, there may have been a paucity of low-lying vegetation capable of inducing or stabilizing fine sediment deposition.

4.5.4 1989-1999: Rapid Channel and Vegetation Change

During the extremely dry period in the late 1980’s and early 1990’s minor channel narrowing occurred (0.7 m, +/- 0.4 m; Figures 3.4 and 3.8). While there was little channel change, tamarisk width continued to increase at a rapid rate, expanding from 4.2 m in 1986 to 7.7 m in 1992. Small flood years, and relatively dry conditions, created an opportunity for tamarisk to establish and persist at low elevations. Many of the cohorts that we dated to this period established on gravel bars.

This dry period was followed by a span of four wet years (1995-1998), including three successive moderate floods (Figure 3.4). As a result of these higher-than average flows, the channel narrowed by 3.5 m (+/- 0.8 m) between the 1993 and 1999 air photos (Figures 3.4 and
3.9). The flood-related cohorts of the mid- to late 1990’s predominately established in thick deposits of sand along channel margins, increasing the tamarisk coverage by 0.8 m.

The widespread tamarisk establishment followed by rapid floodplain construction that occurred in the 1990’s is preserved in the trenches (Figures 3.10 and 3.11). Trenches 2, 3, 4, and 5 show the progression of tamarisk (and willow) establishment along the active channel margins and through secondary channels. Vegetation establishment was followed initially by deposition of flood packages from small floods in and around the young vegetation, eventually overtopped by the larger floods of the mid-1990’s. Inset floodplain formation both along channel margins and in the mid-channel (e.g. trenches 2 and 3), mid-channel bar stabilization (e.g. trench 4), and eddy/backwater infilling (e.g. trench 5) all contributed to channel narrowing in the 1990’s.

While many of the drought-related cohorts of this time period contributed to channel changes, such as those excavated in the trenches, not all of these cohorts were associated with floodplain construction during the 1990’s or later. We attribute this spatial variability to local hydraulic conditions. For example, along a point bar in Harding Hole, nearly all tamarisk plants established between 1987 and 1992 (Figure 3). Those plants located at the downstream end, an area that ponds during high flows, are now found growing in thick, i.e., > 2 m, sand deposits, while the plants at the upstream end remain rooted in exposed gravels.

4.5.5 1999-2011: Minor Channel and Vegetation Change

The trajectory of widespread channel narrowing that started in the late 1980’s continued into the early 2000’s. During the predominately dry period between the 1999 and 2005 air photos, the channel narrowed by 1.8 m (+/- 1.0 m) (Figures 3.4 and 3.8). Four of the five years had small floods and low total flow volumes. Unlike the substantial increase in tamarisk coverage associated with the dry period between 1987 and 1992, we mapped very few tamarisk cohorts that established during the dry period between 2000 and 2002.
Large floods and wet conditions after 2005 resulted in minor channel re-widening. On average, channel width increased by 0.6 m (+/- 0.2 m). The majority of this change occurred between the 2005 and 2010 air photos, possibly a result of the large 2008 flood, or the combination of this flood closely followed by moderate floods in 2009 and 2010. Little to no change occurred as a result of the second largest flood in the record, 2011, measured from air photos taken between the recession of the snowmelt floods of 2010 and 2011. On the ground observations and surveys supported these results. Similar to the large floods of 1983 and 1984, the large floods of the late 2000’s were closely spaced in time. While these large floods reworked floodplain sediments in only small localized areas, we note that the first of the sequence of large floods reworked greater areas. Additionally, the floods of the 1980’s appeared to have done more localized reworking (Figure 3.9).

4.6 Interactions among Hydrology, Tamarisk, and Sediment

Mutual adjustment of channel form and vegetation distribution and cover during the 50-year geomorphic history of the Yampa River described above, suggests that the successful recruitment of tamarisk influences the style and timing of channel changes. A more detailed look at the pattern of tamarisk germination reveals that the elevations at which tamarisk established vary. Trends in these elevations, particularly within a single trench as the floodplain surface evolved, however, suggest that some aspect of the localized geomorphic/hydraulic setting controls germination elevation. Burial history around individual plants, combined with larger scale phenomena of cohort establishment and floodplain construction and stripping, informs our understanding of the interactions between tamarisk germination timing and elevation, and its control over channel and floodplain morphology.

4.6.1 Hydrologic and Geomorphic Controls on Tamarisk Recruitment

Eighty-nine percent of the plants we analyzed germinated below the stage of the two-year flood (Figure 3.12) despite the fact that the various plants were recovered from different
geomorphic settings including gravel bars and fine-grained deposits. The only exceptions were the six samples that germinated in 1984 at stages between 400 and 600 m$^3$/s. An envelope curve (i.e., recruitment envelope) was defined by the highest and lowest germination elevations. For small flood years, whose peak discharge is less than 400 m$^3$/s, the germination elevation occurred up to the peak flow stage. However, in years of large floods, the envelope curve levels off (i.e., occurs well below peak flow stage). Thus, for large flood years, peak flow does not determine the recruitment elevation.

Successful recruitment requires adequate access to a water source, particularly over the first few years of growth, and this limitation likely influences the upper boundary of the recruitment envelope [Mahoney and Rood, 1998; Horton and Clark, 2001]. We identified the discharge associated with the germination elevation on the falling limb of the hydrograph. We calculated the average post-germination stage defined as the average stage for the period after the seed was deposited (i.e., the day on the falling limb that matched the germination discharge) through the growing season. Elevated post-germination growing season stages maintain moist soil for those seeds deposited higher above the baseflow channel. The maximum post-germination stage increases with greater peak stages (Figure 3.12), a result of typically longer flood recession rates for wet years (Figure 3.6). However, the rate of increase in average post-germination growing season stage relative to a meter increase in the peak stage is small (0.2 to 0.3 m). Even in particularly wet years, when high post-germination flows are relatively high, an upper limit to water access still exists. Thus, tamarisk cannot continue to establish, and subsequently survive, higher above the channel, even if the magnitude of the peak discharge is particularly large.

The lower elevation boundary of the recruitment envelope is determined by a plant’s exposure to intense or chronic physical disturbance [Scott et al., 1997; Birken and Cooper, 2006]. Large floods erode the sediment around plants, or bury them under large bars, such that over time the distribution of vegetation becomes skewed towards higher elevations for older plants. Our tamarisk samples include both old (i.e., 1959) and young (i.e., 2001) individuals that established
below 100 m$^3$/s. As such, erosion of lower-lying plants may not fully explain the lower boundary. Elevated post-germination growing season stages (Figure 3.12), associated with large flood years, likely prevent tamarisk from establishing lower in the channel, as these areas are saturated through most of the growing season.

4.6.2 Tamarisk Controls on Erosion and Deposition

Once established, average sedimentation in and around tamarisk was greatest for low-lying individuals, particularly those that established below the stage associated with the 100 m$^3$/s discharge (Figure 3.13), decreasing rapidly for plants that established at a higher elevation in the channel. More frequent inundation and deeper flows provide greater opportunity for deposition around these low-lying plants. Our sample does not include individuals that have no depositional record, either because they are too young, or are growing in a location where the localized hydraulic conditions prevent deposition (e.g. Figure 3.3). Therefore, our observations are applicable to hydraulic settings that allow for deposition of fine-grained alluvium. These settings may be a result of the imposed channel geometry or of the altered hydraulic conditions as a direct feedback from tamarisk encroachment and a narrowed channel.

Deposition around tamarisk plants is not only a function of elevation or location within the channel. Structural characteristics of vegetation influence the flow field and depositional patterns around vegetation [Corenblit et al., 2007]. These characteristics are often related to the age of a plant. Young seedlings are short and have flexible stems, which allows them to be easily overtopped by floods at which point they lay flat against the channel bed. More mature plants are taller, have thicker stems and a higher density of stems and leaves, which enhances their ability to alter the flow and sediment transport field [Jarvela, 2002; Stephan and Gutknecht, 2002].

We identified a trend in the timing of tamarisk recruitment and floodplain construction rates (Figure 3.14). Floodplain construction rates were calculated as the average decrease in channel width from floodplain construction between successive air photos (Figure 3.9) divided by
temporal air photo spacing. We did not include the 1.6 km of the study area in these analyses where the NPS removed tamarisk of unknown age. We determined that there is a seven year lag between the time when tamarisk plants establish and when floodplain construction rates increase accordingly. This lag can be explained by the fact that young plants on the newly constructed floodplain are inefficient at capturing sediment and also that, by definition, the newly constructed floodplain is relatively higher and is therefore less likely to be inundated by water carrying a high concentration of sediment (Figure 3.15). While 7 years may be an artifact of the temporal resolution of our dataset, it is apparent from both the air photo and floodplain trench analyses, that within a decade of establishment, tamarisk develops the ability to effectively trap sediment.

Over the entire study period, we noted a general reduction in floodplain stripping between successive air photos (Figure 3.9). We linked this reduction to the cumulative influence of greater tamarisk coverage by aging stands (Figure 3.14). As tamarisk stands grew and expanded, increasing the vegetated area, the total erosional area also decreased (Figure 3.15). A comparison between the channel response of two large floods, 1983 and 2008, provides a good example of the stabilizing role of tamarisk. These floods had similar peak discharges (631 m$^3$/s and 662 m$^3$/s in 2008 and 1983, respectively) and occurred first in the sequence of large flood events, yet the 1983 flood locally stripped more floodplain sediment. It is difficult to directly compare the geomorphic response of the channel to these two floods as a result of the temporal resolution of our air photos. However, the 1983 flood eroded more than twice the floodplain area than the 2008 flood. We mapped an average of 2.2 m (+/- 1.1 m) of floodplain stripping in 1983, resetting the channel to its pre-tamarisk width (as measured on the 1961 photo). In contrast, the 2008 flood (or a combination of the 2008, 2009, and 2010 floods) only stripped an average of 0.8 m (+/- 0.2 m) of floodplain along the two reaches. Tamarisk coverage differed between these two years. Average tamarisk width in 1983 was 2.0 m and increased to 7.2 m by 2008. Subtle differences in the hydrograph, such as flood duration or the presence of multiple peaks, may have also contributed to the geomorphic response of the channel.
5. Discussion

5.1 Mechanisms of Vegetation-Induced Channel Change on
an Unregulated River, a Natural Experiment

The Yampa River provided a unique setting to study channel change in an unregulated
western river that has maintained a natural snowmelt flood pulse and sediment supply, but has
experienced significant encroachment of the riparian invasive plant tamarisk. Due to annual and
sub-annual variability in flow we should expect the channel cross section to be dynamic,
experiencing both erosion and deposition. However, the relatively stationary longer-term
hydrology might lead us to expect that over decadal timescales channel width should remain
relatively static. The size of a channel is scaled to the amount of water it must convey [Leopold
and Maddock, 1953], but as we document here, channel width is also a function of the character
of the riparian vegetation that lines its banks [Anderson et al., 2004]. The Yampa River provides
a rare opportunity wherein systematic changes to the channel form can be primarily attributed to
changes in the distribution, cover, and composition of riparian vegetation. We proposed using the
natural, field-scale, experiment that began on the Yampa when the first tamarisk plant established
in 1948, to identify the mechanisms by which vegetation alters fluvial processes to create a
narrower channel.

Identification of these mechanisms relies on the validity of our claim that channel
changes may be explicitly linked to vegetation changes and not changes in the hydrologic regime.
Nearly 90 years of hydrologic observations on the lower Yampa River suggest that the size and
frequency of common floods less than 10-year return recurrence and the annual volume of water
have not changed appreciably. However, we did detect a shift in the sequencing of floods and of
the frequency of wet and dry cycles, and of the size of the large floods, within the past 50 years.
Indicative of a changing climate, where the extremes become more common and often cluster in
time [Dai et al., 1998], the new flow regime is linked with changes in the cover of riparian
vegetation.
A rapid rise in tamarisk coverage corresponded to the series of wet years in the mid-1980’s and the string of dry years that followed in the late 1980’s and early 1990’s. Flow conditions in years following seed germination strongly determine the success of young seedlings [Cooper et al., 2003; Mortenson et al., 2011]. Tamarisk plants that germinated in a dry year, as a result of a small flood, established low in the channel. Subsequent survival generally depends on the following years’ floods causing low physical disturbance [Scott et al., 1996; Polzin and Rood, 2006]. Conversely, tamarisk plants that germinated in a wet year, as a result of a larger flood, established on topographically higher surfaces, often out of the active channel. For these seedlings to survive, subsequent years must have large enough floods with relatively wet conditions to provide these higher plants with adequate water.

It is unlikely that the shift in flood sequencing, however, directly impacted fluvial processes and therefore geomorphic form. Commonly occurring floods (i.e., 2-5 year return period flood), often associated with channel size [Wolman and Miller, 1960; Andrews, 1980], have not changed since the 1920’s. More specifically, we know that any change in the flow regime may alter the capacity of the river, over time, to transport the sediment delivered to it, potentially resulting in either aggradation (reduced capacity) or degradation (increased capacity) [Grams and Schmidt, 2005; Schmidt and Wilcock, 2008]. The occurrence of larger floods, suggests that if any channel changes occurred, they may have tended toward channel degradation. However, we documented that the Yampa River channel has aggraded, narrowing by an average of 6% in two of the widest reaches during the past 50 years. This narrowing has occurred in the absence of any significant changes in the elevation of the bed [Manners et al., 2011].

We recognize that an increase in the sediment supply could explain some portion of the in-channel aggradation documented here. Limited sediment gaging data prevent us from eliminating the possibility that a larger-scale sediment imbalance on the lower Yampa River in Yampa Canyon contributes to the observed channel narrowing. Without evidence of significant
changes in landuse in the basin, we have no reason to believe sediment supply would have increased over the study period.

The detailed reconstruction and mechanisms presented in this paper, however, strongly suggest that fluvial processes did not respond to the flow regime in order to alter the width of the channel. Instead, subtle changes in the flow regime directly impacted riparian vegetation and changes in vegetation cover, in turn, altered fluvial processes.

Many similarities existed between the magnitude and pattern of tamarisk encroachment and that of channel constriction. These adjustments, however, did not occur simultaneously. Rather, channel adjustment trailed tamarisk establishment. The lagged response time may be attributed to the manner in which tamarisk alters fluvial processes to narrow the channel. Channel narrowing on the Yampa was a result of both an increase in the rate of floodplain building and a decrease in the magnitude of floodplain stripping. The impact of vegetation on both of these processes was not immediately apparent. We documented a lag in the time of establishment as it related to the rate of floodplain construction, and determined that the bank stabilizing effect of tamarisk is cumulative. These observations suggest that within a decade of establishment, tamarisk becomes more efficient at altering the flow and sediment transport field to a degree that induces channel narrowing. As nearly all tamarisk established below the 2-year flood stage, seedlings and young plants regularly interact with fluvial processes. As sediment is deposited around these young plants, a process that presumably occurs faster for the lowest-lying plants, the likelihood of inundation and, as a result, deposition decreases. Therefore, it is primarily those young plants, which had the capacity in the first ten years to induce deposition, that directly contribute to floodplain construction.

We also determined that the bank stabilizing effect of tamarisk is cumulative. Our understanding of vegetation-added bank stability has increased recently [Simon and Collison, 2002; Pollen-Bankhead and Simon, 2009]. However, most previous studies have focused on the geometry and composition of the bank and the cover of vegetation close to the channel. Our
finding of the impact of the cumulative age and cover of tamarisk on floodplain stripping is novel. We further expect that the cumulative cover has an impact on both the added stability of the bank itself as well as the larger flow patterns. Greater tamarisk cover on a given bank may shunt flow away from that bank, reducing shear stress and therefore erosion rates. As a result of tamarisks’ alteration of fluvial processes, similar flood events had a fundamentally different geomorphic response, dependent upon the recent and cumulative history of tamarisk recruitment.

5.2 Controls on Tamarisk Recruitment

Our comprehensive reconstruction provides strong evidence that tamarisk was the primary driver behind the narrowing of the Yampa River channel. Our larger scale analyses were bolstered by detailed information collected about individual plants and finer-scale deposition and inundation patterns. Evidence from these analyses identified the spatial and temporal control on tamarisk establishment. As stated above, the hydrologic regime was a primary determinant of successful tamarisk recruitment. However, we also documented an interaction between hydrologic controls and geomorphic or hydraulic conditions for localized tamarisk recruitment. We observed general trends in the location of dry period cohorts (i.e. gravel bars) versus those that established as a result of moderate or large floods (i.e. in floodplain depressions or in fine-grained channel margin deposits), similar to other studies [Birken and Cooper, 2006].

Additionally, we documented a distinct interaction and feedback between hydrologic conditions and geomorphic (and hydraulic) setting. Initial tamarisk establishment occurred exclusively in the mid-channel. These plants took advantage of expansive, exposed sediments, particularly those that remained relatively stable over the hydrograph as a result of their presence upstream from a tight bedrock constriction. Once the first plants matured, their presence likely altered the local flow patterns, opening up a larger area of relatively stable exposed sediment for subsequent tamarisk establishment. This process continued over time and tamarisk expanded beyond the original island [Gurnell et al., 2001].
We identified an elevation gradient of tamarisk recruitment related to peak discharge. This relationship is predominately driven by the shape and duration of the flood peak recession, particularly for those cohorts that established in years with moderate and large flood peaks. Various studies, particularly on cottonwood recruitment, have made the linkage between flood recession rate and seedling establishment [Lytle and Poff, 2004]. Seedling growth is limited by the rate at which their roots can grow, which for cottonwood is at a maximum at 2.5 cm/day [Mahoney and Rood, 1998]. Experimental work has shown that tamarisk roots can maintain root growth for drawdown rates as high as 4 cm/day [Horton and Clark, 2001]. However, our data support an upper limit on growth (Figure 3.12). We calculated the drawdown rate for those samples that established during high flow years (i.e., greater than 400 m$^3$/s) and found a maximum of 2.7 cm/day.

5.3 A New Stable State for the Yampa River

We documented a distinct decrease in the rate and magnitude of both channel narrowing and tamarisk encroachment in the past decade. We believe that the Yampa River has reached a new stable state [Johnson, 1997; Dent et al., 2002]. Prior to the expansion of tamarisk river processes operated in a different state. Lateral erosion rates generally matched floodplain construction rates. Thus, channel morphology was maintained. As tamarisk coverage increased, new floodplain construction outpaced erosion rates. A positive feedback between tamarisk establishment and channel narrowing pushed the Yampa from one stable state to another. The new state is defined by a less dynamic channel. Lateral stability, and little opportunity for new floodplain construction, maintains relatively stable channel morphology in the new state.

We attribute the new state, and its static condition, to the increased vegetation coverage and narrower, deeper channel, that occurred during the transitional period between the two states (approximately from around 1980 to the early 2000’s). These changes reduced (or eliminated) the availability of in-channel seedling establishment sites. Without new tamarisk establishment, the
mechanism for floodplain construction was eliminated. Additionally, those plants currently growing in the canyon are likely no longer capable of altering fluvial processes in a meaningful way. For the current channel geometry, flow regime, and sediment supply a large proportion (45%) of low-lying tamarisk plants do not have the capacity to increase the flow resistance to the degree that these areas become predominately depositional [Birken and Cooper, 2006]. Those plants that contributed to the deposition of inset floodplains (30%), or colonized existing floodplains (25%), interact less frequently with the flow field and exert a fundamentally different control on fluvial processes. While some of the active-channel tamarisk plants may be influencing present-day floodplain building processes, their age (> 10 years) suggests that the majority of these plants do little to locally alter the flow and sediment transport field and induce deposition even though they may be contributing to the larger hydraulic resistance.

The Yampa River faces many possible environmental perturbations that could push the river out of its current stable state. A reduction in tamarisk cover as a result of the tamarisk beetle or NPS management actions, could reintroduce greater channel mobility. In contrast, an increase in the clustering of extreme events as a result of climate change could increase the likelihood of further tamarisk tamarisk (or another riparian plant) establishment, thus leading to additional floodplain construction and channel narrowing. Finally, water development upstream could lead to an imbalance in the sediment budget, resulting in a series of adjustments to the new flow regime.

6. Summary and Conclusions

Encroachment of non-native vegetation into the riparian corridor of the lower Yampa River, an otherwise unregulated river, initiated channel narrowing. Today, the widest reaches of the Yampa are, on average, 6% narrower than they were in 1961. Tamarisk altered fluvial processes by both enhancing floodplain construction, and reducing floodplain stripping. Channel narrowing and planform simplification occurred as a result of four processes; mid-channel bar
stabilization, mid-channel inset formation, channel margin inset formation, and eddy/backwater infilling. These processes dominated at different periods through the record, dependent on the sequence and size of floods, and the spatial pattern of recent tamarisk encroachment.

The hydrologic regime determined the general patterns of tamarisk encroachment. Extreme wet and dry periods were responsible for the majority (nearly 70%) of the recruitment of the existing tamarisk population. The size and shape of the hydrograph during the germination year controlled the vertical distribution (i.e., recruitment envelope). Geomorphic and hydraulic parameters, however, provided a secondary control on tamarisk recruitment. The first tamarisk established on stable mid-channel bars. Large flood peak-related cohorts established in the topographic depressions of the floodplain.

Our analyses suggest that the Yampa River has adjusted to a new set of boundary conditions, introduced in 1948 when tamarisk entered the system. We mapped very few tamarisk cohorts that established after 2000. Channel width has remained relatively static in the past decade. Thus, the system has likely reached a new stable state, driven primarily from the increase in the coverage of riparian vegetation. Additional changes to the boundary conditions, potentially from enhanced climate signals (i.e., longer and more severe wet and dry periods) or from water development upstream, may spark another set of channel and vegetation adjustments.

References


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Table 3.1. Year, date, discharge, and linear digitizing error of nine air photo’s used in channel change analysis.

<table>
<thead>
<tr>
<th>Year</th>
<th>Flight Date</th>
<th>Discharge (m³/s)</th>
<th>Laddie Park</th>
<th>Harding Hole</th>
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<tr>
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<td>6-Sep</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1982</td>
<td>23-Sep</td>
<td>13</td>
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<td>2.7</td>
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<td>19</td>
<td>2.3</td>
<td>2.3</td>
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<tr>
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<td>4.9</td>
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<td>1.3</td>
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Table 3.2. 1D HEC-RAS model evaluation from water surface surveys.

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Table 3.3. Styles of channel changes and tamarisk presence for the 50-year record.

<table>
<thead>
<tr>
<th>Channel Margin</th>
<th>Total Change (m$^2$)</th>
<th>% of total Change</th>
<th>% of total Narrowing</th>
<th>Tamarisk (m$^2$)</th>
<th>% Tamarisk on Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Style 1: Inset</td>
<td>29,862</td>
<td>54%</td>
<td></td>
<td>5,190</td>
<td>17%</td>
</tr>
<tr>
<td>Style 2: Eddy/Backwater Infilling</td>
<td>7,705</td>
<td>14%</td>
<td>1,353</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>Style 3: Inset</td>
<td>9,479</td>
<td>17%</td>
<td></td>
<td>7,364</td>
<td>78%</td>
</tr>
<tr>
<td>Style 4: Bar Stabilization</td>
<td>8,303</td>
<td>15%</td>
<td>3,234</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td>Styles 1-4: Narrowing</td>
<td>55,349</td>
<td>82%</td>
<td></td>
<td>17,140</td>
<td>31%</td>
</tr>
<tr>
<td>Style 5: Floodplain Stripping</td>
<td>11,855</td>
<td>18%</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 3.1. Study areas on the lower Yampa River in Dinosaur National Monument, western Colorado.
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B) Examples of floodplain construction through mid-channel bar stabilization and mid-channel inset deposition, Laddie Park.  
C) Examples of floodplain construction through eddy/backwater infilling and floodplain stripping, Harding Hole.
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CHAPTER 4
ENVIRONMENTAL FLOWS FOR THE MAINTENANCE OF A MULTI-THREAD PLANFORM ON THE YAMPA RIVER

1. Introduction

Over the past few decades, a range of insights and tools from hydrology, geomorphology, and ecology have been used to determine the range of flows, that maintain specific ecosystem functions, referred to as environmental flows [Whiting, 2002]. When the primary goal is the maintenance of a fish population or riparian vegetation community, environmental flows are explicitly linked to specific aspects of the target species’ life history [Bovee et al., 1998; Muth et al., 2000]. For example, successful cottonwood recruitment requires a maximum flood recession rate of 2.5 cm/day [Mahoney and Rood, 1998]. Therefore, for river systems with a native cottonwood population managers should design flood hydrographs in accordance with this trait.

Defining geomorphically-relevant flows is often much more complex. The form and character of a river channel integrates the entire flow regime. In gravel-bed rivers, channel forming flows are typically the larger, less common flows (i.e., floods), particularly those that can mobilize the bed. Commonly, studies identify environmental flows based on the threshold of channel bed mobility. This flushing flow approach makes the assumption that by targeting the minimum discharge of bed movement the river will maintain both a dynamic channel and clean gravels, important for the successful spawning of many key fish species [Reiser et al., 1989; Kondolf and Wilcock, 1996]. In an attempt to maintain channel size and geometry, other studies identify the single discharge responsible for moving the most sediment over time, referred to as the effective discharge [Andrews and Nankervis, 1995; Pitlick and Van Steeter, 1998]. Often, these channel maintenance flows are related to the bankfull discharge and furthermore, associated with relatively common floods (i.e. occurring every one to two years) [Wolman and Miller, 1960; Andrews, 1980].
Isolating a small range of flows may overlook various processes critical for the maintenance of channel form. For example, large floods restrict the encroachment of vegetation [Friedman et al., 1996; Cooper et al., 2003]. If allowed to encroach into a river channel, the presence of vegetation could shift the relationships between sediment movement and discharge [Zong and Nepf, 2010]. These approaches also assume that by preserving the balance between water and sediment, channel size, form, and character will be maintained. However, the various degrees of river channel adjustment suggest that any alteration to the flow regime will have some impact on the geomorphic template. And while the channel may still transport the water and sediment delivered to it, cross-sectional adjustments could have significant implications for ecosystem functioning.

In this study, we present a unique approach to defining channel maintenance (i.e., environmental) flows. We make an explicit linkage between various flood magnitudes, their corresponding frequency, and the maintenance of a critical aspect of channel form. This aspect is dependent on the geomorphic setting and the highly valued ecological services. With a detailed understanding of the relationship between floods and specific processes, we can ask the fundamental question, “What is the flow regime needed to maintain a critical aspect of channel form?” We focus on this question as it applies to the Colorado River basin, where the widest reaches, often with a multi-thread planform, are the first to respond to changes in stream flow [Van Steeter and Pitlick, 1998; Allred and Schmidt, 1999]. These reaches lose the capacity to maintain multiple channels. Vegetation encroachment and the aggradation and infilling of secondary channels disconnects flows, thereby creating a much simplified, single channel cross-section. This loss of channel complexity has resulted in a general deterioration in aquatic habitat quality [Poff and Ward, 1990; Ligon et al., 1995] and specifically to the decline [Tyus and Karp, 1989] and extirpation [Vanicek, 1970] of the endangered native fish species of the upper Colorado River basin.
Unlike the majority of the mainstem and large tributaries of the Colorado River, the lower Yampa River has maintained a strong native fish population, particularly Colorado pikeminnow (*Ptychocheilus Lucius*) and razorback sucker (*Xyrauchen texanus*) [Tyus and Karp, 1989, 1990]. With a relatively natural hydrograph, channel geometry, and planform, the Yampa River channel changed only where the non-native riparian shrub tamarisk encroached into the riparian corridor [see Chapter 3]. Key spawning bars and backwaters for rearing associated with wider multi-thread reaches remain viable habitat [U.S. Fish and Wildlife Service, 2002]. We focus on this geomorphic style and present a novel approach for defining geomorphically-relevant environmental flows. The Yampa provides a unique opportunity to isolate geomorphic processes, absent of major perturbations to the water or sediment load. Its ecological importance in the Colorado River basin and upstream water resources available for development, make the lower Yampa River an ideal place to investigate these questions.

**2. Lower Yampa River, Dinosaur National Monument**

Generally flowing west, the Yampa drains the Park Range of the southern Rocky Mountains (Figure 4.1). The annual hydrograph is dominated by spring snowmelt, and annual differences in the hydrograph are related to differences in the magnitude of the early spring snowpack and the timing of its melt. The annual flood peaks in early spring in years of low snowpack and/or early snowmelt, and the annual flood peaks in late spring in years of large snowpack and/or late snowmelt. There are relatively few dams and diversions in the watershed, and the Yampa still has a relatively natural hydrology. Mean annual runoff of the Yampa River, measured at Deerlodge Park at the eastern edge of Dinosaur National Monument, is 60 m³/s for the period between 1923 and 2011.

The estimated annual sediment load at Deerlodge Park is between 2.04 and 2.42 million tons/year and more than 95% of this load is sand and mud [Andrews, 1980; Elliott and Anders, 2004]. Approximately 70% of this fine sediment is delivered from the Little Snake River, whose
confluence with the Yampa is 6.6 km east from the monument boundary. Despite its significant role in providing fine sediment to the Yampa River, the Little Snake River only provides roughly 30% of the total stream flow of the lower Yampa River.

The lower Yampa River enters Yampa Canyon 1.5-km downstream from the eastern boundary of Dinosaur National Monument (Figure 4.1). The bed of the river is predominately gravel and cobble. Yampa Canyon can be distinguished in two parts. Interbedded sandstone, shale, and limestone of the Permian Morgan formation occur at river level in the eastern, upstream part of the canyon. The width of the valley floor in this resistant rock type is very narrow, and floodplains and bank attached bars of fine sediment only occur in small areas. The alluvial valley is wider, and the channel has a flatter gradient, in the less resistant Permian Weber sandstone that occurs at river level in the western and downstream part of the canyon. In this segment, the lower Yampa has established a series of entrenched meanders, and tight bends and narrow reaches act as hydraulic controls at flood stage [Larson, 2004]. Gravel bars occur upstream and downstream from those incised meanders that have a small radius of curvature, and multi-channel reaches occur in many of these settings.

We investigated three multi-thread reaches in the Weber Sandstone segment of the lower Yampa River in this study (Figure 1). The upstream reaches -- Pouring and Spawning -- are known to be important Colorado pikeminnow spawning habitat [Tyus and Karp, 1990]. The Colorado pikeminnow is a federally listed endangered fish whose adult habitat once extended downstream to the head of the Colorado River delta in Mexico and upstream to southern Wyoming.

Much of this study is focused on a third multi-thread reach: the Laddie Park reach is geomorphically similar to the other study reaches but is not known to support pikeminnow spawning at this time. During the past 50 years, the channel in Laddie Park has narrowed and has gradually been transitioning into a single-thread channel by accretion and infilling of the secondary channel that separates a large island from the left bank (Figure 4.2).
Bed sediment in Laddie Park generally fines downstream and onshore (i.e. away from the main channel). At the head of the large island (Figure 4.2), the median particle size is about 55 mm. In the secondary channel, a smaller bar has a median particle size of approximately 17 mm, and a significant part of this small bar is covered by sand and mud. The bed of the secondary channel is primarily medium to very fine gravel and sand. Sand and mud covers most of the middle and downstream part of the main island and there is less fine sediment at the upstream end where sand and mud only occur in the lee of individual tamarisk and willow plants.

3. Multi-Thread Channel Maintenance

Mid-channel bars form and multi-thread channels develop where there is a downstream decrease in sediment transport capacity. At a large spatial scale, this type of longitudinal divergence in sediment transport results from changes in valley form, such as significant changes in valley width or slope. Bar deposition at flood stage, in turn, induces a division of the flow field at moderate and low flows, and water and sediment transport is divided among multiple channels. The point at which the single-thread channel flow field divides is referred to as the bifurcation (Figure 4.3). The bifurcation and its characteristics ultimately controls the morphological stability of the multi-thread channel pattern [Ashmore, 1991]. A bifurcation that preserves a relatively equal division of water and sediment transport to both downstream branches is referred to as “stable,” whereas a bifurcation that favors one branch over the other is referred to as “unstable” [Federici and Paola, 2003].

Recent experimental, theoretical, and field-based studies have identified geometric and hydraulic dynamics associated with stable and unstable bifurcations [Federici and Paola, 2003; Tubino and Bertoldi, 2008; Hardy et al., 2011; Bertoldi, 2012]. The character of the approaching flow field is a strong determinant of the stability of the bifurcation [Federici and Paola, 2003; Burge, 2006; Hardy et al., 2011]. Uniform flow (i.e., a dominant downstream velocity trajectory without major accelerations or decelerations) promotes the equal distribution of water and
sediment. However, a uniform flow field is not common in nature. Channel planform or the presence of upstream bedforms, for example, often induce cross-stream flow. Variability in flow paths may change with discharge, such that non-uniform flow may be more prominent for only part of the hydrograph (Figure 3). Natural bifurcations are, therefore, relatively unstable features in most rivers [Kleinhans et al., 2008; Ashmore et al., 2011].

In gravel-bed rivers, the mobility of the bed has been identified as a control on the persistence of stable or unstable bifurcations. With high bed-material transport rates over a mobile bed, a bifurcation may be unstable over the timeframe of a flood or series of floods [Ashmore et al., 2011]. Additionally, low magnitude floods have the potential to enhance unstable bifurcations and the associated asymmetrical distribution of water and sediment [Zolezzi et al., 2006]. In rivers with prolonged periods of very low flow, this asymmetrical distribution occurs frequently, and as a result, the probability of secondary channel abandonment increases. Vegetation may exacerbate the asymmetry by encroaching into a secondary channel during a period of relatively small floods, shunting flow into the dominant channel [Tal and Paola, 2007]. Vegetation may, however, contribute to bifurcation stability by limiting the migration rate of the approach channel, stabilizing channel banks, and maintaining the location of the bifurcation and/or the uniform nature of the approaching flow [Bertoldi, 2012]. Thus, changes to the flow regime, sediment supply, sediment transport capacity, or vegetation community structure (i.e., boundary conditions) have the potential to impact the stability of bifurcations and the timescale of their conversion into unstable bifurcations that may ultimately lead to the abandonment of a secondary channel.

Numerous case studies provide evidence supporting the hypothesis that altered boundary conditions affect bifurcation stability [e.g., Church, 1995; Van Steeter and Pitlick, 1998; Allred and Schmidt, 1999; Tal et al., 2004]. The majority of these studies document channel response to water development and/or the expansion of non-native riparian vegetation. Where multi-thread reaches exist, secondary channels are abandoned and as a result, the channel narrows and
simplifies. The consistency in channel response suggests that changes to the boundary conditions have a direct impact on the stability of flow bifurcations. However, no field study has explicitly demonstrated this linkage.

In the high suspended sediment rivers of the Great Plains, Rio Grande, and Colorado River basins, the process of secondary channel abandonment leads to floodplain construction [Moody et al., 1999; Dean et al., 2011]. Typically, fine sediment first accumulates at the downstream end of mid-channel or bank-attached gravel bars. Fine sediment deposits that persist for many years or decades indicate that the bar is being transformed into an island [Reinfelds and Nanson, 1993]. Over time, the island grows in size by vertical accretion and inset floodplain deposition. When the secondary channel is completely abandoned, the former island merges with the adjacent floodplain or valley wall, and only a single channel remains [Van Steeter and Pitlick, 1998]. As such, the presence/absence of persistent fine sediment deposits on gravel bars might be used as a proxy for assessing future changes in planform. At one end of this continuum are stable multi-thread channels with little fine sediment accumulation on gravel bars. At the other end of this continuum are single-thread channels.

In this sense, maintenance of multi-thread channels in rivers with large fine-sediment loads transported over gravel beds is measured by the ability, over time, to maintain the throughput of fine sediment through the study reach. As a reach loses the capacity to transport its sediment load, the channel responds by creating a smaller, more efficient cross-section. Reduced transport may be a result of localized changes in the flow field [e.g., Gurnell et al., 2005] or systematic changes in the flow regime and/or sediment supply [e.g., Van Steeter and Pitlick, 1998]. The wide, shallow channels characteristic of multi-thread reaches give way to narrow deep channels.
4. Methods

The fundamental goal of this paper is to identify the flow regime required to maintain the multi-thread planform in the lower Yampa River. Although a relatively rare planform in the canyons of the Colorado Plateau part of the Colorado River drainage network, multi-thread channel reaches play a disproportionately important role in many native ecosystem processes of the watershed, including as critical spawning and nursery habitat for endangered fish and as areas of large native cottonwood riparian forests [Van Steeter and Pitlick, 1998].

Our larger goal is to inform the science of quantifying channel maintenance flows. Unique values of the channel maintenance flow, such as the bankfull discharge or the effective discharge, typically are used as surrogates for the entire flow regime, but channel form is ultimately determined by the entire flow regime. Here, we illustrate an approach for quantifying the channel maintenance flow regime of multi-thread reaches of rivers with high, suspended, fine-sediment loads, such as elsewhere in the Colorado River basin. Our approach especially focuses on the relative roles of large floods and of common floods in maintaining the multi-thread planform, and our approach accounts for the role of riparian vegetation that invades the active channel during periods of drought.

The bulk of our work was conducted in the Laddie Park reach where a large proportion of an active gravel bar was covered by fine sediment during the past 50 years (Figure 2). Our analysis focused on the gravel bar, island, and secondary channel that collectively we refer to as Laddie Park Bar (Figure 4.2). We took a mechanistic approach to defining the role of individual floods in transporting fine sediment through this reach. We developed a predictive model of topographic adjustment based on field measurements and interpretation of historical changes using LiDAR-derived maps of geomorphic change and output from a 2D-hydraulic model. We applied this model to the Laddie Park reach and interpreted model results in relation to the current hydrologic regime. To gain a better understanding of the processes associated with multi-thread planform maintenance, we also applied the model to earlier time periods when the flow regime
was relatively similar to today, but bed topography and riparian vegetation distribution differed. Model runs based on historical conditions allowed us to evaluate the changing spatial pattern of fine sediment accumulation and evacuation that occurred during floods of different magnitude. We explain why the Yampa River in Laddie Park has gradually been transformed from a multi-thread to a single-thread planform. We estimate the impact of potential, future upstream surface-water diversions on maintenance of the multi-thread planform by evaluating flow regimes with reduced flood flows. We apply our results to the other multi-thread reaches of our study in order to generalize our results. The work presented here builds on a detailed historical geomorphic interpretation of the narrowing process in lower Yampa Canyon (see Chapter 3) and on a strategy to characterize present-day geomorphic, vegetation, and hydraulic conditions in a spatially explicit way (see Chapter 2).

4.1 Hydrology

Our hydrologic analysis focused on the 50-year period between 1961 and 2011. The size and frequency of common floods less than 10-year recurrence and the annual volume of water have not changed appreciably since gaging began in the watershed in 1923. However, prolonged wet and dry periods are now more common than they were in the early part of the 20th century (see Chapter 2). We analyzed the hydrologic record measured at Deerlodge Park (USGS gage 09260050) that began operation in 1983. We extended that record by adding the measured discharge of two upstream gages: one on the Yampa River near Maybell (USGS gage 09251000) upstream from the confluence with Little Snake River and the other on the Little Snake River near Lily (USGS gage 09260000) (Figure 4.1). We constructed flood frequency curves based on estimated instantaneous discharge, using Log Pearson III analysis for the 50-year period. We also calculated flood frequency curves for two shorter time periods: 1961-1983 and 1984-2011. For the period before 1983, we estimated instantaneous peak flow by taking the larger of the two values: 1) instantaneous peak measured near Maybell and the mean daily discharge near Lily for
the same day, or 2) instantaneous peak near Lily and the mean daily discharge near Maybell for the same day.

We refer to floods whose return period is equal to or less than 2-years as common floods, as these are the floods that occur with great frequency. Floods that have a recurrence between 2 and 10 years are referred to as moderate and those between 10 and 20 years are large. Those floods whose recurrence is rarer than 20 years are referred to as exceptional.

Development of the water resources of the Yampa River, as proposed within the past decade, would involve almost exclusively, the diversion of a portion of the peak snowmelt flood. Thus, water development would reduce peak flood magnitude and have little impact on the rest of the flow regime. To simulate water withdrawal scenarios on the Yampa, we shifted the flood frequency curve for the 50-year record by a uniformly reduced proportion of flow for those floods whose recurrence is more frequent than 20 years. We used three scenarios: 5%, 10%, and 20% discharge reduction. We assumed that future water development will not affect exceptional floods [Gordon et al., 2004].

4.2 LiDAR and Topographic Change Maps

Utah State University’s Center for Advanced Imaging flew three LiDAR flights in Yampa Canyon (Table 4.1). All data were collected after recession from the snowmelt flood peak. Post-processing, using a series of morphological filters classified LiDAR returns as either ground or vegetation. Average point density ranged from 0 pts/m² in thick vegetation to 2.5 pts/m². We ignored returns from the water surface, because these data are unreliable in a standard LiDAR system. We created 1-m digital elevation models (DEM) using the ground points and masking the water surface.

We determined topographic changes among LiDAR surveys by subtracting the 2008 DEM from the 2010 DEM and similarly subtracting the 2010 DEM from the 2011 DEM. Thus, we developed two sets of geomorphic change maps; one that represented the cumulative
topographic changes caused by the 2009 and 2010 snowmelt floods and one that represented
topographic change caused by the 2011 flood. We evaluated topographic change higher than the
160 m$^3$/s stage (the discharge at the time of the 2010 LiDAR survey), which is approximately the
1-year recurrence flood. We have no data on topographic changes of the lowest elevation parts of
the active channel bed. There are inherent errors in any single LiDAR survey due to the high
elevation of the plane used to collect the data, oblique angle of some images, seasonal changes in
vegetation cover, and other factors. Detection of topographic change between two surveys must
account for these errors, because they are propagated from one dataset to the next. We accounted
for these errors by using a spatially variable, propagated error model [Wheaton et al., 2010]. This
error model is based on point density and slope data from a single LiDAR survey; those areas
with high point density and low slope have the lowest error. Using the error model as a threshold
for change detection, we identified areas that have a 90% chance that observed change is real.

Maps of topographic change served as the basis for much of our analyses. We used the
topographic change maps, in conjunction with water surface predictions from a 1D-hydraulic
model (see Chapter 3) to identify patterns of geomorphic change. These patterns were described
for different categories of elevation above the stage of the typical base flow (10 m$^3$/s) at the three
study sites (Figure 4.1). Additionally, the topographic change maps were used to develop the
observation-based predictive model of topographic change that is described below.

4.3 Topographic Reconstruction and Hydraulic Modeling

We built 2D-hydraulic models representative of the topographic and vegetation
between 2008 and 2011, each year’s flood was run on a topography that had been formed by the
immediately preceding flood. The earlier periods were chosen because of the availability of high
quality air photos taken in 1961 and 1983. The 1983 photos were taken immediately before the
flood of record (933 m$^3$/s) in 1984; we reconstruct the post-flood topography of 1984.
Bathymetric surveys using ADCP and RTK-GPS were collected in 2011. We assumed that the bathymetry below the 160 m³/s stage did not change substantially during this 3-year period. Thus, the same bathymetry was combined with the different DEMs constructed for higher elevations. We believe that this assumption does not significantly impact our results. A strong downstream hydraulic control, specifically the tight bedrock bend (Figure 4.2), suggests that the rating relation, especially for the flood flows we are interested in, is not sensitive to the bathymetry.

We constructed DEMs for 2008, 2010, and 2011 using the LiDAR datasets. For the two earlier periods, we reconstructed the historical topography by extrapolating the topography interpreted from the stratigraphy exposed in four floodplain trenches and three pits (Figure 4.2) dug in the major floodplain deposits (see Chapter 3). We extrapolated historical elevations beyond the trenches to the edge of the low-flow channel whose elevation we assumed was fixed. We interpolated among the trenches, the edges of the low flow channel, and the edges of the dense vegetation that existed in either 1961 or 1983. The edges of the vegetation marked a topographic transition from the more gently sloping areas of the bar to the mounds of fine-sediment that had accumulated in and around the vegetation. The air photo analysis and stratigraphic interpretations suggest that Laddie Park has been accreting since 1961, with little accompanying erosion or reworking. Thus, topographic reconstructions involved the lowering of floodplain elevations relative to today. Where appropriate, we mimicked the present day topography. Otherwise, surface reconstruction was accomplished using nearest neighbor analyses between known points. Comparison of aerial photography taken in 1983 and 1989 indicates that there was little topographic change in non-vegetated areas caused by the 1984 flood or by other floods of that period. We assumed that all vegetated areas on bars increased in elevation between the 1983 and 1984 consistent with the changes in elevation measured in the trenches and pits. We interpolated elevations in the secondary channel based on interpretation of air photos. We acknowledge that the reconstructed topographies we used to create DEMs for 1961 and 1984
have substantial uncertainty associated with them, particularly with increasing distance from the trenches and pits. Our goal, however, was to identify the general patterns of topographic change and as such, accounting for relative elevation change and for the locations of topographic highs (i.e. vegetated areas) and topographic lows (i.e. secondary channel location) adequately achieves this objective.

We used the River2D modeling package to develop model meshes and run various discharges for different flow scenarios. River 2D uses the finite element method to solve the basic equations of vertically averaged 2D flow [Steffler and Blackburn, 2002]. Mass and momentum are conserved in the horizontal dimension by solving for bed and side shear stresses from Manning’s equation and a Bousinessq type eddy viscosity, respectively. We took advantage of the TIN-based unstructured mesh of River2D to define a higher node density for parts of Laddie Park and other sites; we used 1-m nodes in within the boundary of the Laddie Park Bar and 8-m nodes elsewhere.

Stands of tamarisk and willow dominate the woody vegetation cover in Laddie Park. We represented tamarisk and willow in the 2D models with a spatially variable, depth-dependent vegetation roughness value (see Chapter 2). Vegetation roughness for the 2008-2011 period was estimated using the TLS-ALS model described in Chapter 2. Field observations and air photo comparisons suggested that vegetation cover remained relatively similar during this 4-year period. Vegetation roughness for the two historical periods were characterized using information from air photos and a depth-dependent roughness value based on the vegetation roughness classes identified in Chapter 2. In Chapter 3, we determined the germination dates of 35 tamarisk and 1 willow stem recovered from the trenches and pits. Plants suspected of growing in channel sediments were assigned a depth-dependent roughness value based on the sparse density classification. Those growing in floodplain sediment were assigned a value based on the moderate density classification. We ran each model at steady flow conditions. Vegetation roughness for each mesh was solved iteratively. The downstream boundary was defined by a stage-discharge
relation created from pressure transducer measurements collected during the 2011 flood. ADCP profiles collected at four transects along the secondary channel at a discharge of 450 m$^3$/s during the 2011 flood were used to validate hydraulic model output (Figure 4.2).

4.4 Development of an Observation-Based Predictive Model of Topographic Change

We constructed an observation-based predictive model of topographic change by linking the results of the 2D flow models to the measured topographic change maps for the period 2008-2011. The model predicts whether erosion, deposition, or no change in fine sediment coverage occurs in a given cell. This prediction is based on the calculation of specific discharge from the 2D hydraulic model for a single peak discharge. As such, these predictions integrate the likely scour and fill that occurs during a flood event and represents the net change. While this model was built on observations from three flood events, we use it to evaluate the likely topographic impact of any flood. The model only predicts the potential occurrence of erosion or deposition, and does not predict the magnitude of either process. Interpretation of model results is primarily focused on the distribution of cells where deposition of fine sediment is predicted to be unlikely, because progressive accumulation of fine sediment on top of gravel bars is the primary process by which planform simplification in Yampa Canyon occurs (see Chapter 3).

Flow models estimating the peak discharges of 2010 (493 m$^3$/s) and 2011 (776 m$^3$/s) were compared to maps of topographic change that were computed from LiDAR surveys. Based on field observations, the majority of detectable topographic change at Laddie Park was a result of either the erosion or deposition of sediment finer than pea gravel. As described above, the comparison of the 2008 and 2010 LiDAR surveys unavoidably describes topographic changes caused by the snowmelt floods of 2009 and 2010. The annual peak flow of 2009 (461 m$^3$/s) was only 6% less than the magnitude of the peak flow in 2010. We assumed that the 2D model predictions for these two floods were indistinguishable, and we compared the map of topographic change with estimated hydraulic conditions of the 2010 flood. We also compared the predicted
hydraulic conditions at peak flow in 2011 with the topographic changes measured between the 2010 and 2011 LiDAR surveys.

For each node of the 2D hydraulic model, we compared the predicted specific discharge (i.e., velocity*depth) with the corresponding topographic change that occurred at the corresponding cell on the topographic change map. Specific discharge at each node is a surrogate for the divergence of the sediment transport field that ultimately drives topographic change. Many studies have used this surrogate [e.g., Costa and O’Connor, 1995]. We used specific discharge because of the simplicity of the metric. Depth and velocity are the primary solutions of a 2D hydraulic model, and one does not need to make any assumptions about the vertical structure of the velocity profile. Each pair of predicted specific discharge and observed topographic change values for the two measurement periods were used to develop a relation between specific discharge and topographic change. We classified the topographic change maps into three categories; erosion, deposition, or no change. Cells classified as either experiencing erosion or deposition were those whose change in elevation was greater than the spatially variable error. Cells classified as no change made up the remainder of the area analyzed.

Because of the large number of nodes computed for the two flow conditions, there were many nodes with the same value of specific discharge (depth * velocity). We examined all of the nodes that had the same specific discharge and computed a probability distribution of the measured topographic change of all of those nodes. We assigned a probability that erosion, deposition, or no change occurs based on the calculated probability distribution associated with a particular specific discharge value. Since there were many more observations of no change, we normalized the number of observations for each of the three classified cell types. As a result, the number of observations (cells) used to build the relationship between specific discharge and topographic change was the same for erosion, deposition, and no change. A given specific discharge was related to erosion if the probability of erosion was greater than 0.50; and to deposition if the probability of deposition was greater than 0.50. If a given specific discharge
value had either a probability of no change greater than 0.50 or all probabilities were less than 0.50, that specific discharge value was related to no change. As such, the no change classification also represents values that may not be strongly erosional or depositional. We developed separate relationships for changes within and outside of tamarisk and willow, the dominant woody species, to increase the predictive accuracy of our observation-based model.

The approach described here links measured topographic change with estimated hydraulic conditions at peak flood stage. An alternative approach would be to compute the total specific discharge for each node over the entire period of the spring snowmelt flood. Such an approach might better capture the total effect of the flood regime, but initial experimentation with this alternative approach did not increase the predictive success of the model. In fact, we determined that conditions at peak discharge provided a more accurate characterization of the spatial pattern of erosion and deposition.

4.5 Application of the Observation-Based Predictive Model of Topographic Change

We applied the relationship between specific discharge and likely topographic change described above to the 2D hydraulic model output for the peak discharge of a given flood event. Model results were reported as maps showing areas where deposition of fine sediment, erosion of fine sediment, and no change were most likely to occur (Figure 4.4). Thus, we identified the likelihood that a cell was likely, or unlikely, to accumulate fine sediment in a discrete flood. Often a cell that is likely to accumulate fine sediment for a given flood is likely to evacuate fine sediment in a flood with a different peak discharge (e.g., Figure 4.4). To account for the temporal variability of fine sediment erosion or deposition, we applied the predictive model of topographic change to peak discharges for floods with a recurrence between 1.5 and 20 years. The peak discharge associated with a flood of a given return period was dependent on the time period being analyzed. For the current flood regime, we used the 50-years between 1961 and 2011. For the historical periods, we used the corresponding flood frequency curve; 1961-1983 or 1984-2011.
Each discrete flood event had a unique map of likely topographic change. That unique map in turn had a probability of occurrence in any given year and was a function of the frequency of the flood event. For example, areas of likely deposition predicted for the 2-year flood had a 0.50 probability of occurring in a given year, whereas likely depositional areas predicted for the 10-year flood had a 0.10 probability of occurring in a given year. Each cell in the study area, therefore, had multiple predictions of topographic change, each with its own associated probability of occurrence (Figure 4.4).

As described above, we are primarily interested in the maintenance of bare gravel on bars, i.e., that there is no progressive accumulation of fine sediment. Our model exclusively applies to fine sediment dynamics and not the movement of gravel based on the observations made during the 2009, 2010, and 2011 floods. We interpreted deposition strictly as the accumulation of fine sediment. Our interpretation of erosion, however, was dependent on the specific analysis. In general, we interpreted erosional areas as those that do not accumulate fine sediment, and as such, maintain channel form. Evacuation of sediment did not necessarily occur. For example, the elevation of areas predicted to be erosional that already consisted of exposed gravel does not decrease. In analyzing topographic changes over time, i.e., likely changes as a result of the entire flood regime, we did interpret erosion as the evacuation of sediment. Since a cell may experience net deposition from one flood, the prediction of erosion from another flood was interpreted as removing the fine sediment that previously accumulated.

5. Hydrology and Hydraulic Model Results

5.1 Hydrology

The 2-year recurrence flood for the 50-year study period is approximately 412 m$^3$/s, and the magnitude of this common flood has not significantly changed during this period (Figure 4.5). The 2-year flood for the period between 1961 and 1983 was 405 m$^3$/s, and the magnitude of this recurrence flood for the period between 1984 and 2011 was 384 m$^3$/s. In contrast, the variability
of flood magnitudes increased during the study period; there have been larger floods and short periods of smaller floods since 1984. The magnitude of the 20-year recurrence flood for the period between 1984 and 2011 was 753 m$^3$/s, whereas the magnitude of the 20-year recurrence flood was 615 m$^3$/s for the earlier part of the study period. The flood of record occurred on May 18, 1984, and was 940 m$^3$/s. The second largest flood of record occurred on June 9, 2011, and was 776 m$^3$/s. In 6 of the 8 years between 1987 and 1994, the annual peak discharge was less than the long-term 2-year recurrence flood.

We pay particular attention to the 2009, 2010, 2011 snowmelt floods whose peak discharges of 461, 493, and 776 m$^3$/s have a recurrence of 3.4, 4.0, and 50 years, respectively for the 50-year study period. These three years were part of a string of relatively wet years and followed a large flood in 2008 whose peak discharge (631 m$^3$/s) had a recurrence of 10 years.

5.2 Two-Dimensional Hydraulic Model

5.2.1 Model Validation

We validated the 2D hydraulic model by comparing model predictions with ADCP measurements of depth and velocity in the secondary channel at Laddie Park. There was good agreement in the area of comparison, suggesting that the model does a good job in characterizing the depth-velocity field (Figure 4.6). Two of the four ADCP transects (transects 1 and 3) described the complete cross-section across the secondary channel (Figure 4.2). We compared the measured to modeled discharge for these two transects as a whole; modeled values were within 5% of measured values. Depth-averaged velocity from the ADCP measurements matched the general trend of predicted velocity from the model (Figure 4.6). Model predictions deviated from measured velocities, where topographic measurements were poor or where there were field measurement problems. An undercut bedrock bank along the valley wall prevented good LiDAR measurements and thus topographic inputs to the model were poor. In transect 3, shallow flow through the middle of the transect was less than the ADCP’s blanking depth (30 cm).
5.2.2 Observation-Based Predictive Model of Topographic Change

In the creation of our model, we analyzed two topographic change maps, each consisting of the 33,352 m$^2$ of the Laddie Park bar whose elevation was above the 160 m$^3$/s stage in 2010. We determined that geomorphic change below the 160 m$^3$/s stage was minimal. By evaluating the difference between the 2011 and 2008 LiDAR datasets, we determined that the total volume of sediment not incorporated in our analysis accounted for less than 10% of the total sediment eroded or deposited between 2008 and 2010. Seventy-seven percent of the cells on the topographic change maps had no detectable change. Cells on geomorphic change maps were 1 m$^2$. Twenty and three percent of the cells documented deposition and erosion, respectively. Spatially variable errors ranged from 0.06 m of change predominately for relatively flat surfaces with no vegetation to 0.90 m of change for steep slopes (i.e., cut-banks) under thick canopies. Specific discharge values for the Laddie Park bar ranged from 0.001 to 9.2 m$^3$/s, however no values above 5.7 m$^3$/s were associated with detectable topographic change.

Within tamarisk and willow plants, peak specific discharge values for a discrete flood event between 0.7 and 1.9 m$^3$/s had a high probability (>0.50) of fine sediment deposition (Figure 4.7). Erosion of fine sediment from tamarisk and willow predominately occurred in areas with a higher specific discharge, 2.2 to 4.6 m$^3$/s. Extremely high and low specific discharge values were associated with areas of no topographic change. In unvegetated areas, a high probability of fine sediment deposition was confined to a small range of low specific discharge values (0.2 to 0.7 m$^3$/s). Patterns of erosion outside of tamarisk and willow were relatively similar to inside the plants, with two differences. Slightly lower specific discharge values in unvegetated areas were associated with a higher probability of erosion than in vegetated areas, (i.e., 1.9 m$^3$/s was the lower threshold for unvegetated areas vs 2.2 m$^3$/s for vegetated areas). Additionally, specific discharge values in unvegetated areas between 2.5 and 3.0 m$^3$/s were not predominately associated with erosion. In fact, areas with these specific discharges were almost equally likely to experience fine sediment deposition or experience no topographic change.
Application of this observation-based predictive model to the hydraulic model output for the 2010 and 2011 floods resulted in an accurate prediction of 65% of the 66,704 cells used in the development of the model (Table 4.2). The model was most accurate in predicting erosional cells (76%) and least accurate in predicting depositional cells (59%); 66% percent of the cells with no detectable change from the LiDAR analysis were correctly identified. As a result of our probabilistic approach, we expected error in our predictions. However, we are confident that our model has the capability to identify the trends of interest. Our primary interest in the application of our observation-based model is the maintenance of channel form through the prevention of fine sediment accumulation. Erosion of fine sediment is the most direct way to accomplish this and these areas had the greatest predictive success. Those cells not identified as erosional were predominately (70%) predicted to have no change. Additionally, when cells with no detectable change were incorrectly identified, half the time they were predicted to be erosional and half depositional. Thus, there was no systematic bias in our model predictions.

6. Maintenance of a Multi-Thread Planform, Laddie Park Bar

We took advantage of the robust contemporary and historical datasets for the Laddie Park Bar to identify the mechanisms by which a multi-thread planform on a high suspended sediment, canyon-bound river is maintained, through the continual evacuation of fine sediment; or not maintained, through the progressive accumulation of fine sediment. Using these datasets, and the observation-based predictive model of topographic change, we built a series of observations of the roles of topography, vegetation, and flood regime in controlling the temporal and spatial accumulation (and evacuation) of fine sediment. Here, we present the collection of these observations. Each subsection below builds on the knowledge from the previous subsection(s). This section culminates in the application of our collective understanding of the important mechanisms and corresponding floods required to maintain a multi-thread planform at the Laddie Park Bar.
First, we describe the topographic response of the present day Laddie Park Bar to three discrete flood events. Next, we extend these temporally limited observations to the entire flood regime. Using the observation-based predictive model for the current topography, vegetation cover, and flood regime, we identify the importance of different flood sizes in restricting the accumulation of fine sediment. Reconstruction of the topographic and vegetative conditions for two periods in the past 50 years provides a platform for the application of the observation-based predictive model for evaluation of historical conditions. From these historical reconstructions, we constrain the driving forces in the evolution of the Laddie Park Bar as an exposed gravel bar evolved into a permanent, vegetated island. Finally, these observations and the application of the observation-based model are projected in the future to determine the sensitivity of the Laddie Park Bar to water development scenarios.

6.1 Topographic Response to Three Recent Floods

Comparison of LiDAR datasets among 2008, 2010, and 2011 allowed us to distinguish the patterns of topographic change caused by moderate floods and by an exceptional flood. The combined effects of the 2009 and 2010 floods are described by comparison of the 2008 and 2010 LiDAR datasets. As these two floods had similar magnitudes (i.e., only 6% difference), we make the assumption that the topographic response in each of the years was comparable. Therefore, we attributed half of the topographic change captured in the 2008 to 2010 change maps to a single moderate flood.

The exceptional flood resulted in more topographic change (3,704 m³) than the combination of the two moderate floods (760 m³) at the Laddie Park bar (Figures 4.8 and 4.9). As stated above, topographic changes at the Laddie Park bar were a result of the evacuation or accumulation of sediment finer than pea gravel (i.e., < 4 mm). Total topographic change was computed as the sum of the volume of fine sediment that was eroded plus the volume of fine sediment that was deposited and was computed for all areas higher than the stage of 160 m³/s,
because comparative bathymetric data were not available, as explained above. The total topographic change caused by the moderate and exceptional floods was depositional. Most topographic change at the Laddie Park bar occurred below the stage of the 2-year flood ($Q_2$) (Figure 4.8). Obviously, erosion and deposition occurred at higher elevations and over more of the valley floor during the larger flood. Less deposition also occurred at lower elevations as a result of the larger flood.

In order to explain the spatial pattern of these topographic changes, we compared the topographic change map of erosion and deposition created from comparison of the LiDAR datasets with the predicted distribution of velocity at the peak of the 2010 and 2011 floods (Figure 4.9). The area of deposition was larger than the area of erosion during both floods. Erosion occurred on the main-channel side and at the upstream end of the Laddie Park Bar. This area also was the location of the largest velocity measured during the 2010 moderate flood and the 2011 exceptional flood. As flow continued across the bar, the topographically higher and hydraulically rough vegetated mid-island area and smaller vegetated mounds deflected flow to either the main or secondary channel. Erosion occurred where the flow accelerated around vegetation and elevated mounds.

The location of the flow bifurcation differed between the moderate and the exceptional flood. During the moderate flood, the predominant flow division occurred further upstream than during the larger flood. We attribute this difference in part to the fact that water did not overtop the entire bar during the moderate flood. Less flow momentum during the moderate flood and a greater backwater effect from the vegetated island that remained dry, resulted in flow accelerations upstream of the dense vegetation where bare gravel occurs; there was little to no fine sediment accumulation at the head of the island. Conversely, the greater momentum during the large flood, along with greater depth of inundation pushed the bifurcation point further downstream into the tamarisk and willow (Figure 4.9). These vegetated surfaces had fine sediment deposited in and around individual plants or groups of plants during the large flood. As
flow accelerated around the large vegetated part of the island, the flow field also interacted with
the vegetated mounds to the left of the bifurcation, causing further, small-scale flow bifurcations
and accompanying accelerations. As a result, greater erosion occurred during the exceptional
flood, because these bifurcations and accelerations occurred on topographically higher vegetated
surfaces with fine sediment. Deposition occurred at points of flow deceleration. During the
moderate flood, these areas were located at the edge of the tamarisk and willow stands. During
the exceptional flood fine sediment was deposited deeper past the edge of these stands.

6.2 Maintenance of the Contemporary Laddie Park Bar: Application of the Observation-Based
Predictive Model to the Current Topography, Vegetation Cover, and Flood Regime

To integrate the topographic response of the Laddie Park Bar for the contemporary flood
regime we applied the observation-based predictive model to floods with a recurrence between
1.5 and 20 years, as determined for the 50-year period, 1961-2011. For a given cell, we identified
the smallest flood (i.e., the highest probability of occurrence in a given year) that results in
erosion, and the one that results in deposition. As a result, we produced a map of the most
frequent occurrence of topographic change (Figure 4.10).

By integrating the flood regime, it is apparent that much of the Laddie Park Bar
experiences no topographic change for floods up to the 20-year flood. These static surfaces are
vegetated and fine sediment has accreted around the vegetation over time (see Chapter 3). Thus,
these surfaces are inundated less frequently. Fine sediment erosion is restricted to the secondary
channel and the main-channel side at the head of the bar. Common floods (i.e., those floods that
have a greater than 0.50 probability of occurring in any given year) are responsible for the erosion
of fine sediment on a very small portion of the bar. The majority of the areas maintained by fine
sediment evacuation are erosional during moderate floods. Moderate floods are particularly
important for the maintenance of the downstream portion of the secondary channels. Large floods
(i.e., probability less than 0.10) expand the erosional area further onshore at the head of the Laddie Park Bar and to the edges of the secondary channel.

Deposition occurs on much of the lower-lying portions of the Bar and in the margins of the vegetated areas. Additionally, deposition occurs across the top of the Bar. Here, close to the bifurcation, water is diverted to either side of the vegetated island and into the secondary channel, and, as such, is critical to the maintenance of the secondary channel. Those areas that do not accumulate fine sediment include the secondary channel thalweg and the portion of the Bar head closest to the main channel. Common floods are predominately responsible for fine sediment deposition on the lowest surfaces that contain only sparse vegetation. Much of the fine sediment deposited in common floods is removed by moderate or large floods. Moderate and large floods deposit fine sediment around, and within, the more densely vegetated surfaces. As observed above, the greater momentum of these floods carries water and sediment further into the dense vegetation. Where the flow decelerates, deposition occurs. The flood regime that includes floods up to the 20-year flood does not evacuate the fine sediment deposited by moderate or large floods.

6.3 Evolution of the Laddie Park Bar: Application of the Observation-Based Predictive Model to a Historical Topography, Vegetation Cover, and Flood Regime

We reconstructed the topographic and vegetation conditions at the beginning of the study period in 1961 and for conditions following the flood of record in 1984. We applied the observation-based predictive model to the flood regime specific to the two time periods evaluated; 1961-1983 and 1984-2011 (Figure 4.5). We predominately focus on changes in the distribution of areas where fine sediment deposition is unlikely. To summarize spatial and temporal changes, we created cumulative curves of the probability of fine sediment erosion for the two historical snapshots and the contemporary condition. These cumulative curves were created from maps that identified the smallest flood (i.e., the highest probability of occurrence in
a given year) that results in erosion (e.g., Figure 4.10). We also highlight changes in areas where no topographic change is likely.

In the 50-year evolution of the Laddie Park Bar, the role of common, moderate, and large floods has changed (Figure 4.11). Initially, common floods became less effective at restricting fine sediment accumulation. Between 1961 and 1984, the area that was likely to be erosional during these commonly occurring floods decreased by more than half, from roughly 23,000 to 7,000 m². The effectiveness of larger floods, however, was essentially unchanged between these two periods. By 2011, all floods were less effective at restricting fine sediment accumulation through erosion. In the 50 years, the area that experienced no topographic change increased from 4,500 m² in 1961 to 17,000 m² in 2011. As described above, floodplain building and fine sediment accumulation increased the elevation of many surfaces, disconnecting them from many flood events, and therefore preventing any topographic change.

In order to identify driving forces controlling the evolution of the Laddie Park Bar, including the changing effectiveness of common, moderate, and large floods, we focus on the mechanisms responsible for vegetation encroachment. In Chapter 3, we made the linkage between vegetation encroachment and channel narrowing on the lower Yampa River. Detailed stratigraphic and dendrogeomorphic analyses of the Laddie Park Bar established the importance of tamarisk (and willow) establishment, low in the channel during dry periods, for the promotion of fine sediment deposition that led to channel narrowing. Thus, vegetation encroachment is critical to our understanding of the evolution of the Laddie Park Bar, and the maintenance of a multi-thread planform. We hypothesized that areas of likely deposition, without subsequent erosion, have a high probability of being colonized by vegetation. We make the assumption that the limiting factor of establishment at Laddie Park is physical disturbance, specifically scouring of fine sediment that could lead to seedling dislodgement, and not the availability of fine sediment or access to water. Fine sediment accretes in and around vegetation, particularly towards the downstream portion of the Bar (see Chapter 3). Therefore, we consider these two
processes, tamarisk and willow recruitment and the accretion of fine sediment, as mutually accommodating. By focusing on the processes that promote fine sediment deposition and vegetation encroachment, using the robust and dynamic spatial and temporal analyses afforded by the observation-based model, we build on the findings of Chapter 3 to further identify the interactions and feedbacks among floods, sediment, and vegetation.

6.3.1 1961 to 1983

Reconstruction of the topographic and riparian-vegetation conditions in 1961 suggests that low magnitude, high frequency common floods were sufficient to maintain a large portion of the gravel bar free of fine sediment (Figure 4.12). However, not all areas were maintained by these small floods, or even by larger ones. Flows moving across the gravel bar towards the secondary channel had enough specific discharge, even during the smaller floods, to prevent progressive fine-sediment accumulation here. At the bifurcation point, a substantial portion of the total discharge, on average 30%, was routed towards the secondary channel. While the volume of water flowing down the secondary channel was much greater during this period than today (2010 flood, 8% of total discharge), the unequal distribution of water between the two channels indicates that the bifurcation was unstable.

Key to these flow patterns, and the resulting topographic signature, was the low elevation of the vegetated island. All floods overtopped the island, and as a result, the flow field did not experience a backwater. As we observed in the 2010 flood, water stacked up behind the island, resulting in a more upstream flow bifurcation. For the 1961 vegetation and topographic conditions, the flow bifurcation was located further downstream. Thus, more water moved across the bar and as a result was routed into the secondary channel. Even though the vegetated island was low, it still diverted water out towards the main channel, or through the secondary channel. The resulting flow field created a hydraulic shadow downstream. Predicted flow patterns and
associated topographic change suggest that in the lee of the vegetated island, erosion of fine sediment did not occur within the 22-year period from 1961 to 1983.

We matched the predicted patterns of topographic change to those areas with known net deposition and vegetation recruitment between 1961 and 1983 (Figure 4.12). In 1961, 36,000 m² of the total 41,000 m² of the Laddie Park Bar (not including the upper secondary channel) were unvegetated. We constructed a cumulative curve of the highest probability of fine sediment erosion for the unvegetated areas, similar to those shown in Figure 4.11. The cumulative curve supports the observation that smaller floods were responsible for most of the prevention of fine sediment accumulation.

We assumed that if tamarisk plants were limited by physical disturbance it is unlikely that vegetation would have established in the areas with predicted fine sediment erosion. The assumption appears to hold true in the lee of the island. Here, erosion did not occur in this time period and vegetation expanded nearly to the edge of where erosion begins to occur. To explicitly address our assumption, we created cumulative curves that show how much vegetation did establish in those areas with a chance of erosion and in those areas without a chance of deposition (Figure 4.12A). In the 22-year period, vegetation established in less than 10% of the all areas with some probability of evacuating fine sediment. While more vegetation established in those areas in which fine sediment was not predicted to be eroded during any floods, nearly 50% of this “non-erosional” area remained unvegetated in 1983.

This observation that vegetation did not establish in all areas in which deposition, without subsequent erosion, occurred has many possible explanations. For one, our predictive model only determines the probability of net topographic change in fine sediment for a flood event. As a result, a cell with a high likelihood of deposition or no detectable change may, in fact, experience scour during the flood event. In cells with a high probability of deposition, burial may, have also been an important mechanism of seedling mortality. During this early period, the limiting factor for vegetation establishment may not have been exclusively physical disturbance. Other factors,
such as seed source, access to water, or precipitation patterns may have limited the expansion of tamarisk. Additionally, vegetation may have established in these areas, only to be scoured out by the large floods of 1983 and 1984.

6.3.2 1984-2011

By 1984, the importance of the smaller more frequent flood in preventing the accumulation of fine sediment had greatly diminished (Figure 4.11). This is most apparent along the pathway from the main channel to the secondary channel (i.e., to the left of the bifurcation) (see Figure 4.9). The common flood had been capable of preventing the accumulation of fine sediment here in 1961. However, by 1984, only large floods were erosional (Figure 4.13). This area, therefore, became much more sensitive to vegetation encroachment. Similar to the above observation, we attribute this change predominately to the elevation of the vegetated island. The increased elevation of the bar, a result of fine sediment deposition from the large floods in 1983 and 1984, and increased coverage and density of vegetation on and around the island (Figure 4.2), controlled the location of the bifurcation point. Whereas with the 1961 reconstruction, all modeled flows overtopped the bar, after the flood of 1984, only discharges in excess of the 5-year flood inundated the top of the bar. As a result of the resistance caused by the higher, more hydraulically rough island, and the stacking of water during moderate to large floods, the bifurcation point moved upstream. Less water moved across the top of the bar, and by 1984 only 20%, on average, of the total discharge was routed towards the secondary channel. The decrease in the proportion of water flowing in the secondary channel suggests that in fact the bifurcation is unstable. From 1961 to 1984, the Laddie Park Bar moved closer to abandoning the secondary channel.

In 1984, 31,000 m² of the total 41,000 m² of the Laddie Park Bar (not including the upper secondary channel) was unvegetated. The majority (i.e., more than 80%) of the unvegetated area had the capability to prevent fine sediment accumulation, either through fine sediment erosion for
some part of the flood regime, or through no change for the entire flood regime. In contrast to the cumulative curve of erosional areas from 1961, the cumulative curve for 1984 highlights the importance of moderate and large floods in preventing the accumulation of fine sediment. However, much of the vegetation that established on the Laddie Park Bar between 1984 and 2011, colonized these unvegetated areas that had a low probability that erosion of fine sediment will occur in any given year. We documented vegetation establishment on surfaces that were predicted to have a low probability of erosion in any given year along the transect characterized by two of the floodplain trenches (Figure 4.13C). All plants along the transect that established in this period, did so on surfaces with less than a 0.30 probability of erosion. Fine sediment deposited in and around these newly established plants. This observation, that our predictions implicate moderate and large floods as important for preventing the accumulation of fine sediment over a larger area of the Bar, yet these areas experienced significant vegetation encroachment and subsequent fine sediment accumulation, suggests that during this time period the frequency of events was critical to maintaining channel form. We believe that this was a function of the ability for tamarisk to encroach onto surfaces that were only erosional during moderate or large floods. Many of the new tamarisk established in the late 1980’s/early 1990’s, during which only common floods occurred. A lack of erosion for a string of more than 4 years provided these plants with enough time to resist subsequent erosion by later moderate or large floods, and even induce deposition (see Chapter 3). Very few plants established on surfaces that had more than a 0.40 probability of being erosional in a year. Similarly, these surfaces did not accumulate fine sediment. By 2011, new vegetation had also established on all surfaces for which no erosion was predicted to occur for the flood regime. Thus, during this time period, vegetation establishment appeared to be limited by physical disturbance; new plants established where erosion was limited and did not establish where erosion did not occur, or rarely occurred.
6.4 Water Development and Channel Maintenance Floods: Application of the Observation-Based Predictive Model to Future Flood Regime Scenarios

We used the modeling approach described above to estimate the impact of potential future water development (i.e., diversion of a portion of the snowmelt flood) on channel form at Laddie Park. We assumed that the magnitude of those floods of 20-year recurrence or more frequent was reduced (Figure 4.14). These changes to the flood regime caused the area of likely fine sediment erosion and deposition to decrease. As a result, some areas had a greater likelihood of fine sediment accumulation while others less so. Thus, the changing topographic signature in response to declining floods was non-linear, and the style and rate of predicted sediment accumulation informs decisions about those aspects of the flow regime that are most sensitive to water development. Here, we also define a series of environmental flows necessary for the preservation, or delayed abandonment, of two channels in Laddie Park. We focus on two zones important for the maintenance of multi-thread planform: the exposed channel sediment of the downstream secondary channel and the flow bifurcation that includes the zone where the flow field diverges around the island (Figure 4.15).

6.4.1 Secondary Channel

For the current hydrologic regime that has existed for at least the past 50 years, exposed channel sediments in the secondary channel are maintained by moderate and large floods (i.e., there is less than a 0.50 probability of such a flood occurring in a given year). Cumulative curves of the likelihood of deposition at a given cell, indicates that small floods deposit the majority of the fine sediment (Figure 4.16). A reduction of flood magnitude has the general effect of increasing the area susceptible to fine sediment accumulation. However, maintenance of channel form is a balance between fine sediment erosion and deposition and these two processes have different responses to reduced flood magnitudes. With increasing flood reduction, less erosion would occur. The effectiveness of moderate floods would be lost more rapidly than that of large
floods. Conversely, fine sediment deposition initially decreases with increasing flood reduction. Deposition in the secondary channel occurs almost exclusively along the edges of the channel within stands of tamarisk and willow. The range of specific discharge values for which it is likely that deposition occurs for vegetated areas is between 0.7 and 1.9 m$^2$/s. With modest decreases in flood magnitude (5-10% reduction), specific discharge values fall below this range within the vegetation, and smaller areas are susceptible to deposition for all flood sizes. With even further reductions in flood magnitude, however, the specific discharge for unvegetated areas drops to the range of likely deposition (i.e., 0.2-0.7 m$^2$/s). The total area for which deposition is likely increases for all flood sizes.

To get a general sense of the likely balance between fine sediment erosion and deposition for each water removal scenario, we integrated the likelihood of erosion, deposition, and no change that a given cell was predicted to experience. Those cells that, cumulatively for the flood regime, have a greater chance of deposition (or erosion) in any given year, were identified as depositional (or erosional). Those cells that had no change for any of the floods, were identified as no change. The results from this analysis indicate that for the existing flood regime, a larger area (3,260 m$^2$) has a higher probability of accumulating fine sediment than it does of eroding sediment (1,937 m$^2$), for any given year (Table 4.3). A 5% reduction in flood magnitude results in a slight increase in erosional areas and decrease in depositional areas. Further reductions increase the area susceptible to fine sediment accumulation. Thus, the fine sediment dynamics in the secondary channel are not in equilibrium, even for the current hydrologic regime. The secondary channel, as it exists today, cannot maintain the throughput of fine sediment for floods with a recurrence of 20 years or less. A reduction of more than 5% of the magnitude of floods would further reduce the capacity of the secondary channel to maintain exposed channel sediment.
6.4.2 Flow Bifurcation

Unlike the secondary channel, the flow bifurcation experiences no fine sediment erosion for the current flood regime; only fine sediment deposition, or no change. The majority (90%) of the fine sediment deposition occurs as a result of moderate or large floods (Figure 4.16). Thus, the bifurcation is aggrading for the current flood regime. Common floods do not contribute to fine sediment deposition for any of the water removal scenarios. Reduced flood magnitudes decrease the total area susceptible to fine sediment accumulation, thereby increasing those areas with no topographic change for the flood regime (Table 4.3).

6.5 Channel Maintenance Floods

These analyses demonstrate that the existing flood regime, which includes floods with a recurrence of 20 years or less, cannot maintain the present day topographic and vegetation conditions of the Laddie Park Bar. For the integrated flood regime, more than 60% of the secondary channel has a higher probability of accumulating fine sediment than evacuating fine sediment or remaining as exposed channel sediment. Additionally, as water diverges around the island and enters the secondary channel, the specific discharge is not great enough to erode fine sediment at the bifurcation. Over time, portions of these two critical zones will accumulate fine sediment. The area susceptible to fine sediment accumulation decreases with reductions in flood magnitude, from 68% of the total area across the bifurcation and secondary channel for the existing flood regime to 59% of the total area with a 20% reduction (Table 4.3).

However, not accounted for in these observations, is the occurrence of exceptional floods that, because of the difficulty in predicting them, would likely not be included in water development scenarios. We documented erosion along the pathway towards the secondary channel as a result of the exceptional flood of 2011 (Figure 4.9). The volume of sediment both evacuated and deposited as a result of this flood was much greater than from the sum of two common floods (Figure 4.8). Thus, these exceptional floods have the potential to remove the fine
sediment that accumulates otherwise. We matched the predicted topographic patterns for an exceptional flood (776 m³/s, 50-year return period) to the integrated topographic response for the different water removal scenarios. Accounting for the exceptional flood, the total area susceptible to fine sediment accumulation is much less for all scenarios, and increases with greater reductions in flood magnitude (Table 4.3).

Over the 50-year study period, the Laddie Park Bar has accumulated fine sediment, particularly in the secondary channel, and thus moved closer to abandoning a multi-thread planform. Our analyses suggest that the Bar will likely continue to accumulate fine sediment, even with the existing flood regime. However, water removal scenarios will hasten this process. These analyses demonstrate that the various flood sizes (common, moderate, and large floods) play unique roles in maintaining channel form at the Laddie Park Bar and the different water removal scenarios has a different impact on each of them. We identify the importance of each flood type and its sensitivity to changes in magnitude as a way of defining channel maintenance floods.

Common floods deposit fine sediment in the secondary channel and cause no topographic change on the bifurcation. Modest changes to the common flood (< 10% reduction in the magnitude of common floods) decrease the area susceptible to fine sediment accumulation. These areas increase when the magnitude of common floods is reduced by more than 10%. Moderate and large floods erode fine sediment from the secondary channel and deposit fine sediment around the bifurcation. The significance of those floods with a recurrence between 2 and 20 years is, therefore, spatially variable. We note the importance of vegetation encroachment on enhancing fine sediment accumulation. This mechanism has been critical in the narrowing of the secondary channel, particularly in the period between 1984 and 2011. We documented that a dry period of more than 4 years made those areas with less than a 0.30 probability of erosion in any given year susceptible to vegetation encroachment. Subsequent to vegetation establishment, fine sediment accumulated around the plants, even though these areas had a likelihood of being
erosional. While the larger floods prevent fine sediment accumulation for greater areas of the secondary channel, their infrequent occurrence may not prevent vegetation establishment by scouring seedlings before they become established. Thus, moderate floods, particularly those that have a probability of occurrence in any given year greater than 0.30, are critical for the maintenance of the secondary channel. Any reduction in the magnitude of these floods allows more area to be colonized by vegetation. Reductions in the magnitude of moderate and large floods decrease the area susceptible to fine sediment accumulation at the bifurcation. Reductions in flood magnitude for the moderate floods results in a smaller reduction in the susceptible area than does a reduction in the large floods. As such, the integrated impact of reducing moderate floods would be greater than large floods on the future maintenance of the Laddie Park Bar.

7. Morphologic and Process-Based Classification of Multi-Thread Reach Sensitivity

From a robust analysis of contemporary and historical data at the Laddie Park Bar, this study characterized the mechanisms responsible for the transition of a reach from a multi-thread planform to a much simplified single channel. We identified the corresponding morphologic characteristics of this transition. We also defined the importance and sensitivity of different flood sizes on the maintenance of multiple channels. With this suite of observations we created a morphologic, process-based, classification of the stages in this transition (Figure 4.17). We discuss the response to the 2009, 2010, and 2011 floods of two Bars on the lower Yampa (Spawning and Pouring) in light of their morphologic characteristics to extend our observations and analyses from Laddie Park and provide a larger context for this conceptual model. Our classification may be used as a proxy of the sensitivity of canyon-bound, high suspended sediment, multi-thread reach to alterations of different aspects of the flood regime.

Mid-channel bars, void of fine sediment define one end-member (Figure 4.17). Morphologically, these settings are characterized by low elevations and relatively equally-sized channels on either side of the bar. Smaller floods frequently overtop the bar. As such, large
specific discharge occurs over the entire bar, thus evacuating fine sediment on a regular basis. The Spawning Bar has morphologic qualities similar to this end member. Here, the gravel bar is bounded on either side by relatively equally-sized channels [Harvey et al., 1993]. The highest part of Spawning Bar is inundated by the 2-year recurrence flood (Figures 4.18 and 4.19), and the entire bar was overtopped during the 2009, 2010, and 2011 floods. Walking around the bar, it was apparent that erosion and deposition signatures from the difference in LiDAR maps were predominately a result of the reworking of gravel. Very little fine sediment has accumulated in the hydraulic shadow of the few tamarisk and willow plants that are currently growing on the bar. The net topographic change from the two moderate floods was erosional (Figure 4.19).

The transition from one end-member to the next is morphologically defined by the vertical and lateral growth of the mid-channel bar and conversion to a stable island. Often, vegetation establishes on the bar and assists in constructing the floodplain. A more dominant channel forms such that one can distinguish between a main and secondary channel. The transition is controlled by the location, and therefore the dynamics, of the flow bifurcation. When the bifurcation at Laddie Park was located further downstream, a larger proportion of the flow was diverted into the secondary channel. Greater volumes of water moving through the secondary channel helped to evacuate fine sediment and scour out seedlings, therefore maintaining the character of a multi-thread planform.

In a partially confined valley, such as the lower Yampa River, the upstream flow conditions are generally spatially static. Thus, the valley geometry exerts a strong control on the dynamics of the flow bifurcation, and therefore, the sensitivity of the setting to changes in the boundary conditions. An approaching flow field that is predominately uniform (i.e., little to no cross-stream component) supports a stable bifurcation. Additionally, maintenance of the downstream momentum as flows cross the mid-channel bar promotes the continued stability of a flow bifurcation. When flow bifurcations are unstable, they are more sensitive to changes in boundary conditions than stable bifurcations. At Laddie Park, the bifurcation was likely always
unstable as a result of the valley geometry. A bedrock wall on river left upstream of the site creates non-uniform flow conditions. A tight bend in the valley downstream limits the momentum of the approaching flow field by backwatering the flow. Prior to the encroachment of tamarisk, the Laddie Park Bar had a relatively persistent accumulation of fine sediment (see Chapter 3). In 1938, the Bar was much closer to the multi-thread end-member (Figure 4.2). When tamarisk began to colonize the Yampa riparian corridor, Laddie Park was susceptible to invasion because of the valley geometry. Tamarisk encroachment and the further accumulation of fine sediment continued to push the bifurcation further back. The feedback between tamarisk and fine sediment drove the transition of the Laddie Park Bar.

The presence of fine sediment and vegetation at the Pouring Bar indicates that the valley geometry promotes an unstable bifurcation. This setting has topographically elevated surfaces (Figures 4.17 and 4.18) that influence the location of the bifurcation. Erosional patterns from the 2009, 2010, and 2011 floods are similar to Laddie Park; small erosion towards the upstream end of the Bar for the moderate floods and larger erosion further downstream, close to the edge of a topographically raised surface, for the exceptional flood (Figure 4.17). As noted above, these patterns suggest that the location of the flow bifurcation changes with flood level. Thus, the Pouring Bar has likely been transitioning away from the multi-thread end member, particularly since the encroachment of tamarisk. Net depositional signatures, from both moderate and exceptional floods, support this observation (Figure 4.18). However, the proportion of fine sediment that was eroded relative to that which was deposited at Pouring is greater than at Laddie Park. This observation suggests that Pouring is not as close to secondary channel abandonment as is Laddie Park.

The role of the three flood types, common, moderate, and large, uniquely contribute to the maintenance of reaches, depending on where they lie along the transition. The effectiveness of common floods at preventing the accumulation of fine sediment diminishes first in the transition from one end member to the next, increasing the importance of moderate and large floods. As
fine sediment accretes and vegetation encroaches, the effectiveness of large and moderate floods also diminishes. Moderate floods remain important for a longer part of the transition, as the frequency of these events prevents further vegetation encroachment.

8. Discussion

We documented that the maintenance of a critical aspect of channel form in the Colorado River basin, the multi-thread planform, requires a variety of flood magnitudes. As such, an environmental flow designed to maintain channel geometry cannot be described by a single, dominant discharge. Commonly, geomorphologists make assumptions about the interactions of water and sediment in defining channel maintenance flows [Whiting, 2002]. By calculating the flood event that moves the most sediment over time, and assuming that the current channel is in equilibrium with the existing water and sediment loads, this single flood will preserve channel form [Andrews, 1980; Pitlick and Van Steeter, 1998]. Such an approach takes the spatial and temporal complexity out of the process of channel maintenance.

In this paper, we present a novel approach to defining channel maintenance flows. Our approach relies on the idea that for the system of interest, there is a definable aspect of channel form that is critical to the continued ecological functioning of the river. In the Colorado River Basin, this measurable feature, the multi-thread planform, is critical for various life stages of many of the native, endangered fish species [Stanford and Ward, 1986]. Additionally, this channel feature has been identified as the most sensitive to changes in water, sediment, and/or vegetation [Van Steeter and Pitlick, 1998; Allred and Schmidt, 1999]. Prescribing environmental flows for the maintenance of this critical aspect of channel form requires a basic understanding of the relationship between streamflow, including its temporal variability, and geomorphic response. Using a robust historical and contemporary dataset, we identified the floods necessary to maintain the multi-thread planform. We focused on a single reach with multiple channels, the Laddie Park
Bar. For this reach, we identified various floods essential for the maintenance of two critical zones; the bifurcation and the secondary channel.

We also identified that, because of the spatial and temporal variability of these critical floods, a uniform reduction of the flow regime has a variable impact. Consideration of the balance between erosion and deposition at the secondary channel and bifurcation, suggests that the impact of small and large floods on fine sediment erosion and deposition is fairly insensitive to small reductions in flood magnitude (i.e., < 10%). Conversely, the moderate flood is highly sensitive to small changes in the peak magnitude. These findings highlight the non-linearity inherent in the relationship between discharge and channel form [Schumm, 1979; Phillips, 2006]. While the process of sediment transport itself is a threshold phenomenon with exponential changes in transport rates for small changes in discharge [Erwin et al., 2011], the mediation of vegetation on the interaction of water and sediment, significantly enhances this non-linearity [Temmerman et al., 2005; Corenblit et al., 2007].

Additionally, our results highlight the importance of adaptively incorporating channel maintenance flows into a management plan [Poff et al., 2010]. We defined the flood regime, within the relatively common range of floods (1.5 to 20-year flood), that is necessary to maintain the multi-thread planform. Due to the difficulty in planning for exceptional floods, water development schemes often have no impact on larger, rare events [Gordon et al., 2004]. However, our geomorphic change maps captured the geomorphic response of multi-thread reaches to a 50-year flood and suggest that these exceptional floods are important. The 2011 flood deposited fine sediment on the vegetated mid-channel bar, increasing its elevation by as much as 1.5-m. Similarly, in Chapter 3, we documented substantial deposition elsewhere on the vegetated bar as a result of the 1984 flood, the largest on record. The elevation of this bar controls the location and strength of the bifurcation that in turn controls the amount of water entering the secondary channel. Additionally, the 2011 flood evacuated fine sediment from the area around the bifurcation that serves as the major pathway for water entering the secondary channel. We
predicted this area to be exclusively depositional for the < 20-year flood regime. Therefore, an exceptional flood may reverse the impacts of more commonly occurring floods or it may alter the flow patterns and resulting topographic change of those floods. Such impacts have the possibility of shifting the flood regime required to maintain multi-thread channel form.

We focused on the Laddie Park Bar because of the abundance of both historical and contemporary data. We took advantage of a site that has made much of the transition along the multi-thread to single channel continuum. Our analyses suggest that Laddie Park cannot maintain its current channel form, regardless of water development. Thus, at least some reaches on the Yampa are not in equilibrium. However, water development is likely to hasten the full transition to a single-thread planform.

Development of a robust set of channel maintenance flows should synthesize information for a range of multi-thread morphologies. Our observations helped us construct a conceptual model of the evolution of a multi-thread reach, its dominant morphologic characteristics, and its sensitivity to alteration of various aspects of the flow regime. Based on this model, we can, in a general way, identify the types of floods that likely maintain different multi-thread reaches, predominately based on morphologic characteristics. For example, the equal distribution of water in two channels and topographically low mid-channel bar that lacks substantial fine sediment, suggests that the Spawning Bar is characteristic of the stable multi-thread reach end-member. These morphologic indicators inform us that common and moderate floods are most important for the maintenance of multiple channels. We can make inferences about the sensitivity of these reaches to altered flood magnitudes. Fine sediment dynamics at the Spawning Bar are likely most sensitive to changes in common floods, and relatively immune to alterations in large floods. Conversely, as Pouring Bar is further along in the transition to a single-thread planform, it is more sensitive to changes in moderate floods.

Our approach to defining channel maintenance flows is novel in both its focus on a critical aspect of channel form and its use of an observation-based predictive approach to
identification of those floods needed to preserve that critical aspect. In this paper we applied our methodology to a multi-thread reach and identified peak flood magnitudes and their corresponding frequency, critical for the maintenance of two channels. We recognize that the peak magnitude and frequency of a flood are not the only geomorphically relevant parameters. Hydrograph shape (i.e. flood duration) is a crucial component to the amount of geomorphic work a flood accomplishes [Costa and O'Connor, 1995]. We believe that part of the difference in volume of sediment reworked between the exceptional flood of 2011 and the moderate floods of 2009 and 2011 is the extremely long duration of the 2011 flood. We focused on the peak because after experimentation with various indicators of flood duration, we determined that this value was a better predictor of the pattern of erosion and deposition.

Since our focus was only on the peak magnitude, we treated all floods as having the same capacity to remove fine sediment. Thus, we made a major simplifying assumption; the frequency of a flood event and its resulting topographic change patterns is more important than the magnitude of change from any given event. Differences in the magnitude of topographic change for floods of different magnitude can be great, as observed for the 2009, 2010, and 2011 floods. Our focus on the general patterns of likely morphologic change given the probability of erosion matched the observed patterns of change for the 50-year period between 1961 and 2011. In particular, the exclusion of riparian vegetation was well described by frequently occurring fine sediment erosion. Where vegetation was able to establish, morphologic change occurred.

This study takes the first step towards advising river managers of which floods are necessary for the maintenance of geomorphic form. Management of a river system through flow manipulation alone, however, may not be sufficient to achieve desired geomorphic outcomes. Additional management options (e.g., vegetation removal) may be necessary. Future work on channel maintenance flows should include these alternatives.
9. Conclusions

This paper presented a new approach to defining channel maintenance flows. Instead of identifying a single dominant flow, we identified the importance of various flood sizes for maintaining a critical aspect of channel form. Working in the Colorado River Basin, we chose to define channel maintenance flows for reaches with a multi-thread planform. Identification of the role of various flood sizes required a detailed understanding of the processes by which multi-thread reaches are (not) maintained, by the exclusion (accumulation) of fine sediment. The transition from a multi-thread planform to a more simplified, single-thread planform is controlled by the dynamics of the flow bifurcation. In the canyon-bound reaches of the lower Yampa River, the valley geometry exerts a dominant control on the stability of the flow bifurcation, and thus on the sensitivity of a reach to changes in boundary conditions. In the case of the Yampa, changes to the boundary conditions in the past 50 years have occurred predominately through the encroachment of tamarisk. Where tamarisk has established, fine sediment accumulated converting the mid-channel bar to a stable island. Such morphologic changes altered the location of the bifurcation. An increase in the elevation and vegetation coverage of the mid-channel bar creates a backwater effect, resulting in a flow bifurcation located further upstream. Floods then have less momentum as they diverge, and less water enters the secondary channel. The role of various flood sizes changes as the morphology of a multi-thread reach evolves towards a single-thread planform. Common floods are most effective at maintaining channel form when multi-thread reaches have not experienced significant vegetation encroachment and fine sediment accumulation. Moderate floods are most effective at maintaining channel form as a reach transitions towards a single-thread planform.

Our approach provided the tools to evaluate the sensitivity of different water development scenarios on the maintenance of the existing topography. This sensitivity analysis highlighted the aspects of the flood regime that, if reduced by water development, would (not) have a great impact. Our analysis focused on one multi-thread reach, Laddie Park. However, by
synthesizing our understanding of the mechanisms driving the maintenance of multi-thread reaches, we extended our analysis to other reaches on the Yampa that are critical habitat for endangered endemic fish species. An analysis similar to what we did for Laddie Park of these critical reaches may be done to develop a more robust set of channel maintenance floods for the Yampa River.

References


Cooper, D. J., D. C. Andersen, and R. A. Chimner (2003), Multiple pathways for woody plant establishment on floodplains at local to regional scales, J Ecol, 91(2), 182-196.


Table 4.1. Summary of LiDAR datasets collected for the lower Yampa River, Dinosaur National Monument.

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Discharge</th>
<th>Ground Points/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³/s</td>
<td>Average</td>
</tr>
<tr>
<td>2008</td>
<td>29-Oct</td>
<td>12.8</td>
<td>0.75</td>
</tr>
<tr>
<td>2010</td>
<td>23-Jun</td>
<td>160</td>
<td>0.8</td>
</tr>
<tr>
<td>2011</td>
<td>21-Sep</td>
<td>23.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 4.2. Application of the observation-based predictive model of topographic change to the topographic change maps from 2011-2010 and 2010-2008. Results indicate that of the total 66,704 m² area observed from the two change maps, the predictive model correctly identified 43,296 m² (or 65%).

<table>
<thead>
<tr>
<th>No (Detectable)</th>
<th>Change</th>
<th>Deposition</th>
<th>Erosion</th>
<th>Total Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Area (m², 1m² cells)</td>
<td>51,651</td>
<td>13,181</td>
<td>1,872</td>
<td>66,704</td>
</tr>
<tr>
<td>Correctly Predicted Area (m², 1m² cells)</td>
<td>34,149</td>
<td>7,732</td>
<td>1,415</td>
<td>43,296</td>
</tr>
<tr>
<td>Percentage of Observed Area Correctly Predicted</td>
<td>66%</td>
<td>59%</td>
<td>76%</td>
<td>65%</td>
</tr>
</tbody>
</table>

Incorrectly Identified as Deposition: 47%
Incorrectly Identified as Erosion: 53%
Incorrectly Identified as No Change: 80%
Table 4.3. Integration of the flood regime for the three water removal scenarios, including the impact of an exceptional flood, at two zones identified as critical for the maintenance of a multi-thread planform- the side channel and flow bifurcation.

<table>
<thead>
<tr>
<th>Area of Change</th>
<th>Existing</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Change</td>
<td>105</td>
<td>94</td>
<td>249</td>
<td>484</td>
</tr>
<tr>
<td>Deposition</td>
<td>3,260</td>
<td>3,105</td>
<td>3,339</td>
<td>4,086</td>
</tr>
<tr>
<td>Erosion</td>
<td>1,937</td>
<td>2,103</td>
<td>1,714</td>
<td>732</td>
</tr>
<tr>
<td>Resulting Depositional Cells After Exceptional Flood</td>
<td>1,007</td>
<td>954</td>
<td>1,113</td>
<td>1,856</td>
</tr>
</tbody>
</table>

**FLOw Bifurcation**

<table>
<thead>
<tr>
<th>Area of Change</th>
<th>Existing</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Change</td>
<td>1,684</td>
<td>2,010</td>
<td>2,609</td>
<td>3,521</td>
</tr>
<tr>
<td>Deposition</td>
<td>4,519</td>
<td>4,193</td>
<td>3,581</td>
<td>2,682</td>
</tr>
<tr>
<td>Resulting Depositional Cells After Exceptional Flood</td>
<td>2,047</td>
<td>2,109</td>
<td>1,923</td>
<td>1,489</td>
</tr>
</tbody>
</table>

Total Depositional Cells For Typical Flood Regime (1.5-20 yr flood) 68% 63% 60% 59%

Total Depositional Cells After Exceptional Flood 27% 27% 26% 29%
Figure 4.1. Lower Yampa River study area in Dinosaur National Monument. Three multi-thread study reaches are identified.
Figure 4.2. Air photos showing A) the Laddie Park Reach (2010 photo used because of shading in 2011), B) the area around the Laddie Park Bar, and C) historical aerial photographs from 1938, 1961, and 1983. The four floodplain trenches and four floodplain pits used in the reconstruction of the historical topography and vegetation cover are shown in (B). Additionally the location of the four ADCP transects (dashed lines) are marked.
Figure 4.3. Potential controls on stable and unstable bifurcations in multi-thread reaches. Uniform flow promotes equal distribution of flow between channels. Non-uniform flow promotes an unequal distribution of flow between channels, that is exacerbated with lower discharges.
Figure 4.4. Application of the observation-based model to peak specific discharge conditions for a single flood event resulted in topographic change maps. Results from the 2-year flood and 20-year flood are shown. Each discrete flood event had a unique map of likely topographic change. That unique map in turn had a probability of occurrence in any given year and was a function of the frequency of the flood event. The 2-year flood map has a probability of 0.50 associated with it; 0.05 is associated with the 20-year flood map. Each cell, therefore, had multiple predictions of topographic change. To summarize the impact of the flow regime, each prediction had a direction of topographic change and an associated probability of occurrence. For example, cells in box A had a 0.50 probability of being depositional in any given year and a 0.05 probability of being erosional. Conversely, cells in box B had a 0.50 probability of no change in any given year and a 0.05 probability of being erosional.
Figure 4.5. Flood frequency curve (top) and time series of annual peak discharges (bottom) for the 50-year study period (1961-2011). Separate flood frequency curves for the two time periods, 1961-1983 and 1984-2011, are also shown. Ninety-percent confidence intervals are shown on the curves. For floods with a recurrence less than 20 years, the two time periods are indistinguishable. For floods with a recurrence more than 20 years, peak flood magnitude is greater for the later period.
Figure 4.6. Depth-averaged velocity measured with an ADCP along four transects taken in the secondary channel at a discharge of 450 m$^3$/s during the 2011 snowmelt flood. These measurements are matched to modeled values. Overall, there is good agreement between measured and modeled. We were unable to account for an undercut at the left side of transect 4 in the hydraulic model.
Figure 4.7. Probability distributions for fine sediment erosion, fine sediment deposition, and no change as a function of specific discharge (m$^2$/s). Curves were constructed from matching 2D hydraulic model output for the 2010 and 2011 peak flood conditions to LiDAR-derived topographic change maps for 2010-2008 and 2011-2010, respectively. Specific discharge values that had a greater than 0.50 probability of erosion were classified as erosional. Similarly, those values that had a greater than 0.50 probability of deposition were classified as depositional. Specific discharge values that had a greater than 0.50 probability of no change, or had probabilities for the three types of change (erosion, deposition, no change) all less than 0.50, were classified as no change. We created separate relationships for those cells that were within tamarisk and willow stand (bottom) and those that were not (top).
Figure 4.8. Volume of change in fine sediment (from the LiDAR-derived topographic change maps) as a function of elevation above baseflow (10 m³/s) for the 2009 and 2010 moderate floods and the 2011 exceptional flood for the Laddie Park Bar. The approximate stage of the two year flood is shown for reference. As the topographic change map from 2010-2008 captures two moderate floods with similar peak discharges, we assumed that each flood was responsible for half the change, shown as white bars inset within the gray and black bars. Gray bars indicate depositional volumes; black erosion.
Figure 4.9. Topographic change maps with the modeled velocity field for the 2010 (493 m$^3$/s) and 2011 (776 m$^3$/s) peak discharges. The approximate location of the flow bifurcation for each of these flood events is shown.
Figure 4.10. Most frequent occurrence of A) fine sediment erosion and B) fine sediment deposition in any given year for the present-day Laddie Park Bar and current flood regime, as it has existed for the past 50 years. These maps represent the conditions for floods with a recurrence between 1.5 and 20 years. Gray shading shows those areas that, for the range of floods, are predicted to no experience any topographic change.
Figure 4.11. Cumulative probability curves of fine sediment erosion for the Laddie Park Bar for the two historical topographic and vegetation conditions (1961 and 1984) and for the current condition (2011). These curves were constructed from topographic change maps that identify the most probably occurrence of erosion (e.g., Figure 4.10A). The common flood is less effective at eroding fine sediment by 1984, and by 2011 all floods are less effective. Area of no topographic change (i.e., does not experience erosion or deposition for any of the floods with a recurrence between 1.5 and 20 years), more than double between 1961 and 2011.
Figure 4.12. Most probable occurrence of fine sediment erosion as predicted for the 1961 topographic and vegetative conditions. Floods with a recurrence between 1.5 and 20 years for the period between 1961 and 1983 are included. The cumulative probability curve of fine sediment erosion for unvegetated areas (A) highlights the importance of common floods (> 0.50 probability of occurrence in any given year) for preventing the accumulation of fine sediment. Vegetation that established between 1961 and 1983 did so in both areas that had a probability that erosion would occur and in areas with no erosion (A and B), possibly suggesting that physical disturbance (i.e., erosion) was not the only limiting factor of establishment. We matched the predicted patterns to those we documented in two trenches (C). We did not include the upper secondary channel in these analyses because flow recirculates here during floods and we felt like we did not adequately capture these flow patterns.
Figure 4.13. Most probable occurrence of fine sediment erosion as predicted for the 1984 topographic and vegetative conditions. Floods with a recurrence between 1.5 and 20 years for the period between 1984 and 2011 are included. The cumulative probability curve of fine sediment erosion for unvegetated areas (A) highlights the minimal importance of common floods (> 0.50 probability of occurrence in any given year) and increased importance of moderate floods (when compared to Figure 4.12) for preventing the accumulation of fine sediment. Vegetation that established between 1984 and 2011 did so in both areas that had a probability that erosion would occur and in areas with no erosion (A and B). However, the majority of vegetation that established in erosional areas did so in those areas with a low probability of erosion (< 0.30). This observation is apparent in the transect that includes two floodplain trenches (C). All vegetation that established and fine sediment that accumulated in this time period predominately did so in areas with a <0.30 probability of fine sediment erosion. We did not include the upper secondary channel in these analyses because flow recirculates here during floods and we felt like we did not adequately capture these flow patterns.
Figure 4.14. Flood frequency curves for the water removal scenarios.
Figure 4.15. Predicted impact of water removal scenarios on two zones identified as critical in the maintenance of the multi-thread planform; the secondary channel and the flow bifurcation. The cumulative probability curve of the most probable occurrence of fine sediment erosion and deposition are shown for the secondary channel. No erosion is predicted to occur for any of the floods with a recurrence between 1.5 and 20 years, even for the existing flood regime.
Figure 4.16. The morphologic characteristics associated with the evolution of a stable multi-thread reach towards a much more simplified single-thread channel. This evolution is applicable to canyon-bound, fine suspended sediment-charged settings. The effectiveness of common floods at preventing the accumulation of fine sediment diminishes first in the transition from one end member to the next, increasing the importance of moderate and large floods. As fine sediment accretes and vegetation encroaches, the effectiveness of large and moderate floods also diminishes. Moderate floods remain important for a longer part of the transition, as the frequency of these events prevents further vegetation encroachment.
Figure 4.17. Topographic change maps for the two moderate floods and exceptional flood at the Spawning Bar and Pouring Bar. The elevation of the 2-year flood is shown on the Pouring Bar as a reference point. Spawning Bar is completely inundated by a 2-year flood.
Figure 4.18. Volume of change in fine sediment (from the LiDAR-derived topographic change maps) as a function of elevation above baseflow (10 m³/s) for the 2009 and 2010 moderate floods and the 2011 exceptional flood for the Spawning and Pouring Bars. The approximate stage of the two year flood is shown for reference. As the topographic change map from 2010-2008 captures two moderate floods with similar peak discharges, we assumed that each flood was responsible for half the change, shown as white bars inset within the gray and black bars. Gray bars indicate depositional volumes; black erosion.
CHAPTER 5
SUMMARY AND CONCLUSIONS

For this dissertation I posited that the Yampa River was the setting of a natural, field-scale, experiment. As an unregulated river that has maintained its natural snowmelt flood pulse with presumably no change in the sediment supply, the invasion of a non-native riparian shrub tamarisk and, therefore, the change in vegetation composition and cover, represents the only major perturbation to the Yampa riparian corridor. Where tamarisk invaded, the channel has narrowed and the planform simplified. Thus, the Yampa has qualities of a laboratory experiment, wherein most environmental conditions have been controlled, and of a field study, where the processes that have created today’s narrower channel have continuously occurred at the large spatial and temporal scales important for understanding river systems. I focused on the Yampa River to identify the mechanisms by which vegetation alters fluvial processes to change channel form.

Identification of these mechanisms, therefore, relied on the validity of my claim that channel changes may be explicitly linked to vegetation changes and not to changes in the hydrologic regime. In chapter 3 I determined that, while there was in fact a shift in the hydrologic regime, this shift, did not affect fluvial processes directly. Instead, a change in the timing and distribution of floods, without a change in the magnitude of the commonly occurring floods, was favorable for vegetation expansion. The increase in vegetation, in turn, caused the channel to narrow.

With a careful reconstruction of both the geomorphic and vegetation history, I presented multiple lines of evidence that support tamarisk encroachment as a driving force of channel change on the Yampa River in chapter 3. In chapter 4, I built on the observations made in chapter 3. I identified the hydraulic conditions (depth and velocity) amenable to tamarisk recruitment and evaluated the subsequent change in hydraulic conditions as tamarisk stands established, grew, and
induced deposition, thereby changing the topography. For this hydraulic reconstruction, I relied on the multi-scalar model I developed in chapter 2 that parameterized the depth-dependent, hydraulic resistance of tamarisk stands in a spatially explicit way. This parameterization allowed me to account for the changing hydraulic impact of tamarisk stands, as the channel narrowed, more tamarisk established, and older stands aged. The novel analyses presented in chapter 4 validated the significance of many vegetation-driven mechanisms of channel change identified in chapter 3. Results from chapter 4 also extend our understanding of the relative driving forces that altered the shape and size of a critical setting along the rivers of the Colorado River basin.

Below, I discuss those mechanisms identified as critical for altering fluvial processes to modify channel form. This discussion synthesizes observations from chapters 2, 3, and 4. Thus, these observations cover a range of scales, from the individual plant to the reach, and draw on a range of tools, from air photo analysis to 2D hydraulic modeling. Additionally, I briefly discuss the implications of these findings for the future management of the Yampa River.

1. The Mechanisms by Which Vegetation Alters Fluvial Processes to Modify the Cross-Section

The fundamental impact of vegetation on fluvial processes may be described by two interrelated mechanisms; vegetation increases the hydraulic resistance and vegetation increases the stability of channel and floodplain sediment [Simon and Collison, 2002; Griffin et al., 2005]. Together, these mechanisms increase the likelihood of sediment deposition and decrease the likelihood of erosion, and as a consequence, reduce channel mobility. On the Yampa, both of these mechanisms resulted in a narrower cross-section that today is less dynamic than it was in 1961. Many surfaces that were once susceptible to topographic change are now unaffected by even large floods.

Tamarisk encroachment into the riparian corridor of the lower Yampa River was primarily a function of hydrologic drivers. The majority of tamarisk established as a result of
either particularly wet or particularly dry years, corresponding to large and small snowmelt floods, respectively. These observations support the widely held notion that the hydrologic regime is a primary determinant of the structure of riparian ecosystems [Merritt et al., 2010].

However, the spatial and temporal patterns of tamarisk establishment suggest that the geomorphic and hydraulic setting restricts (or promotes) the ability for tamarisk to take advantage of the hydrologic signals. It has been well established that riparian vegetation explicitly responds to geomorphic and hydraulic variables [Hupp and Osterkamp, 1996]. These process-based linkages are predominately based on small-scale interactions. For example, seed germination requires bare, moist fine substrate [Scott et al., 1997] and successful recruitment balances the availability of this newly deposited sediment and the likelihood of subsequent erosion or burial [Polzin and Rood, 2006]. On the Yampa River, the large-scale geomorphic setting controlled the likelihood of tamarisk recruitment for a given hydrologic condition. The first plants established in response to the first dry period after seeds entered the system, only on relatively stable fine sediment deposits on mid-channel bars. The presence of these deposits was associated with the valley geometry. Additionally, those plants that germinated after the large floods of 1983 and 1984 predominately did so in the topographic depressions of the unique expansive floodplain of the Laddie Park reach. Others have documented specific geomorphic surfaces supporting tamarisk establishment, particularly in relation to the size of floods [e.g., Birken and Cooper, 2006].

I identified various feedbacks, both positive and negative, as important for the vegetation-induced alteration of fluvial processes. Feedbacks among geomorphic setting, tamarisk establishment, and changes to the cross-section altered the relationship between hydrologic signals and tamarisk recruitment. This observation was most profound at Laddie Park. The lateral and vertical expansion of the island made the site more susceptible to dry-period vegetation establishment, a positive feedback. Channel adjustments over time eventually made the Yampa
less susceptible to tamarisk expansion, a negative feedback. Since 2000, new tamarisk recruitment has been minimal, even though there have been additional wet and dry periods.

Another important feedback exists among tamarisk growth, sediment dynamics, and hydraulic roughness. A fundamental control on the density of tamarisk stands is the substrate in which the plants are growing. Similarly aged plants growing on gravel have a lower stem density than those growing in fine sediment. Many plants establish in gravel. The presence of vegetation increases the hydraulic resistance, thus inducing fine sediment deposition. Fine sediment deposition in and around the plant increases the density and, as such, the hydraulic resistance thus, presumably increasing the likelihood of further fine sediment deposition. However, a negative feedback makes this process finite. I found that as the vegetated islands in Laddie Park accumulated fine sediment and the vegetation increased in density, topographic change no longer occurred in the core of the islands. Deposition occurs where flows decelerate, particularly along the edges of dense vegetation. Therefore, for larger islands, flows decelerated before they reached the core, thereby dropping sediment out along the perimeter.

2. Implications for the future of the Yampa River

Minimal floodplain stripping, floodplain construction, or new tamarisk establishment within the past decade may indicate that the Yampa River has reached a new steady state. Channel width has adjusted to the new boundary conditions of a more densely vegetated riparian corridor. The transition to this new boundary condition began when tamarisk began to invade the riparian corridor in 1948. The new cross-section shape, generally narrower with taller banks, as illustrated in the floodplain trench stratigraphic interpretations and inferred from air photo interpretation, excluded areas susceptible to tamarisk establishment. A more mechanistic evaluation of a single site, Laddie Park, however, suggests that the secondary channel will continue to aggrade. Bare channel sediments are vulnerable to new tamarisk recruitment. Such contrasting observations, made at different scales, imply separate paths for the future condition of
the Yampa. Both observations may be correct. Over a large scale, the Yampa may have reached a new steady state (for the current hydrologic regime), yet for those sensitive reaches (i.e., multi-thread) additional adjustments could still occur. Since Laddie Park has already undergone substantial transformation, additional changes will not significantly impact the average condition of the Yampa.

The future condition of the Yampa may be susceptible to the large resetting nature of exceptional floods. The classic model of vertically-accreting, high suspended sediment rivers, such as the Yampa, was proposed by Nanson [1986]. This model says that over time, inset bars and floodplains build, narrowing the river channel and confining larger and larger floods to the channel. At a certain point, large floods confined within the channel have enough energy to strip that sediment that has built up. This essentially resets the channel back to a pre-narrowing width. Within the ~ 50 year geomorphic reconstruction presented in this dissertation, there were no channel resetting events. I documented the impact of the 1984 flood, the largest in the 89-year record and of the 2011 flood, the second largest in magnitude, and the longest duration. Both of these floods did little to rework the inset floodplain deposits that were deposited within the past century. Instead, the floodplains vertically accreted, substantially (~ 1.5 m) in places. These observations may suggest that the timescale of evaluation may not be long enough. Resetting events may occur once in every few hundred years. However, these observations may also suggest that this model does not apply to the Yampa River or generally, to rivers of the northern Colorado River basin. Variability in annual snowmelt flood peak is relatively small on snowmelt dominated rivers. Therefore, it is possible that even the largest floods that occur on the Yampa River are not large enough to fully reset the channel.

The Yampa River’s unique environmental setting, as a large Colorado River tributary that has retained its natural hydrology, has also made it the target for future water development scenarios. The National Park Service is interested in protecting the water resources of the Yampa. Annual snowmelt floods support the aquatic and riparian ecosystems on the Yampa and on the
middle Green River from the confluence of the Yampa in Echo Park down to the confluence with the Colorado River in Canyonlands National Park. Water development upstream from Dinosaur National Monument would have a significant impact on the form and functioning of these river systems. Even without water development, a changing climate will alter the timing and quantity of water delivered. Climate change may also increase the vulnerability of the Yampa to the expansion of existing or new non-native riparian species. Finally, expansion of a biocontrol agent (*Diorhabda carinulata*), first released in Dinosaur National Monument in 2006, has created a large unknown in the state of the riparian community in the near future.

Documentation of the nature of channel adjustments and the associated processes on the Yampa River for the past 50 years provides a baseline of understanding on how the Yampa River functions (i.e., what has been the role of common floods vs large floods). The process-based approach I have taken to understanding the trajectory of change, including explicitly incorporating the spatially variable hydraulic resistance of vegetation, provides a means to evaluate the future condition. The results from this dissertation have begun to identify the potential implications for water removal scenarios. However, additional research particularly focused on other multi-thread reaches of the Yampa, and the potential impact of climate change and an altered riparian vegetation community is needed.

This dissertation has contributed to the fundamental question of what controls the width of a channel by documenting the narrowing of a river whose flow regime and sediment supply have not appreciably changed. My research provides a critical piece of information on the condition of the rivers of the southwestern United States. This condition is important for the future management as human society continues to alter flows and the climate continues to change. This dissertation also developed one of the first models that links spatially limited, high resolution TLS data, to more spatially robust ALS data. The approach presented here represents a significant advancement in our ability to account for the fine-scale processes that occur among water, stems, and sediment at the larger spatial scales important for understanding river systems.
Finally, this dissertation proposed a new method for defining channel maintenance flows that accounts for the relative role of common vs large floods.

References


APPENDIX
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Full Name: Rebecca Manners
Institution Name: Utah State University
Title (if Author):
Street Address: 5210 Old Main Hill
Date: August 15, 2011
City State Zip Country: Logan, Utah 84322 USA

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ip address: 63.246.131.102
CURRICULUM VITAE

Rebecca B. Manners
Department of Watershed Sciences ● Utah State University
5210 Old Main Hill NR 210 ● Logan, UT 84322
Rebecca.Manners@usu.edu
813-240-6382

EDUCATION

<table>
<thead>
<tr>
<th>Year</th>
<th>Degree</th>
<th>Institution</th>
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<tbody>
<tr>
<td>2013</td>
<td>PhD, Watershed Sciences</td>
<td>Utah State University</td>
</tr>
<tr>
<td>2006</td>
<td>MA, Geography</td>
<td>University of North Carolina, Chapel Hill</td>
</tr>
<tr>
<td>2004</td>
<td>BA, Geography Modified with Earth Sciences</td>
<td>Dartmouth College</td>
</tr>
</tbody>
</table>

EMPLOYMENT HISTORY

Post-Doctoral Research Associate
Department of Geosciences, University of Montana

- April 2013-
  Inter-disciplinary project focused on vegetation-morphodynamic linkages and feedbacks. Will plan and execute laboratory experiments and build 2D morphodynamic models.

Primary Instructor
Fluvial Geomorphology, Watershed Sciences Department, Utah State University

- Fall 2011 and 2012-
  Graduate level course that provided students with a survey of the field. Prepared and delivered all lectures, homework assignments, and exams.

Fluvial Geomorphologist
Inter-Fluve, Inc., Hood River, Oregon

- 2006-2008-
  Consultant for stream restoration and design consulting company focused on natural river design. Major duties included assisting with site visits and collection of field data, hydraulic model development, GIS analyses, and writing project reports.

RESEARCH EXPERIENCE

Department of Geosciences, University of Montana

- 2013-
  NSF-funded interdisciplinary project. Collaboration among geomorphologists, hydraulic engineers, and riparian ecologists. Identify feedbacks among plant morphology and fluvial processes that will inform us on the impact of different vegetation species/guilds on channel form and have environmental flow implications.

Watershed Sciences, Utah State University

- 2008-2013
  Project funded by the National Park Service. Documented the recent environmental history of the Yampa and middle Green Rivers in Dinosaur National Monument. Modeled the impact of water development on the Yampa River on in-channel habitat critical for endangered endemic fish.

Geography Department, University of North Carolina, Chapel Hill

- 2004-2006
  Used regulated river, and regular known releases, in the Adirondack Mountains, NY to measure hydraulic influence of wood jams. Project completed as part of my masters. Collaborated with other geomorphologists and ecologists as part of a larger NSF-funded project that strove to apply geomorphic concepts to ecology.
Geography Department, University of North Carolina, Chapel Hill  
2004-2005  
Research assistant on an urban stream monitoring project in Chapel Hill. Collected and prepared water quality samples from streams that ran through campus.

Geography Department, Dartmouth College  
2004  
Research assistant on an NIH-funded project on the environmental epidemiology of lung cancer. Gathered and organized relevant GIS layers into a database.

Geography Department, Dartmouth College  
2003-2004  
Mapped recent historical channel changes on the Rio Moquegua, Peru as part of my undergraduate honors thesis. Ground trothed observations and mapped and dated alluvial stratigraphy to help contextualize modern observations with the paleo record. Collaborated with archeologists on implications for cultural adjustments.

Geography Department, Dartmouth College  
2001-2003  
Research assistant. Analyzed hydrologic record of dam-impacted rivers across the United States.

TEACHING EXPERIENCE

Primary Instructor  
Fall 2011 and 2012  
Fluvial Geomorphology, Graduate Level  
Department of Watershed Sciences, Utah State University

Teaching Assistant  
Spring 2010  
Small Watershed Hydrology, Upper Level  
Watershed Sciences Department, Utah State University  
Responsible for teaching and grading laboratory exercises for 25 students.

Teaching Assistant  
Fall 2006 and 2007  
Physical Geography, Introductory Level  
University of North Carolina, Chapel Hill  
Responsible for assisting students and grading homework assignments and exams.

PEER-REVIEWED JOURNAL PUBLICATIONS


**BOOK CHAPTERS**


**GRAY LITERATURE PUBLICATIONS**


**SELECTED ORAL PRESENTATIONS**


**SELECTED POSTER PRESENTATIONS**


counts on geomorphology within the Colorado River Basin”, Binghamton Geomorphology
Symposium. October 2-4, 2009, Blacksburg, VA

Hydraulics” American Geophysical Union 2006 Fall Meeting, December 11-15, 2006, San
Francisco, CA.

woody debris (LWD) jams and its influence on local channel hydraulics.” Binghamton
Geomorphology Symposium, October 2005, Buffalo, NY.

Small, M.J. “Dominant Discharge Analysis of Ecological Processes in Streams.” American
Geophysical Union and North American Benthological Society Joint Meeting, May 2005, New
Orleans, LA.

AWARDS, HONORS, AND FELLOWSHIPS
S.J. & Jessie E. Quinney Ph.D. Fellowship, Utah State University, 2008-2012
Association of American Geographers- Reds Wolman Student Research Award, 2005 & 2012
Stirling Hydroecology Student Presentation Winner, ISWWR II, 2006
Magna Cum Laude, Dartmouth College, 2004
Presidential Scholar, Dartmouth College, 2004
George Perkins Marsh Thesis Award, Dartmouth College, 2004
Geography Department Honors Thesis Award, Dartmouth College, 2004

GRANTS
Colorado Plateau Cooperative Ecosystem Studies Unit, 2011-2013 ($13,500)
National Science Foundation Doctoral Dissertation Improvement Grant, 2010-2012 ($12,000)
USGS Southwest Biological Science Center, 2010-2011 ($34,655)
Geological Society of America Graduate Student Research Grant, 2005 ($1,500)
Dean of Faculty Undergraduate Research Grant, Funding for Thesis-Related Research, 2003
John Sloan Dickey Center for International Understanding Undergraduate Research Grant,
Funding for Thesis-Related Research, 2003
Rockefeller Center for Public Policy Grant, Off-Campus Internship with the Friends of the
Animas River and Ecosystem Management International, Durango, Co., 2002