DISSERTATION

CHANNEL DYNAMICS IN CANYON DE CHELLY NATIONAL MONUMENT, ARIZONA, WITH EMPHASIS ON THE EFFECT OF INVASIVE PLANTS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KRISTIN L. JAEGER ENTITLED CHANNEL DYNAMICS IN CANYON DE CHELLY NATIONAL MONUMENT, ARIZONA, WITH EMPHASIS ON THE EFFECT OF INVASIVE PLANTS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

CHANNEL DYNAMICS IN CANYON DE CHELLY NATIONAL MONUMENT, ARIZONA, WITH EMPHASIS ON THE EFFECT OF INVASIVE PLANTS

The purpose of this research was to evaluate the relative regional and local-scale influences on historic and contemporary channel change in Canyon de Chelly National Monument, Arizona, USA, with particular emphasis on the invasive, exotic plant species, tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*). The stream in Canyon de Chelly is characteristic of sand-bed channels in the arid/semi-arid southwestern US, which exhibit dramatic and complex channel morphology at timescales of decades to centuries. In the last 70 years, the channel has experienced substantial narrowing and incision that is apparently concurrent with widespread establishment of tamarisk and Russian olive.

To place this research within a broader context of regional trends in channel change, average rates of erosion (bank widening and bed incision) for stream channels in the southwestern US were statistically compared to southeastern US streams. Likely causes of historic and recent channel change in Canyon de Chelly were evaluated using a combination of a field-surveyed longitudinal profile of the stream channel in Canyon de Chelly, an existing analysis of channel change based on an aerial photograph record, and historical regional climate and land use information. Finally, channel response to the removal of tamarisk and Russian olive by two methods was quantified to determine which of the two methods was more effective at limiting bed incision and promoting bank widening. One method involved cutting the above-ground portion of the plant flush to the ground surface and applying an herbicide (cut-stump method). The second method involved removing the entire plant including the roots using heavy machinery (whole-plant method). The two plant removal methods were implemented at 4 study sites in Fall 2005. Annual surveys of change in cross sectional geometry and bed substrate were conducted until 2008, with additional surveys between individual monsoonal flows at one of the study sites. Channel adjustment was quantified over a 3-year field study period and a 6-year simulation period using the hydraulic model, CONCEPTS.

Systematic differences in erosion rates do not exist between the two regions, suggesting that inferences drawn from channel dynamics in southwestern US streams may be applicable in other regions despite differences in hydroclimatology, geology, and land use. Historic and current channel morphology in Canyon de Chelly reflects ongoing complex response to the combined effect of catchment and local-scale controls. Catchment-scale factors include fluctuations in water and sediment yield from climatic conditions and grazing activities beginning in the 1800s. Local-scale controls include variation in channel bed and bank properties and the presence of in-channel structures. Bed incision, at least in the lower portion of Canyon de Chelly, is likely at a near maximum under the existing hydrologic and sediment regimes. Incision will continue to propagate upstream, but will be limited by coarse bed material in the upper canyon reaches. In both the field study and modeling exercise, there were no statistically significant differences in channel response between stream reaches where exotic vegetation had been removed by the two methods and reaches where vegetation was left intact. Based on field observations, the whole-plant method provides the highest potential for channel widening when coupled with local conditions that facilitate large hydraulic erosive forces (e.g., meander bends). Any substantial geomorphic change in the stream channels will only occur with either the combined effect of severely weakened banks and repeated large flows that exceed several meters in flow depth and are of longer duration than the typical monsoon flow (< 24 hours), or a shift in the sediment regime that results in increased sediment delivery to the channel.

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1 INTRODUCTION

1.1 INTRODUCTION

This dissertation examines channel dynamics in Canyon de Chelly National Monument, in northeastern Arizona, United States in the context of historical (10^1-10^2 yr) changes and contemporary management. The stream channels in Canyon de Chelly, like other sand-bed channels in the arid and semi-arid southwestern US, are extremely dynamic at timescales of decades to centuries, exhibiting dramatic vertical instability and changes in width that can exceed an order of magnitude. This dynamic behavior inherent to fluvial systems in the Colorado Plateau presents unique management challenges for natural resource agencies such as the United States National Park Service (NPS), which manages Canyon de Chelly. Among these challenge are understanding the relative and confounding influences of variable regional hydroclimatology, streamflow regulation, land use changes, and the invasion of exotic riparian species on channel dynamics. All of these factors presumably play a role in the substantial channel changes observed in Canyon de Chelly during the past century, specifically the morphologic shift from wide (200 m), shallow, and braided to narrow (10 m), meandering channels with incision in some portions that exceeds 8 m. As part of a national effort to control invasive plants, however, NPS has chosen to most directly manage the exotic riparian species, tamarisk (*Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro, and their hybrids) and Russian olive (*Elaeagnus angustifolia* L.), within Canyon de Chelly in terms of their influence on current and future geomorphic and ecological processes. The research presented here evaluates all of the potential influences on channel change, with particular emphasis on the exotic riparian species tamarisk and Russian olive.

This introductory chapter provides a brief overview of channel processes in the southwestern US and the influences of exotic riparian vegetation on those processes. In addition, the chapter identifies research objectives for the project and provides an outline of the following chapters that encompass this body of research.

1.2 CONTROLS ON FLUVIAL GEOMORPHIC PROCESSES IN THE ARID AND SEMI-ARID SOUTHWESTERN UNITED STATES

The channel morphology of sand bedded streams is highly dynamic in the arid and semi-arid southwestern US. Perennial channels undergo repeated cycles of widening and narrowing (Osterkamp and Costa, 1987; Schumm and Lichty, 1963; Burkham, 1972; Katz et al., 2005). Ephemeral channels are characterized by episodes of alternating incision and aggradation/widening (Schumm and Hadley, 1957; Leopold, 1976; Patton and Schumm, 1981; Graf, 1983; Elliott et al., 1999). A variable climatic regime drives much of the dynamic character of these fluvial systems, exerting controls on sediment and discharge regimes at multiple spatial scales that extend from catchment-wide to local channel conditions. Arid and semi-arid fluvial systems are characterized by high interannual variability in peak flows, large variation between base flow and peak flow, and an extended persistence of channel change from low frequency, large magnitude flows relative to other climate regions in the US (Wolman and Gerson, 1978; Tooth, 2000).

In addition to hydroclimatology, land use activities over the last two centuries since Anglo-European settlement in the southwestern US have had a substantial impact on fluvial geomorphic processes. Intensive grazing beginning in the 18th century and extending into the first part of the 20th century increased soil erosion rates and altered catchment-wide sediment and hydrologic regimes (Hadley, 1977; Brotherson et al., 1983;

Belnap, 1995; Davenport et al., 1998; Milchunas, 2006; Wilcox et al., 2008). Streamflow regulation through the construction of dams and diversions has reduced peak discharge magnitudes, elevated baseflow conditions, and altered timing of discharge flows (Graf, 1999). Removal of much of the hydrologic variability in the natural flow regime that facilitates dynamic shifts in morphology has had a subsequent effect on channel form and process (Collier et al., 1997, Graf, 1999). In addition, the presence of riparian vegetation, including exotic tamarisk and Russian olive, affects floodplain and channel hydraulic and sediment regimes, which in turn influence channel form and processes (Allred and Schmidt, 1999; Merritt and Cooper, 2000; Tal et al., 2003; Birken and Cooper, 2006). For example, in-channel bar accretion and channel narrowing have been attributed to the presence of tamarisk along portions of the Green River in Utah, US (Allred and Schmidt, 1999; Birken and Cooper, 2006).

Extensive research exists on the relative roles of these confounding factors of climate and land use activities on channel processes, particularly in ephemeral channels, which comprise a large portion of the region's channel network. Ephemeral stream channels have been characterized throughout the Holocene by the arroyo cycle, in which channels repeatedly incise, widen, aggrade, and re-incise (Schumm and Hadley, 1957; Leopold, 1976; Patton and Schumm, 1981; Graf, 1983; Elliott et al., 1999). Debates as to the cause of the transitions between incising and aggrading systems have centered on external drivers of climate change and/or land use impacts (Schumm, 1973; Cooke and Reeves, 1976; Hereford, 1984; Graf, 1987; Graf et al., 1991; Hereford et al., 1996; Allred and Schmidt, 1999; Hereford, 2002; Gellis et al., 2004) and internal drivers or intrinsic thresholds within the fluvial system that trigger channel change (Schumm and Hadley, 1957; Schumm, 1973; Womack and Schumm, 1977; Patton and Schumm, 1981; Patton and Boison, 1986; Phippen and Wohl, 2003). Although there is general consensus that the specific factors that initiate and maintain an incision cycle are a combination of external and internal drivers, the dominance of one particular factor over another is site-specific.

Regardless of the initial cause of incision, channels in the arid and semi-arid southwestern US consistently exhibit a complex response in which incision propagates upstream as a migrating knickpoint (Schumm and Parker, 1973). Progression of this knickpoint increases sediment yield to downstream portions of the channel, which begin to aggrade even while incision continues upstream. When the knickpoint eventually ceases in headward migration, sediment supply to downstream channel segments decreases, and these channel segments begin to incise again. A given portion of the channel network can undergo several episodes of alternating incision and aggradation before stabilizing. These episodes are asynchronous throughout the channel network and can persist for decades or longer (Womack and Schumm, 1977).

1.3 IMPLICATIONS OF EXOTIC PLANT ESTABLISHMENT IN THE SOUTHWESTERN US

Within the broader context of anthropogenic activities affecting fluvial systems, the exotic plant species tamarisk and Russian olive have become extensive throughout riparian areas of the arid and semi-arid southwestern US (Gaskin and Schaal, 2002; Glenn and Nagler, 2005). Exotic invasive riparian plant species are considered an external factor that exerts a strong influence on channel erosion processes, and consequently the arroyo cycle. Riparian vegetation can increase resistance to bank erosion, promote floodplain accretion, decrease channel width, and change channel morphology from braided to meandering (Graf, 1978; Allred and Schmidt, 1999; Millar, 2000; Simon and Collison, 2002; Merritt and Wohl, 2003; Tal et al., 2003; Wynn and Mostaghimi, 2006).

After initial introduction into the western US, both plant species have become prolific through natural dispersal (Robinson, 1965; Katz and Shafroth, 2003). Flow regulation throughout the region has provided conditions that foster the spread of both plants, specifically the elimination of high flows and the presence of stable low flows that inhibit native species colonization and favor the more drought-tolerant exotic species (Sher et al., 2002; Stromberg et al., 2007). Coincident with plant invasion is geomorphic change to river and stream channels; vegetated banks have increased resistance to erosion, allowing for channel narrowing, bed incision, and/or floodplain accretion (Graf, 1978; Allred and Schmidt, 1999; Birken and Cooper, 2006). Subsequent alterations in ecological functions of riparian areas have ensued, including diminished native vegetation establishment, increased soil salinity, and modified native wildlife habitat and assemblages (Zavaleta, 2000; Tickner et al., 2001; Shafroth et al., 2005).

The United States Department of the Interior has identified addressing the negative effects of invasive plant species on ecosystems as an agency priority (Executive Order 13112), and substantial funds at multiple government levels are annually spent specifically on tamarisk control efforts in riparian ecosystems (US House of Representatives 2720 and US Senate 177: Saltcedar [Tamarisk] and Russian-olive control and demonstration act, http://www.govtrack.us/congress/bill.xpd?bill ¼ h109-2720). Research related to exotic woody riparian vegetation removal has emphasized recovery of ecological functions and water salvage (Culler et al., 1982; Welder, 1988; Harms and Hiebert, 2006); however, little is known about the geomorphic adjustment following plant removal. As land managers are increasingly interested in rehabilitating stream channels in arid and semi-arid regions through control of exotic plants, there is an inherent need to understand which plant removal methods are the most appropriate for recovery of stream channel morphologic functions, which in turn influence ecological functions. It is particularly important to consider effective plant removal methods within the context of the broader-scale factors such as the hydroclimatology and land use history that can confound channel response to plant removal.

In coordination with the US Department of Interior's priority to control invasive plants, NPS wishes to determine the most effective plant removal method for recovery of geomorphic and ecological functions along fluvial systems in the southwestern US. Canyon de Chelly National Monument was targeted for an in-depth study to characterize and identify causes of historic and the more recent channel change of narrowing and incision, which appears to have coincided with extensive establishment of tamarisk and Russian olive. In addition, a pilot project was implemented in Canyon de Chelly that evaluates geomorphic and ecological response to two exotic plant removal methods. One method includes cutting the above-ground portion of the plant flush to the ground surface and applying an herbicide (cut-stump method). The second method involves removing the entire plant including the roots using heavy machinery (whole-plant method).

1.4 RESEARCH OBJECTIVES

The research objectives of this dissertation are:

1) Evaluate relative importance of local, regional, and intrinsic controls, including climate, land use activities, specifically grazing, and the introduction of tamarisk

and Russian olive on historic and recent channel change in Canyon de Chelly National Monument.

2) Quantify morphologic channel response to tamarisk and Russian olive removal in Canyon de Chelly National Monument in order to determine appropriate removal methods that promote bank widening and limit bed incision.

In addition, this dissertation includes a comparison of channel erosion rates between the southwestern and southeastern US to provide an overview of erosion within an inter-regional context. As already indicated, substantial research exists on erosion and the dynamic morphology of stream channels in the southwestern US. It would appear that because of the inherently dynamic behavior, erosion rates would be distinctly higher in southwestern US streams relative to other regions. For example, the Rio Puerco River, an ephemeral tributary to the Rio Grande River in New Mexico, is ranked fourth among world rivers in highest average annual suspended-sediment concentration (Gellis et al., 2004). An understanding of magnitudes and rates of erosion within the southwest region, as well as other regions of the US, can provide perspective on the observed erosion within the contemporary channels in Canyon de Chelly National Monument. In particular, this type of analysis will help determine how channel erosion within the national monument compares to stream channels within the US as well as identify whether the observed erosion is within the range of regional variability. This dissertation builds on existing graduate research that quantified both historic channel change (the past 70 years), in terms of active channel width, and riparian vegetation establishment (Cadol, 2007). Evaluation of ecological response to exotic plant removal is included in other doctoral research (Lindsay Reynolds, PhD Candidate, CSU). The research presented in this dissertation on channel adjustment to exotic plant removal within the context of historic basin-scale watershed conditions will expand our understanding of the influence of riparian vegetation on channel dynamics and be used to guide management choices that invest in erosion-control measures through management of invasive plants within a given site.

1.5 ORGANIZATION OF THE DISSERTATION

The dissertation is divided into three separate studies and sequentially organized by decreasing spatial scale. The first study is a statistical comparison of average bed incision, bank widening, and knickpoint retreat rates to determine whether regional differences in erosion rates exist between the southwestern and southeastern US (Chapter 2). The analysis uses case studies reported in the peer-reviewed literature and includes a discussion of the hydraulic driving and substrate resisting forces that govern channel change and regional differences in those forces. The second study focuses on the southern Colorado Plateau in general and the Canyon de Chelly basin specifically (Chapter 3). In this study, the longitudinal profiles of the stream channel in Canyon de Chelly National Monument and of the larger basin to which Canyon de Chelly is tributary, Chinle Wash, are evaluated to determine longitudinal patterns of channel adjustment. I reconstruct the historic watershed conditions, in terms of climate and land use, that could explain channel changes in the late twentieth century and the most recent channel change of incision in de Chelly. Channel change observed in Canyon de Chelly is also compared to what has been documented within the Colorado Plateau. The third study quantifies channel adjustment to exotic plant removal by cut-stump and whole-plant methods (Chapter 4). Short-term (three-year) channel response is evaluated from repeat cross section elevation surveys and longitudinal profiles of the channel thalweg. Longer term (six years) channel response is simulated using CONCEPTS (CONservational Channel Evolution and Pollutant Transport System), a hydraulic model developed by the United States Department of Agriculture (Langendoen and Alonso, 2008; Langendoen and Simon, 2008).

The specific study sites, methodology, results, and discussion for each study are presented in separate chapters. Each of the three separate studies is presented in a stand-alone chapter that includes introduction, literature review, description of study area and methods, and presentation and interpretation of data. The study area and methods have been modified to limit repetition between chapters. Each of these chapters has been or will be submitted to a peer-reviewed journal. The dissertation concludes with a final chapter (Chapter 5) that summarizes the most significant findings and provides management and future research recommendations.

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2 A COMPARISON OF AVERAGE RATES OF ALLUVIAL EROSION BETWEEN THE SOUTHWESTERN AND SOUTHEASTERN UNITED STATES

2.1 INTRODUCTION

Numerous studies have documented rapid alluvial channel incision within the past century in both the southwestern and southeastern US (e.g., Schumm and Hadley, 1957; Patton and Schumm, 1981; Murphey and Grissinger, 1985; Hereford, 1986; Simon and Thomas, 2002) (Figure 2.1).

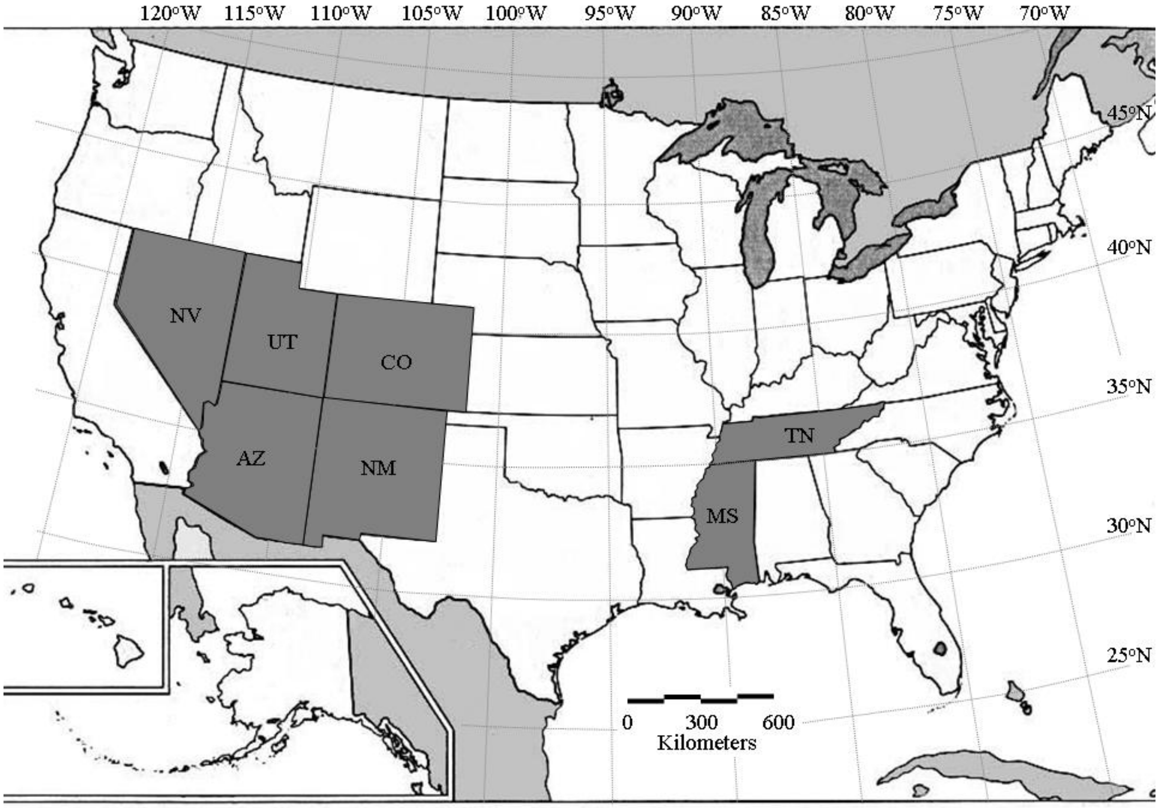

Figure 2.1 The regions designated in this study as the southwestern and southeastern United States are shaded.

Paleochannels and alluvial stratigraphy in the southwestern US indicate that channel networks in the region have undergone repeated cycles of incision and alluviation during the Quaternary (Graf, 1988; Love, 1997). Investigations of potential external drivers of channel change have emphasized either climatic variation (e.g., Balling and Wells, 1990) or changes in land use (e.g., Cooke and Reeves, 1976; Bocco, 1991), whereas other studies of incised channel dynamics in the region have emphasized the role of internal thresholds in driving channel change (e.g., Schumm and Hadley, 1957; Patton and Boison, 1986). The southwestern US is predominantly arid and semiarid, with annual precipitation less than 38 cm and many ephemeral channels. The southeastern US is a humid temperate region that receives annual precipitation in excess of 125 cm. Studies of incised channel dynamics in this region are more likely to focus on historical channel changes associated with either upland clearing and agriculture during the 19th and 20th centuries (Grissinger and Murphey, 1983), or dropping base level and altered channel configuration caused by channelization during the 20th century (Simon and Hupp, 1992).

In addition to exploring the fundamental causes of channel incision, the rapidity with which substantial changes in channel morphology have occurred in the two regions has presented a challenge for geomorphologists attempting to explain how fluctuations in potential control variables interact to cause changes in channel form and process. Because the southwestern and southeastern US differ in mechanisms of precipitation and runoff generation (Webb and Bentancourt, 1990; Graf et al., 1991; Ely et al., 1993; Perry et al., 2001), stream flow regime (Graf et al., 1991; Perry et al., 2001; Poff et al., 2006), geology and soils (Dohrenwend, 1987; Graf et al., 1987; Mickelson, 1987; Mills et al., 1987; Walker and Coleman, 1987), riparian vegetation (Hupp, 1992; Shafroth et al., 2000; Stromberg et al., 2007), and land use history (Hadley, 1977; Hupp, 1992; Simon and Thomas, 2002), a comparison of the rate of erosion across regions can be used to explore the relative importance of variables influencing hydraulic driving forces and substrate resistance.

In this chapter I first present an overview of the factors that can influence alluvial channel adjustment and how these factors might be expected to differ between the southwestern and southeastern US. I then examine whether consistent regional differences exist in rate of channel adjustment, which has been alluded to by previous authors (Wolman and Gerson, 1978; Baker, 1977; Osterkamp and Friedman, 2000), but not quantitatively compared. Specifically, I test the hypothesis that the southwestern United States has higher rates of alluvial incision, widening, and knickpoint retreat relative to the southeastern United States, using site-specific data compiled from the existing literature. Finally, I examine potential regional differences in flood magnitude from study sites reported in the published literature, reasoning that erosion rates are higher in the southwestern US as a result of greater hydraulic driving forces relative to substrate resistance. I was not able to quantitatively compare substrate resistance between individual sites included in our dataset because of the absence of site-specific data on channel substrate and riparian vegetation in the published literature. Nevertheless, this investigation provides a starting point to examine potential mechanistic differences in driving and resisting forces between two regions with distinctly different hydroclimatology and physical channel characteristics.

2.2 VARIABLES THAT INFLUENCE ALLUVIAL CHANNEL EROSION

Channel form at any point in time and space reflects ongoing adjustment between hydraulic driving forces and substrate resistance. Hydraulic forces reflect, first, the processes by which water enters the channel. Mechanisms of precipitation generation, infiltration, surface runoff and subsurface flow govern the timing and volume of water reaching the stream, which can be expressed via the magnitude, frequency, and duration of stream flow. Magnitude, frequency, and duration of flow determine energy available to do geomorphic work in the channel (Wolman and Miller, 1960; Costa and O'Connor, 1995). Total stream power is often used as a metric for comparing available energy because it is more easily calculated than stream power per unit area (Bathurst, 1985; Magilligan, 1992; Costa and O'Connor, 1995).

Available energy can be expended against external and internal resistance, and in deforming the channel boundaries and transporting sediment. Substrate resistance influences how available energy is actually expended. Substrate resistance results from interactions between sediment supply (volume, size distribution) and channel geometry (bed gradient, width/depth ratio, bedforms, bank and bed irregularities such as wood and sediment size distribution, and sinuosity) (Julien, 1998; Knighton, 1998). There is no single quantitative measure of substrate resistance that is commonly used for comparisons among channels. Instead, different studies use grain-size characteristics of the stream bed (Wohl, 2004), intact strength of cohesive materials (Wohl and Merritt, 2001), or geotechnical characterizations of bank sediment (Simon et al., 1999). In addition, the presence of riparian vegetation (stem density and root depth and density) can greatly influence bank resistance to erosion (Thorne, 1990; Millar, 2000; Pollen and Simon, 2005; Wynn and Mostaghimi, 2006).

2.2.1 Regional controls on hydraulic forces

Precipitation in the southwestern United States occurs primarily as winter snowfall at higher elevations, summer convective storms associated with monsoonal circulation, winter frontal storms, and dissipating tropical cyclones (Webb and Betancourt, 1990; Ely et al., 1993). The high intensity rainfall associated with convective storms is especially likely to result in large volumes of infiltration-excess overland flow (Tucker et al., 2006). The relative importance of different mechanisms of precipitation generation varies with geographic coordinates, elevation, and drainage area, but both smaller ephemeral and larger perennial channels in the region are characterized by large interannual variability in peak flows, large variations between base flow and peak flow, and infrequent, short duration peak flows (Webb and Betancourt, 1990; Tooth, 2000).

Tropical air masses bringing moisture inland from the Gulf of Mexico provide the principal source of rainfall for much of the southeastern United States (Paulson et al., 1991; Perry et al., 2001). Convective storms produce locally intense rainfall during the summer months; hurricanes and tropical storms can bring moisture from mid-summer to late autumn; and frontal systems that persist for several days create rainfall during late autumn to late spring. The frontal systems occur when cooler, drier air masses from the north collide with tropical maritime air masses from the Gulf or the Atlantic Ocean. Floods associated with rainfall from stalled frontal systems during the winter and spring months are of longer duration and wider extent. Floods from severe thunderstorms associated with cold fronts or squall lines can occur during any month and are more localized and short in duration. Rainfall associated with tropical storms is less frequent, but can produce widespread flooding. As in the southwestern US, the relative importance of different mechanisms of precipitation generation varies across the region and with site-specific characteristics, but streams generally have less interannual variability in peak flows, less variation between base flow and peak flow, and more frequent, longer duration peak flows relative to streams in the southwestern US (Paulson et al., 1991; Perry et al., 2001).

2.2.2 Regional controls on substrate resistance

Substrate resistance integrates numerous variables that influence the ability of stream flow to deform the channel boundaries. The size distribution of sediment in the channel bed and banks (Wolman and Brush, 1961), cohesion between individual grains, the presence of secondary cement, and the roots and above-ground portion of plants all interact to determine substrate resistance (Simon and Collison, 2002). Variables such as substrate grain-size distribution (Anderson et al., 2004) and spatial density and rooting depths of riparian plants are useful metrics for comparing substrate resistance between alluvial channels (Wynn et al. 2004).

Cobble-boulder bed channels are certainly present in the southwestern United States, but many of the arroyos present in the region are incised into fine gravel, sand, silt, and clay (Graf et al., 1991; Gellis et al., 2005). Cohesion of bed and bank sediments, if present, comes primarily from secondary calcium carbonate cement, although higher silt and clay contents can increase cohesion. Native riparian species include palo verde

(*Parkinsonia florida* S. Watson, *Parkinsonia microphylla* Torr.), mesquite (*Prosopis glandulosa* Torr., *Prosopis pubescens* Benth.), cottonwood (*Populus fremontii* S. Watson), and willow (*Salix* spp.), which do not commonly form dense or wide groves along channels (Graf, 1978; Birkeland, 1996; Birken and Cooper, 2006). Invasive exotic species including tamarisk (*Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro, and their hybrids) and Russian olive (*Elaeagnus angustifolia* L.) are also widespread, and are more likely to form dense and wide bands of vegetation. Roots of both native and exotic riparian woody plants commonly extend to depths of 2 m or greater either as a result of plant burial (Friedman et al., 2005; Birken and Cooper, 2006) or natural root growth (Simon et al., 2007).

Channels in the southeastern United States are likely to be formed in fine-grained sediments that vary from highly cohesive clay through moderately cohesive loess to non-cohesive sand and fine gravel (Murphey and Grissinger, 1985; Simon and Hupp, 1992; Simon et al., 2002). Riparian trees common in the southeastern United States include sycamore (*Platanus occidentalis* L.), river birch (*Betula nigra* L.), sweetgum (*Liquidambar styraciflua* L.), black willow (*Salix nigra* Marsh.), silver maple (*Acer saccharinum* L.), boxelder (*Acer negundo* L.), and green ash (*Fraxinus pennsylvanicus* Marsh.). Riparian vegetation, whether woody or herbaceous, is often dense. Roots of woody riparian plants commonly do not extend below 90 cm depth (Simon and Collison, 2002).

2.2.3 Regional channel characteristics

The regionally generalized patterns of precipitation, stream flow, sediment sizes in the stream bed and banks, and riparian vegetation, interact to produce some relatively consistent differences in channel pattern and dynamics between the southeastern and southwestern United States. Channels in the southwestern US are likely to be broad, shallow, braided systems or deeply incised arroyos with limited riparian vegetation and instream wood. Most channels are of low sinuosity (Graf, 1988; Tooth, 2000). Numerous investigators have documented rapid changes in channel morphology across time and space. It is not uncommon, for example, for channel morphology to alternate downstream between incised segments and broad, shallow, braided reaches (Schumm and Hadley, 1957; Tucker et al., 2006). Incised channels can also fill with sediment, or shallow channels can incise several meters, in a few decades or less (Malde and Scott, 1977; Graf, 1987a; Webb et al., 1991). Studies of alluvial stratigraphy in the southwestern US indicate that these alternating episodes of channel cut-and-fill have occurred throughout the Quaternary (Patton and Schumm, 1981; Hereford et al., 1996), and the idea of complex response was developed to describe this channel behavior in arid and semiarid systems (Schumm and Parker, 1973; Schumm, 1974).

Many channels in the southeastern US historically had unincised, swale-shaped cross sectional geometry, a sinuous planform, dense riparian vegetation and large amounts of instream wood (Grissinger and Murphey, 1983; Hupp, 1992). Land-use practices including upland deforestation and cropping, and widespread channelization during the past few decades, have caused numerous channels to incise and develop deep, narrow cross sections with steep banks, straight planforms, and higher gradients (Hupp and Simon, 1991; Thorne, 1999; Simon and Darby, 2002). Channel response to the nearly instantaneous base level change caused by channelization has been particularly rapid and dramatic (Hupp, 1992; Simon, 1994).

2.3 HYPOTHESIZED REGIONAL DIFFERENCES

Osterkamp and Friedman (2000) allude to potential differences in rate and magnitude of channel adjustment between different regions of the United States based on the combined effect of regional differences in rainfall-runoff patterns that control hydraulic driving forces and resisting forces in the channel (e.g., alluvial substrate and riparian vegetation). Specifically, despite higher extreme and mean precipitation amounts in other regions of the United States, the Southwest, in general, is subject to more extreme floods in terms of geomorphic change in part because of higher runoff potential and in part because of reduced channel resistance resulting from a lack of stiff bottomland vegetation and unconsolidated, non-cohesive alluvial sediments (Osterkamp and Friedman, 2000). This argument, coupled with the broad regional characteristics described above, gives rise to the question of whether there are general regional differences in rates and magnitude of channel erosion, in terms of bed incision, bank widening, and knickpoint retreat as a result of larger hydraulic driving forces and smaller substrate resistance.

I test the hypothesis that streams in the southwestern United States have higher average rates of bed incision, bank erosion, and knickpoint retreat compared to streams in the southeastern United States using data compiled from numerous case studies from both regions. Channel change in the Southeast may by dominated by small magnitude, frequent flows. Channel change in the Southwest occurs episodically, with substantial change that persists over decades triggered by large magnitude, infrequent flows (Wolman and Gerson, 1978). I averaged erosion rates over several years to decades in order to determine whether broad regional trends exist over time scales longer than a single flood.

The method of comparing average erosion rates between different studies is not without flaws. There exists a variety of factors that have no connection with the driving and resisting forces governing erosion but nevertheless influence calculated average erosion rates. For example, calculated erosion rates will be affected by the particular measuring technique employed; each technique has an associated timescale for which inference about the calculated erosion rate is appropriate as well as an associated variability in accuracy of that measurement (Lawler, 1993). The timing of the sampling period also will control the calculated erosion rate (Lawler, 1993; Saynor and Erskine, 2006). Erosion rates are not consistent from year to year but will vary according to the climatic conditions of an individual year. Because low frequency, large magnitude flows dominate erosion processes, particularly in semi-arid systems, long term erosion rates should be calculated using records that include the range of variability in the flow regime (Olive and Reiger, 1986). However, the difficulty and expense in conducting detailed long term studies remains a major limiting factor. Some channels in a quasi-equilibrium state exhibit dynamic vertical fluctuations around a bed elevation over a period of years (Kesel and Yodis, 1992). In these cases, the overall erosion rate may be zero; however, a shorter sampling time within that period of vertical fluctuation could result in a substantially different calculated erosion rate. In addition, the sampling time with respect to the timing of a disturbance exerted on the channel will affect the calculated erosion rate. Channel adjustment to a disturbance is non-linear with time such that the rate of the channel adjustment (e.g., bed incision or bank widening) decreases with increasing time since the disturbance (Simon, 1989; Kesel and Yodis, 1992; Simon and Rinaldi, 2006). Erosion rates are also a function of drainage area; specifically, higher erosion rates have been reported in headwater streams relative to lower in the channel network where drainage area is larger (Olive and Reiger, 1986; Parker, 1995).

Under ideal circumstances, erosion rate comparison between the two regions would be partitioned by drainage area, channel substrate and vegetation properties, erosion rate measurement technique, and study time period, including time since disturbance. However, the relatively small sample size of reported erosion rates included in this study does not allow for detailed partitioning. With the understanding of these complicating influences on calculated erosion rates that have little to do with regional differences in driving and resisting forces, the purpose of this study was to determine whether regional differences in erosion rates exist that dominate over these other influences. However, drainage area was an effect that could be accounted for in the analysis. Comparison of erosion rates were between the raw reported values, and were also normalized by drainage area to reflect average annual rate of erosion/km^2.

2.4 METHODS

2.4.1 Comparison of bed incision, bank erosion, and knickpoint retreat rates

I conducted a review of peer-reviewed literature for case studies from which rates of incision, bank widening, and knickpoint retreat rates can be calculated. Values were averaged for sites where more than one study documented erosion rates for the same drainage, as were erosion rates reported at different cross sections in relatively close proximity in the same drainage basin. A region was partitioned by state if distinct differences existed in reported erosion rates between states. Differences in incision, bank widening, and knickpoint rates between the regions or states were determined through the non-parametric Wilcoxon Rank Sum and Kruskal-Wallis tests for significant differences ($\alpha = 0.05$) in medians because the data did not conform to the assumptions of an ANOVA (PROC NPAR1WAY WILCOXON: SAS Institute 2004). Pairwise tests to identify individual groups were performed using Kruskal-Wallis tests. To avoid a type I statistical error, significance level was adjusted using a Bonferroni correction, in which the desired significance level (e.g., p value < 0.05) is divided by the number of comparisons being made. In this case, three comparisons were made, therefore a p value less than or equal to 0.0167 is considered a statistically significant difference.

In addition, incision, bank widening, and knickpoint rates were normalized by drainage area and differences between these normalized rates were determined using the same statistical methods. Both measures of erosion rates (non-normalized erosion and erosion normalized by drainage area) are useful metrics. Channel size (e.g., average width and depth) for a given drainage area will vary regionally (Faustini et al., 2009), therefore comparison of similarly sized channels using non-normalized erosion rates provides insight into channel process that is not possible when the rate is divided by drainage area. The normalized erosion rates, however, provide a metric of erosion that accounts for the scale of the catchment. These metrics are particularly useful when evaluating the relative efficiency in sediment transport processes of different portions of the catchment (e.g., hillslope, headwaters, main channel system) (Olive and Reiger, 1986).

2.4.2 Comparison of hydraulic driving forces

In the absence of discharge records at most sites, I used regional regression equations for flows of specified return intervals to evaluate inter- and intra-regional differences in discharge per unit drainage area as a measure of hydraulic driving forces. These equations are generally developed on a statewide basis by partitioning the state into hydrologic regions (Landers and Wilson, 1991; Thomas et al., 1997; Vaill, 1999; Law and Tasker, 2000). The equations typically include only drainage area for flood magnitude estimation, but elevation, evaporation rates, and general basin shape can be included. Discharge magnitudes of known recurrence intervals were plotted against drainage area and fitted using linear regression. Significant differences ($\alpha = 0.05$) between model slopes, intercepts, and the combined effect of slope and intercept for each region were statistically identified using a general linear model (Proc GLM: SAS Institute 2004). To avoid a type I statistical error in pairwise comparisons, significance level was adjusted using a Bonferroni correction.

2.5 RESULTS

2.5.1 Comparison of bed incision, bank erosion, and knickpoint retreat rates

The literature review found 19 incised stream sites in the southwestern US and 39 in the southeastern US for which rates of channel change can be calculated either in terms of bed incision, bank erosion, or knickpoint migration (Appendix A). Case studies from Arizona, New Mexico, Utah, and Colorado represent the southwestern US. Data from Tennessee and Mississippi represent the southeastern US. Knickpoint retreat rates for the southeastern US include only sites from Mississippi. Both the southeastern and southwestern US include different physiographic provinces (Graf, 1987b) and I expect that substantial variability exists in all of the parameters influencing hydraulic driving force and substrate resistance within each region. The intent, however, is to examine whether broad differences exist between the two regions that exceed intra-regional variability. All of the streams in the southeastern US are perennial, whereas most of the southwestern streams are ephemeral with the exception of the mainstem channels of some of the larger basins (e.g., San Pedro River, Santa Cruz River, Gila River, and East Fork of the Virgin River). Most of the studies extended over a period of one to several decades, with the average study period of 20 years for southeastern US streams and 34 years for southwestern US streams.

Before comparisons of erosion rates were made on a regional scale, summary statistics were calculated on published rates for bed incision and bank erosion stratified by state (Table 2.1). Bed incision and erosion rates are distinctly higher in Tennessee streams compared to Mississippi and any of the southwestern states (Figure 2.2 and

Figure 2.3). Therefore, rates for Tennessee and Mississippi were analyzed individually. Neither incision, bank erosion, nor knickpoint migration rates between southwestern streams appear distinct enough to merit stratifying the analysis by state.

Median incision and widening rates are not statistically significantly different between Tennessee, Mississippi, and southwestern US streams. Median incision rates, however, are more similar between Mississippi and southwestern US streams compared to Tennessee (Figure 2.2). The inclusion of a reported channel widening of 448 m on the middle Gila River, Arizona from a single flow drives the absence of a statistical difference between the three groups. When this widening rate is excluded from the analysis, Tennessee has significantly higher bank widening rates compared to southwestern US streams ($p = 0.0132$). No rates of knickpoint retreat were reported for Tennessee streams, but Mississippi is not statistically different from the southwestern region (Figure 2.4; $p=0.1322$).

The range in drainage area for which there are reported erosion rates is large. Southeastern US streams range in drainage area from less than 10 km^2 to more than 2000 km^2. The range of drainage areas in the southwestern US is substantially larger, where drainage area exceeds 10,000 km^2 and more than 40,000 km^2 in one case. When comparing erosion rates normalized by drainage area, bed incision and bank erosion rates per square kilometer are extremely low in southwestern streams and consequently are significantly lower than both Tennessee and Mississippi streams ($p = 0.0018$ and $p =$

Table 2.1 Mean, median, and associated standard deviation for bed incision, bank erosion, and knickpoint migration rates stratified by state and for grouped southwestern (SW) US streams. Units are in meters/year (m/y).

	Tennessee	**Mississippi**	**Arizona**	**New Mexico**	**Utah**	**Colorado**	**SW US**
Number of case studies	6	10	6	7	1	1	15
Mean Incision (m/y)	0.34	0.11	0.19	0.15	0.23	0.11	0.17
Median Incision (m/y)	0.31	0.13	0.15	0.09	0.23	0.11	0.12
Standard Deviation	0.13	0.05	0.13	0.19	NA	NA	0.15
Number of case studies	11	4	3	5	0	1	9
Mean Widening (m/y)	11.38	1.97	10.49	1.47	NA	1.83	5.89
Median Widening (m/y)	10.30	0.60	1.17	0.30	NA	1.83	0.74
Standard Deviation	10.05	2.82	16.48	1.79	NA	NA	11.67
Number of case studies	0	10	3	3	0	0	6
Mean Knickpoint Migration (m/y)	NA	1.54	0.82	1.10	NA	NA	0.96
Median Knickpoint Migration (m/y)	NA	0.83	0.48	0.78	NA	NA	0.74
Standard Deviation	NA	1.72	0.89	0.64	NA	NA	0.71

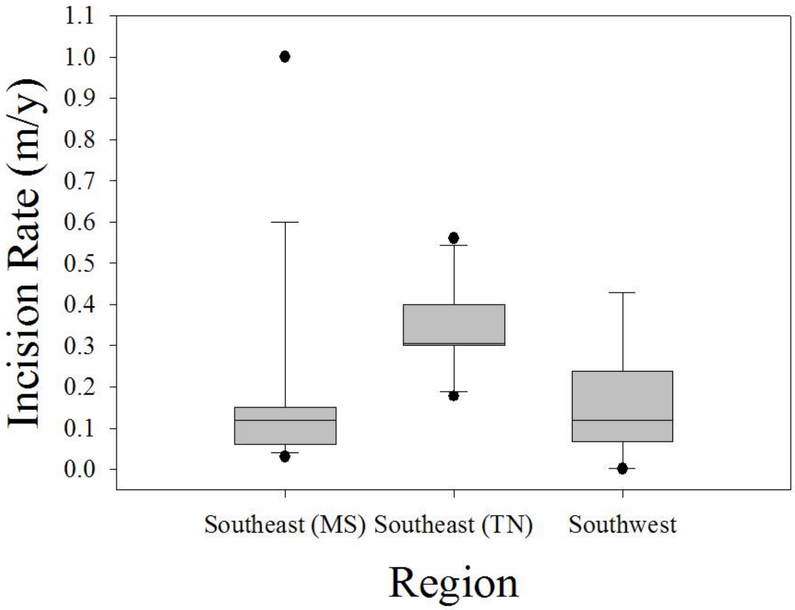

Figure 2.2 Incision rates for Mississippi (n = 10, median = 0.12 m/y), Tennessee (n = 6, median = 0.31 m/y) and southwestern US streams (n = 15, median = 0.12 m/y).

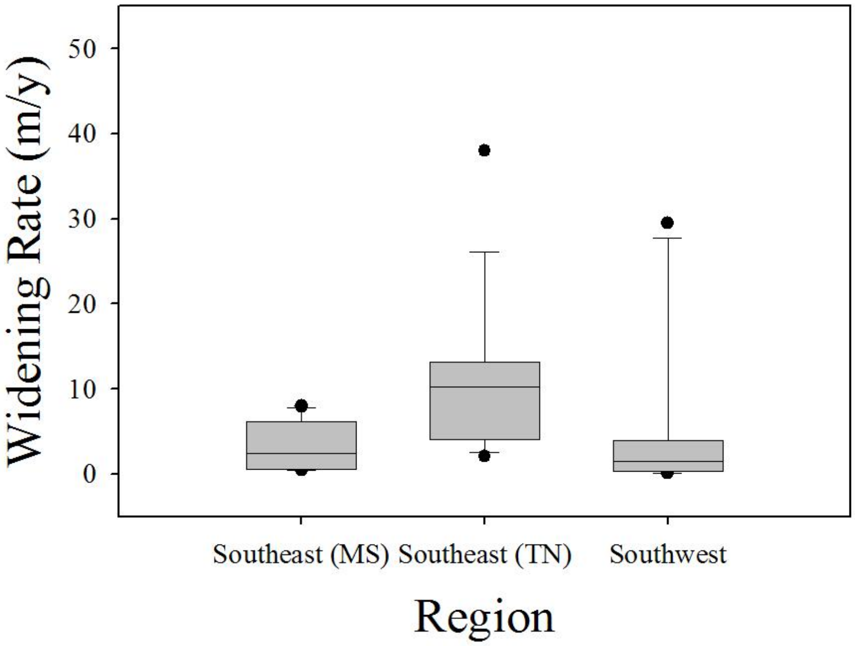

Figure 2.3 Bank widening rates for Mississippi (n = 6, median = 2.46 m/y), Tennessee (n = 11, median = 10.3 m/y), and southwestern US streams (n = 10, median = 96.3 m/y). The Middle Gila River, AZ widening rate (448 m/y) is not shown, but is included in the comparison of median analysis. Median widening rate for southwestern US streams when Middle Gila River is excluded is 8.3 m/y.

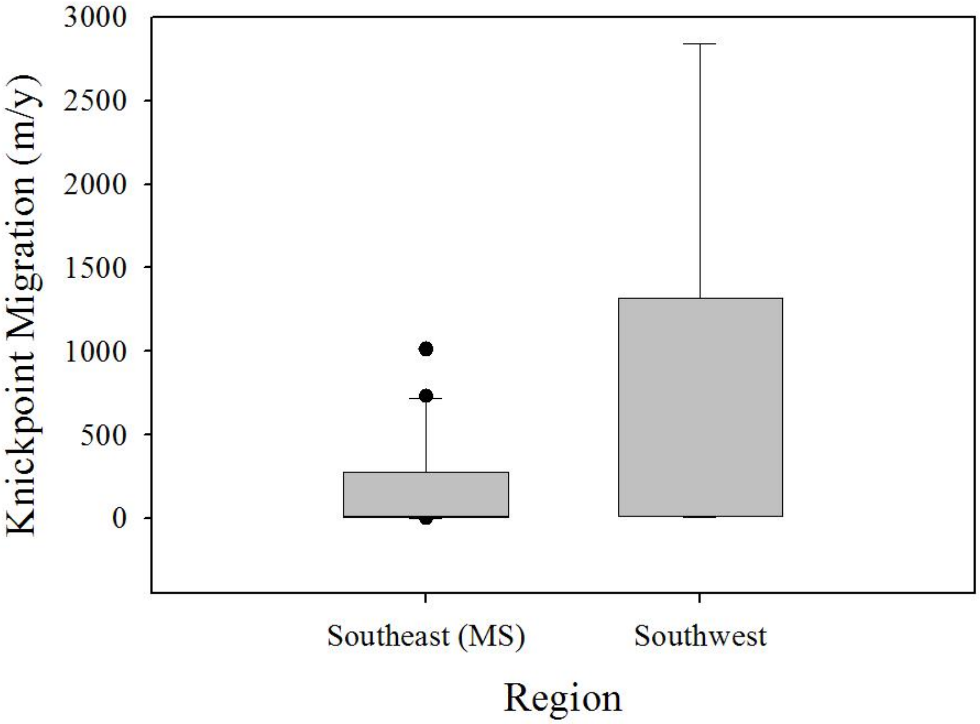

Figure 2.4 Knickpoint retreat rate for Mississippi (n = 18, median = 14.7 m/y) and southwestern US streams (n = 6, median = 410 m/y). San Pedro River, Arizona with 22 km/y of knickpoint migration is not included in the figure, but is included in the median calculation for southwestern US streams. Median is 15 m/y excluding the San Pedro River.

0.0076, respectively) (Figure 2.5 and Figure 2.6). However, knickpoint retreat rates normalized by drainage area are not significantly different between the two regions (p=0.8064) (Figure 2.7).

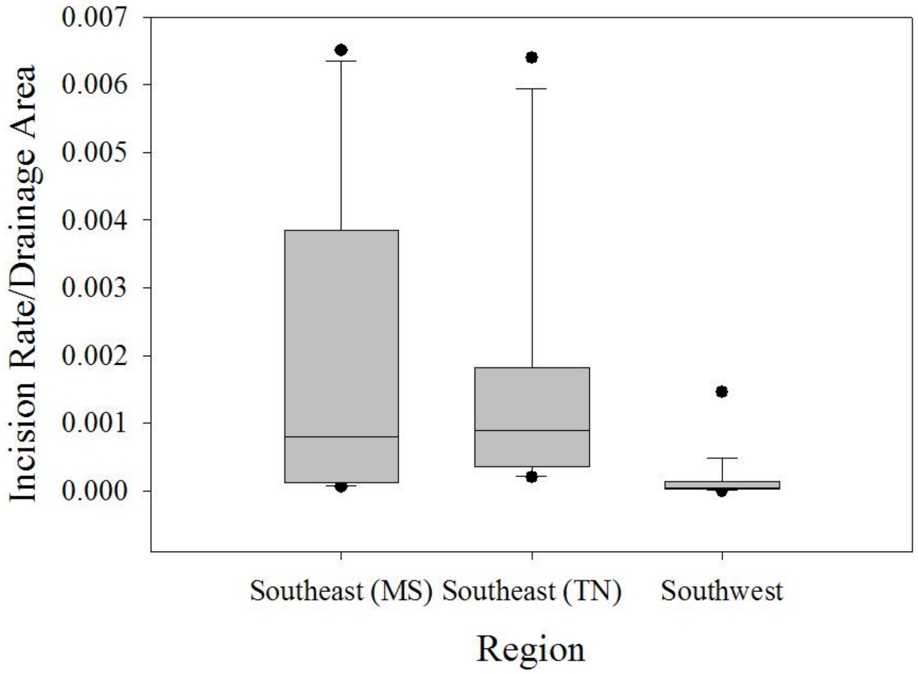

Figure 2.5 Incision rate divided by drainage area for Mississippi (n = 10, median = 8 x 10^{-4} m/km^2 y), Tennessee (n = 6, median = 9 x 10^{-4} m/km^2 y), and southwestern US streams (n = 15, median = 5 x 10^{-5} m/km^2 y).

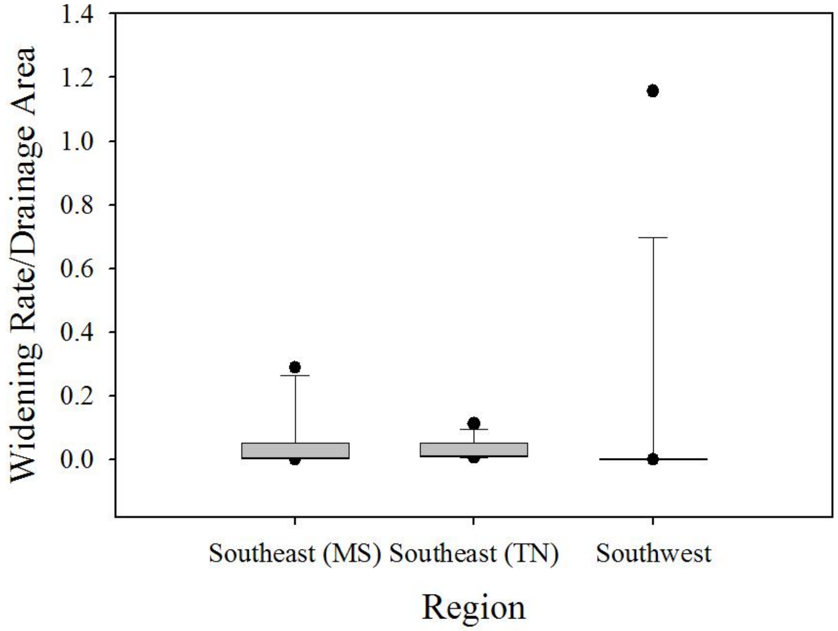

Figure 2.6 Widening rate divided by drainage area for Mississippi (n = 6, median = 6 x 10^{-3} m/km^2 y), Tennessee (n = 11, median = 1 x 10^{-2} m/km^2 y), and southwestern US streams (n = 10, median = 7 x 10^{-4} m/km^2 y).

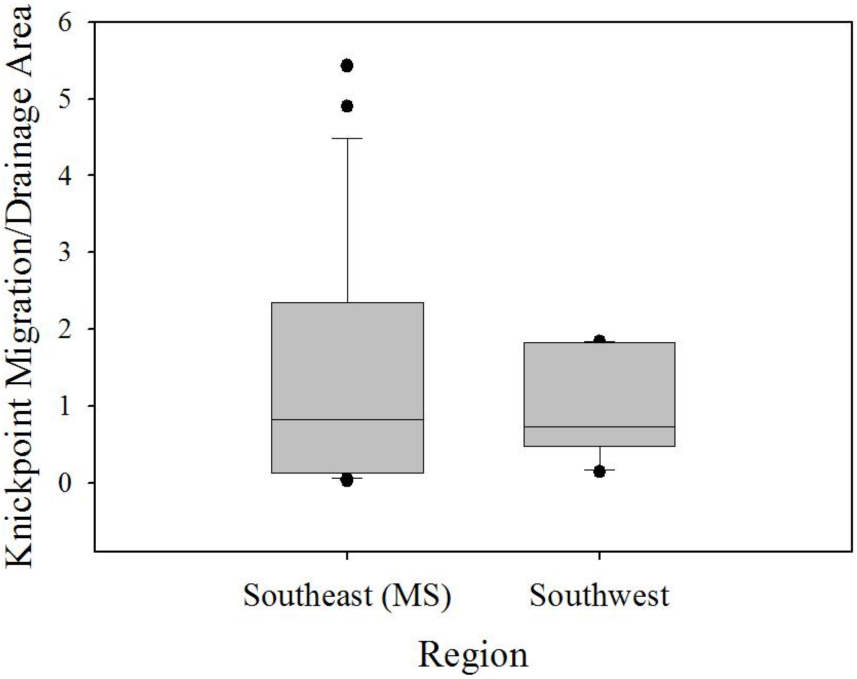

Figure 2.7 Knickpoint migration rate divided by drainage area for Mississippi (n = 18, median = 0.83 m/km^2 y) and southwestern US streams (n = 6, median = 0.74 m/km^2 y).

2.5.2 Comparison of hydraulic driving forces

I used discharge-drainage area relations for a sub-set of streams included in the erosion rate comparison to compare hydraulic driving forces in terms of estimated discharge magnitudes of varying return intervals. This analysis included 19 southwestern US streams and 18 southeastern US streams (Appendix B). From visual inspection, the estimated 2-year, 50-year, and 100-year return interval discharge magnitudes for the same drainage area are substantially larger in the Mississippi streams relative to either Tennessee or southwestern US streams (Figure 2.8, Figure 2.9, and Figure 2.10).

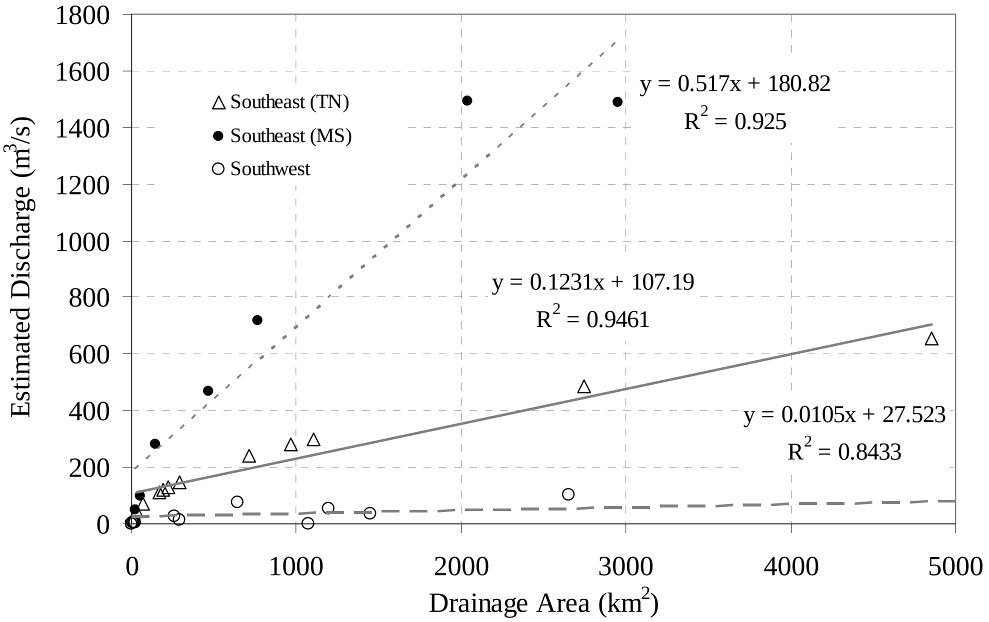

Figure 2.8 Estimated discharge magnitudes for the 2-year flood for select drainages representing a range of drainage area in Tennessee, Mississippi, and southwestern US regions.

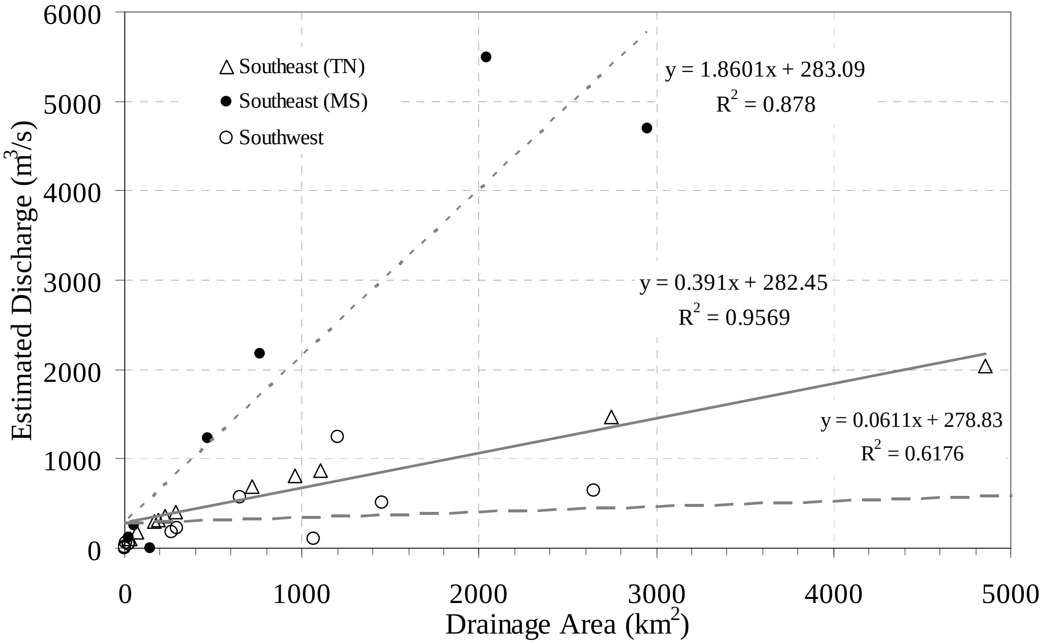

Figure 2.9 Estimated discharge magnitudes for the 50-year flood for select drainages representing a range of drainage areas in Tennessee, Mississippi, and southwestern US regions.

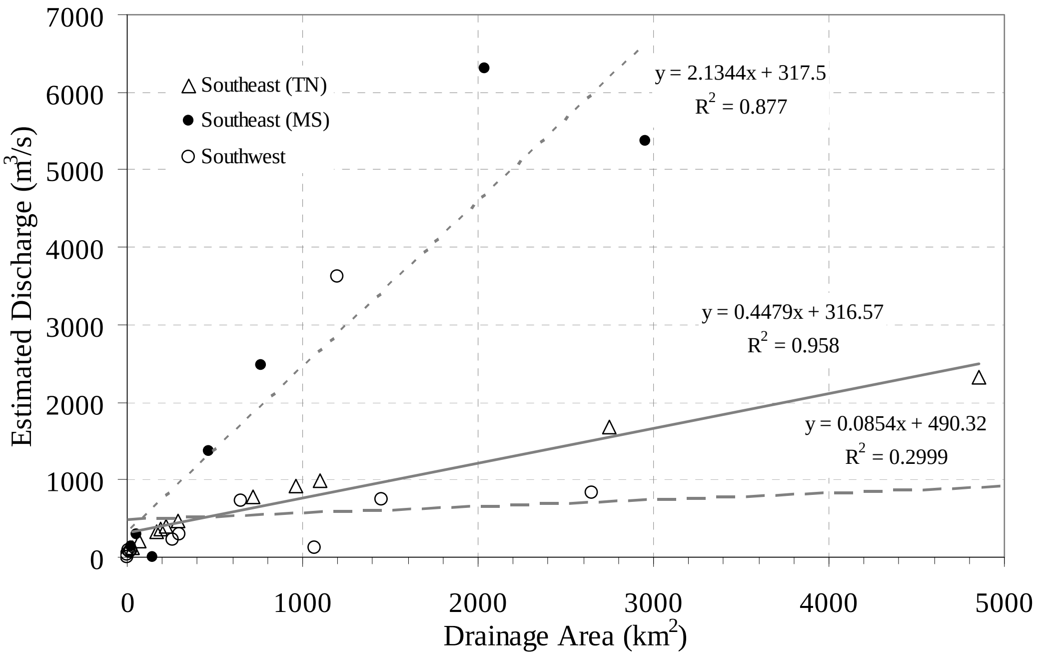

Figure 2.10 Estimated discharge magnitudes for the 100-year flood for select drainages representing a range of drainage areas in Tennessee, Mississippi, and southwestern US regions.

At lower frequency events (50-year and 100-year), estimated discharge values appear similar for southwestern and Tennessee streams with drainage areas of less than 1000 km^2 (Figure 2.9 and Figure 2.10). However, as drainage area increases, Tennessee has larger flood estimates (Figure 2.9 and Figure 2.10). Discharge volumes for streams in Mississippi consistently are the highest for all flood frequencies analyzed. Despite appearance of a similarity in the discharge-drainage area relationship between Tennessee and southwestern US streams, all three groups are statistically significantly different. When discharge magnitude of a given return interval is plotted against drainage area for all three groups and the data are fit using linear regression, significant differences exist between the intercept holding slope constant, slope holding intercept constant, and combined effect of intercept and slope of the individual fitted regression lines (Table

2.2). The one exception is that there is no difference between the intercept of the linear trendline fit through the estimated 100-year return interval discharge magnitudes for Tennessee and southwestern US streams.

Table 2.2. Pairwise comparisons between Mississippi (MS), Tennessee (TN), and southwestern US (SW) streams of intercept holding slopes constant (intercept), slope holding intercepts constant (slope), and combined effect of intercept and slopes (intercept and slope) of fitted linear regression lines for discharge magnitudes of 2-year (Q2), 50-year (Q50), and 100-year (Q100) return interval. Using a Bonferroni correction, p values < 0.0167 indicate statistically significant differences between groups in the pairwise comparison. The p value for pairwise comparison between TN and SW for the Q100 indicated in bold is the only non-significant value.

		p value		
Return Interval	Pairwise Comparison	Intercept	Slope	Intercept and Slope
Q2	MS and TN	0.0001	3.9E-16	1.3E-18
	MS and SW	0.0003	4.1E-12	4.4E-14
	TN and SW	0.0003	1.2E-10	1.3E-12
Q50	MS and TN	0.0004	2.1E-12	2.8E-14
	MS and SW	0.0009	2.7E-09	5.4E-11
	TN and SW	0.0114	1.3E-07	3.0E-08
Q100	MS and TN	0.0005	1E-11	1.9E-13
	MS and SW	0.0012	8.1E-09	2.2E-10
	TN and SW	**0.0354**	3.2E-06	1.8E-06

Higher discharge volumes for Mississippi streams relative to Tennessee may be a result of increased precipitation from dissipating tropical storms in the Gulf of Mexico that affect coastal states, but that do not typically extend inland as far as Tennessee. One southwestern stream, Aravaipa Arroyo (drainage area 1,200 km^2), has a substantially larger discharge estimate for the 100-year flood compared to the other southwestern streams (Figure 2.10). This stream is the only basin in hydrologic region 12 (Thomas et al., 1997). The regression equation for hydrologic region 12 was generated from hydrologic data from basins with a range of drainage area and elevation. Although the Aravaipa Arroyo is within this range, it lies on the edge of the range and therefore estimates may not be as accurate as for other basins that lie closer to the middle range of drainage area and elevation from which the regression equations were calculated. Despite this, I could not justify excluding this site from the analysis.

2.6 DISCUSSION

The absence of statistical differences in median incision rates between southeastern and southwestern US streams and the absence of statistical differences in median widening rates between Mississippi and southwestern US streams do not support my hypothesis that bed incision and bank erosion rates are larger in the southwestern United States. Indeed, widening rates are higher in Tennessee than southwestern streams when a single case study in the southwestern US is excluded from the analysis. The hypothesis is further unsupported by the finding that incision and widening rates, when normalized by drainage area, are significantly lower in southwestern US streams relative to southeastern streams. When evaluating the non-normalized erosion rates, which reflect geomorphic processes across a range of channel sizes, there appears to be no strong evidence for a regional difference in median erosion rates. This absence of statistical difference could be either because there is no statistical regional difference between average erosion rates, or because the range in channel size and type of data (e.g., study duration, data collection methods, and absence of data for southeastern US streams that were outside of Tennessee and Mississippi) is too broad to adequately evaluate erosion rates using average values.

The limitations of the available data set undoubtedly influence the findings of this study. In particular, I was unable to find studies documenting incision, erosion, or knickpoint retreat in any southeastern states with the exception of Mississippi and Tennessee. Some studies identify entrenched or incising channels in the North Carolina piedmont region (Duda et al., 1980; Wilson, 1983), but there is no documentation from which to determine incision or erosion rates. The results presented here thus do not represent all streams in the southeastern United States. In addition, many of the studies in the southwestern US record incision rates during periods of arroyo cutting during the late 19th century and first half of the 20th century. Many of these previously incising channels are now aggrading, such as the Paria River in Utah (Hereford, 1986) or undergoing periods of channel narrowing alternating with periods of channel widening (Burkham, 1972). Therefore, there is a potential that the data set for the southwestern US is biased towards smaller rates of incision, because many of the earlier studies that report dramatic arroyo cutting (Bryan, 1925; Antevs, 1951; Aby 1997), did not quantify bed elevations and thus incision rates could not be derived.

The absence of distinct regional differences in erosion rates also could be a result of averaging rates of channel change over longer time scales in systems that are characterized by substantial geomorphic work resulting from low frequency, high magnitude flows. Some studies in the southwestern US, for example, document erosion rates over very short time scales (i.e., one major flood over a period of less than 2 years; Huckleberry, 1994). The episodic nature of incision, bank erosion, and knickpoint retreat may not be appropriately characterized by average rates unless data are collected over a period of several decades or longer. Therefore, erosion rates from studies over short time periods (e.g., Huckleberry, 1994, which reports large-scale channel widening from a single large magnitude, low frequency event on the Gila River, AZ) may not be directly comparable to erosion rates measured over multiple decades. Instead, comparing the magnitude and persistence of channel change in streams within the two regions from individual flows of similar return interval may be a more appropriate metric for quantitatively identifying potential regional differences. The effect of using event-based rates of channel change in a comparison of average changes would tend to over-estimate the rate of change in streams of the southwestern United States, however, and thus would tend to support my hypothesis.

With these caveats, the absence of statistical regional differences in median erosion rates could reflect either the high variation in site-specific conditions of driving forces and substrate resistance, or the difficulty in evaluating channel change derived from a variety of methods. However, the fact that my comparison does not indicate faster rates of channel change in the southwestern US despite this potential inequality in the type of data analyzed further supports the interpretation that streams in the Southwest are not changing more rapidly than those in the Southeast.

Significant differences exist between Mississippi, Tennessee, and southwestern US streams for estimated discharge magnitudes of a given return interval. However, my findings of more similarity between estimated low-frequency (50-year and 100-year) discharge values for southwestern US and Tennessee streams with drainage areas of less than 1000 km^2 relative to the substantially larger discharge estimates for Mississippi streams support the idea of stronger intra-regional differences relative to inter-regional differences. This finding is also consistent with findings of O'Connor and Costa (2004). An analysis of discharge records of USGS gages identified mountain ranges near coasts such as the Appalachian Range, which includes Tennessee, as regions of high unit discharges as a result of the combined effect of local relief and high precipitation levels (O'Connor and Costa, 2004). In addition, basins less than 1,000 km^2 in the semi-arid western United States have also been identified as experiencing the largest maximum rainfall-runoff events associated with rare and extreme floods (Costa, 1987).

The discrepancy of generally larger hydraulic forces in Mississippi but absence of differences in erosion rates compared to Tennessee must be accounted for by higher substrate resistance in Mississippi to withstand driving forces. There is little to no quantitative information on vegetation and bank strength properties, however, aside from general soil descriptions. From the general descriptions in the case studies, differences in relative substrate resistance are not obvious in streams between the two states. Incision and bank erosion rates reported in Tennessee are from streams where silt and clay comprise the banks (Simon 1989; Simon and Hupp, 1992), whereas reported rates in Mississippi are a mixture of moderate and low cohesive banks characterized by clayey silt, silt, sand, and coarse alluvium (Beidenharn, 1983; Thomas, 2000). It is important to note that virtually all of the streams in this analysis have experienced substantial disturbance, typically through some form of channel reconfiguration. This discrepancy between hydraulic forces and erosion rates suggests that local basin characteristics can dominate over regional characteristics.

2.7 CONCLUSION

A review of the existing literature documenting bed incision, bank erosion, and knickpoint retreat does not indicate consistent regional differences in rates of incision, bank erosion or knickpoint retreat. Instead, our analyses suggest either that local controls exert a stronger influence on rates of channel change than regionally generalized factors, or that averaged erosion rates are not the appropriate metric for identifying regional differences. This preliminary, regionalized comparison provides a hypothesis that can be more rigorously tested using spatially detailed information on hydraulic driving force and substrate resistance in these and other environments; namely, that rates of channel change will reflect primarily local influences rather than regional differences.

In the context of this dissertation, the inter-regional comparison also suggests that, although streams in the southwestern United States are typically regarded as being highly dynamic at timespans of 10^1-10^3 years, the rates of change observed on streams in this region are not necessarily anomalous when compared to streams with very different hydroclimatic and geomorphic conditions. Instead, erosion rates per unit drainage area are significantly lower than southeastern streams.

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3 TWENTIETH CENTURY CHANGES IN CHANNEL MORPHOLOGY OF A SEMI-ARID STREAM IN THE CONTEXT OF REGIONAL AND LOCAL INFLUENCES

3.1 INTRODUCTION

Incised ephemeral channels in the American Southwest exemplify the complex dynamics of channel adjustment (Graf, 1983). These channels have repeatedly incised, widened, aggraded, and re-incised throughout the Holocene, as part of what is known as the arroyo cycle (Schumm and Hadley, 1957; Leopold, 1976; Patton and Schumm, 1981; Graf, 1983; Elliott et al., 1999). Previous investigators have attributed the existence of this cycle to: climatic shifts that alter the supply of water and sediment (Leopold, 1951, 1976; Hereford, 1984, 1986); land-uses that alter vegetation cover, rainfall-runoff relations, and groundwater elevations (Cooke and Reeves, 1976); and the internal dynamics of dryland channels apart from external changes in catchment conditions (Womack and Schumm, 1977; Patton and Schumm, 1981).

As part of the arroyo cycle, ephemeral channels undergo a complex response in which incision, moving in the upstream direction as a migrating knickpoint, supplies sediment downstream, thus promoting aggradation in reaches that previously had been incising. When the sediment supply to downstream reaches decreases as knickpoint migration stops, aggrading reaches begin to re-incise. These episodes of alternating incision and aggradation are asynchronous throughout the channel network and can persist for decades or longer (Womack and Schumm, 1977).

Management of incised ephemeral channels remains a substantial challenge despite the long history of research on these channel networks, as illustrated by channels in Canyon de Chelly. Alluvial terraces record fluctuations in the bed elevation of Canyon de Chelly throughout the Holocene. The channel network has also experienced channel change and alterations in water and sediment supply over the past 200 years in association with catchment-wide changes in livestock grazing and climatic shifts. More recently, bank conditions have changed with the widespread establishment of the exotic invasive tree species tamarisk and Russian olive. Tamarisk and Russian olive have become widespread along riparian areas of both managed and unmanaged systems throughout the Southwest, resulting in large-scale shifts in plant species composition and riparian ecosystem structure and functions and affecting geomorphic processes (Graf, 1978; Zavaleta, 2000).

Stream channel narrowing occurred throughout the national monument during the last 70 years, with incision in portions of the channel beginning in the 1980s. Because this incision affects bottomland farming and the stability of archeological sites along the valley margins, managers seek to understand: the control variables driving channel change; the processes by which channel change is occurring; the likely future direction and extent of channel change; and the effects of different management scenarios on channel morphology.

It is within this context that I evaluated contemporary channel dynamics at Canyon de Chelly National Monument. I examined late 20th-century channel change at the study site within a greater spatial context by comparing it to other sites across the southern Colorado Plateau, and within a greater temporal context by examining historical records of channel dynamics and potential influences from climate and land-use. The primary objective was to evaluate the relative importance of local (riparian vegetation, bank stratigraphy, valley geometry, in-channel structures), regional (climate, land-use, base level), and intrinsic (complex response) controls on channel dynamics in governing channel changes during the late 20th century.

To meet this objective, I evaluated the longitudinal profile, relative stream power, and width/depth ratio of the contemporary channel to investigate longitudinal patterns of channel geometry and adjustment. In addition, I used existing records of regional climate, water discharge, and land-use to determine the relative influence of regional and local control variables on channel form. Incision in portions of Canyon de Chelly is a major concern for canyon residents because of the associated drop in water tables and shift to upland xeric vegetation on terrace surfaces that historically were hydrologically connected to the active channel. Analysis of the longitudinal profile can help to determine the likely extent of further incision.

3.2 STUDY AREA

The study area is Chinle Wash, a tributary to the San Juan River and located on the Navajo Reservation in northeastern Arizona, USA. (Figure 3.1). Field work was conducted in the de Chelly canyon of Canyon de Chelly National Monument (Figure 3.1). The national monument consists of two canyons, Canyon de Chelly (1,250 km^2) and Canyon del Muerto (430 km^2), and an approximately 6-km-long reach of Chinle Wash, beginning at the confluence of the two canyons. Chinle Wash flows west from the national monument and north through the Chinle Valley, receiving inputs from various tributaries until its confluence with the San Juan River near the Arizona-Utah state border. The varied topography of the Chinle Wash watershed reflects alternating relatively resistant geologic units such as the Permian de Chelly Sandstone in which canyons of the national monument are incised, and more readily weathered volcanic and shale units that give rise to badlands (Gregory, 1917; Thaden, 1989).

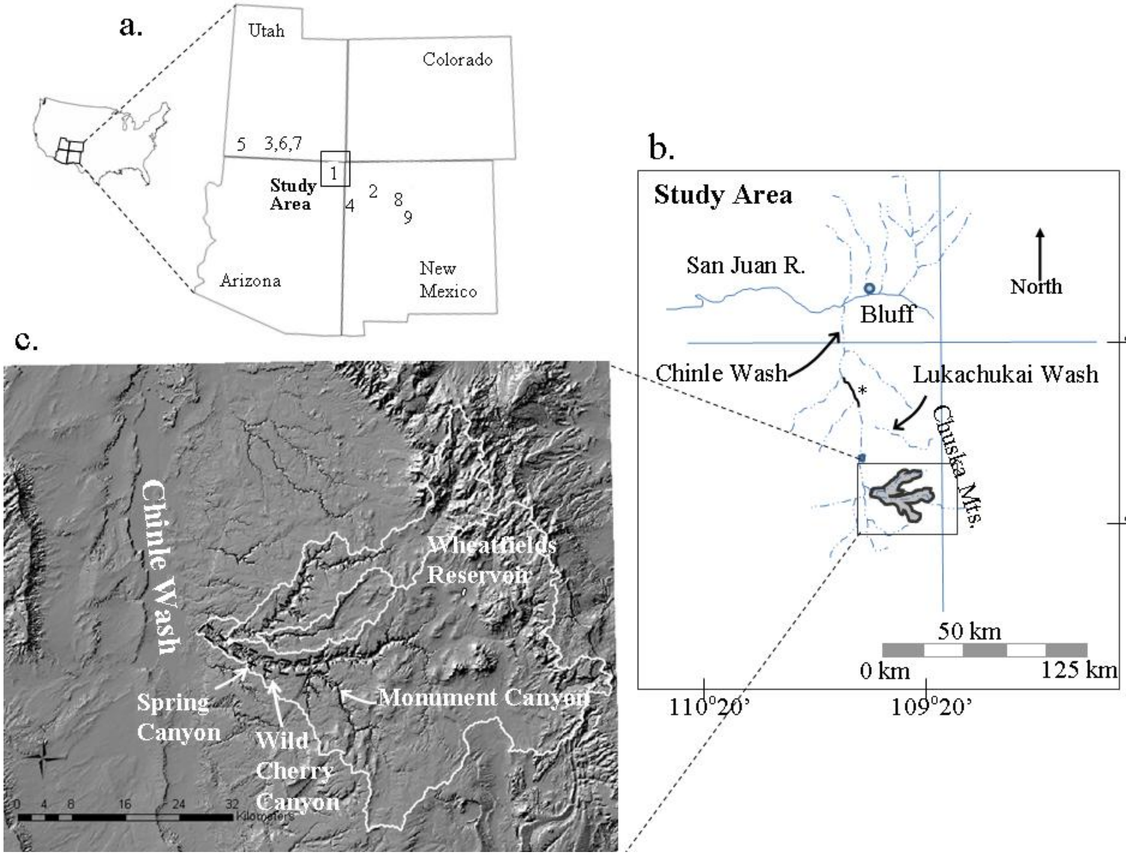

Figure 3.1 Regional and study area map.

a. Numbers identify locations of arroyo research discussed later in text. 1 Chinle Wash, 2 Chaco Wash, 3 Kanab Creek, 4 Zuni River, 5 Virgin River, 6 Paria River, 7 Harris Wash, Escalante River, 8 Arroyo de los Frijoles, 9 Rio Puerco. b. Study area of Chinle Wash. * identifies the location of the subtle concavity in the longitudinal profile corresponding to the confluence of Lukachukai Wash c. Catchment area of Canyon de Chelly National Monument. From north to south, the catchment areas outlined in white are Canyon del Muerto, Black Rock canyon, and Canyon de Chelly, respectively. Black dashed box is extent of field-measured longitudinal profile of contemporary channel in Canyon de Chelly.

Within Canyon de Chelly and Chinle Wash immediately downstream of Canyon de Chelly, the canyon is characterized by vertical walls extending 300 m at their highest. Canyon widths range from approximately 150 m to more than 700 m. The canyon bottom is composed of unconsolidated alluvium that is mainly sand, underlain by weakly to well-consolidated units of sand, silt, and clay. A high and middle terrace approximately 13 and 3 m above the top of bank of the contemporary channel, respectively, occur throughout the length of Canyon de Chelly until its confluence with Canyon del Muerto.

The contemporary channel flowing through Canyon del Muerto and Canyon de Chelly is a sand-bedded dune-ripple channel with a meandering, single thread. Portions of the streambed contain coarser sediments including gravel and cobble. Channels in Canyon del Muerto are less incised than in Canyon de Chelly. Channel sections in Canyon de Chelly are 5-15 m wide and from 1 to 2 m to more than 8 m deep. Chinle Wash within the national monument and along the southern portion of Chinle Valley is braided. The wash becomes more narrow and sinuous as it flows north to the San Juan River.

Vegetation in the Chinle Wash catchment includes several plant community assemblages as a result of the range in elevation in the catchment. The Chuska Mountains are characterized by pure stands of ponderosa pine (*Pinus ponderosa* C. Lawson) and mixed stands of ponderosa pine, aspen (*Populus tremuloides* Michx.), and Douglas fir (*Pseudotsuga menziesii* (Mirb) Franco) (Savage, 1991). US expeditions in the mid 1800's described the forest community in the Chuska Mountains as open woodland with widely spaced trees and grassy meadows (Savage, 1991). Warmer and wetter climate conditions in the early 1900's and a sustained reduction in fire frequency that began in 1830 resulted in a shift in stand structure, with increased ponderosa pine density and tree encroachment into meadows (Savage, 1991). West of the Chuskas and extending along the rim of the canyons, the plant community consists of pinyon-juniper (*Pinus edulis* Engelm. - *Juniperus osteosperma* (Torr.) Little, *J. monosperma* (Engelm.) Sarg.) woodland, which transitions into Colorado Plateau pinyon-juniper shrubland as elevations decrease in the westerly direction. This transition zone is heavily impacted by exotic cheatgrass (*Bromus tectorum* L.). The pinyon-juniper community west of the Chuska Mountains presumably has remained intact for the past 200 years, as evidenced by a mature pinyon-juniper community, which is slow growing and long lived. However, stand density and age classes are unknown. The understory of the mature forest contains substantial areas of unvegetated surfaces. This part of the catchment at the base of the Chuska Mountains is characterized by highly erodible soils of the Triassic Chinle Formation, which are protected by cryptobiotic soil layers. Downstream of the canyons and through the Chinle Valley, the vegetation is predominantly exotic grasses and native shrubs. Riparian vegetation along the length of the channel consists of native cottonwood (*Populus fremontii* S. Watson) and willow (*Salix exigua, S. gooddingii*), and exotic tamarisk (*Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro, and their hybrids) and Russian olive (*Elaeagnus angustifolia* L.).

The climate in northeastern Arizona is semi-arid. Average annual precipitation is approximately 24 cm, with most of the precipitation falling between July and September as local, convective thunderstorms or dissipating tropical cyclones (Arizona Climate

Summaries, 2004; Ely et al., 1993). Winter precipitation occurs in the form of less intense rain or snowfall. The region is subject to climatic shifts that have been documented throughout the southern Colorado Plateau (Ely et al., 1993; Petersen, 1994; Hereford, 1986; Hereford, 2002).

Streamflow in Canyon de Chelly reflects the bimodal character of precipitation in the region. Spring snowmelt produces a runoff season of smaller magnitude and longer duration relative to the typically high magnitude, short duration summer flows that result from convective thunderstorms. Annual peak flows associated with the late summer-early fall monsoon storms characteristically carry more sediment than spring snowmelt. The stream bed is dry between the spring runoff and the start of the monsoon flows, although the upper regions of Canyon de Chelly could be considered nearly perennial. Chinle Wash downstream of the national monument is an ephemeral channel. A stream gage (USGS 09379025) located approximately 6 km downstream of the confluence of Canyon de Chelly and Canyon del Muerto was in operation from November 1999 until August 2006.

Wheatfields Dam is located upstream of Canyon de Chelly and was built in 1964 for recreational purposes. The reservoir is off-channel in a dammed side valley. From early spring until early fall, most water and sediment draining from the Chuska Mountains bypass the reservoir and flow into Canyon de Chelly. In addition, there is a steady release from the reservoir during this time. Beginning in the fall, water is diverted into the reservoir. Winter baseflows are maintained in Canyon de Chelly from other tributaries upstream of the canyon.

A history of channel manipulation projects exists within the national monument, in an effort to protect both archeological resources and personal property of Navajo residents. Two bank-stability and six grade-control structures are located within the contemporary channel in Canyon de Chelly. The structures were built circa 1985 and in the 1990s, presumably in response to channel incision that began at that time (NPS maintenance crew, personal communication, January 2008). The structures are rock gabions and are located in the lower half of Canyon de Chelly. The two bank-stability structures and one grade-control structure are currently intact and functioning, but the remaining five have either partially or completely failed. In addition to these contemporary channel structures and prior to their installation, canyon residents have repeatedly installed other structures to control both bed incision and lateral channel migration. In particular, partially buried remnants of “spider fences” occur at various locations in Canyon de Chelly, which were built parallel to the historic channel to slow flow velocities, promote sedimentation, and presumably inhibit channel migration into canyon resident properties and farming plots. Canyon residents also have placed brush cuttings in the channel and at gully headcuts to limit further erosion.

Livestock grazing, which includes sheep, goats, horses, and cattle, has been the primary land-use of the upper catchment (the canyon rim area and Chuska Mountains) since the mid 1700s (Stewart, 1936; Savage, 1991; Travis, 2007). Intense grazing results in the removal of herbaceous cover, an increase in bare soils, and destruction of protective cryptobiotic soils, which together can increase soil erosion rates (Brotherson et al., 1983; Belnap, 1995; Davenport et al., 1998; Milchunas, 2006). Grazing intensity increased throughout the 1800s, exceeding estimated grazing capacity by two to three times for most of the century, with particularly high herd numbers from 1880-1900 and 1911-1920 (Savage, 1991; Travis, 2007). Herd numbers declined drastically beginning in the 1930s with a large-scale livestock reduction campaign on the Navajo Reservation (Savage, 1991; McPherson, 1998; Weisiger, 2000). Grazing continues today throughout the watershed, although herd numbers remain extremely low relative to pre-1940 grazing levels. Within the Chuska Mountains, a drastic reduction in fire frequency beginning around 1830 is closely coupled to high grazing intensity (Savage, 1991). Small-scale timber harvest has occurred for centuries throughout the watershed, as Navajo and prehistoric cultures used wood for fuel and building (Betancourt and Devender, 1981; Travis, personal communication, March 10, 2008).

By the early 1700s, the Navajo farmed and grazed livestock throughout the canyon (Travis, 2007). Orchards on terraces closer to the canyon wall and floodwater farming on open alluvium characterized farming techniques. A shift to more mechanized row crop farming occurred in the 1930s as part of Soil Conservation Service campaign efforts within the canyon. It was also during this time that tamarisk was planted as an erosion-control measure. Russian olive was planted within the canyon in the 1960s. The majority of the agricultural fields in Canyon de Chelly are currently fallow, and bottomland grazing remains the predominant land use.

3.3 METHODS

3.3.1 Longitudinal profiles

Using a 30-m horizontal resolution digital elevation model (DEM) with 7- to 15-m vertical resolution, I analyzed the longitudinal profile of Chinle Wash including the Canyon de Chelly branch from its beginning in the Chuska Mountains and extending approximately 320 km downstream to the San Juan River confluence. The longitudinal profile was generated from the DEM (USGS, 2007) using ArcMap GIS software (ArcMap 9.3). The DEM was generated using 7.5-minute elevation data, which are the 1:24 000 scale data for standard USGS topographic maps and are the best available data for the region.

The longitudinal profile of the Canyon de Chelly contemporary channel extending upstream from the town of Chinle was generated by surveying the thalweg elevation along approximately 28 km of stream channel in Canyon de Chelly and Chinle Wash using standard field surveying methods. Vertical and horizontal error associated with the surveying technique was limited to approximately 7 cm between survey points spaced 50 to 200 m apart. Distances between channel survey points were calculated from aerial photographs taken in 2004 to account for channel sinuosity.

Surveyed elevations of the high and mid terrace surfaces were used to generate longitudinal profiles based on the distance between the surveyed points, which is assumed to represent canyon length. Because of the sinuosity of the contemporary channel, the overall thalweg longitudinal profile was approximately 2.5 km longer than the profiles of the middle and high terraces. To makes these profiles comparable, the points used to generate the profile of the sinuous thalweg were reduced to include only channel points that were at the same locations as surveyed terrace points.

Cross-sectional geometry and local slope were surveyed at 37 locations randomly distributed along the length of Canyon de Chelly (29) and Chinle Wash (8). Canyon width for each cross-section was calculated using aerial photographs. The general longitudinal canyon slope at these cross-sections was calculated from the difference in elevation of the middle terrace points near cross-section locations, under the assumption that this slope represented the channel bed slope prior to the most recent incision episode because it was active channel in 1935 aerial photographs. The 37 cross sections represented 37 reaches along the length of the longitudinal profile.

Relative unit stream power was calculated for each reach using

$$\omega = AS/w \tag{1}$$

where ω is relative stream power, A is drainage area used as a surrogate for discharge, S is channel reach bed slope used as a surrogate for friction slope, and w is channel width. The specific weight of the water-sediment mixture is assumed to be constant throughout the length of the longitudinal profile and therefore is not included in the equation.

The stratigraphy of the high terrace was characterized at 5 locations chosen for their nearly vertical exposed faces. Detrital charcoal was sampled near the top and base of the terraces for radiocarbon dating. The date of the charcoal represents a maximum age of the depositional surface because of the possibility for reworking and transport from older deposits (Hereford, 1986; 2002). Laboratory analysis was conducted by

BetaAnalytic, Inc., which dated individual samples using the Accelerator Mass Spectrometry (AMS) analysis procedure for all samples with the exception of one sample dated with the standard radiometric analysis procedure because of the larger amount of carbon available for dating (2 to 4 grams). Dates from individual radiocarbon samples in Canyon de Chelly were compared to remnant alluvial terrace dates in Canyon del Muerto from Dolan (1993).

3.3.2 Reconstruction of historic climate, catchment, and channel conditions

I gathered information on the regional climate and land use variables known to influence catchment-wide sediment production as well as water and sediment delivery to the channel. Existing information included historic aerial photograph records, grazing information synthesized from regional literature, regional historic precipitation records, and paleoflow records of nearby basins (Table 3.1 and). Cadol (2007) used 6 aerial photograph series from the years 1935, 1964, 1975, 1981, 1989, and 2004 to quantify changes in channel width and vegetation cover along the canyon bottom within Canyon de Chelly National Monument. The 1935, 1981, and 2004 photographs cover the complete length of Canyon de Chelly; the remaining three series partially cover the canyon, although the 1964 series has nearly complete coverage. Information on historical grazing practices on the Navajo Reservation was obtained from the literature (Stewart, 1936; Savage, 1991; McPherson, 1998; Weisiger, 2000; Travis, 2007). Monthly precipitation records for northeastern Arizona for 1895 through 2007 were obtained from the National Climate Data Center (NCDC) (NCDC, 2008).

Table 3.1 Existing information for reconstruction of watershed conditions.

Existing information	**Reference**	**Years of information**	**Watershed Inferences**
Historical aerial photographs of Canyon de Chelly National Monument	Canyon de Chelly National Monument archives	1935-2004	channel width, riparian vegetation coverage
Historic grazing intensity	Stewart, 1936; Savage, 1991; McPherson, 1998; Weisiger, 2000; Travis, 2007	1700-1960s	catchment vegetation coverage, upland sediment production
Monthly precipitation records for northeast Arizona	National Climate Data Center, 2008	1895-2007	flood magnitude, catchment vegetation coverage, upland sediment production, sediment delivery to channel
Reconstructed streamflow record for San Juan River near Bluff, UT USGS gage 9379500	Woodhouse et al., 2006	1569-1997	flood magnitude, catchment vegetation coverage, upland sediment production, sediment delivery to channel
Paleoflow records of nearby basins	peer-reviewed literature (see Table 2)	1700-1990	flood magnitude, sediment delivery to channel

Table 3.2 Regional paleoflow and climate records for reconstruction of watershed conditions.

Drainage	**Summary**	**Reference**
Chinle Wash	drought at end of 19th century; climatically wet 1905-1925 and 1979-2000; climatically dry 1945-1979 and 2000 to 2008	National Climate Data Center, 2008
Tributary to Chinle Wash west of Canyon de Chelly	dry conditions 1720-1740, 1770-1780, 1890-1905; wet conditions 1740-1750, 1760-1780, 1905-1925, 1975-1990	McAuliffe et al., 2006
Kanab Creek, southern Utah/northern Arizona	large magnitude flows 1960-1990, particularly 1960-1975	Webb et al., 1991
Escalante River south-central Utah	large magnitude flows 1960-1990, particularly 1960-1975; large floods in 1909, 1932, and potentially in 1916 and 1927	Webb et al., 1988
Paria River, southern Utah	Less climatically wet years associated with El Nino events 1700-1880	Hereford, 2002
San Juan River near Bluff, Utah	1700-1750 stable flow conditions; alternatively fall and rise at approximately 25-year intervals after 1750; higher flow conditions 1825-1875; lower flow conditions 1875-1900; highest flows for the period period of record at start of 20th century	Woodhouse et al., 2006
Zuni River basin, northwestern New Mexico	Drought at end of 19th century; high flood frequency after 1904	Balling and Wells, 1990

The cumulative precipitation was calculated for months that represent the two distinct seasons of summer monsoons (July-September), which produce flash flows, and winter precipitation (November-February), which produces spring snowmelt. Differences between the actual cumulative seasonal precipitation and average cumulative seasonal precipitation were plotted for the period of record, and continuous time periods of positive or negative values were identified as climatically wet or dry, respectively.

Flow records for Canyon de Chelly only exist from 1999 until 2006, but paleoflow records exist for nearby basins that extend from 1569 to 1990 (Table 3.2). A reconstructed precipitation record for a tributary to Chinle Wash and flow record for the San Juan River at Bluff, Utah, which includes the Chinle Wash catchment, were used as a proxy in determining historic catchment conditions (McAuliffe et al., 2006; Woodhouse et al., 2006). Annual precipitation and stream flows were reconstructed based on existing gage records and tree ring analyses. Strong correlations have been found between tree-ring widths and precipitation during the cooler months, which reflect snowmelt flow in the semi-arid region (Meko et al., 1995). Tree-ring widths are less well correlated with summer monsoon precipitation, which typically causes the peak floods in this system. Therefore, from the reconstructed flow record I infer broad precipitation patterns within the region and general flow conditions within Canyon de Chelly that affect snowmelt prior to 1895, for which regional monthly precipitation records exist, but I cannot infer flow conditions that result from the monsoon precipitation. Using the combined existing information and a basic understanding of geomorphic processes at a watershed scale, I develop a suite of scenarios with regard to sediment and flow regime within the Canyon de Chelly catchment that could explain the observed channel change throughout the 20th century, with an emphasis on the second half of the century. Finally, I propose methods to quantitatively test the accuracy of these scenarios.

3.3.3 Statistical Analyses

I used statistical and graphical analyses to determine whether distinctly different portions of the canyon exist based on canyon or contemporary channel morphology. Statistical analyses were conducted using SAS statistical software package (SAS, 2003).

To identify correlations between channel morphology and potential larger scale geomorphic controls, cluster analysis (Proc cluster) was conducted on the 37 cross-sections to group cross sections based on their similarities in canyon width and canyon slope. Clustering methods included both the average linkage method, where the cluster distance is the average distance between observation pairs, and the Ward minimum-variance method, in which cluster distance is the Analysis of Variance (ANOVA) sum of squares between two clusters summed over all the variables (Sokal and Michener, 1958; Ward 1963). At each generation where previous clusters of cross sections are combined, the within-cluster sum of squares is minimized over all possible groupings. The criterion to determine the final number of clusters from all generations of the cluster analysis was a function of the largest increase in R^2 between cluster generations. An analysis of covariance (ANCOVA) was conducted to determine differences in cross-section morphology, specifically width, depth, width/depth ratio, relative stream power, and local slope between clusters. Within the same cluster, portions of the canyon were further subdivided based on the residual bed elevations. An ANCOVA was conducted to determine differences within this cluster as a function of residual bed elevations, relative stream power, and cross-section properties of width/depth ratio and depth.

3.4 RESULTS

3.4.1 Longitudinal profiles

3.4.1.1 Chinle Wash

The longitudinal profile of Chinle Wash is generally concave up with the exception of the obvious knickpoint (500 km) demarcating the head of Canyon de Chelly (Figure 3.2) and a gentle convexity from approximately 280 km to 380 km (Figure 3.3). The knickpoint reflects the geologic boundary between the more erodible Chinle Formation and the resistant Shinarump Member, which serves as a local base level for the upper portion of the watershed. The upstream extent of the convexity is approximately located at the confluence of Lukachukai Wash, an ephemeral sand-bedded channel that drains a portion of the Chuska Mountains and the region underlain by the Chinle Formation. Downstream of this convexity, the channel gradient is steeper and bed elevations are lower than predicted by the trendline for the upstream portion of the profile from the head of Canyon de Chelly to approximately 370 km, but the exponential growth trendline for this lower portion of the profile matches well with the trendline for the overall profile (Figure 3.3). The abrupt breaks in slope in the downstream portion of the longitudinal profile (approximately 120-300 km) result from error inherent to the coarse DEM resolution and extremely low channel gradients. The field-surveyed longitudinal profile of the contemporary channel in Canyon de Chelly is less steep than the gradient of the coarser DEM (Figure 3.2).

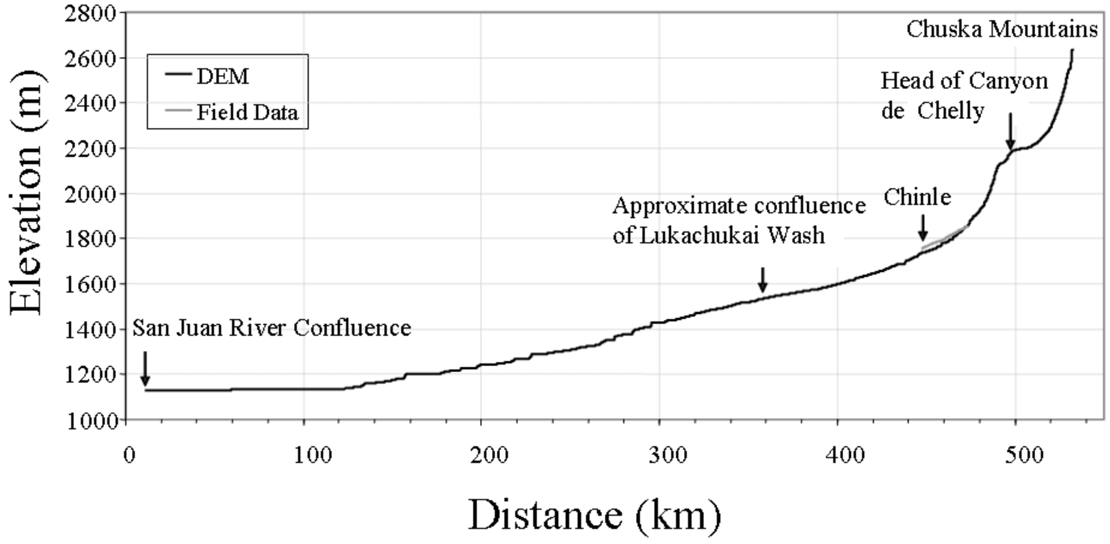

Figure 3.2 Longitudinal profile of Chinle Wash using 10-m resolution DEM from headwaters in Chuska Mountains to confluence with San Juan River.

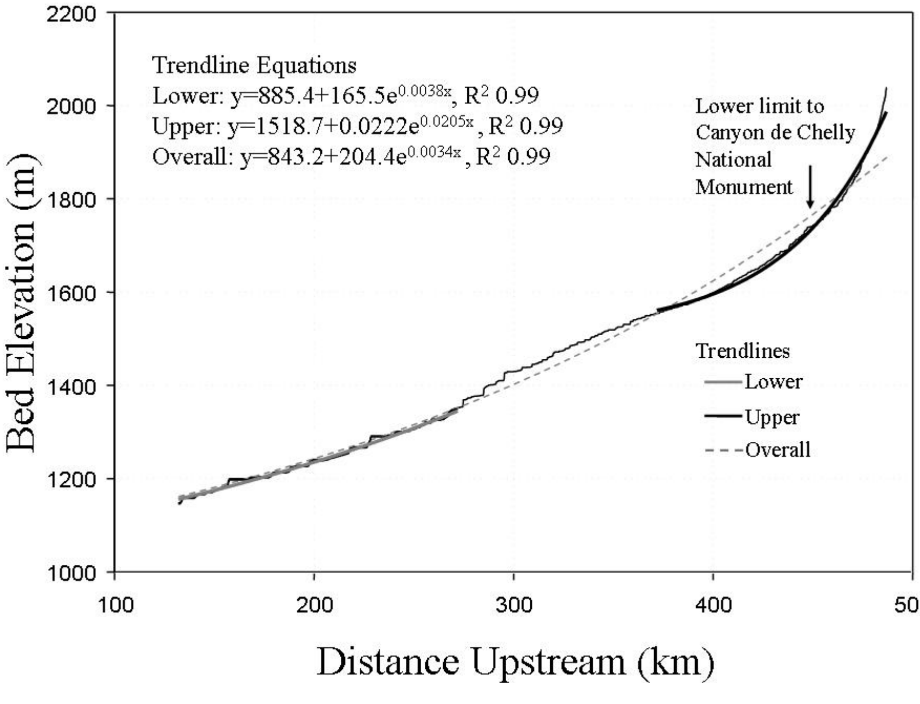

Figure 3.3 Chinle Wash longitudinal profile using 10-m resolution DEM from the head of Canyon de Chelly to approximately 100 km upstream of the confluence with the San Juan River. Exponential trendlines fit separately through entire profile, through field-measured profile, and through profile downstream of Canyon de Chelly.

3.4.1.2 Contemporary channel

The longitudinal profile of the contemporary channel within Canyon de Chelly can be partitioned into four reaches based on channel residual bed elevations, channel cross-sectional geometry, and canyon width (Figure 3.4, Table 3.3). These reaches are referred to respectively as Chinle Wash, Lower de Chelly, Middle de Chelly, and Upper de Chelly. The longitudinal profile is generally straight, with the exception of a concave-up reach extending from approximately 6 km to 13.5 km (Figure 3.4). The downstream extent of the concavity corresponds to the junction of Canyon de Chelly and Canyon del Muerto and demarcates a distinct morphologic shift from braided in Chinle Wash to single thread, meandering in Canyon de Chelly.

Table 3.3 Summary statistics of mean channel depth, width/depth ratio (w:d), canyon width, and the cluster analysis for the 4 reaches of the contemporary channel. Canyon width values correspond to the median width identified in the cluster analysis. Chinle Wash included two cluster groups and therefore two median canyon widths.

Section	**Channel Distance (km)**	**Channel Slope**	**Canyon Width (m)**	**Cluster**	**Channel Depth (m)**	**Channel W:D**
Chinle Wash	0-6.0	0.0036	139, 440	1,2,3	0.5	154
Lower de Chelly	6.0-13.5	0.0033	316	3	2.3	7
Middle de Chelly	13.5-22.0	0.0035	440	1	0.9	12
Upper de Chelly	22.0-28	0.0037	316	3	0.9	13

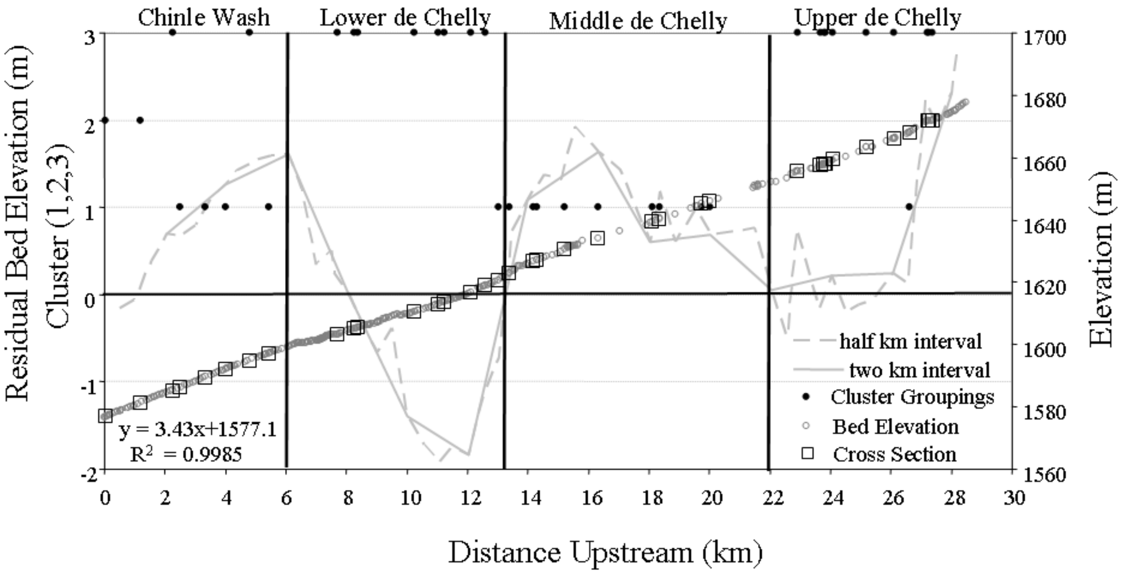

Figure 3.4 The contemporary channel is partitioned into 4 distinct geomorphic reaches based on a combination of cross-sectional geometry, residual bed elevation, and cluster analysis groupings. Channel elevations (grey open circles) are on y-axis on right. Residual bed elevations (gray solid and dashed lines) and cluster groups (black solid circles) are y-axis on left. Residual bed elevations were calculated by taking the difference between the elevation of the surveyed channel point and the value predicted by the linear trendline. Residual elevation values for channel points at 0.5 and 2 km intervals were plotted against distance upstream.

Trends in residual bed elevation values correspond to the partitioned regions of the longitudinal profile (Figure 3.4). Downstream of the junction of Canyon del Muerto and Canyon de Chelly (Chinle Wash), bed elevations are higher than the overall linear trendline. Residual elevations sharply decrease in the concave-up region of the channel (Lower de Chelly), reaching a maximum of 2 m below the trendline elevation. This indicates that this portion of the channel is generally more incised than the rest of the contemporary channel; stream banks rise 8 m above the bed in this section. At approximately 13.5 km (Middle de Chelly), bed elevations exceed those predicted by the trendline, but begin to fluctuate around 0 at 22 km (Upper de Chelly).

Chinle Wash is geomorphically distinct because of its consistent braided morphology. Width/depth ratios are larger ($p < 0.0001$) and relative stream power is lower ($p = 0.0033$) compared to other canyon reaches, both of which are driven by increased channel widths rather than slope or drainage area in this portion of the canyon (Figure 3.5, Figure 3.6, Figure 3.7, Figure 3.8). In addition, residual bed elevation values are positive in Chinle Wash. Although the cross-sectional geometry is similar between the Lower and Middle de Chelly reaches (Table 3.3), the reaches are considered to be geomorphically distinct because of the contrasting differences in residual bed elevations (Figure 3.4).

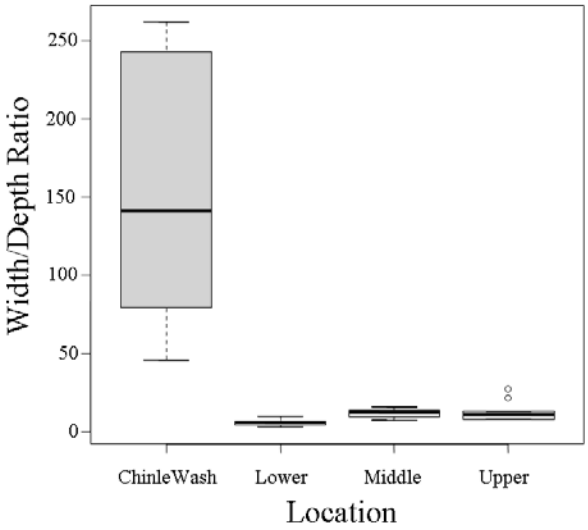

Figure 3.5 Boxplot of width/depth ratio for 4 canyon sections, Chinle Wash, Lower de Chelly (Lower), Middle de Chelly (Middle), and Upper de Chelly (Upper). Solid line represents mean width/depth ratio value for each canyon location. ^{o} identifies two outliers of high width/depth ratio in Upper de Chelly. Width/depth ratio is larger in Chinle Wash than other canyon reaches ($p<0.0001$). Lower de Chelly has slightly smaller width/depth ratio than Upper de Chelly, although this difference is not statistically different.

Lower de Chelly is significantly more incised ($p < 0.0001$, Figure 3.8) than other canyon reaches and has smaller width/depth ratio values, although this difference is not statistically significant. Relative stream power increases in the upstream direction between reaches but decreases slightly in Upper de Chelly (Figure 3.7). Results from the cluster analysis indicate that cross-sections along the longitudinal profile can be separated into three clusters as a function of canyon width ($R^2 = 0.85$, Table 3.4). Canyon slope was not useful in the cluster analysis ($R^2 = 0.03$). Cluster analysis results were the same for both the average linkage and Ward minimum variance methods. The clusters correspond reasonably well to continuous regions of Canyon de Chelly and generally follow the trends evident in the residual bed elevation (Figure 3.4).

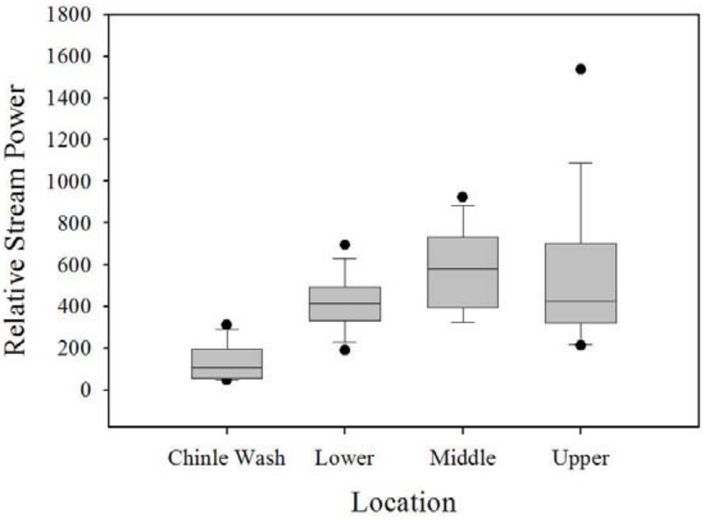

Figure 3.6 Boxplot of relative stream power for the four sections in Canyon de Chelly, Chinle Wash, Lower de Chelly (Lower), Middle de Chelly (Middle), and Upper de Chelly (Upper). Relative stream power is lower in Chinle Wash ($p = 0.0033$) as a result of increased stream width compared to the other three canyon partitions. Relative stream power increases in the upstream direction.

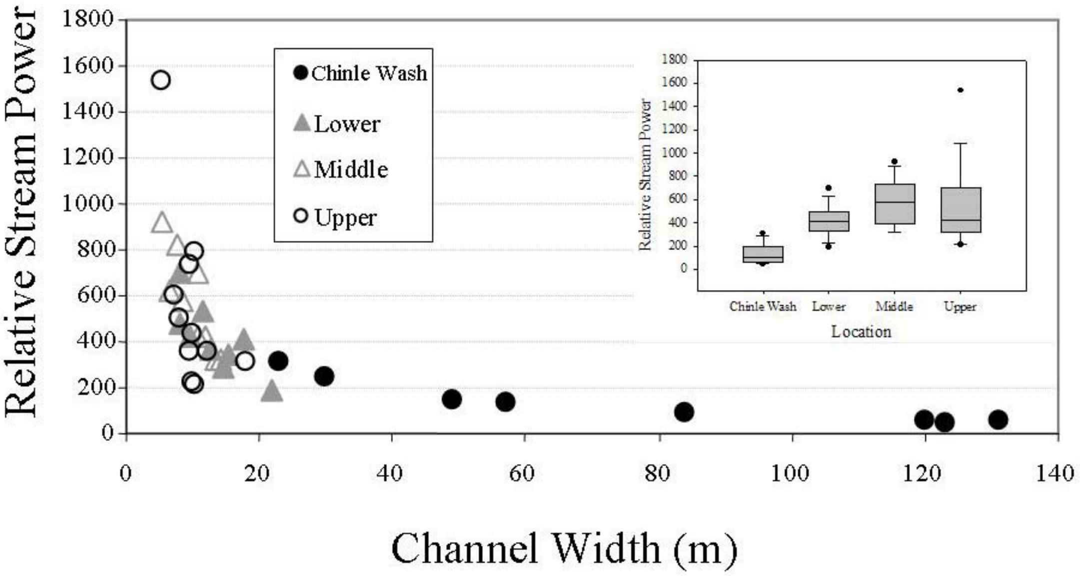

Figure 3.7 Scatter plot of relative stream power and channel width for cross section locations within the four canyon sections, Chinle Wash, Lower de Chelly (lower), Middle de Chelly (Middle), and Upper de Chelly (Upper). Inset graph is boxplot of relative stream power within each of the four sections.

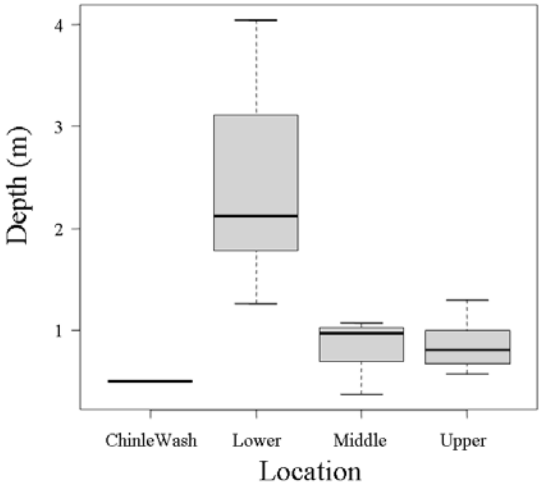

Figure 3.8 Boxplot of channel depth for 4 canyon sections Chinle Wash, Lower de Chelly (Lower), Middle de Chelly (Middle), and Upper de Chelly (Upper). Channel depths at cross sections in Lower de Chelly are deeper than other reaches within the canyon ($p<0.0001$).

Table 3.4 Cluster analysis summary statistics.

Cluster	**Frequency**	**Canyon Width (m)**	**Standard Deviation (m)**
1	12	440	36
2	2	139	13
3	23	316	33

A knickzone exists at approximately 13.5 km in the longitudinal profile, downstream of the confluence of the small tributary, Spring Canyon, which is also the transition between Lower and Middle de Chelly (Figure 3.9). Knickzone bed gradient is more than twice the overall channel gradient (0.0077 compared to 0.0034). The contemporary channel has incised below the outlet of Spring Canyon. Therefore, although tributary canyon alluvium likely contributes to this locally steep section of the contemporary channel, it appears that the knickpoint has propagated from downstream. Three in-channel grade-control structures are located in this knickzone region. The knickzone is located upstream of a channel-wide rock gabion that has partially failed and appears to exert only a limited control on bed incision (Figure 3.10). Upstream channel structures are rock gabions that have partially or mostly failed. The three downstream in-channel structures below the knickzone have failed and no longer influence gradient.

The vast majority of the contemporary channel is sand bedded. The first 13 km of the longitudinal profile, which include Chinle Wash and Lower de Chelly, are sand bed with a veneer of small gravel in patches and along channel margins. In the upper portion of Lower de Chelly, the channel is currently incising into a clay layer. Upstream of Lower de Chelly, the channel bed is predominantly sand, with channel-wide patches of

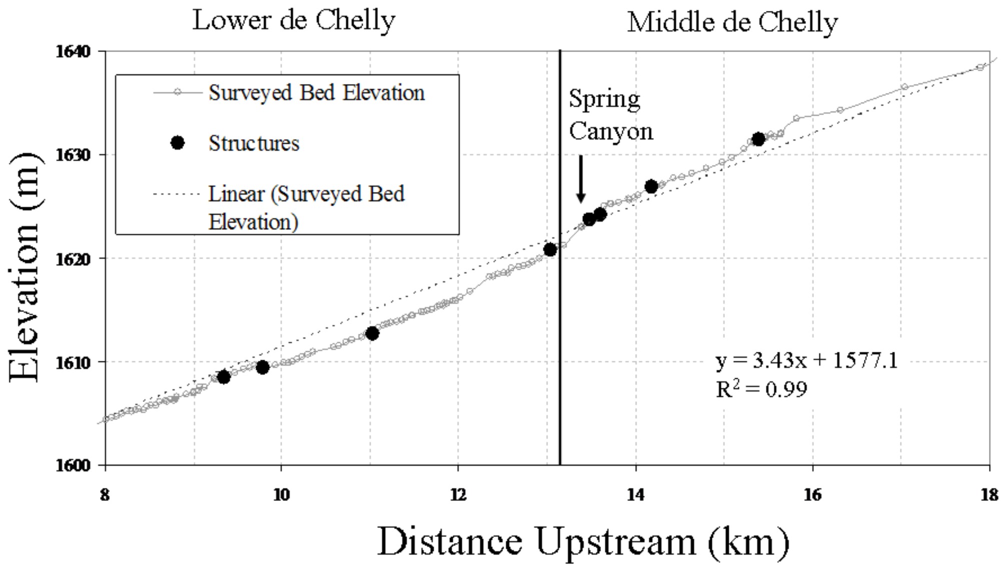

Figure 3.9 Detailed portion of Canyon de Chelly contemporary channel from Figure 3.4 that contains a knickzone beginning at approximately kilometer 13.2 and is demarcated by the solid black vertical line. Knickzone coincides with the outlet of tributary side canyons and in-channel grade control structures (black solid circles). The three most downstream structures in Lower de Chelly are not functioning. Grey circles are locations of surveyed bed elevations. Discontinuities in the longitudinal profile are attributed to in-channel structures, side canyon sediment contributions, and bed coarsening. Regression equation is for linear bed elevation trendline (gray dashed line).

Figure 3.10 In-channel structure immediately below knickzone in longitudinal profile at 13.0 km that partially functions as a grade control. Erosion is evident at top center of structure. Differences in bed elevation immediately upstream and downstream from structure is 0.42 m.

embedded large gravel and cobble-sized clasts that extend longitudinally for 10-20 m. Bed coarsening is evident in the longitudinal profile beginning at approximately 22 km (Upper de Chelly), where the profile becomes less smooth compared to downstream sections. At approximately 27.5 km, bed material abruptly shifts to an armored layer of large gravel, cobble, and boulders. This shift occurs immediately upstream of the confluence with Monument Canyon at approximately 27.2 km (Figure 3.11), and is evident in the longitudinal profile by the local steepening in the gradient immediately downstream of the confluence. This suggests that Monument Canyon, which is sand-bedded, is a sediment source for Canyon de Chelly. A similar local steepening at 15.8 km exists upstream of an in-channel structure (Figure 3.9). Although this steep area is not attributed to a specific control, the sediment wedge could be a result of current or past in-channel structures.

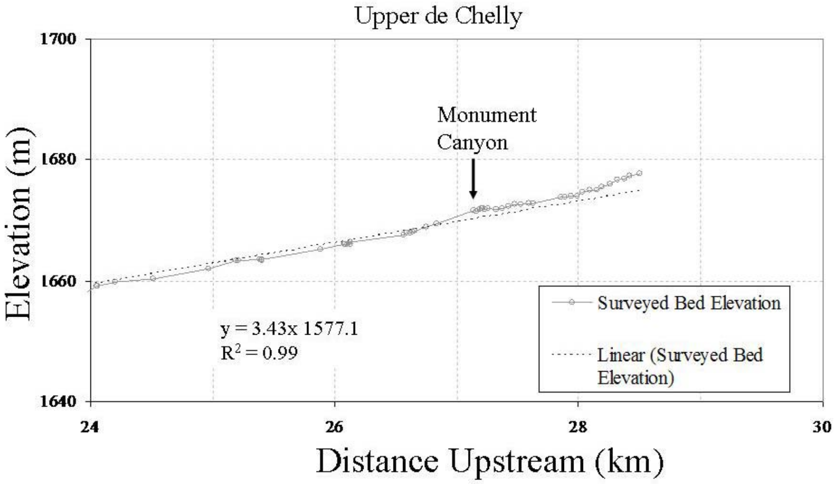

Figure 3.11 Detailed portion of Canyon de Chelly contemporary channel longitudinal profile from Figure 3.4 that contains locally steep region at confluence of Monument Canyon (27.2 km) in the Upper de Chelly section. Bed armoring occurs upstream of Monument Canyon confluence and is evident in the increased gradient beginning at 28 km. Regression equation is for linear bed elevation trendline (gray dashed line).

There are multiple places where the channel is forced against the canyon wall, but there is no obvious visual correlation between canyon wall confinement and channel planform, narrowing, or degree of incision. Confined sections of the canyon do not exhibit a different or characteristic shift in channel morphology.

Based on the analysis of aerial photographs, the channel within the Middle and Upper de Chelly reaches narrowed prior to vegetation establishment along channel margins (Cadol, 2007). Vegetation along channel margins effectively maintains the recently established narrow channel and facilitates further narrowing. Contrasting with this pattern, exotic riparian vegetation in Lower de Chelly appears to have established rapidly over a large floodplain or active channel area, which forced flow into a single-thread channel (Tal et al., 2004; Cadol, 2007). The channel was braided until this widespread vegetation establishment, which occurred in the 1980s based on aerial photograph analyses (Cadol, 2007) and tamarisk tree-ring dating (Reynolds, unpublished data). Therefore, historical narrowing in Canyon de Chelly appears to have different patterns; in the upper and middle reaches, narrowing followed a piecemeal pattern and preceded widespread riparian vegetation growth (Figure 3.12); in the lower reach, narrowing occurred simultaneously and is closely coupled to vegetation coverage (Figure 3.12).

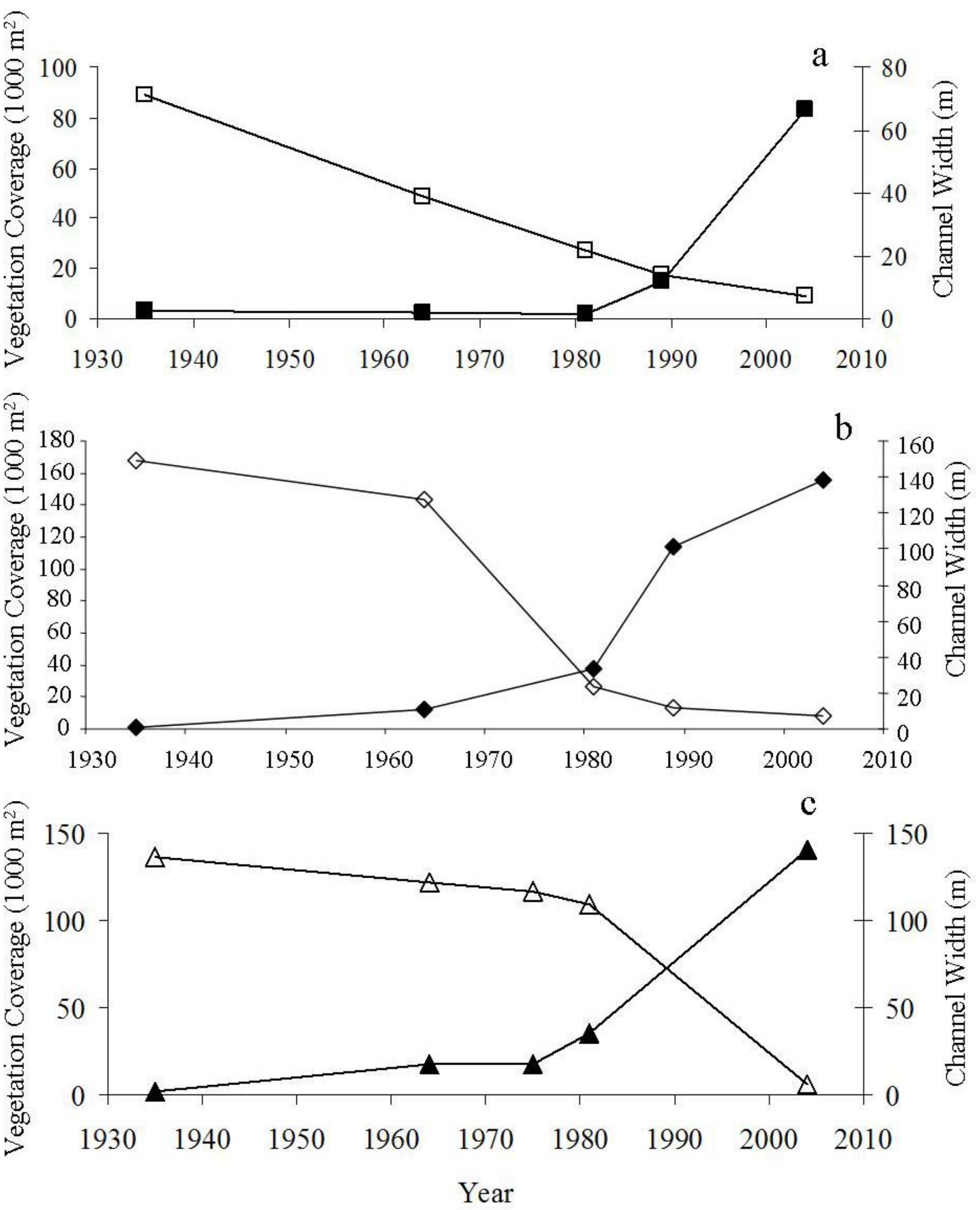

Figure 3.12 Historical channel narrowing and vegetation coverage a. Upper de Chelly b. Middle de Chelly, c. Lower de Chelly (after Cadol, 2007, Figures 3.1 and 3.4). Vegetation coverage (left vertical axis) calculated from the air photograph record is in area units of thousands of square meters. Channel width (right vertical axis) is in units of meters. Black closed points indicate vegetation coverage. Open points indicate channel width. Data are from representative 1-km-long reaches for each portion of the canyon. Channel narrowing occurred prior to widespread vegetation coverage in Upper and Middle de Chelly whereas channel narrowing coincides with vegetation coverage in Lower de Chelly.

3.4.1.3 Terraces

The high and middle alluvial terraces extend along the length of Canyon de Chelly, converging at the junction of Canyon de Chelly and Canyon del Muerto (Figure 3.13). The slopes of the longitudinal profiles of the high and middle terraces and the contemporary channel are generally parallel.

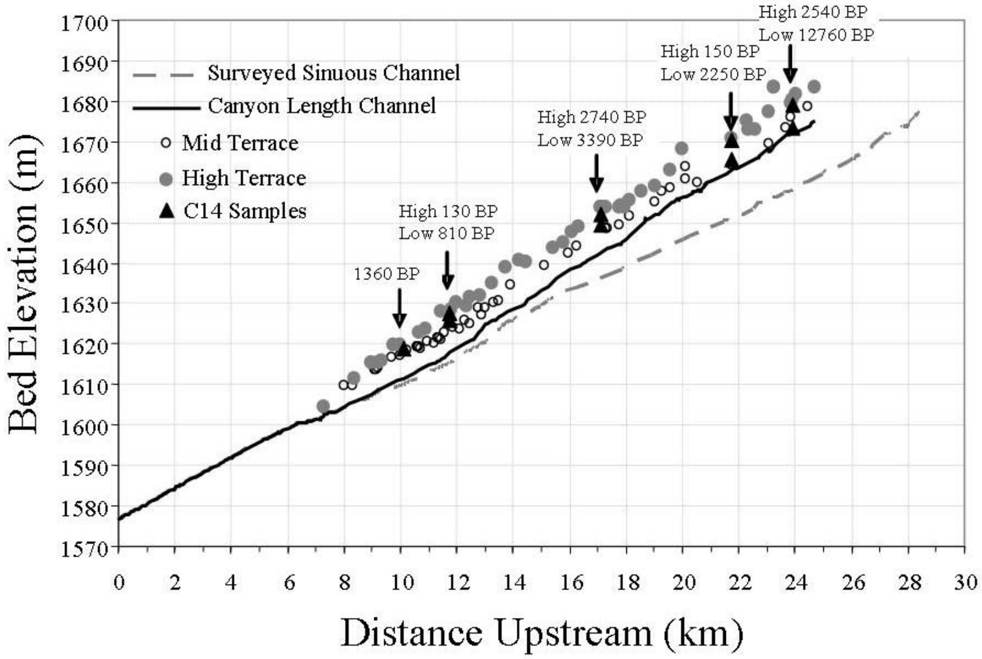

Figure 3.13 Longitudinal profile of Canyon de Chelly remnant terraces and contemporary channel. The surveyed sinuous channel (grey dashed line) is the same as in Figure 3.4 and therefore includes approximately 6 km of Chinle Wash downstream of the confluence of Canyon del Muerto and Canyon de Chelly. The canyon length channel (solid black line) does not account for contemporary channel sinuosity, only canyon sinuosity, causing the canyon length channel profile to be shorter and steeper than the surveyed sinuous channel profile. Linear trendlines fit through the canyon length channel, sinuous channel, low terrace and high terrace. Sinuous channel trendline $y = 3.57x$ 1577. Channel trendline $y = 4.01x + 1575$. Middle terrace trendline $y = 4.26x + 1574$. High terrace trendline $y = 4.46x + 1576$. C^{14} sample locations include two dates, the elevations of which are identified by black triangles. Samples are dated as before present (BP). “High” is the date for material near the top of the high terrace identified by the black triangle on the top. “Low” is the date for material near the base of the high terrace identified by the black triangle on the bottom.

There is evidence, however, of a complex history of incision over the last few thousand years based on inconsistencies in the radiocarbon dates within a terrace, subtle fluctuations in height along a single terrace surface, and the disappearance of the middle terrace from approximately 20.5 km to 23.7 km.

The number of radiocarbon samples for dating was limited because of the paucity of charcoal. I interpret anomalously young ages at some sites along the high terrace as indicating that these radiocarbon samples are compromised by substantially younger organic material. Older samples range in age from approximately 2,500 to 12,800 before present (BP). This corresponds fairly well to the relative age span of the high terrace surface in Canyon del Muerto, dated at approximately 4 to 10 ka (Dolan, 1993). The younger age of most of the Canyon de Chelly samples (less than 3,000 years BP, Figure 3.13) suggests that incision occurred later in Canyon de Chelly than in Canyon del Muerto. The terrace dates at approximately 11.7 km are very young (130-810 BP), which could result from discontinuous incision cycles along the canyon or from contamination by charcoal not fluvially deposited, but instead is the remains of a pit fire. Although the high terrace appears to reflect an early-mid Holocene depositional surface, it appears to also have experienced much more recent deposition during a subsequent phase of aggradation. The presence of cottonwood gallery forests on the middle terrace throughout the canyon indicates that this surface was at least active floodplain, if not active channel, within the last 100 years.

3.4.2 Historic climate and channel conditions

Only a very general assessment of climate conditions from 1700 until 1895 AD is possible as a result of the absence of systematic records. Although individual years of floods are identified in the paleorecord for nearby catchments (e.g., Webb et al., 1988; Webb et al., 1991), this information does not provide insight into general climate conditions, but rather serves to pinpoint timing of local arroyo cutting. Regardless, there appears to be a general absence of large floods in the paleorecord from approximately 1700 to 1880 (Webb et al., 1988; Hereford, 2002), which may be indicative of a broader climatic trend of smaller floods.

The reconstructed flow record of the San Juan River near Bluff indicates that the period from 1700 to 1750 had relatively stable discharge conditions (Woodhouse et al., 2006), although precipitation records derived from a pinyon pine tree-ring record developed for a tributary to Chinle Wash located downstream of Canyon de Chelly indicate fluctuations between wet and dry periods during this time (McAuliffe et al., 2006). After 1750, flow appears to alternate between lower and higher discharge on an approximately 25-year interval (Woodhouse et al., 2006). From about 1825 to 1875, however, discharges were high in the San Juan River (Woodhouse et al., 2006). This period (1825-1875) of sustained higher discharge corresponds to average or above-average winter precipitation within the region based on the pinyon pine tree-ring records from the Chinle Wash tributary downstream of Canyon de Chelly (McAuliffe et al., 2006). Based on the historic precipitation record (Figure 3.14), the San Juan River reconstructed flow record, and the Chinle Wash tributary predicted precipitation record, the end of the 19th century was characterized by drought, which abruptly transitioned to a wetter climate in 1905 that lasted until approximately 1920, although summer monsoon precipitation remained higher than average until about 1938 (McAuliffe et al., 2006; Woodhouse et al., 2006; NCDC, 2008).

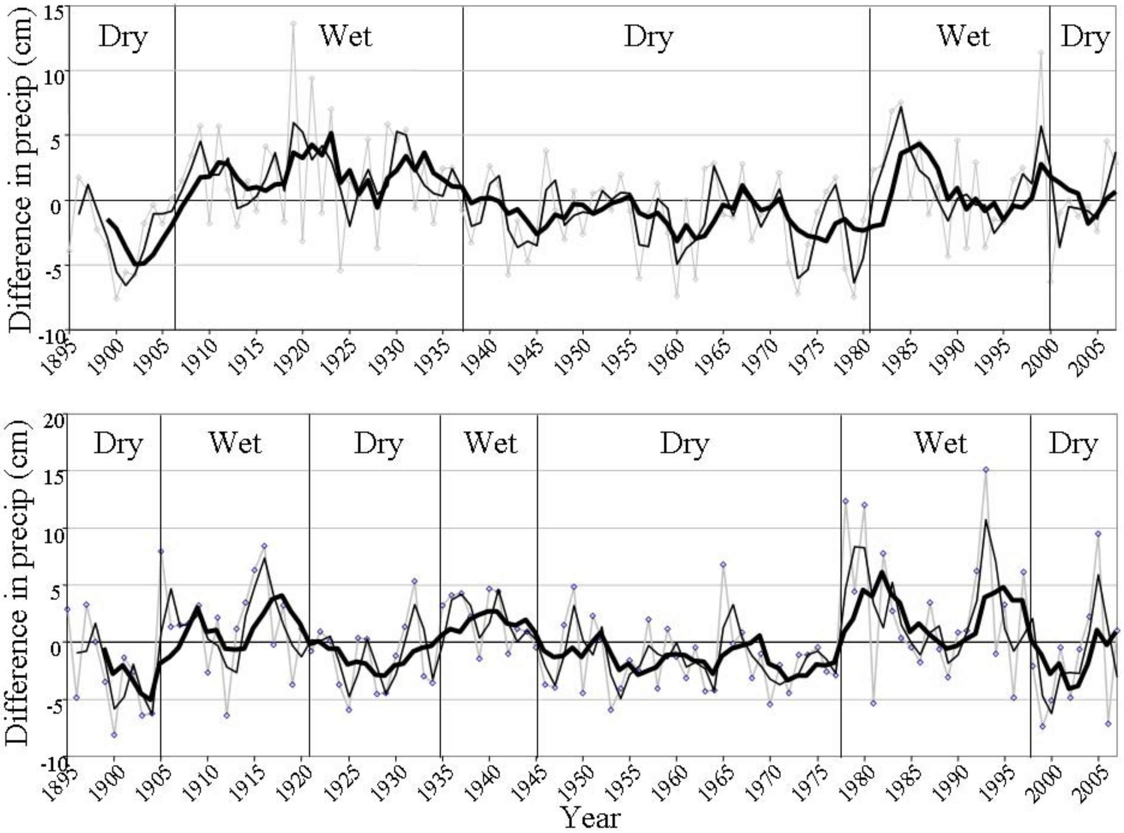

Figure 3.14 Precipitation record for northeast Arizona. Top graph is summer monsoon season (July, August, September), bottom graph is winter snowpack season (November, December, January, February). Seasonal cumulative precipitation values were subtracted from average cumulative values for that season for the period of record. Grey lines are differences in seasonal values. Thin black line is 2 year moving average. Thick black line is 5 year moving average.

This regional trend is corroborated by records from the Escalante River in south-central Utah, which experienced a series of large floods during the first three decades of the 20th century (Webb et al., 1988). Similarly, the Zuni River basin in northwestern New Mexico saw drought conditions in the last years of the 19th century and a high flood frequency after 1904 (Balling and Wells, 1990). The period from 1945 until 1977 had drier-than-average monsoon seasons (Figure 3.14); drier-than-average conditions extended longer for winter season months (1942-1980). The majority of the 1980s were wetter than average for both monsoon and winter seasons, but the Chinle Wash catchment has been under drought since 2000 (Figure 3.14).

Channel conditions within Canyon de Chelly are unknown for the 18th and most of the 19th centuries. The agricultural practice of floodwater farming suggests that the channel was not incised during this period. Historic photographs from the late 1800s depict an open, braided channel throughout Canyon de Chelly, which persisted until at least 1935, after which time channel narrowing became evident in some portions of Canyon de Chelly (Cadol, 2007). Arroyo cutting was anecdotally documented in Chinle Wash by Bryan (1925) and by Reagan (1924), who identified an approximately 30-m-deep channel downstream of Lukachukai Wash confluence and extending into the Laguna Creek tributary. There is no historical information indicating that this arroyo migrated upstream into Chinle Wash within the national monument. Based on conversations with residents within Canyon de Chelly, channel incision in Lower de Chelly began in the 1990s.

3.5 DISCUSSION

3.5.1 Longitudinal profiles

3.5.1.1 Chinle Wash

The degree of concavity of the Chinle Wash profile beginning at the head of Canyon de Chelly is typical of other longitudinal profiles at this scale (Wheeler, 1979; Ohmori, 1991; Knighton, 2000), but the presence of the gentle convexity at approximately 280 km to 380 km suggests ongoing adjustment within the system. The subtle convexity could result from the presence of near-surface bedrock or a sediment slug originating from Lukachukai Wash or upstream tributaries. In the case of a bedrock control on convexity, persistence of this feature will extend for a substantially longer time period (10^6 years) than if the feature is a sediment slug (10^2 years) (Nickolas et al, 1995). It is worth noting that the agreement between the trendlines for the lower portion of the longitudinal profile and for the overall profile indicates that the channel is not responding to changes in base level. A drop in base level would induce incision in the lower portion of the longitudinal profile, which would generate a trendline in disagreement with the overall trendline.

3.5.1.2 Canyon de Chelly

<u>Scenarios of channel response to changes in catchment-scale sediment supply and discharge conditions</u>

Stream channels will adjust vertically (depth and slope) and laterally (width and sinuosity) from the complex interplay between alterations in water and sediment supply, which result from catchment-wide changes in climate or land-use, and local factors such as valley width, bank composition, and riparian vegetation. The role of riparian vegetation on channel morphology is a confounding factor because vegetation establishment can be a response to flow and sediment supply conditions, but in turn directly influences channel change by increasing bank resistance. Therefore, it is difficult to determine whether channel morphology primarily reflects adjustment to the local influence exerted by vegetation or to larger-scale morphologic controls of sediment and discharge regimes. In an attempt to explain the causes of observed channel change in Canyon de Chelly, with emphasis on recent historic changes (last 70 years), the following is a discussion of the potential pathways within a watershed regarding relative amounts of discharge and sediment and the subsequent channel change likely to result (Figure 3.15). These scenarios are presented as a beginning framework in which to evaluate historic channel change with the understanding that a complex interplay occurs between these catchment-scale factors and local-scale controls. Low discharge conditions are interpreted as low flood magnitudes or low flood frequencies occurring individually or together. The end members of possible scenarios (high and low) are presented and encompass the overall range of potential conditions and outcomes, although changes in sediment and discharge regime occur along a gradient of magnitude.

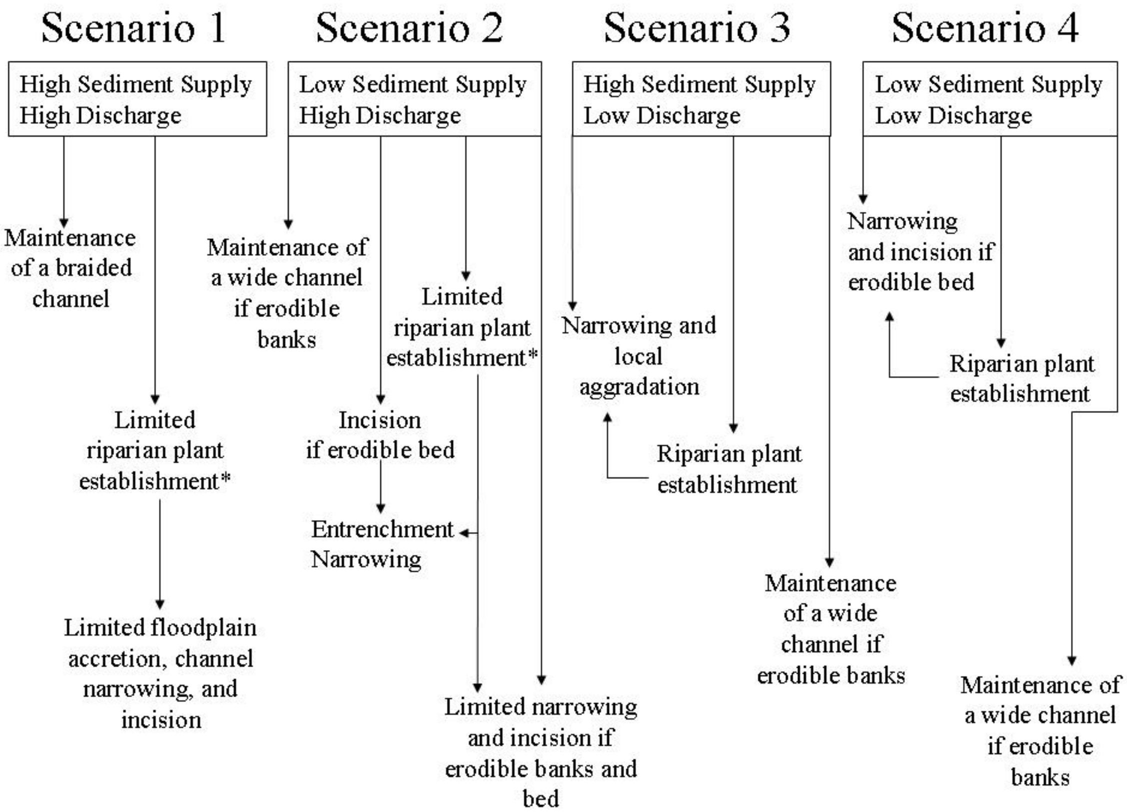

Figure 3.15 Potential watershed scenarios after 1935. Narrowing and incision occur if the channel bed is erodible. Maintenance of a wide channel occurs under high or low discharge conditions if channel banks are erodible.

Sufficient sediment and discharge are necessary to maintain a braided channel morphology, such as was documented in Canyon de Chelly by historic photographs in the late 1800s and 1935. In the first scenario, where high discharge and sediment yield conditions are sustained within the watershed, the channel would continue to be braided and narrowing and incision would be limited (Figure 3.15, Love, 1980). Maintenance of a wide channel would also occur if the flow regime remained high, but sediment supply was reduced (scenario 2), although incision could also occur associated with the diminished sediment supply and sustained high stream power (Merritt and Wohl, 2003). Channel response to changes in sediment and discharge supply is dependent on local-scale channel bank properties. If stream banks are adequately resistant, such as clay or substrate reinforced by riparian vegetation, channel narrowing would ensue under a reduced discharge regime regardless of sediment supply conditions (scenarios 3 and 4, Schumm, 1977). If banks are erodible, however, channel widening may occur (Merritt and Cooper, 2000). Riparian vegetation could establish under all four scenarios, but it is important to note that under scenario 1 of high discharge and sediment conditions, the increased hydraulic roughness from the presence of vegetation would likely result in floodplain accretion (Allred and Schmidt, 1999).

Observed channel narrowing since 1935, coupled with the existing information on climate and streamflow, does not support the two high discharge regime scenarios. The period of approximately 1942-1975 experienced drier-than-average climate conditions in northeast Arizona for both monsoon and winter snowpack conditions and generally low streamflows in the San Juan River (Figure 3.14; Woodhouse et al., 2006), which corresponds to timing of channel narrowing in the upper and middle portions of Canyon de Chelly. Rather, climatically dry conditions during the mid 20th century support the two scenarios of a diminished discharge regime. Unfortunately, the limited floodplain deposition at field sites in Canyon de Chelly does not lend support for scenarios of either high or low sediment yields. Specifically, the absence of substantial deposition (less than 10 cm) around exotic riparian plants at study sites in Lower de Chelly (L. Reynolds, unpublished data) could be an artifact of the timing of channel incision coinciding with establishment of these plants in the 1980s and subsequent narrowing based on air photograph analysis conducted by Cadol (2007) and may not necessarily indicate a period of low sediment yield. Indeed, modest floodplain accretion occurred at one study site located at approximately km 28 in the upper portion of Canyon de Chelly, where average cumulative floodplain deposition was 30 cm with a maximum of 65 cm. Accretion depths were determined by identifying the plant germination elevation of tamarisk and Russian olive plants (Friedman et al., 2005).

Although sediment supply is more difficult to determine in the absence of quantitative data, some hypotheses about historic (1800-1940) changes in watershed sediment supply can be made based on a general understanding of geomorphic response to changes in land use and climate conditions. In particular, there is a potential that catchment-wide sediment yield was at elevated levels throughout the 19th century and first few decades of the 20th century as a result of high intensity grazing practices on the Navajo Reservation. Parman (1976, p.37-38) estimated that seventy percent of land on the Navajo Reservation was eroded by the 1930s. Recovery from the impacts of livestock grazing, specifically soil compaction and destruction of cryptobiotic soil, is slow. Compaction recovery has been estimated to take 100-130 years in the Great Basin area of the US (Knapp, 1992). Re-establishment of the cyanobacteria crusts can take 35-65 years and can be slower in large areas of disturbance or in landscapes such as the Colorado Plateau, which developed under very low levels of surface disturbance (Belnap, 1995). Without data, however, I cannot infer the level of recovery (if any) during the years after the livestock reductions in the 1930s, and particularly during the climatically dry period of the mid 20th century, when there was less opportunity for sediment delivery to channels and more opportunity for upland recovery. Regardless, although the channel morphology in Canyon de Chelly prior to the historical photographs of the late 1800s is uncertain, the braided morphology was likely either created or sustained by high sediment yields, which are inferred to be elevated as a result of high livestock herd numbers. There is a potential that sediment yields could have been particularly high during the first part of the 20th century, which was characterized by an abrupt shift from a multi-year drought to a climatically wet period (NCDC, 2008). High hillslope erosion rates have been correlated to this climatic shift in the Chinle Wash tributary basin (McAuliffe et al., 2006). In addition, it is likely that sediment yield remains at a heightened level relative to pre-grazing conditions because of ongoing catchment disturbance and recovery.

Testing these scenarios would require an analysis of historical catchment conditions upstream of Canyon de Chelly to determine changes of relative sediment yield from 1800 until present. This type of analysis is extremely limited, however, by the available information of historical documents that reference range conditions anecdotally and oblique photographs, which are open to interpretation. Studies that date and source sediment on surfaces in Canyon de Chelly that had been active channel in the 20th century but are now abandoned floodplains, could provide valuable quantitative data on the relative volume and timing of sediment historically delivered to the canyon (Walling et al., 1999). Accurate estimates of current sediment yield require event-based sediment sampling over a period of several years and ideally over multiple decades (Nearing et al., 2007).

Upper de Chelly relative to Lower de Chelly and Chinle Wash: Differences in timing and character of channel response

Combined analysis of the longitudinal profile, cross-sectional geometry, and 70-year history of channel narrowing and vegetation coverage along a 28-km reach of stream channel within the national monument indicates that geometrically distinct reaches of the channel are responding differently to local and system-wide influences. In Upper de Chelly, channel narrowing occurred earlier, beginning in the 1960s (Cadol, 2007), and incision has been limited. Within the lower half of Canyon de Chelly, widespread riparian vegetation was not present until the 1980s, at which point extensive coverage of exotic tamarisk and Russian olive along the once-active channel or floodplain occurred (Cadol, 2007). Temporally coupled with the vegetation coverage is an abrupt shift from braided to a single-thread morphology and several meters of bed incision in some parts of the channel. Narrowing continues in the downstream direction into Chinle Wash, with apparently direct replacement of open channel with vegetation cover, although the channel currently maintains a braided morphology.

Inferences regarding system-wide and local controls on timing and pattern of channel response

Potential variables influencing the contemporary channel morphology and longitudinal profile include historical-channel morphology and profile, vegetation encroachment patterns, channel bed and bank material, in-channel structures, off-channel dams, climatic conditions, and land-use activities (past and present). I present a conceptual model (Figure 3.16) that illustrates observed and inferred timing of changes in control variables relative to channel response.

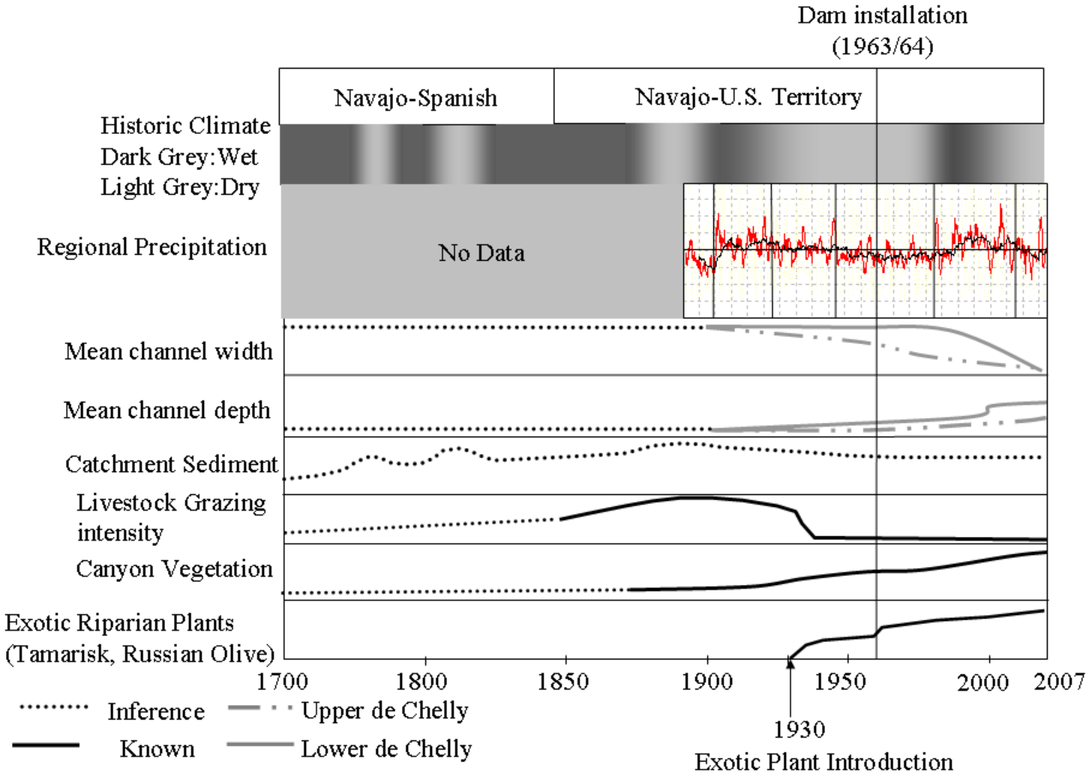

Figure 3.16 Conceptual model of Chinle Wash of controls and channel response on an historical timescale. Dotted lines indicate parameter conditions inferred from historical documentation and an understanding of probable conditions based on climate and land-use controls. Solid lines and solid-dashed lines are known conditions based on historical written records and ground and air photographs. Rates of change are indicative between high and low. Proposed sequence of changes in control variables and channel morphology in study area: late 1800's drought and intense grazing caused high sediment yield to stream channels maintaining a braided morphology, 1900-1920 climatically wet period maintained high sediment yield to channels and a braided morphology, 1945-1975 climatically dry period coupled with a decline in grazing and a potentially already depleted upland sediment supply reduced sediment to channel and narrowing began in upper de Chelly, 1980s climatically wet period allowed widespread exotic riparian establishment of active channel and floodplain in lower canyon resulting in channel narrowing and incision in lower and middle de Chelly. The two elevated catchment sediment supply periods from approximately 1750 to 1775 and 1800 to 1825 are inferred based on regionally climatically dry conditions during those time periods (Woodhouse et al., 2007).

I hypothesize that channel morphology in Canyon de Chelly reflects ongoing complex response to both system-wide and local-scale factors. Specifically, historic channel narrowing is a response to system-wide fluctuations in sediment yield and discharge regime, but the particular pattern of bed incision reflects local-scale controls. High sediment yield from degraded range land coupled with a high discharge regime through much of the mid 1800s, which is inferred from the reconstructed flow records of the San Juan River, supported a braided channel in Canyon de Chelly throughout the 19th century and into the 20th century. Channel narrowing in Upper de Chelly after 1935 could have resulted from a climatically drier period and reduced flood magnitudes and frequencies. Sediment yield may have been reduced in subsequent years after livestock reduction, although there are no quantitative data to test this possibility.

Lower de Chelly and, in general, the downstream half of Middle de Chelly, maintained a braided morphology until at least the early 1980s (Cadol, 2007). Delayed channel narrowing may be a result of sufficient sediment supply to the lower half of the canyon from upstream sources, including side canyons, to maintain the braided morphology, or could represent the remains of a sediment pulse from a previous incision event that has not yet fully translated downstream (Nickolas et al., 1995). Local conditions within this portion of the canyon during the 1980s favored widespread establishment of predominantly tamarisk and Russian olive and subsequent abrupt channel narrowing. Birken and Cooper (2006) reported maximum recruitment of tamarisk on floodplains of the Lower Green River, Utah during periods of high peak flow followed by years of low peak flow. Precipitation records from Chinle and from northeastern Arizona indicate above-average precipitation in the 1980s, coinciding with widespread establishment of tamarisk in Lower de Chelly. Tamarisk establishment across an active channel could effectively constrict flow into a confined, narrowed channel (Tal et al., 2003).

The observed character of bed incision in Canyon de Chelly indicates that the extent, timing, and magnitude of channel adjustment are influenced by local-scale controls, identified as variability in local bed and bank material, including riparian vegetation establishment and the locations of in-channel structures. Substrate in the downstream half of the canyon is largely unconsolidated, non-cohesive sand and silt, facilitating bed incision within channel banks reinforced by exotic vegetation (Pollen and Simon, 2005). Further entrenchment has occurred as the channel has incised below the unconsolidated alluvium into a clay unit, which maintains vertical channel banks as competently as sand and silt reinforced by vegetation roots. Upstream propagation of bed incision, however, appears to be temporarily limited by the presence of quasi-functioning in-channel structures at approximately 13.0 km and potentially by sediment supply from side canyons at the knickzone location. I expect that as these structures fail completely, incision will continue upstream. The extent of incision will be limited by coarse bed material within the contemporary channel and mitigated by sand supply from Monument Canyon.

The presence of Wheatfields Dam appears to have limited, if any, influence on channel morphology within the canyon. The annual peak discharge in Canyon de Chelly typically occurs during the summer monsoon season, when discharge is not regulated by the dam. These discharges are highly turbid and supply substantial sediment to the system despite their short duration. Several centimeters of new deposition of both coarse and fine sediment have been observed on the stream bed and along channel banks throughout Canyon de Chelly following a monsoon discharge event. Because sediment and water are not being trapped in Wheatfields Reservoir at this time, but instead flow freely from the Chuska Mountains over the rim area and into the canyon, I expect that the sediment regime is less altered than if flow were diverted during this time. Sediment trapped behind the Wheatfields Dam comes from winter flows that typically carry less sediment and are of smaller magnitude, but longer duration. These flows from the Chuska Mountains likely carry coarse bedload that are trapped behind the dam. Bed incision and armoring downstream of a dam can occur from a reduced sediment supply to downstream portions as a result of the dam, but this channel response typically occurs immediately downstream of the dam (Kondolf, 1997). Channel incision in Canyon de Chelly is located more than 30 km downstream of Wheatfields dam, and, therefore likely is not a result of diminished sediment supply from the Chuska Mountains. In addition, flow is not diverted away from the canyon during the late spring runoff and recruitment window for native riparian cottonwood and willow seeds (Mahoney and Rood, 1998; L. Reynolds, unpublished data).

Residual bed elevations are higher than the predicted trendline elevation within Chinle Wash, indicating the potential presence of a sediment pulse. There is no evidence of historical incision within the past 80 years, which would preclude the idea that the knickzone currently at 13.5 km in Canyon de Chelly had propagated from within Chinle

Wash, although it is expected the knickpoint began in Lower de Chelly as a consequence of channel narrowing. Sediment produced from recent channel incision in Lower de Chelly likely is not volumetrically sufficient to maintain the braided morphology of Chinle Wash. This pulse of sediment might be from a previous incision cycle and is either being maintained by sediment from the current limited incision in Canyon de Chelly or is degrading over time through a net export of sediment over the entire braided channel. Vegetation encroachment and channel narrowing are evident within Chinle Wash, however, and I expect channel incision through the non-cohesive alluvium to occur once the channel reaches a critical minimum.

3.5.1.3 Terraces

The discontinuities in terrace ages illustrate the complex alluvial history characteristic of Canyon de Chelly. The earlier dates of the high terrace compared to Canyon del Muerto indicate that incision may have occurred later in Canyon de Chelly. Asynchroneity between canyons in smaller catchments has been interpreted to result from local intrabasin controls of sediment supply and transport capacity; specifically, the episodic timing of mass wasting in small tributary canyons (Boison and Patton, 1985; Patton and Boison, 1986). Asynchroneity of incision and fill events between canyons within larger basins can occur as the channel network gradually responds to internal variation in sediment transport and storage or to external variation in base level, sediment supply, or flow regime (Gellis et al., 1991; Graf et al., 1991). Substantial differences in catchment area and local variability in precipitation, by creating differences in the timing and frequency of the flow regime and magnitude of sediment delivery, can exacerbate asynchronous responses across a larger channel network such as that of Chinle Wash. The range of terrace ages suggests that the spatial variability in timing and magnitude of channel adjustment present within the contemporary channel network reflects asynchronous channel adjustment in the area throughout the Holocene.

Cycles of incision, filling, and discontinuous gullying have been extensively documented throughout the southern Colorado Plateau (Schumm and Hadley, 1957; Cooke and Reeves, 1976; Hereford, 1986; 2002). These records indicate that most channel networks in the region incised from the late 19th century through the mid 20th century and subsequently aggraded (Figure 3.13b). This contrasts with the timing and direction of channel change at Canyon de Chelly, although asynchroneity in the specific timing of incision and filling between basins has occurred elsewhere. According to Graf (1987), the Canyon de Chelly catchment area (1 250 km^2) places the study area within the category of streams on the Colorado Plateau that are sensitive to climatic and land-use changes and will alternatively retain or export large amounts of sediment in response to these external forces (Graf, 1987). In contrast, larger streams will only retain or export moderate amounts of sediment in response to upstream events. Chinle Wash downstream from the national monument fits the description of a larger stream based on the general absence of inset terraces and the potentially temporary storage of sediment from some upstream source in the subtle concavity at approximately 160 km in the longitudinal profile.

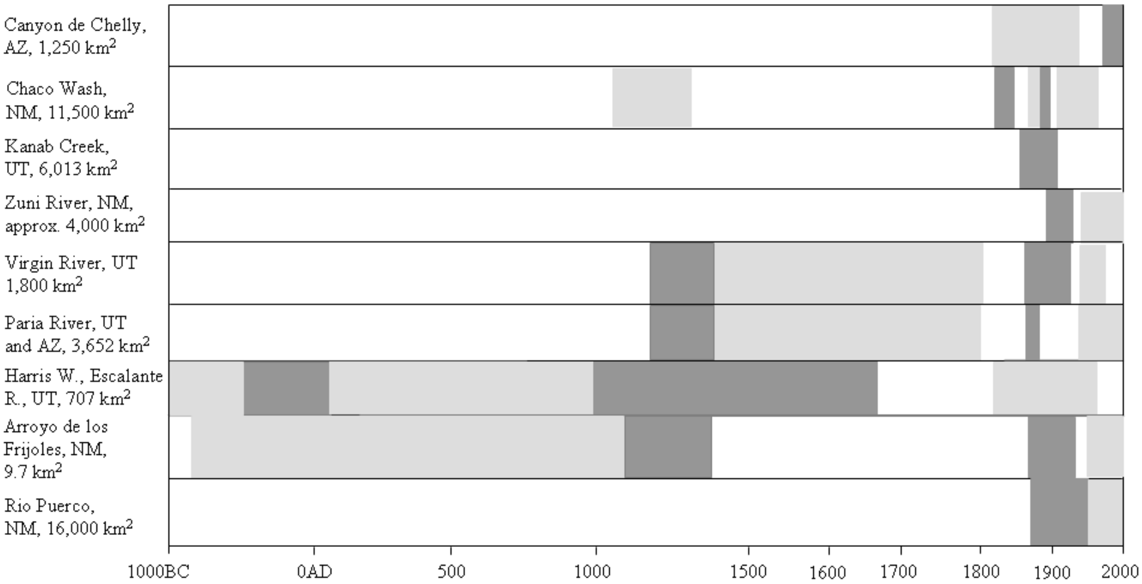

Figure 3.17 Timeline of arroyo incision and filling for basins on the Colorado Plateau near Canyon de Chelly. Dark periods indicate incision, light periods indicate aggradation. Arroyo los Frijoles, NM: Gellis et al., 2005; Chaco Wash, NM: Gellis et al., 2002; Kanab Creek, UT: Webb et al., 1991; Zuni River, NM: Balling and Wells, 1990; Virgin River, UT: Hereford et al., 1996; Paria River, UT and AZ: Hereford 1986, Graf et al., 1991, Hereford 2002; Harris Wash, Escalante River, UT: Patton and Boison, 1986, Coyote Terrace, Santa Fe, NM: Leopold 1976, Leopold et al., 1966; Rio Puerco, NM: Aby et al., 1997, Molnar and Ramirez, 2001.

3.6 CONCLUSION

Vertical channel instability is apparent within Chinle Wash at multiple spatial and temporal scales. Although tamarisk and Russian olive are potentially exerting a strong influence on the contemporary channel morphology, the current channel form, in particular, and the historic narrowing that occurred, could primarily reflect watershed-scale changes, specifically a diminished flow regime during the mid 19th century. In the absence of quantitative data on sediment yield, I cannot determine whether sediment supply to Canyon de Chelly was also diminished. In terms of channel incision, the relative magnitude, extent and timing of incision appear to be dominated by local-scale controls, specifically riparian vegetation, bed and bank material, and in-channel structures. Once vegetation became established, it is an effective agent in maintaining a narrow channel and aiding bed incision. In addition, differences in stream bank and bed material have facilitated incision in some channel reaches while impeding incision in other reaches. Further, the presence of quasi-functioning in-channel structures limits the upstream extent of channel incision, although this local control will become obsolete if the structures fail.

A predicted climatic shift to more arid conditions within the American Southwest (Seager et al., 2007) could cause an increase in sediment production in the upland areas and subsequent delivery to the channel. In this scenario, channel aggradation could occur, although the channel is unlikely to return to conditions present prior to 1935 unless exotic riparian vegetation is actively removed. An exotic plant removal program was implemented in Canyon de Chelly in 2005 with the objective of facilitating bank erosion and presumably channel widening and aggradation. Although the magnitude of widening and aggradation will depend on multiple factors (climate, flow regime, extent and manner of removal of exotic riparian vegetation, continuing complex response throughout the channel network), removal of exotic riparian vegetation on spatial scales of 10^1-10^3 m^2 is unlikely to cause the channel to resume its historically braided planform, in the absence of changes in other controlling factors, because of the continuing presence of relatively abundant native riparian species. A return to the braided planform of the earlier 20th century would likely require substantial increases in sediment yield at the watershed scale, an increase in flood magnitude and/or frequency caused by regional climate change, and perhaps complete removal of riparian vegetation. Projected increases in aridity under global warming make this scenario unlikely, particularly with respect to changes in flow regime. Chapter 4, however, will provide insight on channel adjustment to a portion of this scenario by quantifying channel change to the removal of tamarisk and Russian olive in test reaches in Canyon de Chelly.

3.7 REFERENCES

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4 PREDICTED AND OBSERVED CHANNEL RESPONSE TO REMOVAL OF EXOTIC RIPARIAN VEGETATION IN A SEMI-ARID STREAM

4.1 INTRODUCTION

The exotic plant species tamarisk (*Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro, and their hybrids) and Russian olive (*Elaeagnus angustifolia* L.) have become widespread throughout riparian areas of the arid and semi-arid American West (Gaskin and Schaal, 2002; Glenn and Nagler, 2005). Initially introduced as an erosion control measure, windbreak, and ornamental, the plants have become prolific through natural dispersal (Robinson, 1965; Horton, 1977; Katz and Shafroth, 2003), which has been facilitated in some streams by anthropogenic alterations in flow regimes (Sher et al., 2002; Stromberg et al., 2007). Coincident with plant invasion is geomorphic change to river and stream channels (Graf, 1978; Allred and Schmidt, 1999; Birken and Cooper, 2006), and subsequent alterations in ecological functions of riparian areas (Zavaleta, 2000; Tickner et al., 2001). Management-induced alterations in the natural flow regime confound the geomorphic influence of exotic vegetation (Stromberg, 1998) but, aside from this point, vegetation along channel banks increases bank strength properties and resistance to erosion, thus facilitating channel narrowing and incision and/or floodplain accretion (Graf, 1978; Allred and Schmidt, 1999; Tal et al., 2003). Ecological processes are altered by monotypic stands of tamarisk and Russian olive, which can hinder native vegetation establishment, increase soil salinity, and modify native wildlife habitat and assemblages (Shafroth et al., 2005).

The extensive colonization of tamarisk and Russian olive along fluvial systems throughout the southwestern US and subsequent degradation of these landscapes has generated a need to address rehabilitation efforts that specifically target the management of exotic riparian species. Methods to manage exotic plants once they have established include burning, cutting and herbicide application, entire plant removal including their roots, and applying biological agents such as a plant-eating insect (Shafroth et al., 2005; Shafroth and Briggs, 2008). Exotic woody riparian vegetation removal projects have tracked ecological response in terms of water salvage (Culler et al., 1982; Welder, 1988), native plant recovery (Harms and Hiebert, 2006), and wildlife response (Nelson and Wydoski, 2008), but little work has been done that quantifies geomorphic channel response to plant removal. With an increase in stream rehabilitation projects in arid and semi-arid regions that specifically target exotic riparian plant control, comes the need to understand which removal methods are most effective for recovery of stream channel morphologic functions.

Both short-term (1-5 years) and particularly long-term (>10 years) channel response to exotic plant removal are of interest to land managers. Although field-measured data on channel adjustment are ideal, management decisions sometimes must be carried out in a shorter time frame that does not allow for longer term (>10 years) monitoring of channel response. In the absence of field data, physically based models that reasonably describe the driving and resisting forces controlling channel adjustment can provide a range of realistic scenarios of channel response to exotic plant removal over the long term (10-100 years). Models are particularly useful when the field survey period is short or does not include the large magnitude, low frequency stream flows during which the most geomorphic work occurs, and which are characteristic of semi-arid fluvial systems (Wolman and Gerson, 1978). In these scenarios, models can be used to test hypotheses related to channel change resulting from such flows for use by land managers.

As part of a national effort to control tamarisk, the US National Park Service wishes to determine the most effective plant removal method for recovery of geomorphic and ecological functions along semi-arid, sand-bedded river systems. Over the last part of the 20th century, stream channels in Canyon de Chelly have experienced channel narrowing and incision that are concurrent with widespread establishment of tamarisk and Russian olive. With narrowing and incision has come a decline in groundwater elevations, a loss of traditional farming, and a loss of the historic canyon view of open landscape. Canyon de Chelly was identified as a study site for implementation of a pilot project that evaluates geomorphic and ecological responses to two exotic plant removal methods. One method included cutting the above-ground portion of the plant flush to the ground surface and applying an herbicide (cut-stump method). In this first method, the roots along channel banks can persist for several decades, thus potentially providing sustained increased resistance to bank erosion even in the absence of the above-ground portion of the plant. The second method involved removing the entire plant including the roots using heavy machinery (whole-plant method). The two plant removal methods were implemented in Fall 2005 at four study sites in Canyon de Chelly. During the field study from Summer 2005 until Spring 2008, the study sites were subject to flows typical of the semi-arid region, which ranged from no flow periods to bankfull or slightly overbank flows associated with late summer monsoons.

The objectives of the work presented here are to 1) quantify short-term (3 years) geomorphic channel adjustment, specifically cross section geometry, slope, and channel bed grain size, to the two exotic vegetation removal methods through direct field observation, 2) simulate channel response to vegetation removal and a series of relatively small magnitude flows using CONCEPTS, a 1-dimensional hydraulic model, and validate simulations using field data, and 3) simulate channel response over a longer time scale (10 years) which includes lower frequency, larger magnitude flows using a surrogate discharge record. Specific hypotheses to be tested are 1) the whole-plant removal treatment will result in a larger increase in cross sectional area through channel widening relative to the cut-stump method, 2) the cut-stump removal method will have similar but decreased effect on the channel geometry as a result of the remaining plant roots providing higher erosive resistance, and 3) channel morphology adjustment will depend on the magnitude of flows, with the largest flows causing the most channel change. This work presents not only field results of channel response to exotic plant removal, but also the first application of the CONCEPTS model to semi-arid stream channels. Prior to this study, application of CONCEPTS has been limited to the mid-south and midwestern United States and California (Wells et al., 2007; Langendoen and Simon, in press; Langendoen et al., in review).

4.2 STUDY AREA

Field work was conducted at four study sites located within the de Chelly portion of Canyon de Chelly National Monument. The four study sites listed in downstream direction are Spider Rock (SPR), Sliding Rock (SLR), Upper White House (UWH), and Lower White House (LWH) (Figure 4.1). Sites were chosen because of the relatively consistent channel conditions throughout the extent of each site in terms of cross section geometry, bed gradient, bank and bed sediment properties, and riparian vegetation characteristics (Table 4.1). The channel at all study sites is a single thread meandering

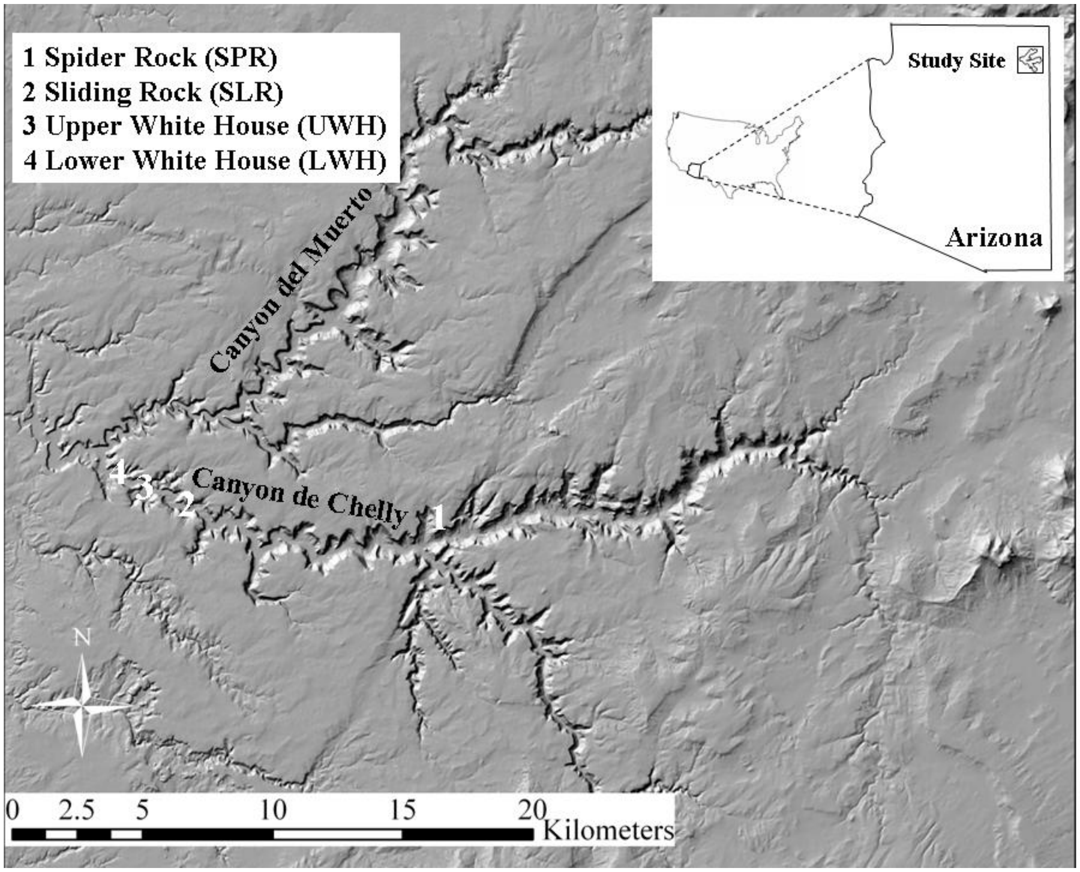


Figure 4.1. Map of Canyon de Chelly National Monument, Arizona, USA. and 4 exotic plant removal study sites.

Table 4.1 Study site summary statistics for all four study sites listed in downstream direction in Canyon de Chelly, Spider Rock (SPR), Sliding Rock (SLR), Upper White House (UWH), and Lower White House (LWH). Reach type includes the control and plant removal treatments cut-stump and whole-plant removal.

Site	**Drainage Area (km^2)**	**Reach**	**Cross Sectional Area (m^2) (st dev)**	**Top Width (st dev)**	**Thalweg Depth (st dev)**	**Width/ Depth Ratio (st dev)**	**Slope (st dev)**	**D84 (mm)**	**Vegetation**
SPR	655	Control	13.43 (2.96)	13.03 (3.01)	1.63 (0.13)	8.07 (2.23)	0.0073 (0.0022)	122 (85)	Russian olive/Tamarisk
		Cut-stump	11.62 (3.52)	11.09 (4.04)	1.60 (0.29)	7.11 (3.15)	0.0053 (0.0031)	92 (60)	
		Whole-plant	11.39 (1.00)	10.11 (0.96)	1.55 (0.12)	6.51 (0.47)	0.0031 (0.002)	40 (42)	
SLR	1012	Control	22.69 (10.15)	11.24 (3.32)	2.60 (0.43)	4.44 (1.48)	0.0037 (0.0008)	31 (45)	Mixed Cottonwood, willow, Russian olive, tamarisk
		Cut-stump	14.66 (3.64)	8.45 (0.91)	2.42 (0.57)	3.62 (0.69)	0.0034 (0.0027)	0.5 (0.02)	
		Whole-plant	22.57 (5.01)	11.25 (2.15)	2.89 (0.39)	3.98 (1.10)	0.0052 (0.0031)	0.4 (0.0)	
UWH	1019	Control	27.71 (11.02)	11.94 (2.56)	2.57 (0.67)	4.75 (0.81)	0.0034 (0.0017)	18 (24)	Russian olive/Tamarisk
		Cut-stump	28.89 (12.46)	13.90 (4.70)	2.92 (0.69)	4.77 (1.02)	0.0029 (0.0008)	19 (21)	
		Whole-plant	34.67 (15.73)	17.33 (6.22)	2.86 (0.63)	6.07 (1.61)	0.0029 (0.0011)	24 (53)	
LWH	1461	Control	11.56 (2.87)	10.01 (1.61)	1.61 (0.27)	6.36 (1.60)	0.0026 (0.0013)	16 (26)	Russian olive/Tamarisk
		Cut-stump	20.68 (3.03)	13.75 (2.27)	2.14 (0.17)	6.48 (1.31)	0.0036 (0.0021)	17 (20)	
		Whole-plant	30.27 (15.35)	17.12 (4.95)	2.59 (0.85)	6.79 (1.19)	0.0021 (0.0008)	0.5 (0.0)	

morphology 5-15 m wide and from 1 to 2 m to more than 8 m deep. The stream banks consist of sequences of sand, silt, and clay. In SLR, the channel has incised approximately 1.5 m into a clay layer, which is at least 3 m thick as determined by augering into the channel bed at this location. In UWH, the stream channel is only beginning to incise into the clay layer; the toe of the banks consists largely of silt and sand. Bed material is mainly sand with a veneer of small gravel in patches and along channel margins. However, in SPR, the farthest upstream site, bed material is an armored layer of large gravel, cobble, and boulders.

The canyon bottom is characterized by a wide belt (approximately 200 m in some areas) of riparian vegetation with more xeric shrub and grass species on higher terrace surfaces. Riparian vegetation is a combination of native cottonwood (*Populus fremontii* S.Watson) gallery forest, mixed stands of cottonwood, willow (*Salix exigua* Nutt., *S. gooddingii* C. R. Ball), exotic tamarisk (*Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro, and their hybrids) and Russian olive (*Elaeagnus angustifolia* L.), and dense stands of tamarisk and Russian olive. The upland vegetation community, which includes prickly pear and cholla species (*Opuntia spp.)*, rabbitbrush (*Chrysothamnus nauseosus* Britton), and cheatgrass (*Bromus tectorum* L.), is indicative of areas impacted by grazing.

4.3 METHODS

4.3.1 Study Design

This study included evaluation of two exotic plant removal methods. One method, termed cut-stump removal, involves cutting vegetation flush to the ground, leaving the root structure in place, and applying herbicide to the above-ground stumps. The herbicides used were Tricoplyr Triethylamine Salt (Tahoe 3A, Nufarm Americas, Inc.)

and Butoxyethyl Tricoplyr (Tahoe 4e, Nufarm Americas, Inc.). The second method, whole-plant removal, is the removal of the entire plant using a back hoe and re-grading surfaces disturbed by back hoe digging. Each of the four study sites was divided into three 300-m-long reaches. A 300-m-long control reach was located at the upstream extent of the treatment reach, followed by a 300-m-long cut-stump removal treatment reach and a 300-m-long whole-plant removal treatment, respectively. An approximately 200-m length of untreated channel separated the two plant removal treatments. Because of the difficulty in obtaining reasonably uniform channel characteristics over channel lengths extending beyond approximately 1.5 km, the reach types (control, cut-stump, and whole-plant) were located immediately upstream or downstream of each other in a sequential order that prevented downstream effects of one reach type on another. As a result, the whole-plant removal reach, which was hypothesized to have the most channel adjustment, was positioned downstream of the control and cut-stump reach and a 200-m buffer separated the cut-stump from the whole-plant reaches to minimize effects of the cut-stump reach on the whole-plant reach. Cross sections within each reach were spaced approximately 50 m apart, with 7 cross sections located within the control and whole-plant treatment plot, and 6 cross sections in the cut-stump plot. Native riparian vegetation, which occurred along portions of the SLR and LWH whole-plant and cut-stump treatment reaches, was left intact.

Plant removal treatments were initiated in Fall 2005. The cut-stump removal method was carried out at four study sites, with re-application occurring as needed in some sites. Whole-plant removal occurred in the spring and summer of 2006 for UWH, SLR, and SPR and fall 2006 for LWH. In the LWH and UWH sites, the whole-plant removal treatment could not take place along the right bank and left bank, respectively, as a result of limited access for back hoes. Instead, the cut-stump treatment was applied to these banks.

4.3.2 Field Methods

Elevation surveys of stream channel cross sections were conducted prior to plant removal treatment during Summer 2005 using standard surveying methods. Annual post-treatment repeat surveys of the cross sections at all sites occurred during Summer 2006 with the exception of the whole-plant treatment reach in LWH because treatment for this reach was incomplete by the end of that summer field season. All cross sections at all site reaches were re-surveyed during Summer 2007 and approximately every other cross section was resurveyed at the UWH and LWH site reaches during Spring 2008. Additional surveys were conducted at every other cross section in UWH immediately following three late summer monsoon season individual flows (July 24, 2006, July 31, 2007, and August 5, 2007). During these surveys between individual flows, the high water mark of the most recent flow was documented. Cross sections were surveyed at sub-meter distances within the channel and at distinct topographic breaks on stream banks and floodplain surfaces. Repeat surveys only included the channel unless overbank flows had occurred onto the floodplain, as evidenced by fresh fine-grained and other flood-debris deposits on overbank surfaces. Vertical and horizontal error associated with the surveying technique was limited to less than 5 cm, determined by the difference in elevation or horizontal distance between annual surveys of cross section benchmarks.

Channel banks at each cross section were characterized based on a visual estimate according to the general substrate that composed the banks (sand, silt-sand, silt-clay-sand,

and clay) and density of roots (high, medium, low, or none) exposed and occurring along the bank. In addition, a pebble count at each cross section was conducted for the 2006 and 2007 annual survey (Wolman, 1954; Kondolf, 1997). Pebble counts were carried out by using a zig-zag method that extended approximately 10 m upstream and downstream from each cross section. Finally, a general assessment of bank stability was made for each reach within each study site using a ranking scheme developed by Simon and Castro (2003).

A continuously recording stream gage (Judd Ultrasonic Depth Sensor) was installed between the LWH and UWH study sites (approximately 1 km downstream of UWH) in February 2006. Streamflow stage was recorded at 5-minute intervals. The distance between the depth sensor and the streambed was updated after most individual flows to account for changes to the streambed elevation that may have occurred during the previous flow. The difficulty of maintaining gage operation at this particular location resulted in gaps within the hydrograph record, which is limited to the time period between February 2006 and August 2007. In August 2007, a high flow inundated the gage sensor, rendering it inoperable.

4.3.3 Statistical Analysis

Statistical analyses were used to determine whether 1) differences in channel change over time exist between the control and plant removal treatments, and 2) potential differences in channel change correlate with different plant removal methods. Additional analyses included a comparison with channel change to cross section-average unit stream power to determine whether areas of maximum channel change are also regions of maximum stream power and to facilitate a comparison of channel change within the same cross section as a result of seasonal differences in discharges (e.g., monsoon discharges versus winter baseflow and spring runoff).

To address the first objective, statistical analysis for differences in channel change between reach types (e.g., control, cut-stump, whole-plant) were conducted using a parametric ANOVA test for differences in means or the non-parametric Wilcoxon Rank Sum test for significant differences ($\alpha = 0.05$) in medians when the data did not conform to the assumptions of an ANOVA (PROC NPAR1WAY WILCOXON: SAS Institute 2004). Pairwise tests to identify individual groups were performed using Kruskal-Wallis tests. To avoid a type I statistical error, significance level was adjusted using a Bonferroni correction. Pairwise comparisons for significant differences in variance between reaches were performed using Levene's test for homogeneity of variance using a Bonferroni correction. Channel change response variables included the channel cross sectional geometry metrics *area*, *perimeter*, *width*, *depth*, *average depth*, *hydraulic radius*, and *width/depth ratio* (using both depth and average depth). These metrics were calculated using the same top of bank elevation between survey years. Channel depth was calculated by taking the difference between the top of bank and thalweg elevations. Average channel depth was calculated using

$$\text{Average depth} = \text{Area}/\text{Width} \tag{2}$$

Differences in channel adjustment for the channel geometry metrics listed above and d84 streambed clast size were calculated by taking the difference between the pre-treatment 2005 and either 2007 or 2008 post-treatment measurement for all channel metrics for each cross section. Negative values indicate an increase in channel geometry (e.g., channel widening or deepening) or increase in d84. Differences were normalized by dividing the values by 2005 geometry values to produce a percent change of the pre-treatment cross section.

Unit stream power was calculated for each cross section using

$$\omega = QS/w \tag{3}$$

where ω is unit stream power, Q is the estimated peak discharge magnitude (m^3/s) for highest measured stage during the study period, S is channel cross section bed slope used as a surrogate for friction slope, and w is channel width the base of the bank (w_b). Width at the base of the bank was used because wetted width was not measured at all cross sections during this peak discharge event and top width is not be a suitable metric for channels that are incised such that even high flows do not overtop the bank. Methods to estimate the peak discharge are described below (Section 4.3.4.2). Channel cross section slope (S) was calculated based on the distance and elevation of the downstream and upstream cross sections. Unit stream power at a cross section was compared to the total change in cross sectional geometry in terms of area, top width, thalweg depth and average depth to determine if areas of maximum cross section change correspond to maximum unit stream power.

In order to look at differences between different types of discharge events (e.g., monsoon versus spring runoff), cross section change was calculated using repeat surveys within the UWH study site. Channel adjustment (area, width, average depth, and depth) resulting from monsoon discharges was calculated by taking the difference between pre-monsoon (June 2006 and July 2007) cross section geometry and post-monsoon/pre-winter (September 2006 and August 2007) cross section geometry. Winter baseflow and spring runoff channel adjustment was calculated by taking the difference between the pre-winter cross section surveys (September 2006 and August 2007) to post-spring runoff surveys (June 2007 and May 2008). Significant differences in channel adjustment resulting from the different seasonal discharges were identified using a paired T-test (Proc T-Test, SAS, 2004).

Correlations between channel geometry metrics and plant removal methods were evaluated using a univariate randomized block design with repeated measures. The reach types (control, cut-stump, and whole-plant) were treated as randomized blocks because it was assumed that there were no downstream effects of one reach on another (e.g., no effect of the cut-stump reach on the downstream whole-plant reach). Because cross sections were surveyed repeatedly, a repeated measures statement is included to account for interdependence between measurements. Explanatory variables included ***reach*** (control, cut-stump removal, and whole-plant removal), the particular ***year*** that the survey took place, and an interaction term that combined ***reach by year***. Because only four study sites were included in the statistical analyses, including additional potential explanatory variables other than reach type, year, and the interaction term reach by year resulted in over-parameterization of the statistical model and were thus not included in the model. A first-order autoregressive covariance structure (ar(1)) was included to account for autocorrelation between measurements on cross section geometry repeated through time. In addition, the denominator in the degrees of freedom for tests of fixed effects was calculated using methods that account for unequal variances among treatment reaches (Kenward and Roger, 1997).

Significant ($\alpha = 0.05$) correlations between differences in channel change and plant removal methods were identified using both a mixed effects model, that included both fixed and random effects, and a fixed effects model, where no effects were treated as random (PROC MIXED, SAS Institute, 2003). In the mixed effects model, the four study sites represent sites selected from a larger population. They are treated as random effects in the mixed effects model and inferences regarding model results are extended to stream channel reaches throughout Canyon de Chelly. This analysis allowed for evaluation of potential correlations across time between channel geometry and the explanatory variables identified above while accounting for the variability that exists at several spatial levels (across study sites, plant treatment within a site, and within individual cross sections) when each of these levels is included as a random effect. Through inclusion of an intercept statement, I was able to account for inherent correlation of measurements within the same level of inference. For example, if the analysis included correlations between channel geometry and treatment at the treatment-by-site level, the intercept statement accounts for correlation that exists for cross sections located within the same study site and plant removal treatment. In addition, the effect of exotic plant removal on channel adjustment was evaluated within an individual year. In the fixed effects model, the effect of study site is fixed, which prevents inference beyond the individual study site. Explanatory variables significant at $\alpha = 0.05$ indicate a correlation between that variable and the response variable. Models with minimum Akaike Information Criterion$_C$ (AIC$_C$) and which included only significant variables ($\alpha = 0.05$) constituted the selected, final model. Only one model was selected among the models of various levels of random effects. The AIC$_C$ values include a second-order correction within AIC for small sample sizes (Akaike, 1974; Burnham and Anderson, 2004). This type of model selection is based on the accuracy of the maximum likelihood estimator to the true parameter value. The maximum likelihood estimator is the most likely estimate of a parameter value, giving the observed data the largest possible probability of occurring. For example, for a dataset of normal distribution, the maximum likelihood estimator of the population mean is the sample mean. The AIC_{min} is interpreted as the smallest estimated loss of precision as a result of using the maximum likelihood estimate instead of the true, but unknown, values in the likelihood function (Dayton, 2003).

Channel bank characteristics including average calculated bank angle and presence of clay at the bank toe are covariates that likely influence channel adjustment, but they were not included as explanatory variables in the mixed and fixed effects statistical models because of the over-parameterization issue. Instead, these variables were evaluated qualitatively to identify potential mechanisms of channel response beyond implementation of plant removal treatments. Bank angle was computed by calculating the slope from the top of bank to bank toe and converting the value to degrees. The bank stability rank value is a treatment-averaged value and therefore could not be included in the statistical analysis of individual cross sections, but was included for statistical analysis of reach-averaged values of channel response.

4.3.4 Modeling Analysis

The channel evolution model, CONservation Channel Evolution and Pollutant Transport System (CONCEPTS), was used to simulate channel change in response to vegetation removal at the UWH study site. The simulation time period included the 3-year study period of direct field measurements as a model calibration exercise and a 60-

year time period using a surrogate discharge record to simulate long-term channel adjustment including adjustments during high magnitude, low frequency discharges not experienced during the 3-year field study. CONCEPTS, developed by the USDA-ARS National Sedimentation Laboratory (Langendoen, 2000, 2002; Langendoen and Alonso, 2008), is a one-dimensional, reach-scale model that incorporates bank erosion processes, open-channel flow hydraulics, and sediment transport. This model was chosen specifically because it allows for partitioning of streambanks into separate soil layers with distinct geotechnical strength properties and therefore accommodates the different erosion processes associated with cohesive and non-cohesive substrates as well as strength properties associated with riparian vegetation.

4.3.4.1 Modeling Scenarios

The model exercise included three simulation periods with the objective of identifying the larger magnitude, lower frequency flows that are likely to create substantial channel change in these arid/semiarid channel systems (Wolman and Gerson, 1978; Graf, 1983, 1988; Tooth, 2000). The first simulation period extends from July 2006 until August 2007, which includes the period of record for the stream gage located downstream of the UWH study site. This simulation period serves as model calibration, where parameter inputs were adjusted until simulated channel response was adequately similar to channel response surveyed in the field.

The second and third simulation periods use surrogate 15-minute interval discharge data collected from the USGS gage stations on the Zuni River, New Mexico (USGS Gage 09386950) and the Jemez River, New Mexico (USGS Gage 08324000). All discharge magnitudes were adjusted to the Canyon de Chelly drainage area. The Zuni

River, with a drainage area of 2,162 km^2, was chosen because of the similarity to Canyon de Chelly in climate, catchment land cover, and flow regime. Similarity in flow regime to Canyon de Chelly includes timing of spring runoff, a dry streambed in the summer, and short duration (<24 hour) monsoon discharges. The simulation period using the Zuni River discharge record includes the highest flood on record, which occurred on August 16, 2006 with an instantaneous peak discharge of 198 m^3/s; this is 93 m^3/s when adjusted to the Canyon de Chelly drainage area. The Jemez River, with drainage area 1,217 km^2, was chosen as a surrogate discharge to Canyon de Chelly because of its similarity in elevation and drainage area. The flow regime is moderately different from the flow regime in Canyon de Chelly; specifically, the Jemez River has a consistent baseflow during the pre-monsoon dry season, and a later and longer spring runoff period. A total of 6 years of discharge (Water Years 1991, 1992, 1993, 1995, 2002, and 2006) from the Jemez River record were used to simulate channel change in the UWH simulation reach. Water years 1993, 2006, 2002, and 1995 include the four largest instantaneous annual peak discharge magnitudes, respectively, for the period of record for which 15-minute discharge data are available. Although the entire water year was used in the simulation exercise, each water year was subdivided into individual discharge “events” for which CONCEPTS generated output. A discharge “event” could either include a single peak or series of peaks in the hydrograph. It is important to note that the available flow record is limited to after 1990 and represents a climatically drier-than-normal period. Daily average discharge values are available for years prior to 1990 but, because of the flashy nature of monsoon discharges, these values, when averaged over a 24-hour period, are not representative of the actual discharge magnitudes.

Model scenarios of the UWH study site included approximately 300 m of a control reach, and two 300-m reaches of exotic plant removal by the two methods. It was not possible to include scenarios that simulated plant removal treatment of the entire reach, which would require decreasing bank strength properties in the control and cut-stump reaches to simulate that plants had been removed in these locations. Bank strength properties, when adjusted individually for each cross section during model calibration to develop the best fit between simulation and field-measured channel change, did not exhibit systematic differences between banks that had intact vegetation and banks where exotic vegetation had been removed. As a result, it was not possible to decrease bank strength properties to account for exotic vegetation removal in the control, for example, with any confidence.

4.3.4.2 Boundary Conditions

Simulation Reach

The simulation reach corresponds to the UWH study site. Approximately every other cross section (11 total) in the study site was included in the modeling exercise. The cross sections used were spaced roughly 100-m apart, generating an approximately 1.2-km-long simulation reach, consisting of 3 cross sections each in the control and cut-stump reaches, and 4 cross sections in the whole-plant removal reach. The downstream boundary control for the modeling reach was extended 200 m downstream through the addition of two generated cross sections. The generated cross sections have the same geometry and bed slope as the farthest downstream cross section (XS 11.0) of the whole-plant removal reach. This allows simulated channel response at XS 11.0 to not be affected by the downstream boundary controls imposed by CONCEPTS, which limited simulated bed elevation changes during model runs that did not include these generated cross sections.

The banks for each cross section within the simulated reach were first characterized based on visual field observations of soil type (sand, silty sand, clay-silt-sand, and clay). For most cross sections, the banks were partitioned into two layers, with a clay layer typically existing at the bank toe and an upper layer of silty sand or clay-silt-sand. It was also noted whether vegetation including roots were present at each bank layer and in the immediate upstream and downstream vicinity. Bank strength properties for each soil type were assigned values for porosity, bulk weight, critical shear stress τ_c and erodibility k (parameters for resistance to erosion), and cohesion, friction angle, and suction angle (parameters for resistance to failure) based on values reported in the literature for these soil types and on field data from one cross section in the simulation reach, which included calculation of particle size distribution by sieving and using an Iowa Borehole Shear Tester to determine geotechnical properties (Hanson, 1990; Allen et al., 1997; Allen et al., 1999; Hanson and Simon, 2001; Potter, 2002; Simon and Thomas, 2002; Gaskin et al., 2003; Julian and Torres, 2006; Wynn et al., 2006; Wynn et al., 2008; Pollen-Bankhead et al., 2009). During model calibration, the number of soils within each category (e.g., coarse sand, silty sand, clay-silt-sand, and clay) was expanded to include a range of erodibility, critical shear stress, and cohesion values (Table 4.2).

Table 4.2 Particle distribution and soil strength properties for stream bank soil inputs in CONCEPTS.

		COARSE SAND		SILTY SAND		CLAY SILTY SAND		CLAY	
Diameter (mm)	**Parameters**	Weakest	Strongest	Weakest	Strongest	Weakest	Strongest	Weakest	Strongest
16-8	gravel (%)	5	5	0	0	0	0	0	0
2-0.5	coarse sand (%)	40	40	10	10	10	10	0	0
0.5-0.25	medium sand (%)	40	40	30	30	20	20	55	55
0.25-0.062	fine sand (%)	10	10	35	35	30	30	10	10
0.002-0.062	silt (%)	5	5	20	20	25	25	10	10
<0.002	clay (%)	0	0	5	5	15	15	25	25
	total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
	bulk density (kg/m^3)	1.86	1.86	1.59	1.59	1.46	1.46	1.51	1.51
	particle density (kg/m^3)	2.65	2.65	2.65	2.65	2.65	2.65	2.75	2.75
	porosity	0.30	0.30	0.40	0.40	0.45	0.45	0.45	0.45
resistance to erosion	critical shear stress (Pa)	0.1	0.5	0.1	1	0.5	5	5	15
	erodibility (cm^3/Ns)	7.09	0.34	1.22	0.10	0.34	0.05	0.16	0.03
resistance to failure	cohesion (Pa)	0	0	0	0	0	2.2	5	12
	friction angle (degrees)	35	34.5	35.5	35.5	20.9	20.9	20	20
	suction angle (degrees)	12	12	12	12	12	12	12	12

These values were adjusted to simulate channel bank change that matched well with field-measured channel response. Increased bank strength values associated with the presence of riparian vegetation were taken from Pollen-Bankhead et al. (2009), who documented a general increase of 2.8 Pa in critical shear stress as a result of vegetation along stream banks at the UWH study site. Finally, Manning's roughness coefficient values were visually estimated for the bed, banks, and floodplain for each cross section using Barnes (1967) and Phillips and Ingersoll (1998).

Discharge

A discharge record was created using a stage-discharge relationship that was developed by comparing the longitudinal profile of field-surveyed high water marks for three individual flows (22 July 2006, 29 July 2007, and 5 August 2007) to peak water-surface elevation profiles generated in CONCEPTS for those same flows. Simulations to develop the stage-discharge relationship in CONCEPTS only included hydraulics and did not include sediment transport or bank erosion processes. Under the assumption that I accurately estimated the Manning n values for each cross section in the study site, I adjusted the peak discharge magnitude for the three flows to generate water-surface profiles in CONCEPTS that best matched the three field-surveyed water-surface profiles. The criterion for the best match was the minimum sum of elevation differences between field-measured water-surface profiles and those generated in CONCEPTS for each cross section. Emphasis was put on minimum elevation differences along the downstream 300 m of UWH, where field-surveyed high water marks (HWM) were considered to be the most accurate based on the consistency between markings at different locations within this treatment reach. Discharge values that generated water-surface profiles that matched well with the field-surveyed HWM profiles of the entire study reach were plotted against the HWM values at the farthest downstream cross section of the study reach (XS 11.0) to form a stage-discharge relationship consisting of three points. The data were log-transformed and a power trendline was fit and the equation applied to the stage record from the continuous gage located 1 km downstream from the simulation reach. This stage-discharge relationship represents a first-order approximation of discharge magnitude for the period of record, with a better estimation of timing and duration of flows.

The discharge event on August 5, 2007 overtopped the banks at the stage gage location, destroying the gage such that only a portion of the rising limb of the event was recorded. The remaining portion of the hydrograph, including rise to the peak and the falling limb, was synthesized using the shape of a previous monsoon flow that occurred on August 11, 2006. The hydrograph of this flow has a nearly vertical rising limb to the estimated peak magnitude of 6 m^3/s and a falling limb with a 4-day duration.

Sediment

Sediment transport in CONCEPTS is calculated as total load by size fraction for computational ease over long simulation periods (Langendoen and Alonso, 2008). Sediment transport equations based on clast size are employed and include Meyer-Peter-Mueller (1948) for gravel and coarser (> 2mm), Yang (1973) for sand (0.25 mm to 2 mm), Laursen (1958) for silt (0.025 mm to 0.25 mm), and a wash load equation for sizes finer than 10 μm (Langendoen, 2000b). The sediment transport rate is determined by the bed material, incorporating surface and subsurface layers. Sediment clast size inputs were based on field pebble counts of streambed surfaces at each cross section. The field pebble counts did not include clast sizes finer than medium sand (0.25 m), although finer sediments were a minor component of bed sediments in some cross sections. No subsurface field sampling occurred. Instead, clast size distribution for each cross section was extended at depth below the streambed during simulation exercises. The bed sediments at all cross sections were assigned the same values for resistance to erosion parameters critical shear stress τ_c and erodibility k as the bank soil type *sand*, which was the primary component of the bed in the UWH study reach. Resistance to failure parameters (suction angle and cohesion) are not necessary as a strength property input in CONCEPTS for the bed material.

4.3.4.3 Modeling Assumptions

A major uncertainty regarding the inputs for CONCEPTS is the generated discharge record. Under ideal circumstances, coupled velocity and flow depths at multiple cross sections over a range of discharges should be measured to develop a stage-discharge relationship that is then applied to a continuous gage located within the simulation reach. Velocity measurements were not possible, however, because of the flashiness of the flow regime and remoteness of the UWH study site. In addition, the nearest feasible location for continuous gage installation was approximately 1 km downstream of the study site. As a result, the discharge record is built on three major assumptions; 1) accurate, visually-estimated roughness coefficients for cross sections along the simulation reach, 2) accurate stage measurements by the continuously recording gage, and 3) accurate field-measured HWM along the simulation reach for the three flows used for comparison with the simulated depths for those flows.

Manning *n* values were visually assigned using Barnes (1967) for the bed, banks, and floodplains at each cross section along the simulated reach. Roughness values for the channel bed ranged from 0.03 to 0.04 for the channel bed, 0.05 to 0.1 for the banks, and 0.07 to 0.1 for the floodplain (Table 4.3). While developing a stage-discharge relationship that resulted in a reasonable fit between simulated water surface profiles and field-measured HWM, I was not able to simultaneously adjust the roughness coefficient values at individual cross sections and discharge values because of the interdependence of the roughness value on the discharge estimate. Instead, I held roughness estimates constant while adjusting discharge values to obtain the best fit. With the understanding of the important, yet difficult, task of accurately estimating roughness values in the absence of field-measured velocity and stage data, a sensitivity analysis was conducted to evaluate the discharge magnitudes that result from a range of Manning *n* values for the simulated reach. The sensitivity analysis consisted of developing two additional stage-discharge relationships for the simulated reach with minimum and maximum Manning *n* values for each cross section. The stage-discharge relationships were developed using the same methods described previously of adjusting discharge magnitudes for the three flows to generate water-surface profiles in CONCEPTS that best matched field-measured HWM. Minimum and maximum roughness values represent cases of extremely smooth and rough channels, respectively, based on previous research in Arizona streams (Phillips and Ingersoll, 1998) (Table 4.3).

Table 4.3 Roughness coefficient estimates for UWH simulation reach.

							Minimum			Maximum		
Treatment Reach	**Cross Section**	**Left Floodplain**	**Left Bank**	**Bed**	**Right Bank**	**Right Floodplain**	**Flood-plains**	**Banks**	**Bed**	**Flood-plains**	**Banks**	**Bed**
Control	0.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Control	1.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Control	2.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Cut Stump	3.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Cut Stump	4.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Cut Stump	5.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Cut Stump	6.0	0.1	0.1	0.04	0.1	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Whole Plant	8.0	0.1	0.07	0.03	0.08	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Whole Plant	9.0	0.07	0.07	0.03	0.05	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Whole Plant	10.0	0.1	0.09	0.03	0.05	0.1	0.05	0.03	0.015	0.12	0.1	0.05
Whole Plant	11.0	0.1	0.07	0.03	0.06	0.1	0.05	0.03	0.015	0.12	0.1	0.05

The streambed at the gage site is composed of sand and therefore subject to bed fluctuations from both scour and aggradation during flows. Bed fluctuations of less than 0.1 m were documented between individual flows that had resulted in approximately 1 m of stage. In addition, repeat surveys of the cross section at the gage site indicate 0.4 m of streambed aggradation between July 2006 and July 2007. The distance between the streambed and stage recorder was measured after most individual flows to account for these changes to streambed elevation for future stage readings. Between flows, these changes were typically less than 10 cm. However, a stable bed elevation was assumed during flows, resulting in stage readings that are too shallow or deep depending on the degree of aggradation or scour at the gage site. Although I have no direct indicators of the depth of scour and fill during recorded flows, data from analogous sites suggest that ± 1 m is a reasonable maximum estimate for this channel setting (Colby, 1964; Foley, 1978). A 1-m-change in bed elevation at the stage gage site can greatly alter discharge estimates. The range in discharge estimates from the sensitivity analysis of adjusting Manning roughness values likely includes as least some of the range in discharge values that result from bed elevation fluctuation, but I was not able to specifically and entirely account for this uncertainty.

High water marks along a stream reach serve as a surrogate for the longitudinal water-surface profile during peak flow. Turbulent flow in natural, irregular channels can create marks at discrete locations that are higher or lower than the true water-surface elevation, resulting in discontinuity in the longitudinal water-surface profile. To account for this discontinuity, care was taken to match water-surface profiles simulated in CONCEPTS to the linear trendline of the field-measured HWM, rather than the maximum or minimum water mark elevation for the reach, to determine appropriate peak discharge magnitudes. Taking all of these factors into account, the stage-discharge relationship developed in this study represents a first-order approximation of discharge magnitude for the period of record, with a better estimation of flow timing and duration.

The second major uncertainty with CONCEPTS inputs is the absence of field data on stream bank particle distribution and strength properties along the simulation reach with the exception of one cross section (XS 10.0) in the whole-plant removal treatment reach. The initial model inputs were based on values for soils containing sand, silt, and clay reported in the literature and field measurements at XS 10.0 (Hanson, 1990; Allen et al., 1997; Allen et al., 1999; Hanson and Simon, 2001; Potter, 2002; Simon and Thomas, 2002; Gaskin et al., 2003; Julian and Torres, 2006; Wynn et al., 2006; Wynn et al., 2008; Pollen-Bankhead et al., 2009). With the understanding that soils and their associated geotechnical properties are highly spatially and temporally variable, these initial inputs served only as a starting point during model calibration. Adjustments were primarily for erodibility and critical shear stress, with some adjustment of cohesion values. Field measurements at cross section 10.0 within the simulation reach and at another cross section in the SLR control site indicated that an average increase of 2.8 Pa in soil cohesion occurred as a result of the presence of riparian vegetation (Pollen-Bankhead et al., 2009). Therefore, an initial value of 2.8 Pa was added to all soil layers at all cross sections where vegetation was present. This increased cohesion from the vegetation, however, had no effect on channel response during model simulations. Cross section geometry was the same in simulations with bank soil profiles that only differed in cohesion by 2.8 Pa. Therefore, no systematic increase in cohesion was made for soil types where vegetation was present. Geotechnical properties were adjusted on an individual cross section basis to generate simulated channel response that best fit field-measured channel change. CONCEPTS cannot predict the increased hydraulic forces acting on the outer bank of a meander, which was the case for the right bank of XS 10.0. The increased shear stresses were represented by increasing the erodibility of soils along this portion of the bank, and thus decreasing the bank's resistance to erosion (Langendoen and Simon, 2008).

4.3.4.4 Statistical Analysis of Modeling Results

For each of the three simulation scenarios, the geometry of each cross section simulated in CONCEPTS was graphically compared to either the geometry measured in the field over the same simulation period (in the case of the calibration exercise) or the initial cross sectional geometry used at the start of the simulation periods that included the Zuni River and Jemez River discharge records. In addition, the simulated thalweg longitudinal profile was compared to the field-measured or initial conditions. A survey for each of the 10 cross sections conducted at the start of the 2006 monsoon season served as the initial surveys from which both simulated and field-observed channel change were measured. Differences in cross sectional geometry were quantified in terms of both total change in cross sectional area (ΔA_{Total}) and partitioning the cross section into banks (ΔA_{Bank}), bank toe (ΔA_{Toe}), and channel bed (ΔA_{Bed}). Partitioning the cross section allows for detailed evaluation of the ability of CONCEPTS to simulate the various erosion processes that dominate the different areas along a cross section. Negative values indicate erosion, positive values indicate deposition. Statistically significant ($\alpha = 0.05$) differences among treatment means for cross section geometry parameters were calculated using the non-parametric Wilcoxon Rank Sum and Kruskal-Wallis tests for significant differences in medians because the data did not conform to the assumptions of an ANOVA (PROC NPAR1WAY WILCOXON: SAS Institute 2004).

4.4 FIELD RESULTS

4.4.1 Flow regime in de Chelly for post-treatment (2006-2008) study period

Channel adjustment measured through change in cross sectional geometry is, in part, a function of the previous year's flow regime. Annual surveys took place between May and July, during the end of the spring runoff and before the start of the monsoon season. Therefore, measured channel change reflects the previous year's monsoon season and the winter and spring runoff for the year of the annual survey. Repeat surveys also occurred in UWH after individual monsoon flows. No precipitation stations exist within the upper portions of the de Chelly watershed. However, comparing monthly precipitation in the headwaters of an adjacent watershed, Lukachukai, to the station's 1971-2000 normal values and drought surveys synthesized from monthly streamflow discharge for Chinle Wash (to which de Chelly is tributary), provide some context on the climate, antecedent moisture conditions, and streamflow in Canyon de Chelly during the study period. The precipitation data are available from the Western Regional Climate Center (WRCC) at http://www.wrcc.dri.edu. Drought surveys are compiled by the USGS and available at http://az.water.usgs.gov/drought/index.html. Because of the spatial variability of climate conditions in semi-arid landscapes, the drought surveys provide only general information about climate conditions within the watershed.

Monthly precipitation totals in Lukachukai indicate a generally drier-than-normal 2005 monsoon season and an extremely dry winter of 2005-2006 (Figure 4.2). Drought surveys corroborate this finding, showing that the watershed experienced long periods of no precipitation from July through October and was consistently in varying extreme degrees of drought from November until May. During the start of the 2006 summer field season, streamflow had ceased by mid-May with the exception of standing pools in SPR, reflecting a relatively short spring runoff.

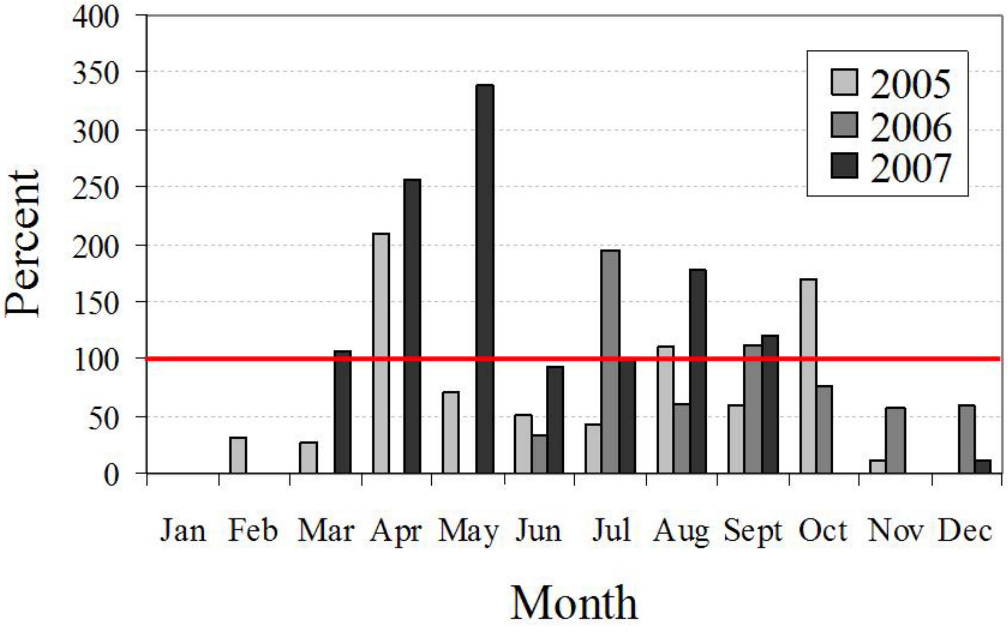


Figure 4.2 Percent difference between monthly precipitation at Lukachukai rain gage station, an adjacent watershed to Canyon de Chelly, and 1971-2000 normal precipitation (solid red line) over the three-year study period.

The 2006 monsoon season was moderate, with 100% of the monthly precipitation reached at the Lukachukai station in July and September (Figure 4.2). The stage gage in de Chelly recorded six short duration (<24 hours) flows that resulted in generally 1m to 1.5m of flow depth in the three downstream study sites (SLR, UWH, LWH) and overbank flow in SPR (Figure 4.3). The USGS-compiled drought surveys for the watershed indicate only severe drought during September 2006, with normal flow conditions during the rest of the monsoon period. In addition, spring 2007 was very wet, with March receiving more than 250% of normal precipitation and April receiving more than 300% precipitation relative to normal, and only moderate and intermittent drought conditions for the entire Chinle watershed. Streamflow in de Chelly persisted longer in spring 2007, with the channel not drying until early June.

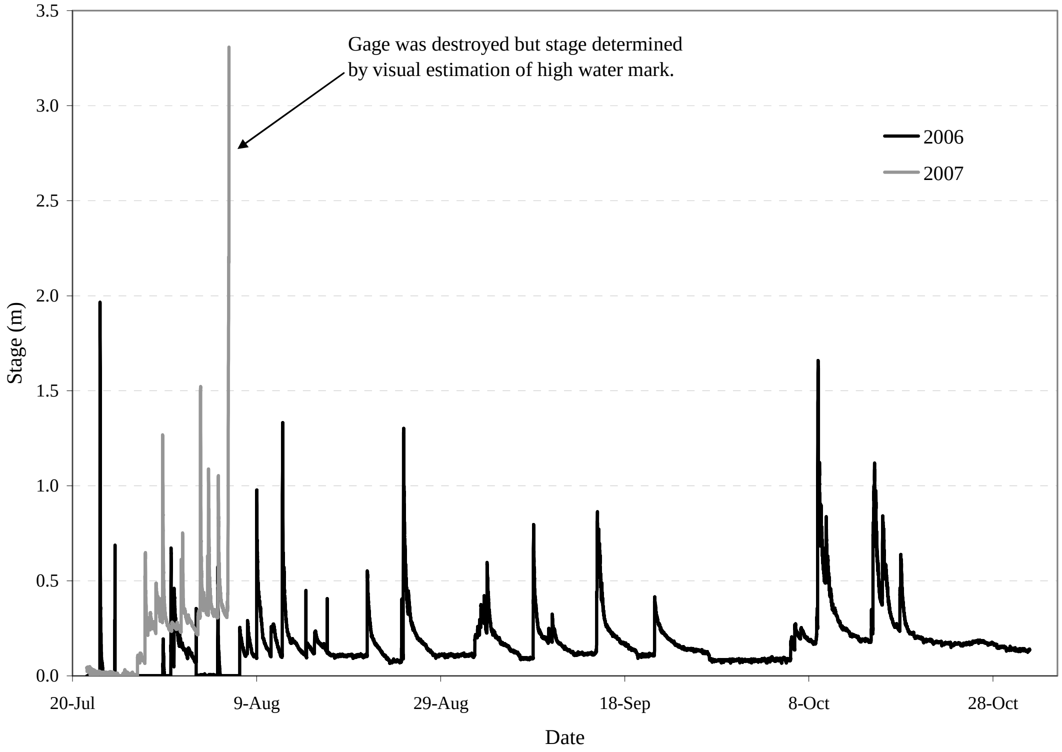


Figure 4.3 Stage record of discharge in Canyon de Chelly monsoon seasons 2006 and 2007. Aggradation occurred at the stage gage location and is reflected in the periods of consistent stage between individual monsoon discharges.

No monthly precipitation data are available for Lukachukai after spring 2007, but from the stage gage in de Chelly, it appears that 2007 was a bigger monsoon year than 2005 or 2006. Two August flows exceeded 3 m in depth in SLR and UWH and caused overbank flooding in SPR and LWH. The first of these flows destroyed the stream gage and so flow records do not exist after August 8, 2007. Canyon de Chelly National Park staff identified a second flow later in August that caused overbank flooding in LWH, but the number of subsequent flows after August 8 is unknown with the exception of the one reported by the Park staff. Drought survey watershed maps do not show drought for June, July, Aug, or Sept of 2007 or during the winter and early spring (December through April). During the May 2008 annual surveys, more than 0.5 m of flow depth existed in the LWH and UWH study sites, indicating at least a moderate spring runoff season.

4.4.2 Differences in channel change between the control and two plant removal treatments

Summary statistics for differences in channel metrics between the 2005 pre-treatment survey and either the 2007 or 2008 post-treatment survey are presented by reach (e.g., control, cut-stump, whole-plant) in Table 4.4 and Figure 4.4 and by study site in Table 4.5 and Figure 4.5. In general, changes in cross section geometry were small, with substantial change occurring locally at a few individual cross sections. Cross sectional geometry (*area, width, perimeter*, *width/depth ratio,* and *hydraulic radius*) on average increased the most in the whole-plant removal treatment reaches, with less change in the cut-stump treatment reaches, and the least change in the control (Table 4.4, Figure 4.4). Depth, which reflects only channel incision without width adjustment, increased the most in the control reaches. The largest channel adjustment was average increased width (1.96 m versus 0.54 m and 0.25 m, respectively) and subsequently cross sectional area (4.40 m versus 1.05 m and 0.45, respectively) and perimeter (1.79 m versus 0.58 m and 0.1.79 m, respectively). Average channel incision (depth, average depth, and hydraulic radius) was small (<0.1 m) in all treatments, but the maximum incision occurred in the control reach of UWH.

Table 4.4 Summary statistics for channel adjustment from 2005 to 2007/2008 by treatment. Hydraulic radius (Rh) is calculated by Area/Perimeter. Depth is the thalweg depth.

Reach	**Sample Size**	**Statistic**	**Area (m^2)**	**Width (m)**	**Average Depth (m)**	**Depth (m)**	**Width/Average Depth Ratio**	**Width/Depth Ratio**	**Perimeter (m)**	**Rh (m)**
Control	28	MIN	-3.61	-2.49	-0.34	-0.58	-3.82	-1.04	-2.88	-0.27
		MAX	1.42	0.72	0.17	0.12	1.75	0.90	0.50	0.09
		MEAN	-0.45	-0.25	-0.01	-0.09	-0.29	0.00	-0.22	-0.01
		STD	1.16	0.65	0.11	0.16	1.08	0.48	0.66	0.08
		MEAN % of 2005 CHANNEL	0.02	0.02	0.00	0.03	0.03	0.01	0.01	0.00
Cut-Stump	24	MIN	-7.69	-3.22	-0.21	-0.21	-1.96	-1.18	-3.01	-0.17
		MAX	2.92	0.17	0.25	0.19	0.60	0.32	0.10	0.22
		MEAN	-1.05	-0.54	-0.01	0.00	-0.43	-0.27	-0.58	-0.01
		STD	2.26	0.80	0.11	0.11	0.75	0.38	0.73	0.09
		MEAN % of 2005 CHANNEL	0.04	0.04	0.00	0.00	0.05	0.05	0.04	0.00
Whole-Plant	27	MIN	-91.04	-25.20	-0.60	-0.50	-6.63	-6.62	-27.50	-0.61
		MAX	3.85	0.97	0.27	0.21	1.28	0.89	1.20	0.21
		MEAN	-4.40	-1.96	0.02	-0.03	-1.44	-0.71	-1.79	-0.02
		STD	17.44	4.77	0.20	0.17	1.93	1.37	5.23	0.18
		MEAN % of 2005 CHANNEL	0.12	0.14	0.02	0.01	0.18	0.14	0.11	0.00

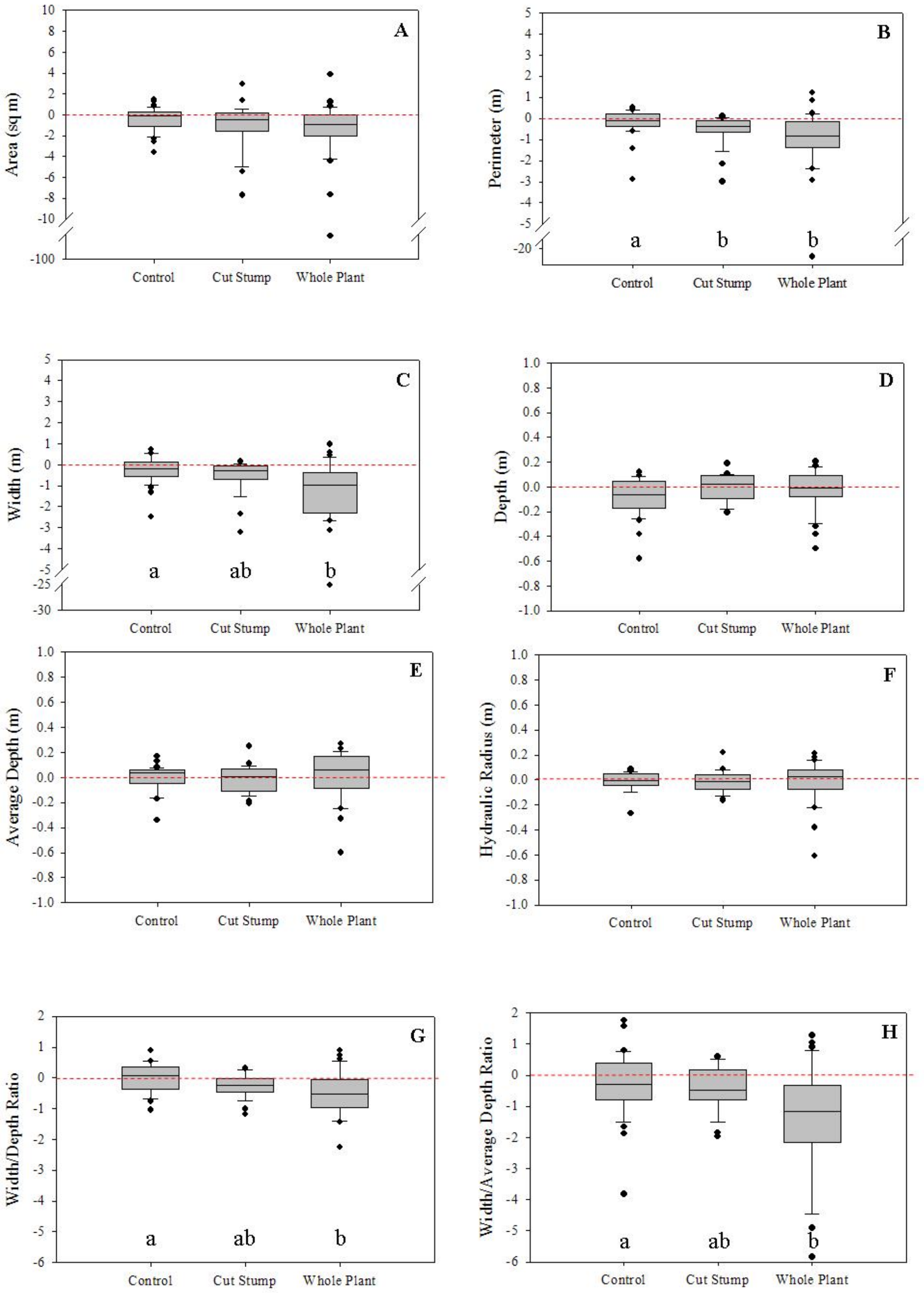


Figure 4.4 Boxplots of differences in cross section geometry metrics by reach (Control, Cut-stump, Whole-plant). A. Area, B. Perimeter, C. Width, D. Depth, E. Average Depth, F. Hydraulic Radius, G. Width/Depth Ratio, H. Width/Average Depth Ratio. Red dashed line demarcates 0. Positive values indicate deposition and aggradation. Negative values indicate erosion and incision. Different letters immediately above x-axis indicate statistically significant differences in medians between reach groups. With a Bonferroni correction in the pairwise comparisons, significant differences between groups have a p value less than 0.0167.

Table 4.5 Summary statistics for cross sectional geometry metrics response by study site and reach.

mean (stdev)	**SPR**	**SLR**	**UWH**	**LWH**	**SPR**	**SLR**	**UWH**	**LWH**
	Area (m^2)				*Average Depth (m)*			
Control	-0.0006 (0.89)	-0.84 (1.03)	-1.29 (1.31)	0.32 (0.71)	0.05 (0.05)	0.0032 (0.10)	-0.09 (0.14)	0.01 (0.08)
CutStump	0.18 (0.25)	-1.30 (0.57)	-3.56 (2.95)	0.49 (1.48)	0.05 (0.05)	-0.11 (0.07)	-0.05 (0.11)	0.07 (0.10)
WholePlant	-0.25 (0.75)	-3.64 (2.20)	-1.35 (0.86)	-12.24 (34.77)	0.12 (0.08)	-0.1 (0.21)	0.04 (0.19)	-0.01 (0.27)
	Perimeter (m)				*Depth (m)*			
Control	-0.55 (1.06)	-0.24 (0.59)	-0.19 (0.37)	0.11 (0.29)	0.05 (0.07)	-0.12 (0.08)	-0.24 (0.19)	-0.03 (0.09)
CutStump	-0.35 (0.25)	-0.35 (0.35)	-1.26 (1.18)	-0.34 (0.32)	0.07 (0.08)	-0.08 (0.09)	-0.03 (0.14)	0.04 (0.08)
WholePlant	-1.31 (0.96)	-0.66 (1.01)	-0.67 (1.25)	-4.37 (10.21)	-0.0034 (0.06)	-0.15 (0.26)	-0.01 (0.19)	0.05 (0.09)
	Width (m)				*Hydraulic Radius (m)*			
Control	-0.65 (0.87)	-0.34 (0.68)	-0.21 (0.34)	0.19 (0.41)	0.03 (0.04)	-0.02 (0.06)	-0.08 (0.09)	0.02 (0.06)
CutStump	-0.33 (0.31)	-0.19 (0.42)	-1.30 (1.27)	-0.33 (0.33)	0.04 (0.04)	-0.08 (0.03)	-0.07 (0.09)	0.06 (0.08)
WholePlant	-1.47 (0.97)	-1.05 (1.27)	-1.11 (1.44)	-4.08 (9.33)	0.09 (0.08)	-0.16 (0.13)	-0.01 (0.12)	-0.02 (0.27)
	Width/Average Depth Ratio				*D84 (mm)*			
Control	-1.33 (1.38)	-0.09 (0.57)	0.26 (0.74)	-0.02 (0.87)	-27 (29)	-22 (70)	-10 (33)	2 (5)
CutStump	-0.79 (0.67)	0.26 (0.39)	-0.47 (0.85)	-0.72 (0.65)	33 (26)	0.1 (0.2)	-3 (22)	-3 (33)
WholePlant	-2.66 (1.93)	-0.15 (1.03)	-0.86 (1.63)	-1.90 (2.19)	-44 (73)	-34 (32)	24 (53)	0.0 (0.0)
	Width/Depth Ratio				*Bank Stability Rank*			
Control	-0.61 (0.27)	0.07 (0.28)	0.31 (0.16)	0.23 (0.48)	6	18	15	12
CutStump	-0.50 (0.33)	0.07 (0.26)	-0.39 (0.42)	-0.26 (0.28)	11	16	19	13
WholePlant	-0.93 (0.70)	-0.07 (0.78)	-0.41 (0.83)	-1.34 (2.34)	13.5	16	20.5	14

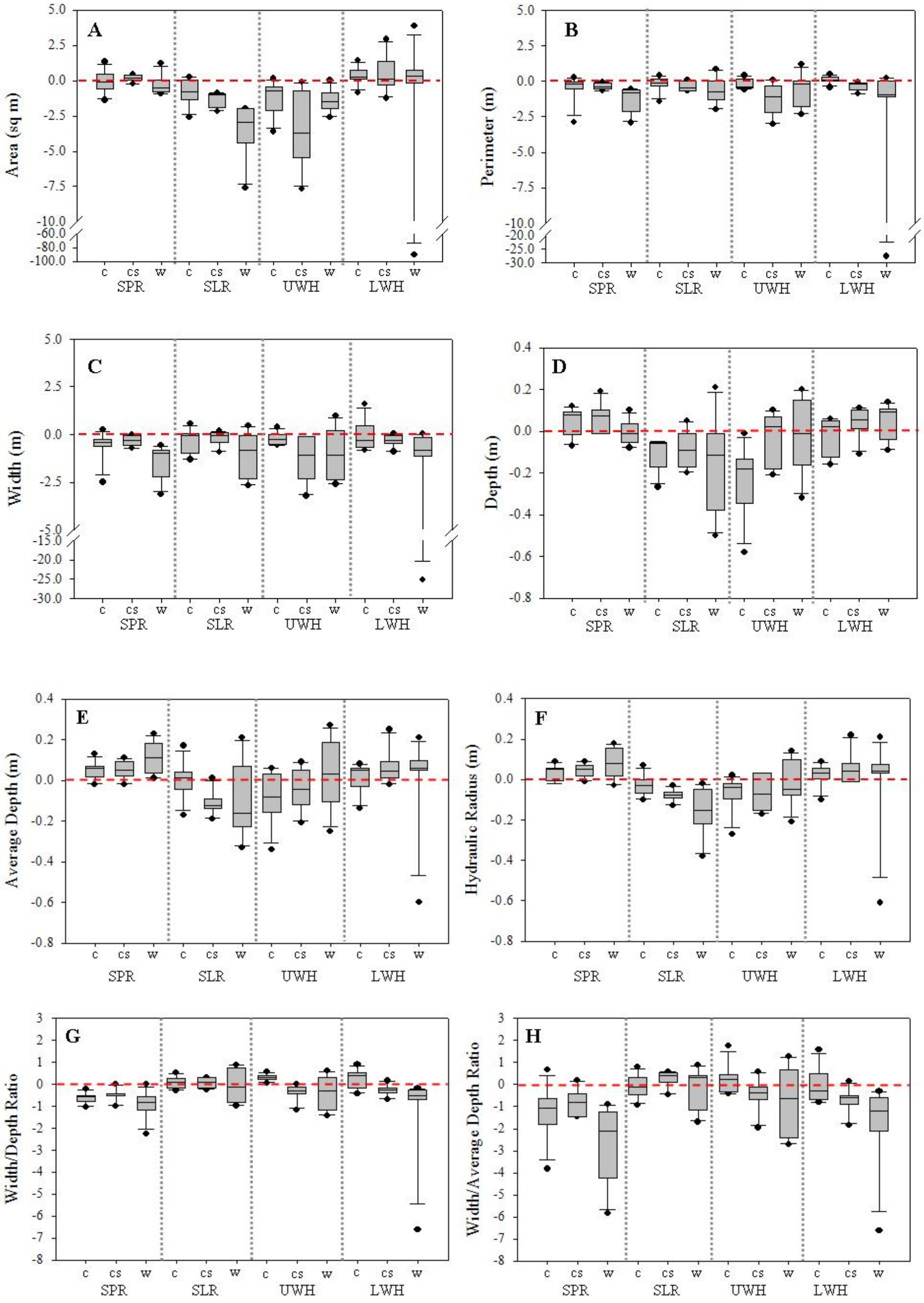


Figure 4.5 Boxplots of differences in cross section geometry metrics by study site and reach. Study sites and treatments are sequenced from left to right in the downstream direction: Spider Rock (SPR), Sliding Rock (SLR), Upper White House (UWH), and Lower White House (LWH). Reach type is abbreviated: control (c), cut-stump (cs), whole-plant (w). A. Area, B. Perimeter, C. Width, D. Depth, E. Average Depth, F. Hydraulic Radius, G. Width/Depth Ratio, H. Width/Average Depth Ratio. Red dashed line demarcates 0. Positive values indicate deposition and aggradation. Negative values indicate erosion.

The measured channel change translates to 5% or less of the pre-treatment channel in control and cut-stump reaches for all cross sectional parameters, and up to 12% to 14% of the pre-treatment channel in whole-plant removal reaches for cross sectional area and channel width (Table 4.4).

Statistically significantly differences in median channel change between reach types exist for channel top width, perimeter, and the two width/depth ratio values (Figure 4.4). Median width and width/average depth ratio change is significantly larger in the whole plant removal reaches than the control reaches. The cut-stump reaches are statistically indistinct from either the whole-plant or control reaches for these cross sectional geometry parameters. Both the whole plant and cut-stump reaches have larger median change in perimeter compared to control reaches.

Based on visual inspection, it appears that the variance of channel change of the whole-plant removal treatment reaches is larger than either the control or cut-stump removal reaches, indicating that the whole-plant reaches experienced a broader range of channel response (Figure 4.4). However, based on the Levene’s test of equal variances, no statistically significant differences in variances between reaches exist for channel change parameters.

A comparison of erosion rates averaged over the study period to erosion rates reported for streams within the southwestern US indicates that bank widening rates in all of the reaches (control and treatment reaches) in Canyon de Chelly are lower than southwestern US streams (5.89 m/y mean, 0.74 m/y median) (Table 4.6), although the widening rates are within the range of variability reported in the literature. In addition, median bank erosion rates normalized by drainage area are an order of magnitude less than southwestern US streams (7 x 10^{-4} m/km^2 y) with the exception of the whole-plant removal reach. Incision rates are also less than southwestern US streams (0.17 m/y mean, 0.12 m/y median), but remain within the range of variability of reported rates, particularly in the control reaches, which continue to incise. Incision normalized by drainage area is one to two orders of magnitude less than southwestern US streams (5 x 10^{-5} m/km^2 y). It is important to note that incision rates were likely much higher during the initial cutting of the channel after historical narrowing; however, there are no quantifiable values for this period.

Table 4.6 Summary statistics for erosion rates by reach. Erosion rates are normalized by drainage area for comparison of state and southwestern US regional rates presented in Chapter 2.

Reach	**Statistic**	**Bank Erosion Rate (m/y)**	**Bed Incision Rate (m/y)**	**Bank Erosion Rate/Drainage Area (m/km^2 y)**	**Bed Incision Rate/Drainage Area (m/km^2 y)**
Control	MIN	-1.24	-0.194	-1.1E-03	-1.0E-04
	MAX	0.36	0.058	2.0E-04	1.0E-04
	MEAN	-0.125	-0.0338	-1.0E-04	-2.2E-05
	MEDIAN	-0.0683	-0.0292	-4.7E-05	-2.0E-05
	STD	0.3185	0.0623	3.0E-04	0.0E+00
Cut-stump	MIN	-1.61	-0.099	-1.1E-03	-1.0E-04
	MAX	0.08	0.097	1.0E-04	1.0E-04
	MEAN	-0.2388	0.002	-1.7E-04	3.3E-06
	MEDIAN	-0.124	0.0093	-8.5E-05	6.4E-06
	STD	0.3611	0.05	3.0E-04	0.0E+00
Whole-plant	MIN	-12.6	-0.25	-8.6E-03	-2.0E-04
	MAX	0.32	0.103	2.0E-04	1.0E-04
	MEAN	-0.957	-0.01	-7.0E-04	-7.0E-06
	MEDIAN	-0.431	-0.004	-3.7E-04	-2.9E-06
	STD	2.3823	0.0808	1.6E-03	1.0E-04

The most pronounced channel change occurred in SLR and UWH, with substantial change at one cross section at LWH and minimal change at SPR (Table 4.5, Figure 4.5). In LWH, channel adjustment was primarily through bank widening, whereas in SLR and UWH, channel adjustment was widening with some incision into the clay bed. Channel change was localized, with the most change occurring near or at the apex of a meander. Substantial channel change occurred at one cross section in LWH (LWH 9.0) after the two overbank flows in August 2007, in which the channel eroded through a sharp meander, widening the channel by approximately 23 m (Figure 4.6). In UWH, approximately 4 m of channel widening at the bank toe occurred between cross sections 10.0 and 10.5 at the apex of a meander during this same discharge event (Figure 4.7).

Based on stream power calculations using toe-width, cross sections with maximum channel change in terms of area, width, and depth (average and thalweg) do not correspond to maximum values of stream power when the data are stratified by study site, reach (control, cut-stump, whole-plant), or reach within a study site (Appendix C). Some reaches within a study site appear to have a mild correspondence between maximum cross sectional geometry and maximum unit stream power, but any potential trend is based on a sample size of 6 or 7 data points (cross sections within a reach within a study site). Because of the relative coarseness of the stream power calculation, the small amount of data is not sufficient to have confidence in a weak trend between channel change and unit stream power.

Differences in the d84 between the 2006 and 2007 survey years did not produce any trends between treatments or study sites (Figure 4.5, Figure 4.8).

From a visual inspection, the bank stability ranking scheme values were not substantially different between treatments within a site (Figure 4.5), but the highest bank stability ranking values correspond to the study sites that experienced the most channel change.

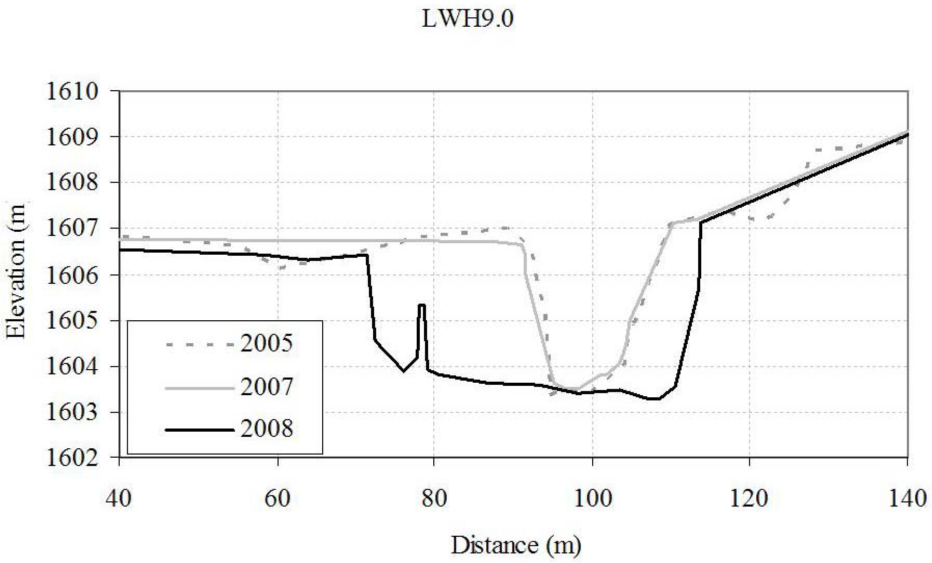


Figure 4.6 Cross Section LWH 9.0 in whole plant removal treatment reach looking downstream.

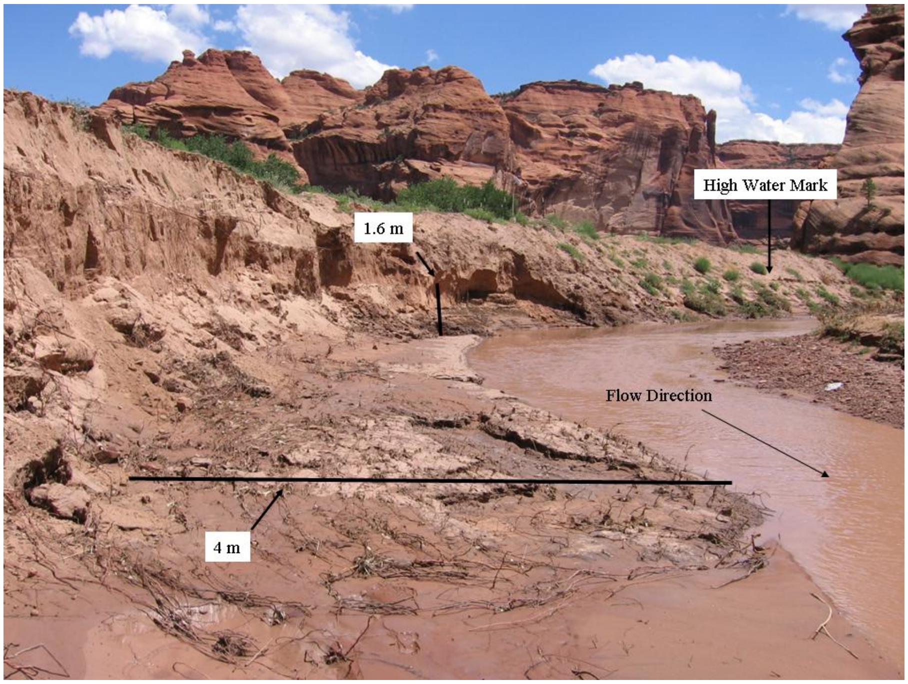
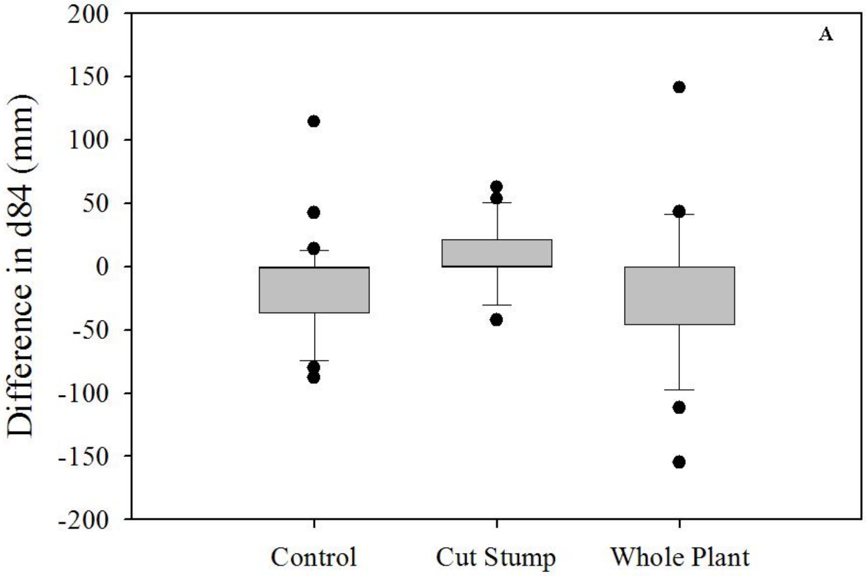


Figure 4.7 Channel widening in whole-plant reach between UWH10.0 and 10.5 at apex of meander from August 5, 2007 discharge event.



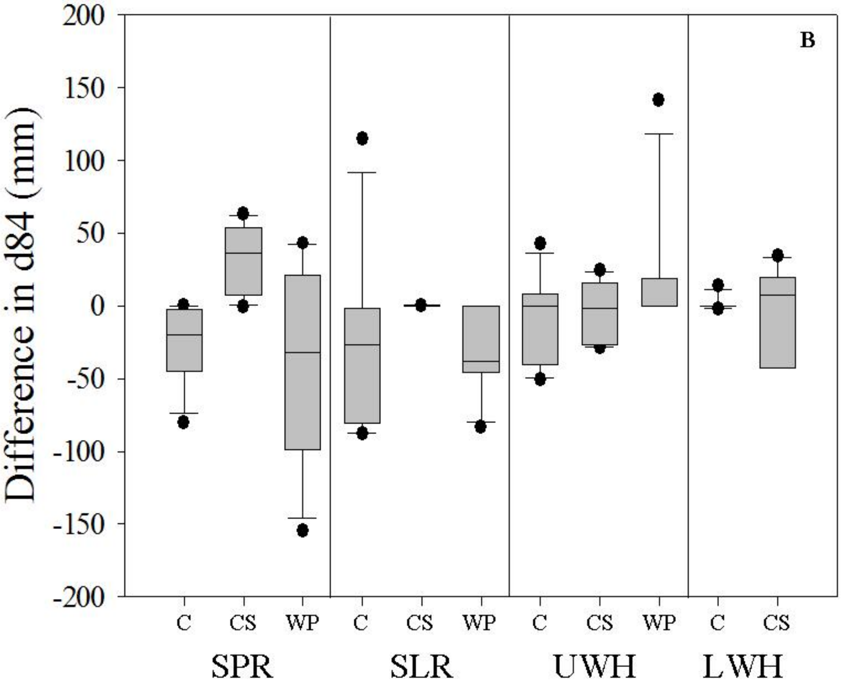


Figure 4.8 Differences in D84 (mm) between 2006 and 2007 survey by reach (A) and by reach (control (C), cut-stump (CS), and whole-plant (WP) within study site (Spider Rock (SPR), Sliding Rock (SLR), Upper White House (UWH), and Lower White House (LWH)) (B). Lower White House whole-plant treatment is not included because treatment had not occurred by the 2006 field season.

Higher rank values indicate higher bank instability, with values exceeding 20 generally indicating highly unstable banks and values of less than 10 indicating stable banks (Simon and Castro, 2003). SPR had the smallest bank stability rank values for all reaches relative to the other study sites and experienced relatively little geomorphic change. Although substantial change occurred at one cross section in LWH, the relatively low bank stability rank values in LWH also are consistent with the small channel response measured within this site.

Bank angle values were generally lower in the whole-plant removal treatment reaches, likely because of the bank disturbance and re-grading during the plant removal process, although no significant differences between the control and treatment groups exist (Figure 4.9). Exceptions to this are the right bank of LWH and the left bank of UWH, where access prevented the whole-plant removal treatment from taking place (Figure 4.9). Bank angles are steepest in SLR and UWH, the sites that are the most incised, have the highest bank stability rank values, and have experienced the most channel change over the study period (Figure 4.9). Again, significant differences (p value < 0.05) do not exist between either the control or the two treatment groups within study sites for bank angles.

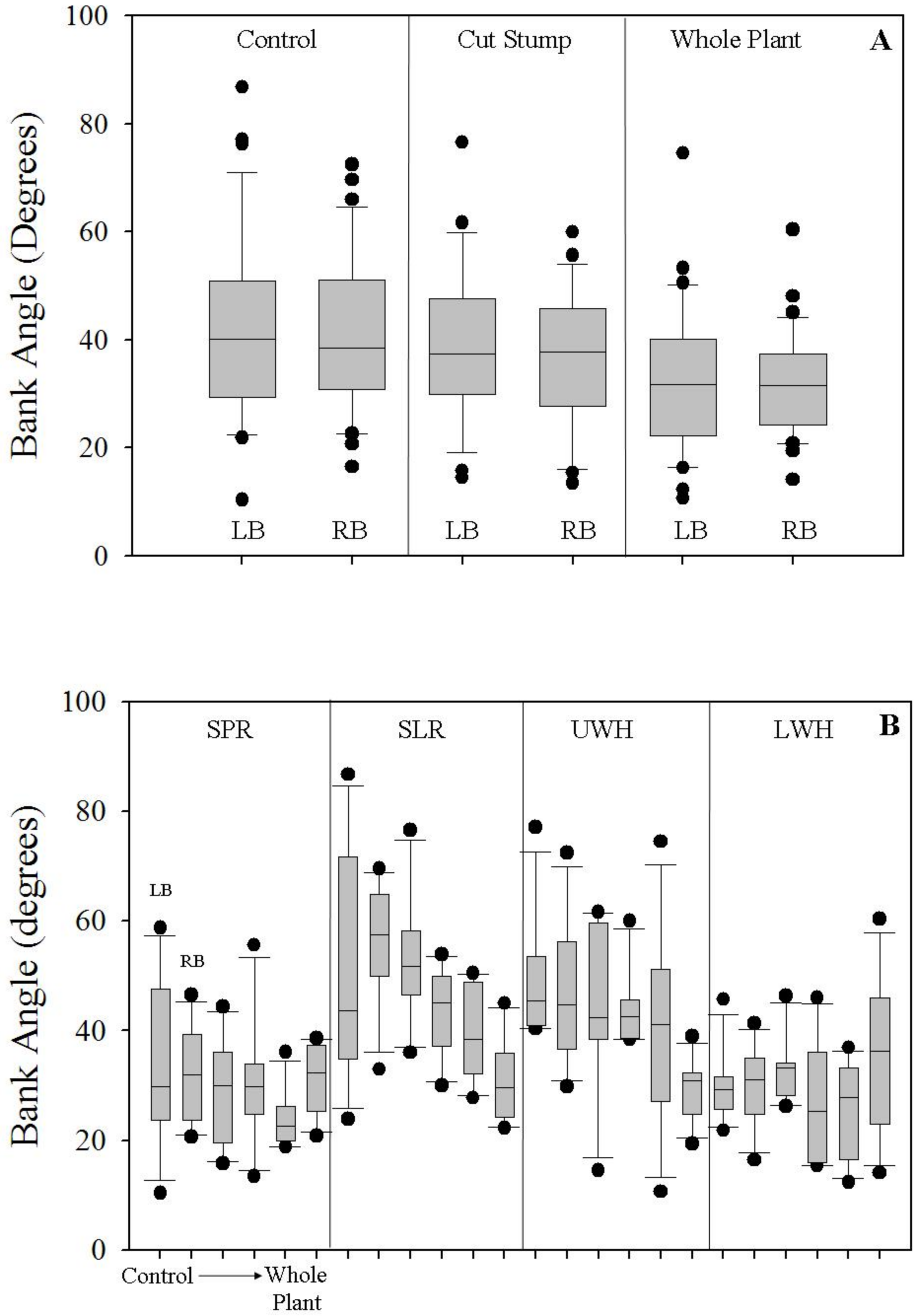


Figure 4.9 Bank angle by reach (control, cut-stump, whole-plant) (A) and reach within study site (B). Presentation order in both A and B is left bank (LB) first followed by the right bank (RB) for each reach type, and control, cut stump, whole plant removal as the reach sequence. In B, study site sequence is in downstream order of Spider Rock (SPR), Sliding Rock (SLR), Upper White House (UWH), and Lower White House (LWH) with reach type within each study site in downstream order (e.g., control, cut-stump, whole-plant).

Longitudinal channel response to exotic plant removal was variable between study sites. Based on differences between the pre-treatment 2005 thalweg elevation and the thalweg elevation of each annual survey, bed change in SPR and LWH was small (approximately 0.1 m), with no distinct trend of aggradation or incision between the control and treatment reaches (Figure 4.10). The most elevation change took place in SLR and UWH.

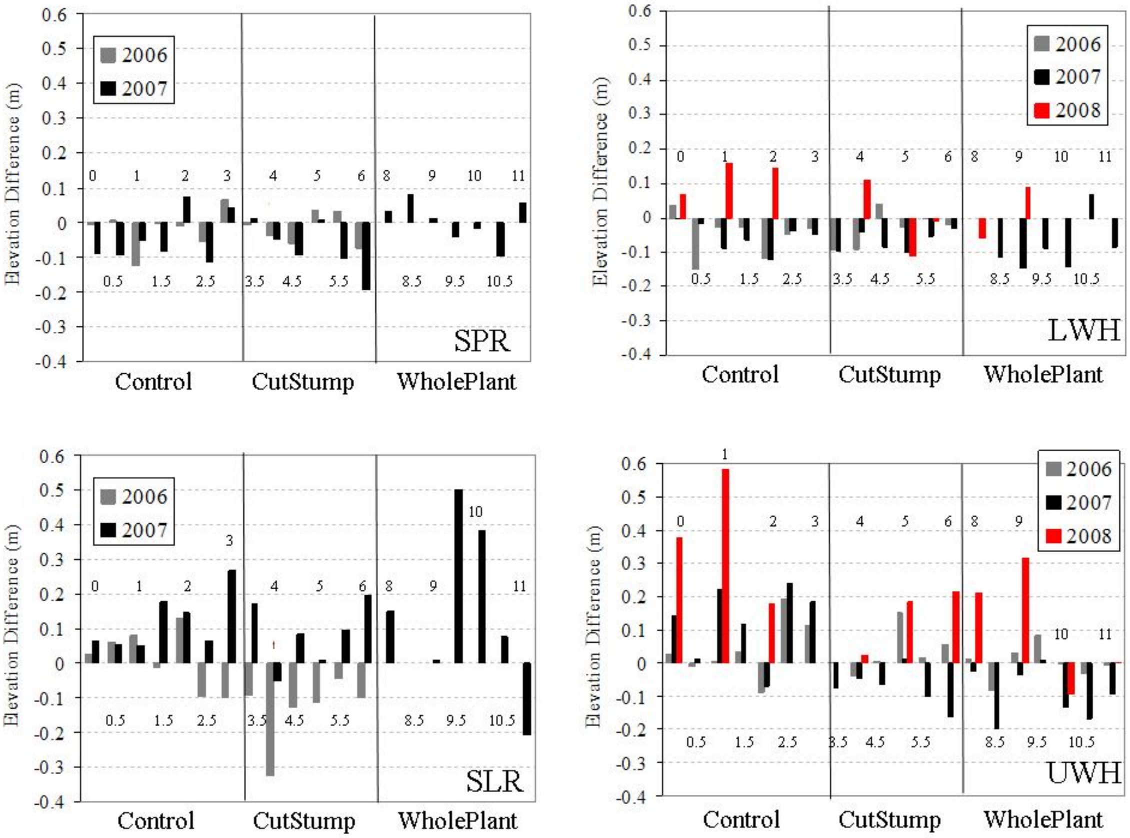


Figure 4.10 Difference in thalweg elevation at individual cross sections for each study site over the study period.

Bed incision had occurred at most cross sections throughout both study sites by 2007 and 2008, respectively, with maximum incision (0.5 m) for SLR in the whole-plant reach and 0.58 m of incision in the control reach of UWH. A total of 8 repeat surveys took place in the UWH study site, allowing for more detailed observations on the longitudinal channel response. In general, the thalweg fluctuated around the initial 2005 longitudinal profile, with no distinct aggradation or incision trends within or between reaches. It is worth noting, however, that the first monsoon flow on July 24, 2006 resulted in deposition of an approximately 200-m-long wedge of sand with maximum height of 0.5 m in the whole-plant removal reach, which was subsequently removed by September 2006. Also, by May 2008, the control reach had incised approximately 0.5 m and approximately 0.2 m in the upstream portion of the whole-plant removal reach (Figure 4.11).

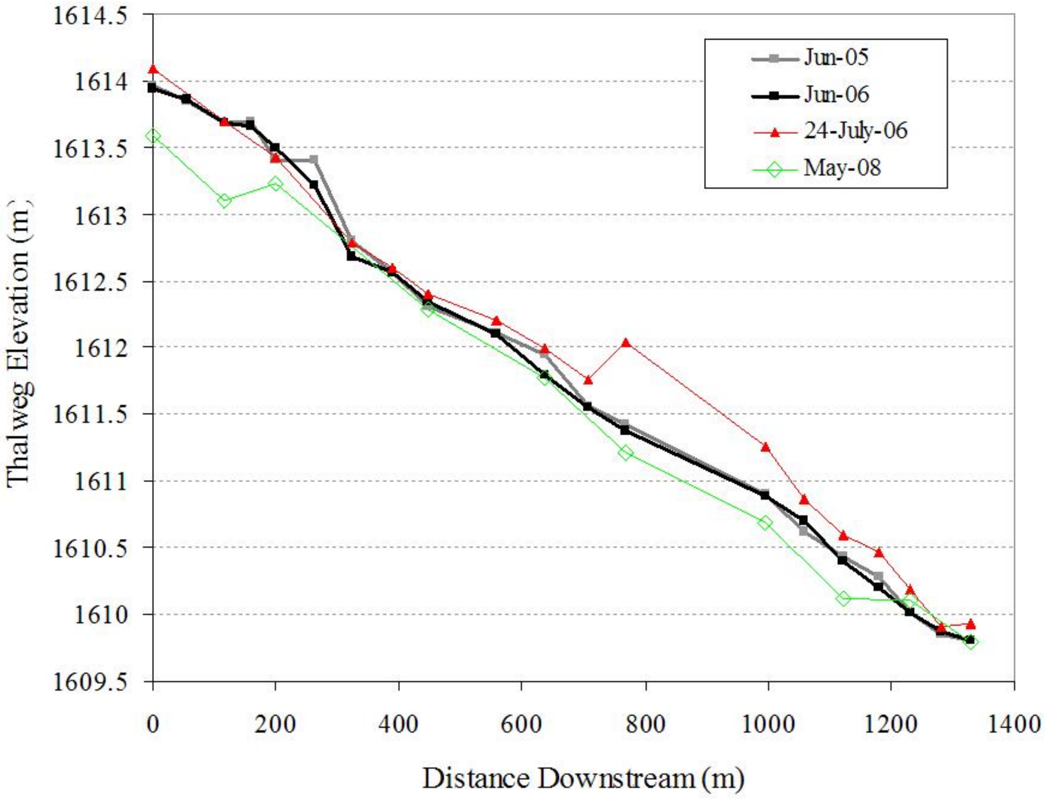


Figure 4.11 Longitudinal profile of thalweg elevation over study period for UWH. Slug of sediment deposited after July 24, 2006 monsoon flow event which was transported through the study site by May 2008.

4.4.3 Controls on channel cross sectional adjustment

Statistically significant correlations exist between adjustment in cross sectional geometry and exotic plant removal treatments, the particular year that the survey was conducted, and the interaction term that includes the survey year and the reach type. Statistical results from both the mixed effects and fixed effects model that show significant correlations between channel change parameters and the explanatory variables are presented together (Table 4.7). The effect of ***reach*** type (control, cut-stump, and whole-plant) statistically significantly correlates with channel adjustment parameters *width* and *perimeter* both when evaluating channel change within only the four study sites (Fixed Effects Model), or when assuming the study sites are from the larger population of channel segments within Canyon de Chelly (Mixed Effects Model). However, the correlation in the mixed effects model, although statistically significant, does not account for the variability between the study sites, or between reaches within study sites. The effect of ***reach*** type on cross sectional *area* also is significant in the fixed effects model; *area* had no significant correlations with variables in the mixed effects model. The variable ***year*** (2005, 2006, 2007, 2008) is the most significant variable and correlates with all cross section geometry parameters in both the fixed and mixed effects model. In addition, ***year*** continues to significantly correlate with all three channel depth values (*depth*, *average depth*, and *hydraulic radius*), while accounting for the variability across study sites, across reach types within a site, and across cross sections nested within a reach within a site. The individual study ***site*** (Spider Rock, Sliding Rock, Upper White House, and Lower White House) correlates with all channel adjustment parameters. The interaction term that includes both the reach and the year (***reach*year***) significantly correlates with *average depth, hydraulic radius,* and the two *width/depth ratio* values in the fixed effects model, although the interaction term also correlates with the *width/average depth* in the mixed effects model.

The high significance of the year term in all of the models indicates that the variability between years is higher than the variability between reach types. As a result, the effect of exotic plant removal on cross sectional channel adjustment was evaluated for individual years (Table 4.8). For the survey year 2007, with channel change resulting from the wetter than normal 2006 monsoon season and 2007 winter/spring season, channel change in the whole plant removal reaches were significantly higher in terms of perimeter and width compared to either control or cut-stump reaches (Table 4.9). Cross-sectional area change was also significantly higher than control reaches during the 2007 survey year, but remained indistinct from cut-stump reaches. For the 2008 survey year, which captured change resulting from the wetter than normal 2006 monsoon and 2007 winter/spring season, channel perimeter, width, and the two width/depth ratio values are significantly higher than control reaches. The width/depth ratio values are also significantly higher than the cut-stump removal reaches. The 2006 survey year, which experienced drier than normal monsoon, winter, and spring seasons, did not result in any statistically significant effect of exotic plant removal on cross sectional geometry change.

Table 4.7 Results from mixed and fixed effects model identifying significant correlations between cross sectional geometry parameters, reach type (control, cut-stump, and whole-plant), the year of survey, an interaction term between reach type and year (reach*year), and study site. Statistical significance at the 0.05 level.

Model type	**Response variable**	**Levels of variability accounted for in model**	**Explanatory variable**	**p value**	**AICC**
Fixed Effects	area	accounts for variability between cross sections within the same reach within the same site	reach	0.0007	1660.3
			year	<0.0001	
			reach*year	0.0001	
			site	0.0002	
Mixed Effects	perimeter	accounts for variability between cross sections within a reach within a site	reach	0.0183	1083.2
			year	<0.0001	
Fixed Effects	perimeter	accounts for variability between cross sections within the same reach within the same site	reach	0.0008	1141.4
			year	0.0003	
			reach*year	0.0003	
			site	0.015	
Mixed Effects	width	accounts for variability between cross sections within a reach within a site	reach	0.0109	1080.4
			year	<0.0001	
Fixed Effects	width	accounts for variability between cross sections within the same reach within the same site	reach	0.0004	1095
			year	<0.0001	
			reach*year	<0.0001	
			site	0.0141	

Table 4.7 Continued

Mixed Effects	depth	accounts for variability between sites, between reaches within a site, and between cross sections within a reach within a site	year	<0.0001	-108
Fixed Effects	depth	accounts for variability between cross sections within the same reach within the same site	year	<0.0001	-115.2
			site	<0.0001	
Mixed Effects	average depth	accounts for variability between sites, between reaches within a site, and between cross sections within a reach within a site	year	<0.0001	-175.3
Fixed Effects	average depth	accounts for variability between cross sections within the same reach within the same site	year	<0.0001	-174.8
			reach*year	0.0005	
			site	<0.0001	
Mixed Effects	rh	accounts for variability between sites, between reaches within a site, and between cross sections within a reach within a site	year	<0.0001	-289.4
Fixed Effects	rh	accounts for variability between cross sections within the same reach within the same site	year	<0.0001	-276.7
			reach*year	0.0139	
			site	<0.0001	

Table 4.7 Continued

Mixed Effects	wd	accounts for variability between cross sections within a reach within a site	year	0.0367	661.4
Fixed Effects	wd	accounts for variability between cross sections within the same reach within the same site	year	0.0003	623.6
			reach*year	0.0009	
			site	<0.0001	
Mixed Effects	wd (average depth)	accounts for variability between reaches within a site, and between cross sections within a reach within a site	year	<0.0001	898.7
			reach*year	0.0041	
Fixed Effects	wd (average depth)	accounts for variability between cross sections within the same reach within the same site	year	<0.0001	882.4
			reach*year	0.0001	
			site	<0.0001	

Table 4.8 Effect of exotic plant removal on change in cross sectional geometry within individual years. Year accounts for channel adjustment from the year’s winter baseflow and spring runoff season and the previous year’s monsoon season. P values associated with pairwise comparisons between reach types indicate significant differences between reach types for the give survey year.

Year	**Response variable**	**Levels of variability accounted for in model**	**p value**	**AICC**	**Pairwise comparison between reaches**	**p value**
2007	area	accounts for variability between sites, and cross sections within reaches within sites	0.0176	579.1	control and whole-plant	0.0194
2008	width	accounts for variability between cross sections within reaches within sites	0.0071	109	control and whole-plant	0.0061
2007	width	accounts for variability between sites, and cross sections within reaches within sites	0.0106	444.6	control and whole-plant	0.0133
					cut-whole	0.0461
2008	perimeter	accounts for variability between cross sections within reaches within sites	0.0127	112.6	control and whole-plant	0.0112
2007	perimeter	accounts for variability between sites, and cross sections within reaches within sites	0.0143	450.6	control and whole-plant	0.018
					cut-whole	0.0541
2008	wd (average depth)	accounts for variability between sites, and cross sections within reaches within sites	0.0017	80.9	control and whole-plant	0.0014
					cut-whole	0.0229
2008	wd	accounts for variability between sites, and cross sections within reaches within sites	0.0023	68.6	control and whole-plant	0.0022
					cut-whole	0.0169

Table 4.9 Summary statistics (mean, median, and standard deviation) and group differences of select cross sectional geometry changes for survey years 2007 and 2008. Reach types (control, cut-stump, whole-plant) with different letters indicate statistically significant differences between reaches for the given year.

Parameter	**Statistic**	**Control**	**Cut-stump**	**Whole-plant**
		2007		
area	Mean	-0.14	-0.59	-1.26
	Std Deviation	0.74	1.34	1.70
	Median	-0.01	-0.42	-1.40
	Group differences	a	ab	b
perimeter	Mean	0.03	-0.29	-0.35
	Std Deviation	0.49	0.68	0.51
	Median	0.04	-0.18	-0.22
	Group differences	a	a	b
width	Mean	-0.01	-0.17	-0.10
	Std Deviation	0.55	0.70	0.46
	Median	0.06	-0.06	0.00
	Group differences	a	a	b
		2008		
perimeter	Mean	-1.16	-2.29	-17.69
	Std Deviation	0.82	3.20	35.89
	Median	-1.21	-1.68	-3.39
	Group differences	a	ab	a
width	Mean	-0.24	-0.13	-0.19
	Std Deviation	0.09	0.14	0.11
	Median	-0.25	-0.11	-0.20
	Group differences	a	ab	a
wd	Mean	0.84	0.10	42.78
	Std Deviation	0.82	0.65	104.86
	Median	0.82	0.16	0.24
	Group differences	a	a	b
wd (average depth)	Mean	-0.08	-0.07	-0.48
	Std Deviation	0.07	0.11	0.98
	Median	-0.10	-0.09	-0.11
	Group differences	a	a	b

4.4.3.1 Differences in channel adjustment during monsoon and winter baseflow/spring runoff seasons

In general, more channel change occurred during the combined winter baseflow and spring runoff season (October through May) than during the monsoon season (July through September) (Table 4.10, Figure 4.12). Channel incision (depth) is statistically significantly ($\alpha = 0.05$) larger after the winter baseflow/spring runoff season compared to the either the 2006 and 2007 monsoon season ($p = 0.0075$ and 0.0018, respectively). Average channel depth is also significantly larger during the 2007 monsoon season relative to the winter/spring season of 2008 ($p = 0.0118$). Aggradation occurs at most cross sections during the monsoon season whereas net bed incision occurs during the winter/spring season. Cross sectional area is also statistically larger during the winter/spring season than the monsoon season ($p = 0.0214$), although this difference exists only for the 2007-2008 data, which compares channel change resulting from a single, large magnitude, monsoon discharge to the cumulative channel change resulting from the remainder of the 2007 monsoon season and the winter and spring seasons of 2008.

Table 4.10 Summary statistics (mean, median, and standard deviation) and p value for significant differences in channel adjustment (area, perimeter, width, average depth, and depth) between monsoon and winter/spring seasons. Statistics were calculated for the 2006 monsoon season, the largest recorded monsoon discharge in 2007, and for the cumulative change of winter baseflow and spring runoff. P values reported for only statistically ($\alpha = 0.05$) differences between seasonal channel change.

		Monsoon 2006-Winter/Spring 2007		Aug 5, 2007 Monsoon - Winter/Spring 2008	
Parameter	Statistic	monsoon	spring	monsoon	spring
area (m^2)	mean	-0.01	-0.68	-0.10	-2.43
	median	0.53	-0.88	-0.16	-2.28
	stdev	1.43	0.97	1.22	2.12
	p value			0.0214	
perimeter (m)	mean	0.01	-0.14	-0.33	-0.29
	median	-0.03	-0.05	-0.13	-0.28
	stdev	0.47	0.57	0.61	0.57
Width (m)	mean	0.05	0.01	-0.14	-0.35
	median	0.19	-0.10	-0.13	-0.06
	stdev	0.49	0.50	0.59	0.92
average depth (m)	mean	-0.01	-0.05	0.01	-0.11
	median	0.001	-0.04	0.00006	-0.10
	stdev	0.11	0.05	0.08	0.08
	p value			0.0118	
depth (m)	mean	0.11	-0.08	0.04	-0.23
	median	0.16	-0.09	0.06	-0.21
	stdev	0.11	0.10	0.13	0.21
	p value	0.0075		0.018	

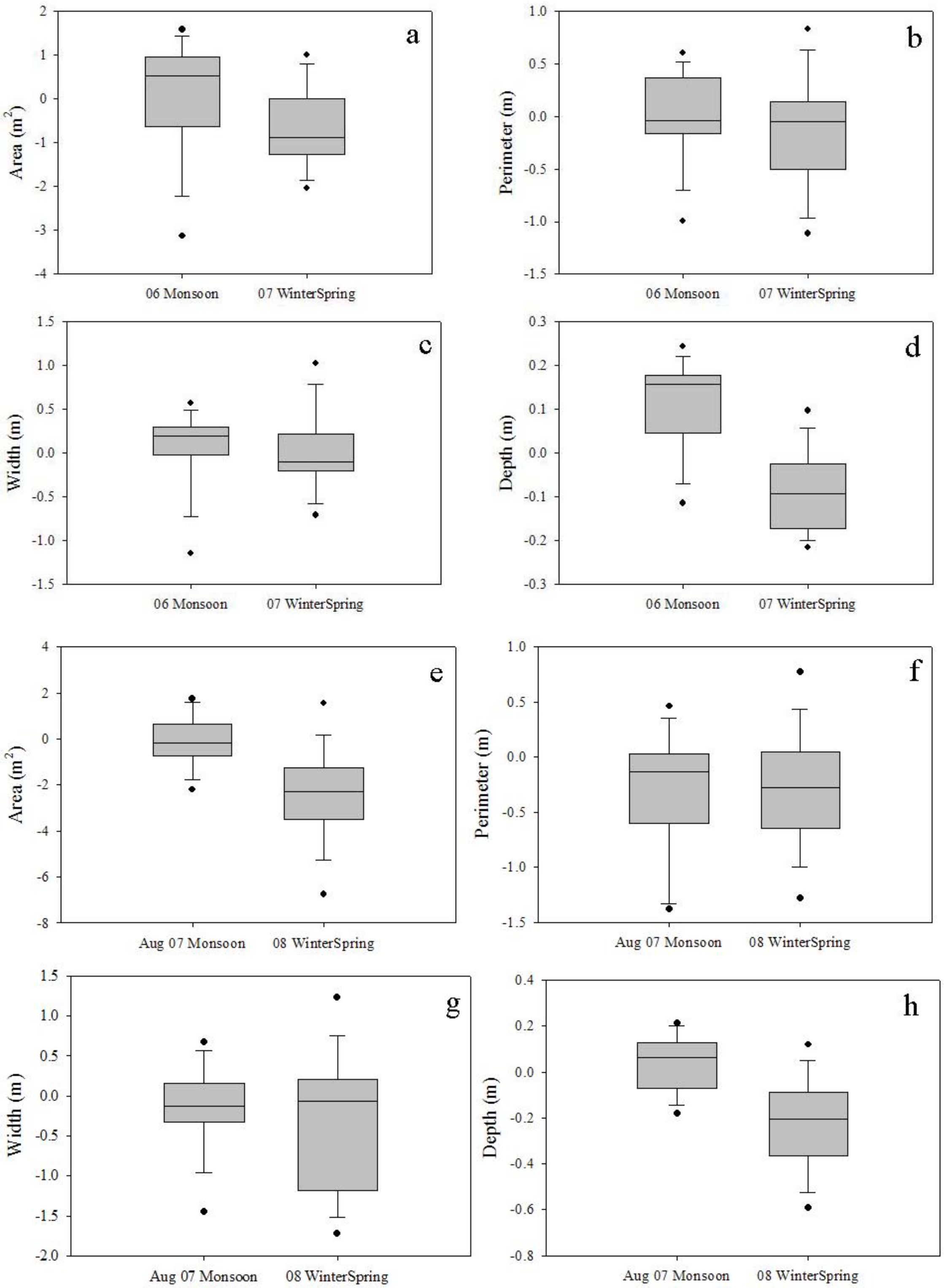


Figure 4.12 Boxplots for channel adjustment by season. Monsoon extends from July to September. Winter baseflow/Spring runoff extends from October to May. a. area, b. perimeter, c. width, d. depth reflect change from 2006 monsoon and 2007 winter/spring season. e. area, f. perimeter, g. width, and h. depth reflect change from a large, individual monsoon discharge on August 5, 2007 and the 2008 winter/spring season.

4.5 CONCEPTS MODEL SIMULATION

4.5.1 Discharge records

Comparisons between field-measured high water marks for three flows and the water-surface profiles generated in CONCEPTS resulted in discharge estimates that ranged from 12 m^3/s to 79 m^3/s (Figure 4.13). The discharge record used for the calibration exercise in CONCEPTS included 36 individual flows ranging in magnitude from 0.25 m^3/s to 79 m^3/s (Table 4.11).

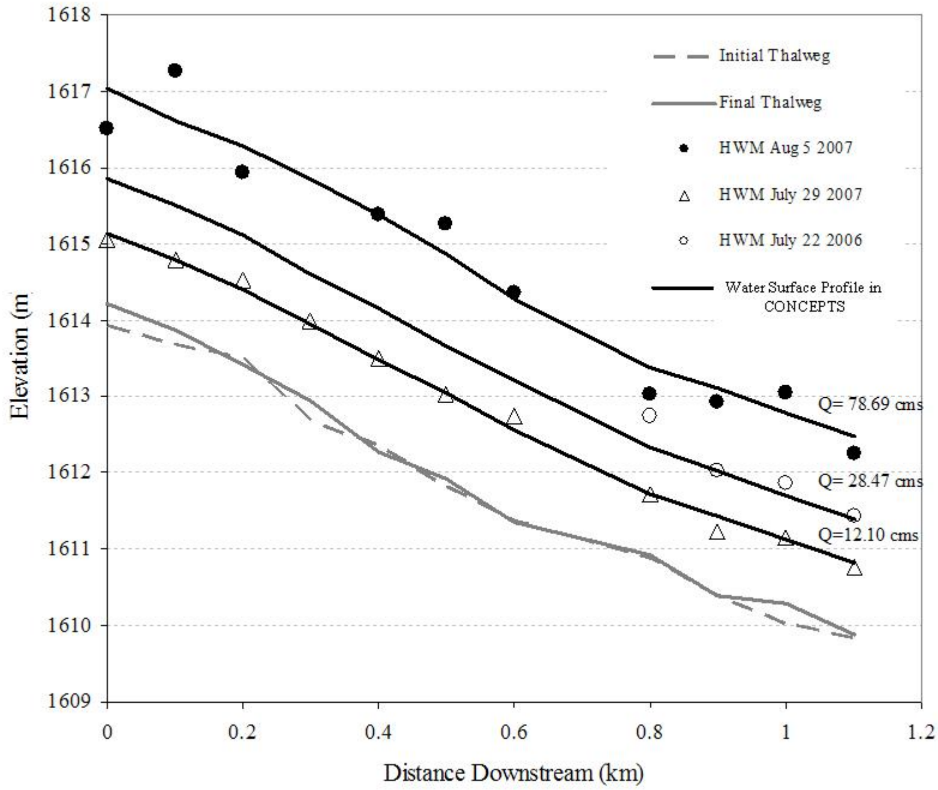


Figure 4.13 Comparison of field-measured high water marks and water surface profiles generated in CONCEPTS.

Although precipitation amounts from storms of known recurrence interval do not necessarily translate to runoff events of similar frequency, precipitation data collected on an hourly basis can provide evidence that there was sufficient precipitation to create runoff within the range of magnitudes estimated using the stage-discharge relationship. However, no stations exist in the upper watershed that measure precipitation on an hourly (or daily) interval, which could be used to make this comparison. Further, because convective thunderstorms that generate these short duration flows do not extend over large areas, precipitation stations lower in the watershed (Chinle station) or in adjacent watersheds (Lukachukai station) are not useful.

The magnitudes of individual flows from the discharge record were compared to discharge magnitudes of known recurrence intervals calculated using regression equations specific to the hydroclimatic region of Canyon de Chelly and developed using basin area and local annual evaporation rates (Thomas et al., 1997). Based on this comparison, the 2006 monsoon season included 4 flows with recurrence interval of 0.5 year (9 m^3/s), 1 flow with recurrence interval of approximately 1 year (20 m^3/s), and 1 flow with recurrence interval of 2 years (28 m^3/s) (Table 4.11). The 2007 monsoon season included 3 approximately 0.5-year recurrence interval flows, one 1-year recurrence interval flow, and a discharge with the approximate recurrence interval of 7 years (79 m^3/s).

Table 4.11 Discharge estimates based on continuously recording stage gage in Canyon de Chelly.

Stage-Discharge Relationship		$Q=7.5975h^{1.954}$			Maximum Manning n value		Minimum Manning n value	
Flow Event Number	**Date**	**Peak Flow Depth (m)**	**Peak Discharge (cms)**	**Recurrence Interval**	**Peak Discharge (cms)**	**Recurrence Interval**	**Peak Discharge (cms)**	**Recurrence Interval**
1	7/22/2006	1.97	28.47	2 year	19.70	1.3 year	56.68	5 year
2	7/30/2006	0.67	3.50		3.19		8.95	
3	8/4/2006	0.58	2.58		2.45		6.85	
4	8/7/2006	0.26	0.53		0.64		1.74	
5	8/7/2006	0.29	0.68		0.77		2.13	
6	8/9/2006	0.98	7.27		6.02		17.05	
7	8/10/2006	0.27	0.60		0.69		1.90	
8	8/11/2006	1.33	13.30	0.5 year	10.17	0.5 year	29.01	2 year
9	8/14/2006	0.17	0.25		0.32		0.86	
10	8/15/2006	0.24	0.45		0.54		1.47	
11	8/21/2006	0.55	2.39		2.29		6.41	
12	8/24/2006	1.30	12.72	0.5 year	9.79	0.5 year	27.89	2 year
13	9/1/2006	0.42	1.40		1.44		4.00	
14	9/3/2006	0.60	2.78		2.61		7.30	
15	9/8/2006	0.80	4.86		4.25		11.96	
16	9/10/2006	0.32	0.84		0.93		2.55	
17	9/14/2006	0.86	5.71		4.88		13.77	
18	9/21/2006	0.42	1.37		1.41		3.92	

Table 4.11 Continued

Stage-Discharge Relationship		$Q=7.5975h^{1.954}$			Maximum Manning n value		Minimum Manning n value	
Flow Event Number	**Date**	**Peak Flow Depth (m)**	**Peak Discharge (cms)**	**Recurrence Interval**	**Peak Discharge (cms)**	**Recurrence Interval**	**Peak Discharge (cms)**	**Recurrence Interval**
19	10/6/2006	0.27	0.60		0.69		1.91	
20	10/8/2006	1.66	20.43	1.5 year	14.77	0.9 year	42.32	<2 year
21	10/9/2006	1.12	9.53	0.5 year	7.61		21.63	
22	10/9/2006	0.84	5.39		4.64		13.10	
23	10/14/2006	1.12	9.50	0.5 year	7.59		21.56	1.5 year
24	10/15/2006	0.84	5.43		4.67		13.18	
25	10/17/2006	0.64	3.16		2.92		8.18	
26	5/20/2007	0.8	4.89		4.26		12.01	
27	7/27/2007	0.6	3.25		2.99		8.39	
28	7/28/2007	0.30	0.75		0.83		2.29	
29	7/28/2007	0.33	0.89		0.97		2.67	
30	7/29/2007	0.5	1.86		1.84		5.14	
31	7/29/2007	1.3	12.10	0.5 year	9.37	0.5 year	26.69	2 year
32	7/31/2007	0.8	4.35		3.85		10.85	0.5 year
33	8/2/2007	1.5	17.28	1 year	12.77	0.5 year	36.53	<2 year
34	8/3/2007	1.1	8.97	0.5 year	7.23		20.51	1 year
35	8/4/2007	1.1	8.42	0.5 year	6.84		19.39	1.3 year
36	8/5/2007	3.3	78.69	7 year	47.65	4 year	138.75	14 year

The fact that the 2006 and 2007 monsoon flow record includes discharges of reasonable frequency (e.g., the 1-year event occurring one time in both years, one 2-year flood, and several 0.5-year floods) provides some confidence that the generated discharge record is at least within the same order of magnitude as the true discharge record. Discharge values estimated using maximum and minimum Manning *n* values provide further support that the generated discharge record is a reasonable estimate of flow magnitudes. Discharges estimated with maximum Manning *n* values have diminished magnitudes relative to the generated discharge record; estimates are larger in the discharge record that used minimum Manning *n* values. Discharge magnitudes ranged from 8.2 m^3/s to 26.6 m^3/s for the smallest of the three flows used in creating the stage-discharge relationship (June 29, 2007) and from 47.2 m^3/s to 138.7 m^3/s for the largest flow on August 5, 2007 (Table 4.11). The recurrence interval for discharges in the generated flow discharge compared to the discharge record using maximum Manning *n* values mostly remained the same, with the exception of lowering the recurrence interval from 7 years to 4 years for the August 5, 2007 flow. However, the discharge record using minimum Manning *n* values elevated the 0.5-year event to a more than 2-year event and the August 5 flow to a recurrence interval of 14 years. Therefore, it is not likely that the generated discharge record is an underestimate of flow magnitude, but rather, may be a slight overestimate.

The six years of discharge from the Jemez River were partitioned into a total of 52 individual flows, of which 26 are characterized as monsoon flows of short duration (<24 hours), 25 are considered spring runoff with longer duration that extends over several days to weeks, and 1 flow in November, which is characterized as a fall event with a duration of several days (Table 4.12). The largest discharge magnitude (65 m^3/s) is associated with the monsoon season, but spring runoff events include 4 relatively large magnitude discharges that range from 25 to 31 m^3/s and one event with magnitude 42 m^3/s (Figure 4.14). These discharge magnitudes are roughly equivalent to flows with recurrence intervals of 3 to 5 years based on the regional regression equations.

Table 4.12 Individual discharge event date and magnitude included in the 6-year simulation period using the Jemez River, New Mexico record. Discharge magnitudes are adjusted for the Canyon de Chelly drainage area.

Storm Type	**Peak m^3/s**	**Date**
MONSOON	65	28-Jul-93
MONSOON	40	30-Aug-95
MONSOON	20	3-Aug-06
MONSOON	16	3-Aug-91
MONSOON	15.3	10-Sep-02
MONSOON	14.5	2-Aug-02
MONSOON	11.8	9-Aug-06
MONSOON	11.6	28-Jun-06
MONSOON	10.6	27-Jul-06
MONSOON	10	6-Jul-06
MONSOON	9.5	8-Jul-06
MONSOON	9	5-Sep-91
MONSOON	7	18-Jul-06
MONSOON	6.3	14-Aug-06
MONSOON	6.2	20-Jul-91
MONSOON	6	11-Aug-91
MONSOON	6	18-Jul-02
MONSOON	5.72	24-Aug-92
MONSOON	5.7	26-Jun-06
MONSOON	5.3	20-Aug-06
MONSOON	5.2	23-Jul-02
MONSOON	4.4	31-Jul-06
MONSOON	4.3	3-Jul-91
MONSOON	4	19-Oct-05
MONSOON	3.3	21-Jul-02
MONSOON	3.2	2-Sept-02
Storm Type	**Peak m^3/s**	**Date**
SPRING	42	21-Jun-02
SPRING	30.8	9-Apr-93
SPRING	29.3	27-Feb-92
SPRING	26.7	12-Mar-95
SPRING	25	1-Apr-91
SPRING	16	19-May-91
SPRING	15.8	17-Jun-95
SPRING	15	1-Apr-93
SPRING	14.25	17-Apr-93
SPRING	13.4	2-Apr-95
SPRING	13.3	21-Apr-93
SPRING	13.08	24-Apr-92
SPRING	12.9	17-Mar-93
SPRING	12.65	27-Apr-93
SPRING	12.59	9-May-92
SPRING	12.25	13-May-95
SPRING	11.4	21-May-95
SPRING	11.1	12-May-93
SPRING	10.64	20-May-92
SPRING	10.2	1-Jun-95
SPRING	8.8	17-Apr-91
SPRING	8.8	11-Jun-91
SPRING	8.3	2-May-91
SPRING	7.6	5-Mar-95
SPRING	5.6	19-Feb-95
FALL	3.5	2-Nov-90

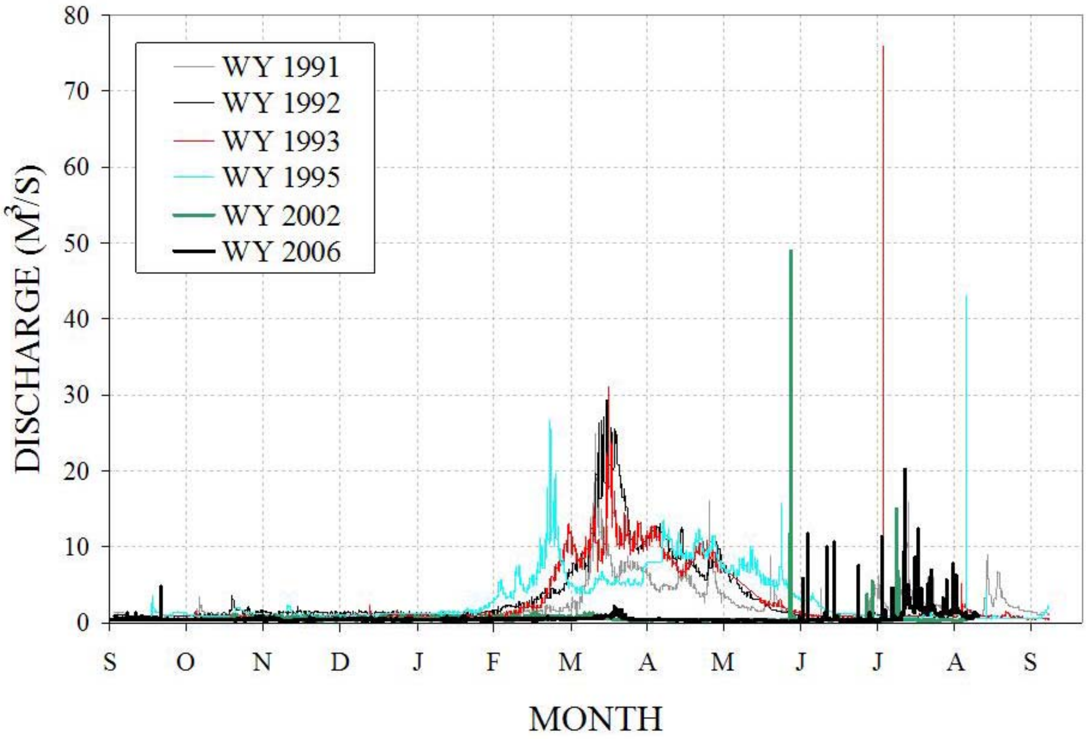


Figure 4.14 Jemez River, New Mexico discharge for water years 1991, 1992, 1993, 1995, 2002, and 2006

4.5.2 Model calibration: comparison of model simulation and field-measured channel change

In general, changes in cross sectional area were in the same direction (erosion vs deposition) for both simulations and field surveys when comparing ΔA_{Total} and ΔA for individual bank toes (Figure 4.15). CONCEPTS was less successful at correctly simulating adjustment of the channel bank above the bank toe (ΔA_{Bank}). Comparisons between simulations and field surveys of individual channel banks resulted in correct simulation of 12 out of 20 banks. These bank failures above the toe typically were caused by sub-aerial processes rather than fluvial erosion. CONCEPTS was least successful at correctly simulating change along the channel bed; 6 out of the 10 cross sections showed either simulated net aggradation where net incision had occurred in the field or simulated net incision where net aggradation had occurred (Figure 4.15).

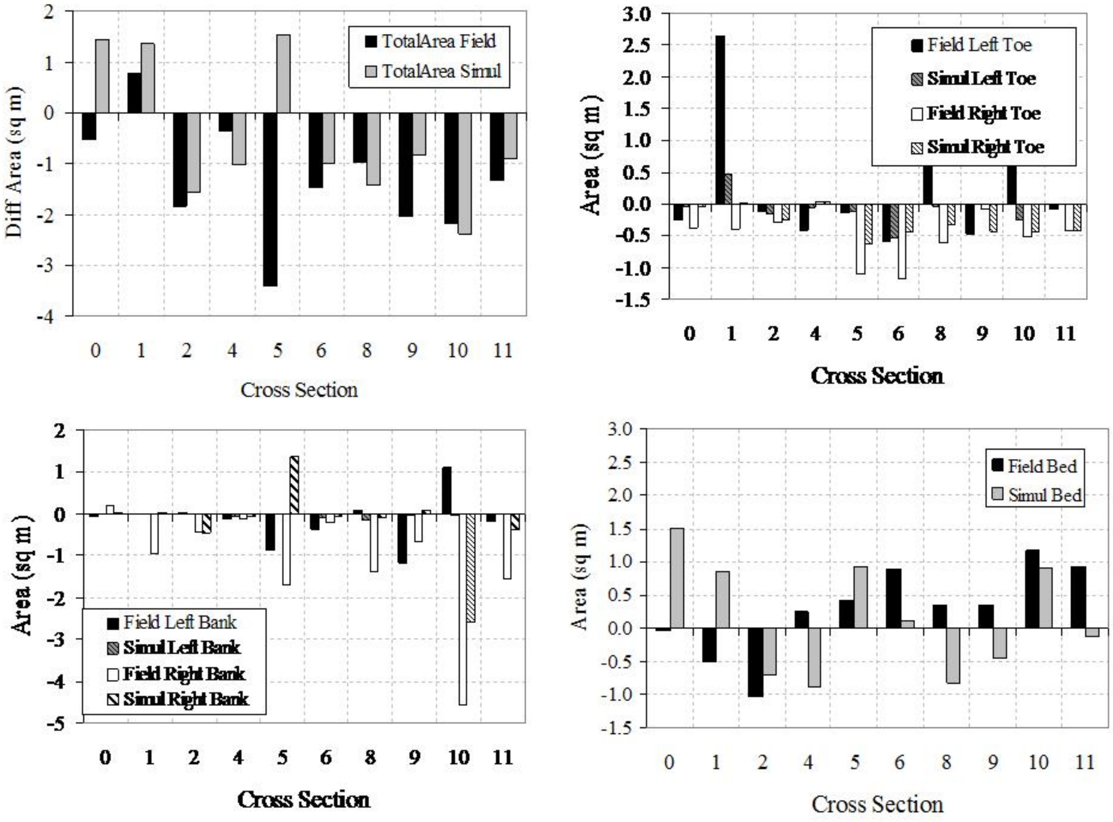


Figure 4.15 Differences in change in cross sectional area between CONCEPTS simulations and field-measured surveys.

Detailed plots that overlay field-measured surveys, CONCEPT simulations, and the initial survey for individual cross sections are shown in Appendix D. Differences were typically a result of under-estimation of erosion by CONCEPTS along the bank and bank toe, and either under-estimation of erosion or over-estimation of deposition on the channel bed. The largest differences between simulations and field cross sections were on the channel bed and in cross sections with complex geometry (e.g., vegetation along channel banks in XS 1.0 and XS 10.0 that resulted in deposition in the field but was not simulated by CONCEPTS, or wood on the channel bed that created dynamic hydraulics that could not be simulated in CONCEPTS (XS 8.0). Channel change simulated in CONCEPTS accounts for 0 to more than 200% of field-measured change along channel banks, 1 to 490% along the bank toe, and 14 to 3800% on the channel bed. However, it is important to note that, as indicated in previous sections, substantial channel change measured in the field over the study period was limited to a few individual cross sections (e.g., 4.5 m^2 erosion on XS 10.0 right bank), with minor adjustments in cross section geometry occurring at all cross sections (less than 1 m^2). Therefore, any change simulated in CONCEPTS results in a simulation-to-field ratio that appears grossly out of proportion, but in reality translates to a difference in erosion or deposition of only a few centimeters.

Channel adjustment along the simulation reach with maximum Manning *n* values and diminished discharge magnitudes was similar to channel adjustment along the reach with visual field estimates of Manning *n* values and the associated generated discharge record (Figure 4.16, Appendix E). The exceptions to this were channel changes along the right bank of two cross sections (XS 5 and XS 10). With respect to XS 5, simulations along the roughened channel were more similar to field conditions, in which deposition did not occur along the right bank inset terrace. With respect to XS 10, simulations along the visually estimated Manning *n* channel were closer to field observations. The similarity in channel adjustment between the two simulation scenarios suggests that either simulation reach could be used in further modeling scenarios. However, because the visually estimated Manning *n* values seem more realistic compared to field conditions, it seems more appropriate to use this simulation reach for modeling scenarios.

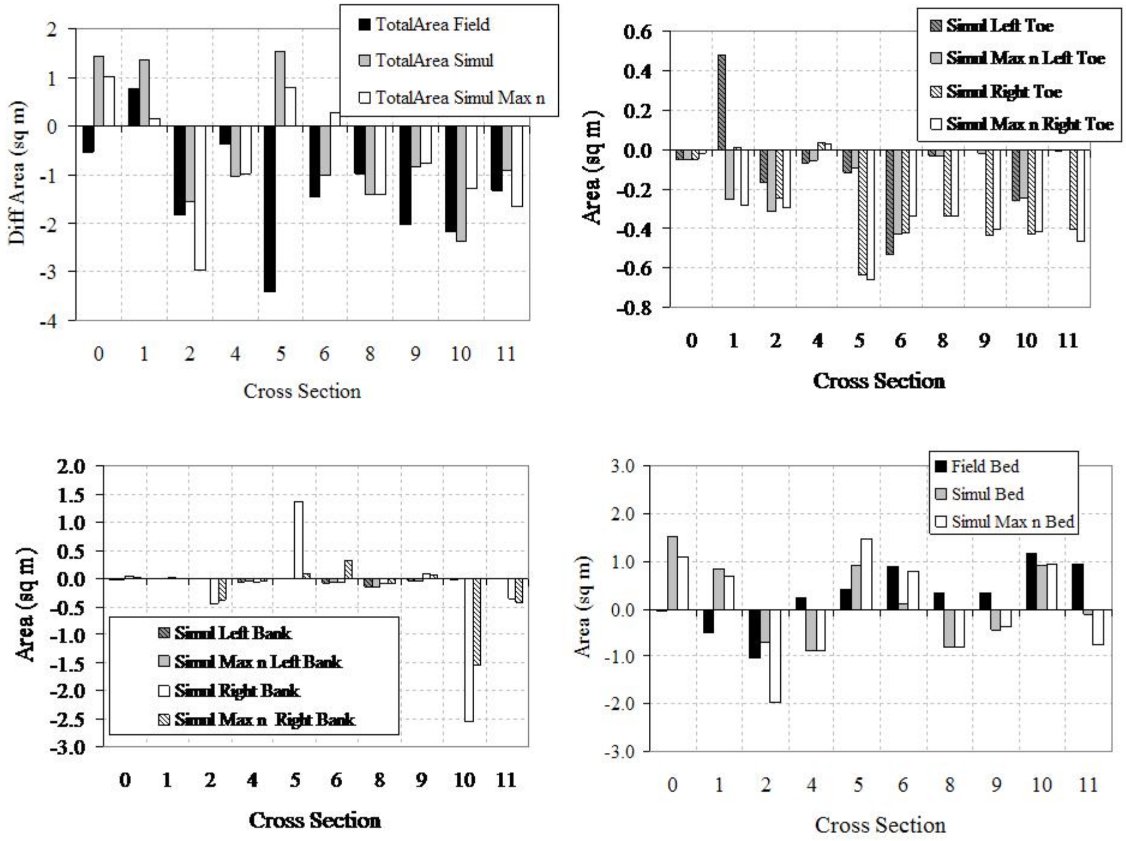


Figure 4.16 Differences in change in cross sectional area between CONCEPTS simulations using visually estimated Manning n values and discharge record and maximum Manning n values and an associated diminished discharge record.

4.5.3 Simulated longer term channel response

A simulation using the Zuni River highest flood on record adjusted for drainage area at Canyon de Chelly resulted in minimal channel change (Appendix F). Although the maximum discharge magnitude was higher than the peak magnitude used in the calibration exercise (93 m^3/s vs 78 m^3/s), the duration was extremely short (< 24 hours compared to 5 days of streamflow used during the calibration exercise). The primary differences when comparing channel adjustment resulting from the adjusted flood of record for the Zuni River to the peak flow used in the calibration exercise are the general absence of bed aggradation at cross sections for the Zuni River flood and the lack of bank failure along the right bank of XS 10. Because the largest flow on record did not result in any substantial channel change, it was not expected that simulations using smaller magnitude flows from continuous years of discharge data would be a useful exercise. Consequently, the largest flow on record was the only simulation using the Zuni River gage data.

Simulated channel change from six complete water years of the Jemez River discharge record resulted in an average 20% increase in cross section area with a maximum of 50% (ΔA_{Total} mean = 6.15 m^2) and 11% increase in perimeter (mean = 1.98 m) (Figure 4.17, Table 4.13). These values are more than twice the values measured in the field over a time period half as long for the same study site (7% increase in cross

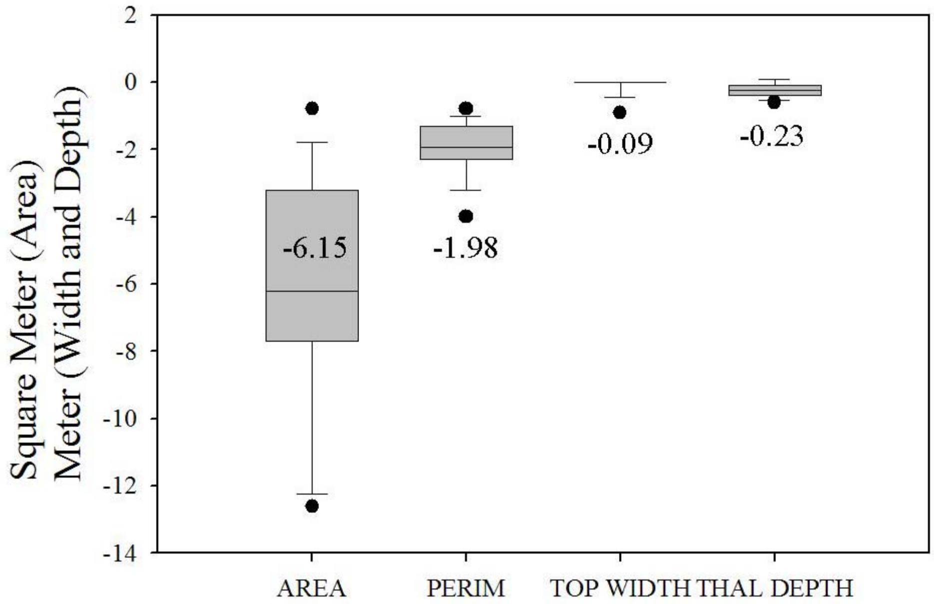


Figure 4.17 Differences in cross sectional geometry parameters for all cross sections in UWH simulation reach simulated using 6 years of discharge data from the Jemez River, New Mexico. Negative values indicate erosion.

Table 4.13 Summary statistics of changes in cross section geometry simulated using 6 years of Jemez River, New Mexico discharge record adjusted for the Canyon de Chelly drainage area.

	Sample Size	**Statistic**	**Total Area**	**Bed Area (m^2)**	**Total Bank Area (m^2)**	**Total Toe Area (m^2)**	**Peri-meter (m)**	**Top Width (m)**	**Average Depth (m)**	**Thalweg Depth (m)**	**Rh (m)**	**Width/ Depth Ratio**	**Width/ Thalweg Depth Ratio**
Total	10	MIN	-12.6	-4.6	-9.7	-4.5	-4	-0.9	-0.7	-0.6	-0.3	0.1	-0.1
		MAX	-0.8	0.6	0	-0.5	-0.8	0	-0.1	0.1	0	2.7	1.6
		MEAN	**-6.15**	**-2.36**	**-2.1**	**-1.69**	**-1.98**	**-0.09**	**-0.37**	**-0.23**	**-0.12**	**1.22**	**0.43**
		STD	3.85	1.75	3.54	1.21	0.89	0.28	0.20	0.24	0.11	0.85	0.61
Control	3	MIN	-6.7	-4.6	-0.4	-2.4	-2	0	-0.6	-0.5	-0.3	0.1	-0.1
		MAX	-0.8	0.6	0	-1	-0.8	0	-0.1	0.1	0	2.7	1.6
		MEAN	**-4.50**	**-2.77**	**-0.13**	**-1.60**	**-1.57**	**0.00**	**-0.37**	**-0.17**	**-0.13**	**1.20**	**0.53**
		STD	3.22	2.92	0.23	0.72	0.67	0.00	0.25	0.31	0.15	1.35	0.93
Cut-Stump	3	MIN	-12.6	-2.9	-7.2	-4.5	-4	-0.9	-0.7	-0.4	-0.2	0.7	-0.1
		MAX	-3.2	-1	0	-0.5	-1.3	0	-0.2	-0.2	0	0.9	0.6
		MEAN	**-6.40**	**-2.00**	**-2.40**	**-2.07**	**-2.30**	**-0.30**	**-0.40**	**-0.30**	**-0.10**	**0.83**	**0.30**
		STD	5.37	0.95	4.16	2.14	1.48	0.52	0.26	0.10	0.10	0.12	0.36
Whole-Plant	3	MIN	-11.9	-4.6	-9.7	-2.6	-2.4	0	-0.6	-0.6	-0.3	0.4	-0.1
		MAX	-2.8	-0.9	0	-0.5	-1.2	0	-0.2	0.1	0	2.3	1.4
		MEAN	**-7.20**	**-2.33**	**-3.35**	**-1.48**	**-2.05**	**0**	**-0.35**	**-0.23**	**-0.13**	**1.53**	**0.45**
		STD	3.76	1.61	4.46	0.88	0.57	0	0.17	0.30	0.13	0.82	0.66
p value for differences between treatments			0.70	0.89	0.99	0.36	0.55	0.31	0.97	0.75	0.97	0.69	0.99

section area, 4% increase in perimeter over 3 years). Cross section geometry simulated for the final discharge for each of the six water years is graphically presented for each cross section in Appendix G. In five of the ten cross sections, channel change occurred through widening at the bank toe (ΔA_{Toe} mean = 1.69) or lower portion of the bank (ΔA_{Bank} mean = 2.1); bed incision (Δ_{Bed} mean = 0.23 m) occurred in the remaining five cross sections (Figure 4.18).

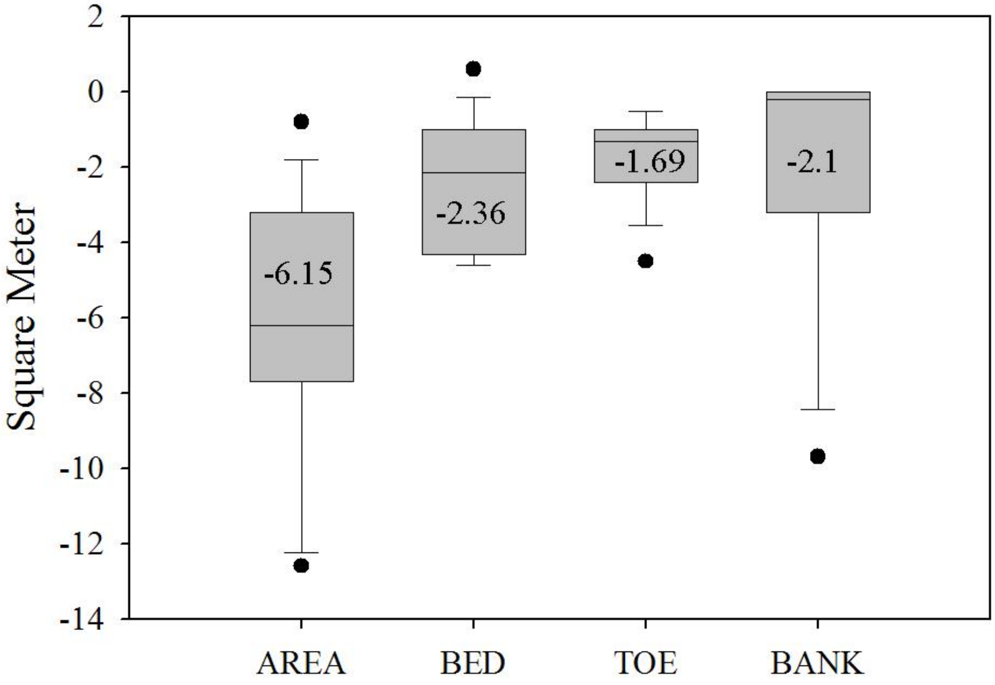


Figure 4.18 Simulated change in total cross sectional area and area partitioned by channel bed, bank toe, and bank for all cross sections using 6 years of discharge data from the Jemez River, New Mexico.

Widening occurred at cross sections located mainly at the upstream and downstream ends of the simulation reach with the exception of XS 6; bed incision occurred primarily at cross sections in the middle of the simulation reach. Average incision over the simulation time period (0.43 m) is more than double the field-measured average incision rate at

UWH (0.09 m) over a time period half as long. In addition, maximum incision was measured in the control reach of the study site, whereas simulations resulted in incision occurring in the middle portions of the reach, which included the cut-stump and whole plant removal reaches. There were no changes in top width, with the exception of XS 6, which experienced entire failure of the bank during the simulation period (Figure 4.17, Appendix G). Increases in average channel width resulted in a slight increase in width/depth ratio parameters (Figure 4.19). When cross sectional parameters are evaluated by treatment, there are no significant differences in channel adjustment parameters between treatments (Table 4.13).

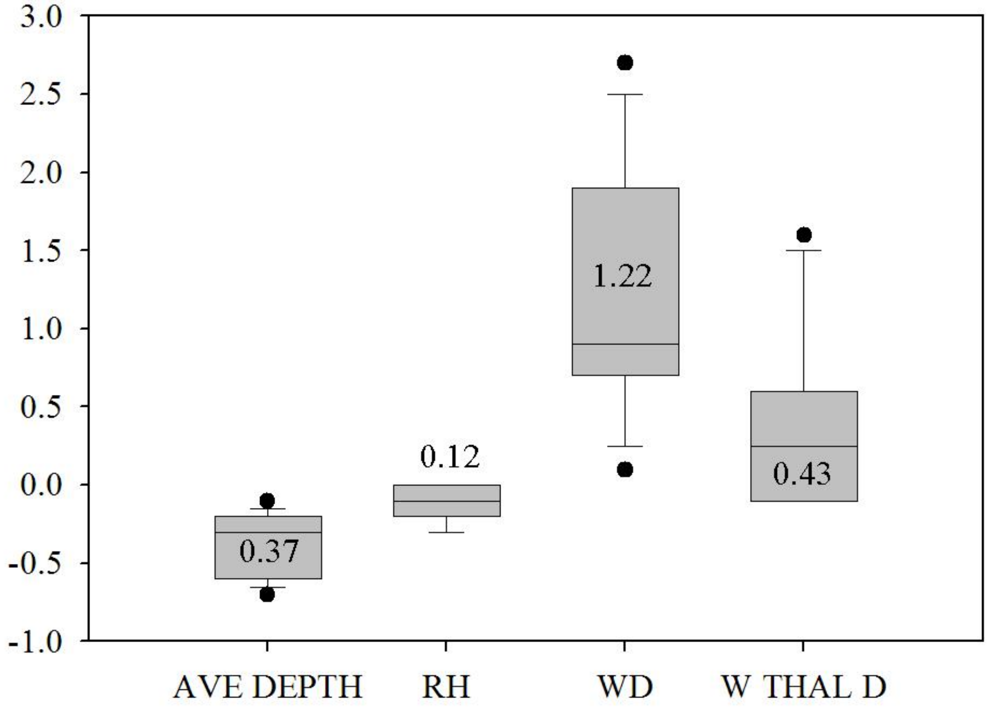


Figure 4.19 Simulated change in cross sectional geometry parameters for all cross sections using 6 years of discharge data from the Jemez River, New Mexico.

The channel thalweg does not approach a graded longitudinal profile after the six years of simulated discharge, but instead results in locally steep regions along two sections of the simulation reach (Figure 4.20). The steepening between XS 6 and XS 8 could be an artifact of the 200-m spacing between these two cross sections rather than the regular 100 m spacing throughout the remainder of the simulation reach.

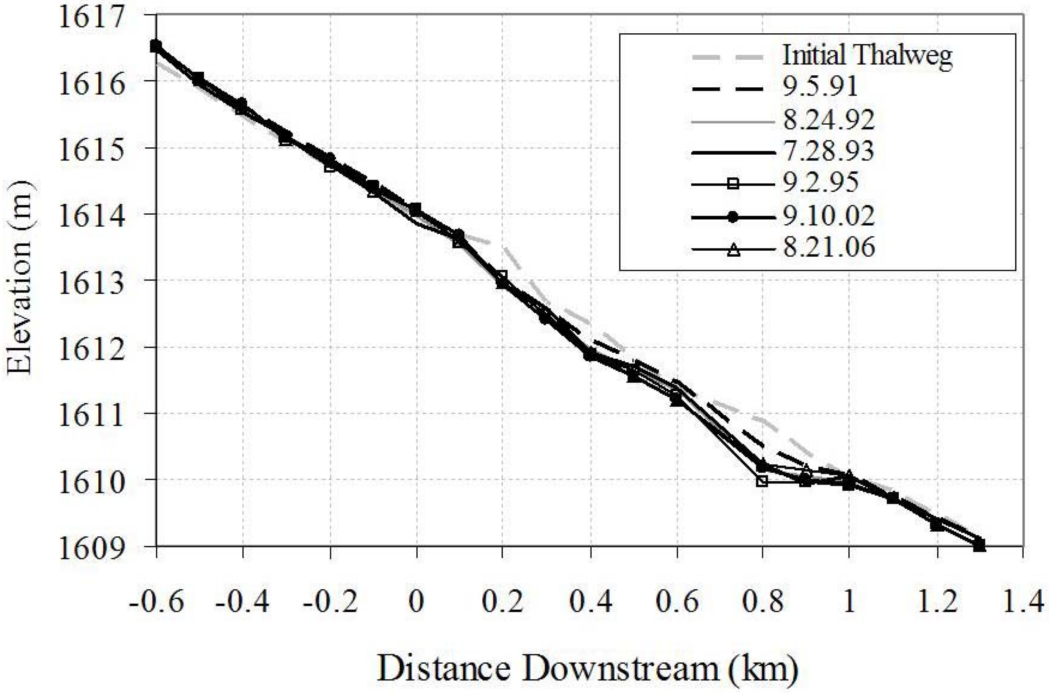


Figure 4.20 Longitudinal profile of simulated channel thalweg for the last discharge event of each of the water years from the Jemez River, New Mexico.

The channel change simulated at each of the ten cross sections occurred primarily during the longer duration spring runoff discharges. In 7 of the 10 cross sections, the majority of the channel change took place during the spring runoff events of the first water year in the simulation exercise, which was 1991. The largest magnitude monsoon event (65 m^3/s) resulted in virtually no channel change along the simulation reach with the exception of approximately 10 cm of incision at XS 9.0. This monsoon event had a duration of less than 24 hours, which was considerably shorter relative to the spring runoff events that sustained discharges ranging from 5 to 15 m^3/s for several weeks to months. Channel change was minimal at all cross sections following the fourth water year of the simulation, 1995 (Appendix G).

4.6 DISCUSSION

4.6.1 Short-term channel adjustment to exotic plant removal

The results from the various analyses indicates that statistically significant differences exist in channel adjustment between control, cut-stump, and whole-plant removal reaches in Canyon de Chelly and that the measured change correlates with exotic plant removal. Significant differences between whole-plant removal reaches and control reaches in mean and median change in channel perimeter, width, and width/depth ratio values and the general lack of statistical distinction of cut-stump reaches from control and whole-plant reaches provides support for the first two hypotheses that channel adjustment will be greatest in the whole-plant removal reaches, with decreased response in the cut-stump reaches. In addition, correlations between channel area, width, and perimeter and reach type (control, cut-stump, and whole-plant) either in the mixed effects or fixed effects modeling further supports the hypotheses that reach type significantly influences channel change. The minor channel changes in the cut-stump reaches and the lack of consistent significant differences in comparisons with control reaches support the second hypothesis, and indicate that removal of the above-ground portion of the plant has less effect than the whole-plant removal method on diminishing bank strength. The absence of diminished bank strength could be because of the presence of the intact subsurface root structure or the presence of cohesive bank substrate, particularly the competent clay layers in SLR and UWH, in addition to mildly indurated silt and sand layers, which have not been disturbed by mechanical grading.

Measured short term (two to three years after plant removal implementation) channel change was primarily through widening, which in turn increased cross-sectional area and perimeter. The most widening occurred at cross sections where the entire plant had been removed along banks consisting of unconsolidated sand and silt and particularly where hydraulic forces are maximized, such as at a meander apex (UWH XS 10.0, LWH XS 9.0). This result provides partial support of the first hypothesis that channel response, expressed as increased cross sectional area through widening, is greatest in the whole-plant removal reaches. However, it is important to note that the maximum channel change was a combined result of reduced bank strength from whole-plant removal treatment and the increased hydraulic forces at the specific location where bank failure occurred.

It was expected that the cross sections with the most unit stream power, which is a combined effect of both discharge magnitude and bed slope, would result in the most channel change. The absence of a correspondence or trend in the scatter plots indicates that either cross section averaged change is not an appropriate measure of driving forces or that local-scale conditions, most notably, bed and bank substrate, presence of vegetation, and the location of the cross section with respect to positioning in a meander bend, may dominate over unit stream power.

The consistent significance of ***year*** as an explanatory variable for most cross section geometry parameters indicates that the variability between years is higher than the variability between reach types and suggests that short term channel response is strongly influenced by the hydrologic conditions of the year. In addition, correlations between channel change and the interaction term ***reach by year*** further suggest that hydrologic conditions influence the effect of exotic plant removal on channel change. The absence of statistical correlations between reach type and channel change measured in the 2006 annual survey is a reflection of the relatively dry monsoon season and regionally dry winter with limited snow melt compared to the other years in the study period. Increases in cross sectional area, perimeter, and width were significantly larger in whole-plant reaches relative to control reaches for the 2007 annual survey. In addition, changes in perimeter, width, and width/depth ratio values in whole-plant removal reaches were also statistically larger than control reaches during the 2008 annual survey. Both survey years were climatically wetter than normal years during both the monsoon and winter baseflow/spring runoff seasons.

The significance of the explanatory variable ***study site*** in the fixed effects model indicates that the character of channel response also depends on the existing conditions of the study site, although these conditions do not extend to the different plant treatments. In particular, channel widening in SLR is likely limited by the presence of a clay layer at the bank toe, where the majority of the bank failure was observed to occur through fluvial erosion. In UWH, because the toe of the banks consists largely of less resistant silt and sand, more channel widening is apparent at this site compared to SLR. The channel in SPR is the least incised (1.1 m) and has the lowest bank stability ranking values relative to the other study sites. In addition, the whole-plant removal treatment reach is located along a largely straight channel in SPR. As a result, this particular site is considered the most stable and thus subject to less geomorphic channel change despite plant removal treatment implementation.

The substantial bank failure at meander bends following the large magnitude August 5, 2007 discharge, in combination with more channel change occurring during the winter and spring seasons relative to the monsoon seasons, provides only partial support of the third hypothesis that channel adjustment will depend on the magnitude of flows, with the largest flows causing the most channel change. Winter baseflows and spring runoff discharges are of smaller magnitude, but substantially longer duration compared to monsoon discharges, which have durations of generally less than 24 hours. Also, it is evident from field observations on water clarity that the sediment load carried by winter and spring season discharges is substantially less compared to the monsoon discharges, which are dark brown in color. The winter and spring runoff discharges therefore potentially have the ability to cumulatively carry out more geomorphic work on the bed, particularly in terms of bed incision. Although the monsoon discharges are typically of much higher magnitude, the short duration, coupled with the extremely high sediment loads, hinder the ability to carry out erosive geomorphic work and instead result in some deposition. Fresh fine deposits along channel banks and field-measured net bed aggradation at cross sections were evident immediately following discharge events. The depositional character of the monsoon discharges is also demonstrated in the seasonal change in the longitudinal profile of the UWH study site (Figure 4.11). Approximately 0.5 m of bed aggradation occurred in the whole-plant reach following the June 24, 2006 monsoon discharge, but the deposition had been removed and net incision had occurred by end of the spring runoff period in 2008.

Monsoon discharges, however, have the ability to carry out geomorphic work, exemplified by the several-meters-wide bank failure at LWH 9.0 and UWH 10.0 from the August 5, 2007 monsoon event. This channel change, however, was not a result of only high discharge magnitude, but because the hydraulic driving forces of the discharge magnitude were maximized along the outside of a meander. Although the erosion resulting from the sustained duration of the winter and spring discharges is at a smaller scale at each cross section compared to the bank failures from the August 5, 2007 event, the cumulative change during the winter and spring is larger relative to the monsoon season. However, it is important to note that the most widening occurred during the monsoon discharges, which were of the largest magnitude and generated more than 3 m of depth in the channel. Therefore, even in the presence of whole-plant removal treatment, substantial geomorphic change through channel widening will only occur as a result of repeated large flows that exceed several meters in flow depth.

4.6.2 Longer term (6 years) channel adjustment to exotic plant removal

Based on the calibration exercise using approximately 2 years of discharge data, CONCEPTS adequately simulates channel change in the UWH study reach. Erosion of the bank toe is simulated most accurately, with less accuracy in modeling changes along the bed and along upper portions of the bank subject to non-fluvial erosion. Channel change simulated using a larger peak magnitude, but substantially shorter duration, was minor. Because of the changes measured in the field and simulated during the CONCEPTS calibration exercise, the Zuni River peak flow was expected to result in comparable bank erosion along the right bank at XS 10, which is located at the outside of the meander bend. The absence of channel change at this location suggests that the larger flow magnitude was not sufficient to compensate for the shortened duration of the flow (< 24 hours) relative to the peak flow used in the calibration exercise.

Using 6 years of discharge records, cross sectional area increased on average by 20% and as much as 50%, which represent a rate higher than what was measured in the field over the same time period. Most of the channel change occurred in the first few years of the simulation period, with less change in subsequent years. Although cross sectional area increased through bank widening at the bank toe, the channel continued to incise, with half of the cross sections experiencing incision as the primary channel adjustment during the simulation period at a higher rate over the same time period and in locations of the simulation reach different than what was field-measured. There were no statistically significant differences in simulated channel adjustment among the exotic plant treatment reaches. Most of the channel change occurred during the spring runoff events, during which moderate to high discharges were sustained over several days to months. The short duration monsoon events produced virtually no channel change in the simulation. Minimal channel change after 1995 could be a result of the absence of these spring runoff events, despite the subsequent water years having several monsoon events of moderately large discharge magnitudes. These results suggest that under existing boundary conditions of the sediment regime, the channels will remain entrenched. Substantial channel widening is limited by the absence of extremely large magnitude, long duration (several weeks to months) discharge events that are more typical of the Jemez River system, but not characteristic of the natural flow regime in Canyon de Chelly. It is important to note that the simulations in CONCEPTS did not address shifts in the sediment regime. An increase in sediment delivery to the channel could produce substantial channel change through aggradation and channel widening. Because of continuing channel adjustment from the study reaches, this is a more likely possibility than a shift in discharge regime that increases flow magnitude and duration.

4.7 CONCLUSION

Invasive, exotic riparian plants are an ongoing management problem in fluvial landscapes. Widespread establishment of tamarisk and Russian olive throughout semi-arid and arid river systems in the United States is coincident with changes to channel morphology, which include channel narrowing, floodplain accretion, and bed incision. Canyon de Chelly National Monument was selected as a case study to implement removal of exotic plant species by two methods and to quantify channel adjustment following plant removal. Over a study period of 3 years, significant differences exist in channel response to exotic plant removal. Channel adjustment to exotic plant removal was primarily through widening with significantly larger changes in cross sectional area, perimeter, and width in the whole-plant removal reaches compared to control reaches. Channel change in the cut-stump reaches were not consistently distinct from either control or whole-plant reaches, indicating that although the cut-stump removal method has an effect on channel change, the effect is smaller than the whole-plant method.

The hydroclimatology of the particular year, both in terms of discharge magnitude and frequency, influences the effect of exotic plant removal on channel cross sectional geometry. During the climatically dry 2006 survey year, there was no effect of exotic plant removal on channel geometry. However, during the climatically wetter 2007 and 2008 survey years, channel width and perimeter changes were significantly larger in reaches where the whole-plant removal method had been implemented relative to control reaches. Large magnitude discharges during the monsoon season have the capacity to result in substantial channel change through bank failure in whole-plant removal reaches, but the observed change occurred at specific locations where hydraulic forces were at a maximum (e.g., meander apex). The smaller magnitude, longer duration, and less sediment-laden winter and spring discharges are less effective at bank erosion, but result in higher bed incision compared to monsoon discharges.

It is important to note that other factors exist at the particular sites in this study that limit response to both types of vegetation removal; specifically, the presence of clay layers at the bank toe and the remaining presence of native riparian vegetation. In addition, these channels, which are characteristic of semi-arid fluvial systems, have undergone repeated episodes of incision and aggradation/widening during the Holocene, with incision dominating during the past few decades. The continuing geomorphic evolution of the channel network, and associated sediment supply from upstream channel segments, presumably exert some influence on channel adjustment to the localized effects of plant removal.

Over a longer period of time, correlations between plant removal and channel adjustment may continue, but the site-specific factors and the particular timing of incision and fill cycles could dominate the potential effects of exotic plant removal. Simulations of channel change over a 6-year period using a surrogate discharge record that is considerably wetter than the natural flow regime of Canyon de Chelly indicate no differences between channel reaches with exotic plants along the banks and reaches where the plants have been removed by different methods. More field data are required that include a range of discharge magnitudes and duration to identify the dominant controls on channel adjustment and better characterize channel response to exotic plant removal. Specific recommendations for continued monitoring of channel response to exotic plant removal are identified in Chapter 5.

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5 SUMMARY

5.1 SUMMARY AND CONCLUSIONS

The stream channels in Canyon de Chelly National Monument, northeastern Arizona exemplify the dynamic morphologic processes characteristic of sand-bedded channels in the arid and semi-arid southwestern US. The stream channels have undergone repeated cycles of vertical instability throughout the Holocene, with dramatic narrowing and some incision over the last 70 years. Management of these stream channels remains a challenge because of the complex interplay among a suite of confounding external influences on the channel processes. Among these influences are a highly variable hydroclimatology, a history of intensive livestock grazing over the previous two centuries, and stream flow regulation, local-scale channel manipulation, and exotic riparian plant invasion in the last century, all of which serve to alter sediment and hydrologic regimes that affect channel form and process.

The invasion of exotic plant species, specifically tamarisk and Russian olive, is of particular concern for land managers in the southwestern US. The introduction of these plants has resulted in extensive colonization and subsequent physical transformation of much of the region's floodplains and riparian areas (Zavaleta, 2000; Shafroth et al., 2005; Birken and Cooper, 2006). Bottomlands that were previously sparsely vegetated with native cottonwood and willow species are now characterized by dense, monotypic stands of tamarisk and Russian olive. Riparian vegetation increases bank resistance to erosion, which facilitates channel narrowing, floodplain accretion, bed incision, and sustained morphologic shifts from braided to meandering (Graf, 1978; Allred and Schmidt, 1999; Millar, 2000; Simon and Collison, 2002; Merritt and Wohl, 2003; Tal et al., 2003; Wynn and Mostaghimi, 2006). Although native riparian vegetation and the influence it has on channel morphology is a natural component of the fluvial landscape, the geomorphic implications resulting from the extensiveness and density of the spread of exotic tamarisk and Russian olive include a potentially severe disruption in the region's channel processes. As interest in stream rehabilitation through exotic plant control increases in the southwestern US, it becomes increasingly important to identify plant removal methods appropriate for the specific channel conditions within a catchment that is subject to additional confounding influences on channel response (e.g., variable hydroclimatalogy and land use history).

The research presented here is a case study of the stream channels in Canyon de Chelly National Monument, which have experienced large-scale colonization of tamarisk and Russian olive in the last 70 years. The specific project objectives were to:

1) Characterize and identify causes of historic and recent channel change within the national monument within the context of climate, grazing history, and the role of tamarisk and Russian olive establishment.
2) Quantify channel response to the removal of tamarisk and Russian olive by two methods (cut-stump and whole-plant removal) to determine which of the two methods was more effective at limiting bed incision and promoting bank widening.

As an additional component, this project included a comparison of average channel erosion rates between the southwestern and southeastern US to provide an overview of erosion within an inter-regional context and determine if the channel erosion observed within Canyon de Chelly is within the southwestern region's variability. Average bank widening and incision rates from case studies in the southwestern and southeastern US were statistically compared to test the hypothesis that erosion rates are higher in the southwestern US. I reasoned that this would likely result from regionally greater flood magnitudes and limited substrate resistance in the southwestern US. Nineteen case studies in the southwestern US were found and included Arizona, Colorado, New Mexico, and Utah. A total of 39 case studies were found in the southeastern US, all occurring in either Mississippi or Tennessee. Based on visual inspection, erosion rates appeared to be distinct between Mississippi and Tennessee. Therefore these two states were analyzed separately and compared to erosion rates in the southwestern US region.

No statistically significant differences in incision rates exist between the Mississippi (median 0.13 m/y), Tennessee (median 0.31 m/y), and southwestern US (median 0.12 m/y) streams. Tennessee streams have significantly higher rates of bank widening (median 10.3 m/y) than southwestern US streams (median 8.3 m/y) if the Middle Gila River in Arizona, which experienced 448 m of widening from a single, extremely high discharge, is excluded from the analysis. When erosion rates were normalized by drainage area, southwestern US streams had statistically significantly smaller rates of bed incision and bank widening per unit drainage area compared to Tennessee and Mississippi streams. The results of the non-normalized erosion rates could indicate that intra-regional or local controls exert a stronger influence on erosion rates than broader inter-regional influences. It is also possible that average erosion rates may not be an appropriate metric for identifying regional differences because substantial channel change could result from a single flood, and thus not truly reflect an average rate over time. In addition, the history of channel disturbance as well as the method used to measure erosion will influence the calculated erosion rate. However, the absence of consistent differences in erosion rates between regions of different hydroclimatic and geomorphic conditions could indicate that some aspects of channel changes observed in southwestern US streams may not be as regionally distinct as previously considered.

To determine the relative roles of climate, grazing history, and exotic plant establishment on historic and recent channel change within Canyon de Chelly National Monument, historic watershed conditions were evaluated using grazing information synthesized from regional literature, regional historic precipitation records, and paleo-discharge records of nearby basins. Previous graduate research associated with this project quantified historic channel narrowing and vegetation establishment within Canyon de Chelly (Cadol, 2007). Finally, a 28-km-long longitudinal profile of the contemporary channel thalweg in Canyon de Chelly was field-surveyed to determine the character of channel incision and likely extent of future incision.

Results indicate that channel morphology in Canyon de Chelly reflects ongoing complex response to the combined effect of both catchment-scale and local-scale influences. Although tamarisk and Russian olive are potentially exerting a strong influence on the contemporary channel morphology, the current channel form, in particular the historic narrowing, could primarily reflect watershed-scale fluctuations in water and sediment yield from climatic conditions and land-use activities beginning in the 1800s. The character of channel incision, however, appears to be dominated by local-scale controls, specifically riparian vegetation, bed and bank material, and in-channel structures. It is hypothesized that high sediment yield, presumably from degraded range land, coupled with a high discharge regime through much of the mid 1800s supported a braided channel in Canyon de Chelly throughout the 19th century and into the 20th century. Channel narrowing in the upper portion of Canyon de Chelly after 1935 could have resulted from a climatically drier period and reduced flood magnitudes and frequencies, and potentially diminished sediment supply from grazing reductions. Delayed channel narrowing in the lower portion of Canyon de Chelly may be a result of adequate sediment supply to the lower half of the canyon from upstream sources to maintain the braided morphology. Alternatively, the delayed channel narrowing could represent the remains of a sediment pulse from a previous incision event that has not yet fully translated downstream (e.g., Nickolas et al., 1995). During the 1980s, local conditions within the lower canyon, coupled with a period of above-average precipitation, facilitated widespread establishment of tamarisk and Russian olive and subsequent abrupt channel narrowing. Upstream propagation of bed incision appears to be temporarily limited by the presence of quasi-functioning in-channel structures and potentially by sediment supply from side canyons at a knickzone location. As in-channel structures fail completely, incision is expected to propagate upstream. The extent of incision, however, will be constrained by coarse bed material within the contemporary channel and mitigated by sand supply from tributary canyons.

There is a potential that stream channels in Canyon de Chelly would have undergone a similar evolution if tamarisk and Russian olive had not established, at least in the upper and middle portions of Canyon de Chelly and potentially in the lower portion. Based on the historical air photograph analysis, channel narrowing in the upper portions of the canyon occurred prior to plant establishment. In addition, extensive gallery forests of native cottonwood exist throughout the middle portion of Canyon de Chelly where density of tamarisk and Russian olive is substantially lower. In the absence of the ubiquitous establishment of both species during the 1980s in the lower portion of Canyon de Chelly, which corresponded to climatically wetter than normal years, native plants could have established instead and presumably would exert some geomorphic effect on the channel, that could include narrowing and incision. However, it is not certain that native plants would have established or established in the densities that tamarisk did in this lower portion of Canyon de Chelly. Therefore, I cannot determine whether the narrow and incised character of lower de Chelly would have occurred in the absence of exotic plant establishment.

It is also important to remember that the channel morphology is inherently dynamic in the semi-arid southwestern US apart from the external influences of land use and exotic plant establishment. Repeated cycles of incision, aggradation, and re-incision are evident in the region’s alluvial stratigraphic record throughout the Holocene, before the contemporary issues of grazing and exotic riparian plants. While these external factors certainly have been shown to exert an influence on channel morphology and the particular expression of the arroyo cycle at a give site, the overall timing of incision and fill cycles may dominate these relatively local-scale influences.

Two plant-removal methods were implemented at four study sites in Canyon de Chelly to determine which method is more effective in promoting channel widening and minimizing bed incision. Change in cross sectional geometry and longitudinal profile was quantified in the field over a three-year-period. In addition, a modeling exercise using the one-dimensional hydraulic model, CONCEPTS, simulated channel changes using surrogate discharge from two nearby basins to quantify channel adjustment over a longer time period and resulting from larger magnitude discharges than the conditions of the three-year field study. The exotic plant removal methods include 1) cutting the above-ground portion of the plant flush to the ground surface and applying an herbicide (cut-stump method) and 2) removing the entire plant including the roots using heavy machinery (whole-plant method). The two plant removal methods were implemented in Fall 2005. Annual surveys of change in cross sectional geometry and bed substrate were conducted until 2008, with additional surveys between individual monsoonal flows at one of the study sites.

Findings from the field study show statistically significant correlations between exotic plant removal and channel change. The most channel change, in terms of increases in cross sectional area, width, and perimeter, occurred in the whole-plant removal reaches, with less change in the cut-stump removal reaches. Channel adjustment over the 3-year study resulted in approximately 12-14% increase in channel cross sectional area in the whole-plant removal reaches, and a 5% or less increase in the cut-stump and control reaches. Hydrologically wetter years resulted in significantly more geomorphic change in reaches where exotic plants had been removed. Statistically significant differences in change in channel depth between monsoon and winter baseflow/spring runoff discharges indicate that small-scale incision has a cumulatively larger effect over the period of a single year. The combined effect of the substantially larger magnitudes, shorter flow duration, and extremely high sediment loads is short-term aggradation within channel reaches and bank deposition, but potentially large-scale channel change such as several meters of bank widening at locations within the whole plant removal reaches where hydraulic forces were maximized at the apex of a meander bend. The diminished magnitude in channel changes in the cut-stump reaches relative to the whole-plant removal reaches suggest that the presence of an intact subsurface root and soil substrate structure provide adequate bank strength to limit erosion of the bank despite the removal of the above-ground portion of the plant. Both bank erosion and bed incision rates measured over the 3-year study period are below the average rates reported for southwestern US streams although they are within the range of variability of reported rates for the region.

Longer term (6 years) channel change simulated through hydraulic modeling did not result in statistically significant differences between stream reaches where exotic vegetation had been removed by the two methods and reaches where vegetation was left intact. Simulated channel adjustment resulted in a 20% average increase in cross sectional area through widening at the bank toe and continued bed incision at all cross sections. The discharge record used in the simulation period included spring runoff discharges of longer duration and potentially larger magnitude than are typical of the Canyon de Chelly natural flow regime, which is likely the reason that most of the simulated channel change occurred during these longer duration discharges rather than the monsoon events. Channel change simulated during monsoon discharges was minimal, likely because of the short duration of the flow (< 24 hours).

Simulation and field results together suggest that under existing discharge and sediment regimes, stream channels will remain entrenched in Canyon de Chelly. Channel reaches with the highest potential for adjustment through widening are characterized by severely weakened banks from mechanical whole-plant removal and soil disturbance and conditions that facilitate large hydraulic erosive forces (e.g., meander bends). Therefore it is expected that any substantial geomorphic change in the stream channels will only occur with either the combined effect of weakened banks and repeated large flows that exceed several meters in flow depth and are of longer duration than the typical monsoon flow (< 24 hours), or a shift in the sediment regime that results in increased sediment delivery to the channel from upstream sources.

The absence of a knickzone or irregularity in the longitudinal profile in the lower portion of Canyon de Chelly suggests that incision may be close to a maximum under the current discharge and sediment regime. Dramatic incision could re-occur within the study sites lower in the canyon if a knickpoint were to be renewed as a result of shifts in either regime. Currently, portions of the channel are actively incising into a several-meter-thick clay layer, which experienced the largest amounts of bed erosion over the three-year field study. However, the largest measured incision remains relatively small; average incision depths into the clay layer were less than 20 cm over a 2-3 year period. It is expected that bed incision will continue at a limited rate as stream reaches approach a quasi-equilibrium between driving and resisting forces, particularly in channel portions incising into clay and where resistant stream banks (e.g., the presence of resistant substrate layers and/or native or exotic riparian vegetation) impede widening. Channel adjustment through widening could be effectively facilitated by the whole-plant removal method only in the presence of sufficient discharges.

5.2 MANAGEMENT AND FUTURE RESEARCH MONITORING RECOMMENDATIONS IN CANYON DE CHELLY

Removing the above-ground portion of exotic plant vegetation while leaving the root structure intact (cut-stump method) had less effect than the whole-plant removal method on promoting geomorphic change through bank widening. The whole-plant removal method resulted in statistically significantly larger increases in channel widening relative to control reaches and, in some cases, cut-stump reaches. The whole-plant removal method is substantially more costly, but it is the method that provides the most potential for geomorphic channel change where channels are already incised. Therefore, I recommend, where possible, implementation of the whole-plant removal method to provide the most effective geomorphic response in terms of channel widening. It is important to note that ecological implications of this removal method are addressed elsewhere (Lindsay Reynolds, unpublished data).

It is not clear whether application of the whole-plant removal method would be effective in promoting bank widening that would dominate over channel incision in channel segments that currently are unincised and have erosive beds (e.g., un-armored). Application of the whole-plant removal method in this study was along channel reaches that are potentially in near quasi-equilibrium with the existing driving and resisting forces and therefore presumably experiencing diminished current incision rates relative to the rates at the onset of downcutting. Future work could include whole-plant removal implementation in channel reaches that have erosive, un-incised beds to determine whether widening dominates in channels that are vulnerable to incision. However, it is important to consider that channel adjustment to broader catchment-scale conditions such as discharge and sediment regime could overwhelm the effect of plant removal along streambanks and limit downcutting. Specific locations for implementation of the whole-plant removal method could be the upstream portions of the Middle de Chelly identified in Chapter 3, where channels have not yet incised and the bed material has not yet coarsened and become resistant to bed incision.

Increasing hydraulic roughness within the channel through the addition of wood jams could facilitate aggradation at the local scale. An inventory of rock/earth and rock/brush check dams on the Zuni Reservation indicated that although approximately 65% of the structures had failed through breaching or flanking (stream flow is diverted around the structure), half of these structures were 50% filled with sediment, presumably providing some level of grade control (Gellis et al., 1995). It is important to note that headcutting after check dam breaching did appear to accelerate incision in some circumstances (Gellis et al., 1995). With the understanding that the channel is dynamic, it is expected that the jams will shift in location and should not be considered permanent or rigid structures. Installation of brush jams, however, could be a relatively cost-effective method to promote aggradation if a high level of maintenance (at least twice a year) could occur through a coordinated effort between NPS and residents within Canyon de Chelly.

Research included in this dissertation evaluated the geomorphic behavior of the contemporary channel in Canyon de Chelly and measured short-term channel response to removal of exotic plant vegetation. As noted above, however, longer term field data on channel change are necessary in order to make more informed management decisions regarding channel geomorphic processes and the role that exotic vegetation and its removal play on those processes. In addition, identifying and monitoring sensitive locations along the channel are necessary for management of those locations as well as the larger channel system. With this in mind, I recommend continued surveying of the 10 cross sections in the Upper White House study site that were repeatedly surveyed between individual monsoon events and were also included in the CONCEPTS simulation exercise. Of course, continued surveying of all cross sections in all four of the study sites would yield useful information on channel dynamics and response to exotic plant removal. Upper White House, however, is particularly recommended because of its accessibility and the existence of the two benchmarks for each cross section, and because this study site was studied in the most detail and therefore has a larger foundation on which to build. Monitoring of this study site through repeat surveys of surface elevation along the channel cross section profile would provide information on the continued bed incision through the clay unit at this site in addition to tracking bank erosion processes along an entrenched channel, which includes both vegetated banks and banks where exotic vegetation has been removed by the two treatment methods. Specific parameters to measure would be change in thalweg elevation to track incision as well as changes in top width and average channel width, which in turn affect cross sectional area. An aerial map and planview map of the cross sections in Upper White House including the UTM units for each benchmark is included in Appendix H. In addition, I recommend monitoring the functionality of the grade-control structure located at the upstream extent of Sliding Rock. The rock gabion structure at this location appears to be temporarily limiting headward incision upstream of Spring Canyon in Canyon de Chelly. Once the structure fails completely, subsequent upstream bed incision will affect upstream road crossings by bank steepening and/or failure.

Supplemental studies could be implemented along any part of the channel either within or beyond the study sites that track channel adjustment over time. Bank erosion pins (Lawler, 1993) and/or scour chains (Leopold et al., 1964; Nawa and Frissell, 1993; Rennie and Millar, 2000) could be installed to quantify bank erosion processes and channel bed scour and fill processes. Because observed channel change occurred locally within the study sites, the use of cross sections limited the potential to capture and quantify that change. Installation of erosion pins and scour chains along a channel reach provides more opportunity to capture change in channel geometry beyond the cross section location.

5.3 IMPLICATIONS OF MORPHOLOGIC CHANNEL CHANGE ON CANYON RESIDENTS.

It would appear that the plant-removal treatment method, which has the objective of destabilizing channel banks and promoting widening, may be in direct conflict with the history of moderate manipulation of channel migration and bank stabilization within Canyon de Chelly (e.g., “spider fences”, gabions, and brush cuttings in channels and gullies). Currently, portions of the stream channel and bank gullies extending out from the contemporary channel are actively eroding into agricultural and pastoral farming plots. As channels become more incised, subsequent bank failure and widening is the typical next step in the channel evolution process (Schumm et al., 1984; Simon and Hupp, 1992). Therefore, even in the absence of plant removal methods, over-steepened banks along already incised portions of the channel (e.g., UWH, SLR, and the downstream portion of Middle de Chelly) will continue to erode. In addition, as incision propagates headward, channel widening is expected to ensue. Successful local-scale stabilization of over-steepened banks (e.g., gabions) is extremely difficult because of the required continued maintenance to control the inherently dynamic morphology of these channels. Based on the short-term field data and hydraulic modeling simulations, implementation of the whole-plant removal method will promote channel widening, but the method does not elicit large-scale bank destabilization over continuous stretches of the channel under the current hydrologic and sediment regimes. Over a longer period of time and particularly if there are shifts in these regimes, implementation of the whole-plant removal method could result in larger-scale changes through major channel widening and aggradation. To some degree, channel widening, with or without exotic vegetation removal, is inevitable. At the same time, channel banks can continue to be stabilized, either artificially or with the use of vegetation (exotic or native). Therefore, from a management perspective, the particular objectives of canyon residents need to be articulated in terms of their needs to use the land for grazing and farming, their desires for the physical aesthetic appearance of the canyon “viewshed,” and their willingness to foster natural geomorphic channel processes. Trade offs will occur, for example property loss caused by bank erosion as the channel widens. At the same time, sufficient widening could promote aggradation downstream, thus inhibiting bed incision and the subsequent lowering of the water table. Once these objectives are identified, the canyon landscape, including channel processes, can be managed at a local scale.

Under the paradigm of sustainable land management, land use should accommodate the natural processes of the landscape (Brookes, 1988; Brookes and Shields, 1996). The naturally shifting morphology of these stream channels may have been less intrusive on the productiveness of historic flood water farming practices of canyon residents relative to the permanent farming plots that were implemented beginning in the 1940s. Movement away from permanent plots towards a method that allows for flexibility in land uses with changes in channel position and process is an alternative management strategy that could potentially meet the needs of canyon residents, while maintaining intact natural geomorphic process.

5.4 RESEARCH CONTRIBUTIONS

This research addresses the relative influences of driving and resisting forces that affect channel dynamics. Within a broader context of regional trends in channel erosion, this work presents the first synthesis of a regional comparison of bank erosion and bed incision rates between the southwestern and southeastern US. In addition, this research provides an evaluation of the influence of climate, land use activities, and local conditions on the historical (10^1 - 10^2 years) and contemporary channel evolution in Canyon de Chelly with emphasis on the exotic riparian species tamarisk and Russian olive. It is the first quantitative study on short-term channel change to tamarisk and Russian olive removal by the cut-stump method and the whole-plant removal method as well as the first application of the CONCEPTS model to a semi-arid channel affected by these plants.

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APPENDIX A

Literature review of streams that included incision, widening, and knickpoint migration rates

Table A.1. Literature review of streams that included incision, widening, and knickpoint migration rates.

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/ Drainage Area (m/y km^2)	Reference
Southeast									
Big Creek	MS	6.2					13.5	2.2	Thomas 2000
Pigeon Roost	MS	8.1	0.05	6.17E-03					Piest and Bowie 1974
Topashaw Creek Trib 1A	MS	8.8					5.5	0.6	Thomas 2000
Goodwin Creek	MS	10			0.53	5.33E-02			Simon and Darby 1996
North Topashaw Creek	MS	14					0.59	0.04	Thomas 2000
Bear Creek	MS	15					15.6	1.04	Thomas 2000
Topashaw Creek	MS	15					1.5	0.10	Thomas 2000
Buck Creek	MS	20					0.54	0.03	Thomas 2000

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/ Drainage Area (m/y km^2)	Reference
Cane Creek	MS	21					2.7	0.13	Thomas 2000
Goodwin Creek	MS	22	0.14	6.51E-03	6.2	4.43E+01			Murphy and Grissinger 1985
Johnson Creek	MS	22					11.7	0.54	Thomas 2000
Mud Creek	MS	26					5.0	0.19	Thomas 2000
Batupan Bogue River	MS	26					61	2.35	Beidenharn 1989
Hyde Creek	TN	28	0.177	6.39E-03	3.1	1.12E-01			Simon 1989, Simon and Hupp 1992
Long Creek	MS	31					152	4.90	Beidenharn 1989
Crooked Creek	MS	52	0.2	3.85E-03					Wilson 1979

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/ Drainage Area (m/y km^2)	Reference
Wolf Creek	MS	59	0.03	5.58E-04	0.49	8.25E-03			Wilson and Turnipseed 1990
Cub Creek	TN	69			2.1	3.04E-02			Simon 1989
Hotophia Creek	MS	91	0.13	1.43E-03					Biedenharn 1989
Batupan Bogue River	MS	91					274	3.01	Beidenharn 1989
Yalobusha River	MS	103					13.8	0.13	Thomas 2000
Tillatoba River	MS	129					700	5.43	Beidenharn 1989
Tillatoba River	MS	140					145	1.04	Beidenharn 1989
Second Creek	MS	143	0.15	1.05E-03	0.67	4.66E-03			Wilson 1979
Tillatoba River	MS	155					335	2.16	Beidenharn 1989

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint /Drainage Area (m/y km^2)	Reference
Porters Creek	TN	165	0.30	1.82E-03	7.7	4.67E-02			Simon and Hupp 1992, Simon 1989
North Fork Forked Deer River	TN	190			10.3	5.42E-02			Simon 1989
Tillatoba River	MS	207					731	3.53	Beidenharn 1989
Cane Creek	TN	224	0.30	1.34E-03	18.2	8.13E-02			Simon and Rinaldi 2006, Simon 1989
Pond Creek	TN	290			2.9	1.00E-02			Simon 1989
Middle Homochitto River	MS	469	0.06	1.18E-04					Wilson 1979
Rutherford Fork Obion	TN	717	0.31	4.38E-04	7.2	1.00E-02			Simon and Hupp 1992, Simon 1989

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/Drainage Area (m/y km^2)	Reference
Yalobusha River at Calhoun	MS	764	0.08	1.07E-04					Simon and Thomas 2002, Wilson 1998
North Fork Obion River	TN	963			10.4	1.08E-02			Simon 1989
South Fork Obion River	TN	1,103	0.40	3.63E-04	11.9	1.08E-02			Simon and Hupp 1992, Simon 1989
Homochitto River at Rosetta	MS	2,040	0.13	6.26E-05					Wilson 1979
South Fork Forked Deer River	TN	2,748	0.56	2.05E-04	13.6	4.95E-03			Simon and Hupp 1992, Simon 1989
Homochitto River at Doloroso	MS	2,900	0.16	5.56E-05					Wilson 1979
Obion River	TN	4,856			38	7.78E-03			Simon 1989

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/Drainage Area (m/y km^2)	Reference
Southwest									
Gunshot Arroyo	NM	0.09	0.002	2.22E-02					Gellis et al. 2005
Canada de la Cueva	NM	2.4			2.7	1.16E+00	4.3		Malde and Scott 1977
Arroyo de los Frijoles	NM	9.7	0.0014	1.44E-04					Gellis 2002
Zuni River	NM	19					15	0.78	Balling and Wells 1990
Pueblo Canon	NM	22			0.25	1.13E-02	15	0.69	Gellis 1998
Chaco Wash at Pueblo del Arroyo	NM	261	0.10	3.69E-04					Tuan 1966, Bryan 1925
Rio Nutria	NM	294	0.43	1.46E-03	0.08	2.83E-04			Gellis 1998
East Fork Virgin River	UT	648	0.23	3.55E-04					Hereford et al. 1996
Douglas Creek	CO	1,070	0.11	9.84E-05					Womack and Schumm 1977

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/Drainage Area (m/y km^2)	Reference
Aravaipa Arroyo	AZ	1,200	0.06	5.39E-05	0.8	6.41E-04			Cooke and Reeves 1976
Puerco River (Little Colorado River)	NM	1,450	0.09	6.54E-05					Leopold and Snyder 1948
Whitewater Draw (Douglas Basin)	AZ	2,650	0.12	4.53E-05	1.8	6.90E-04			Cooke and Reeves 1976
Santa Cruz River	AZ	5,755	0.13	2.30E-05			806	0.14	Bentacourt and Turner 1988
San Simon River	AZ	5,957	0.17	2.91E-05	1.2	1.97E-04	2,840	0.48	Cooke and Reeves 1976
Chaco Wash	NM	11,500	0.04	3.48E-06	0.3	2.61E-05			Gellis 2002

Stream/River	Location	Drainage Area (km^2)	Incision Rate (m/y)	Incision/ Drainage Area (m/y km^2)	Widening Rate (m/y)	Widening/ Drainage Area (m/y km^2)	Knickpoint Migration Rate (m/y)	Knickpoint/Drainage Area (m/y km^2)	Reference
San Pedro River	AZ	12,225	0.43	3.52E-05			22,352	1.83	Cooke and Reeves 1976
Rio Puerco	NM	18,892	0.42	2.22E-05	4	2.12E-04			Wells et al. 1983
Santa Cruz River	AZ	22,224	0.24	1.08E-05	29.5	1.33E-03			Parker 1995

1. State abbreviations: AZ (Arizona), CO (Colorado), MS (Mississippi), NM (New Mexico), TN (Tennessee), UT (Utah)

APPENDIX B

Sites used in comparison of hydraulic driving forces in terms of flow magnitude

Table B.1. Sites used in comparison of hydraulic driving forces in terms of flow magnitude. Area is drainage area, Discharge (Q) is in terms of the return interval (i.e., Q2 is the discharge magnitude with recurrence interval of 2 years).

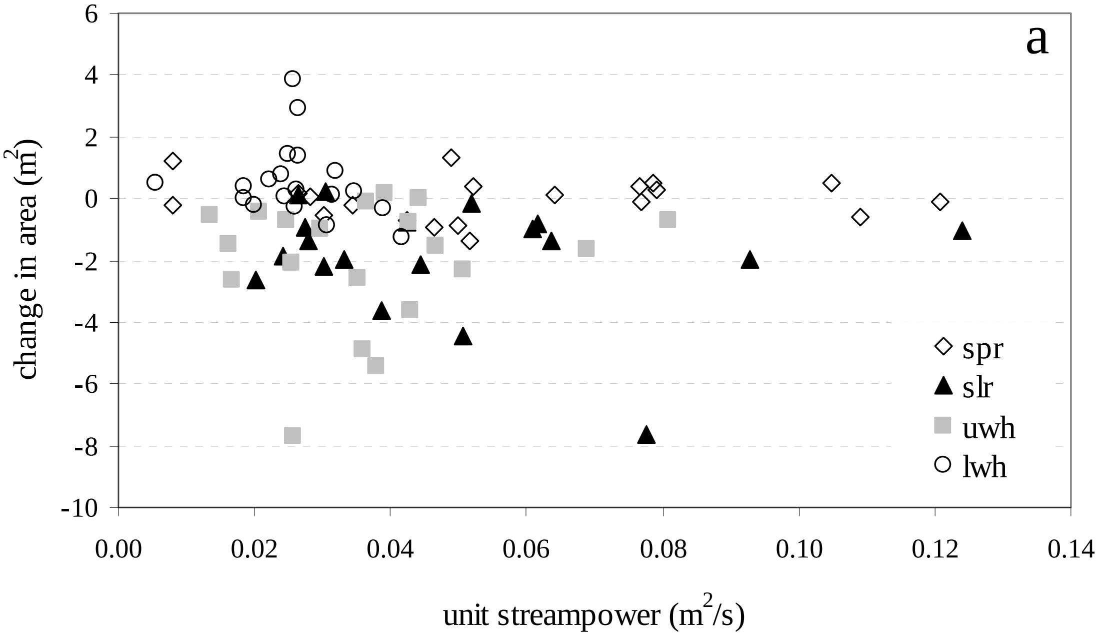
River	Area (km^2)	Q2 (m^3/s)	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)	Reference
Southeast							
Goodwin Creek, MS	22	48	88	110	123	142	Murphy and Grissinger, 1985; Simon and Darby, 1996
Hyde Creek, TN	28	43	77	95	107	119	Simon and Hupp, 1992
Crooked Creek, MS	52	100	185	229	255	295	Wilson, 1979
Cub Creek, TN	69	70	128	158	180	202	Simon, 1989
Second Creek, MS	143	282	597	775	na	na	Wilson, 1979
Porters Creek, TN	165	110	208	259	296	333	Simon, 1989
North Fork Forked Deer River, TN	190	119	225	280	321	361	Simon, 1989
Cane Creek, TN	224	129	246	307	353	397	Simon, 1989
Pond Creek, TN	290	148	284	356	409	461	Simon, 1989
Middle Homochitto River, MS	469	467	889	1090	1225	1373	Wilson, 1979
Rutherford Fork Obion, TN	717	239	469	592	685	775	Simon and Hupp, 1992; Simon, 1989
Yalobusha River at Calhoun, MS	764	719	1472	1871	2173	2476	Simon and Thomas, 2002; Wilson, 1998

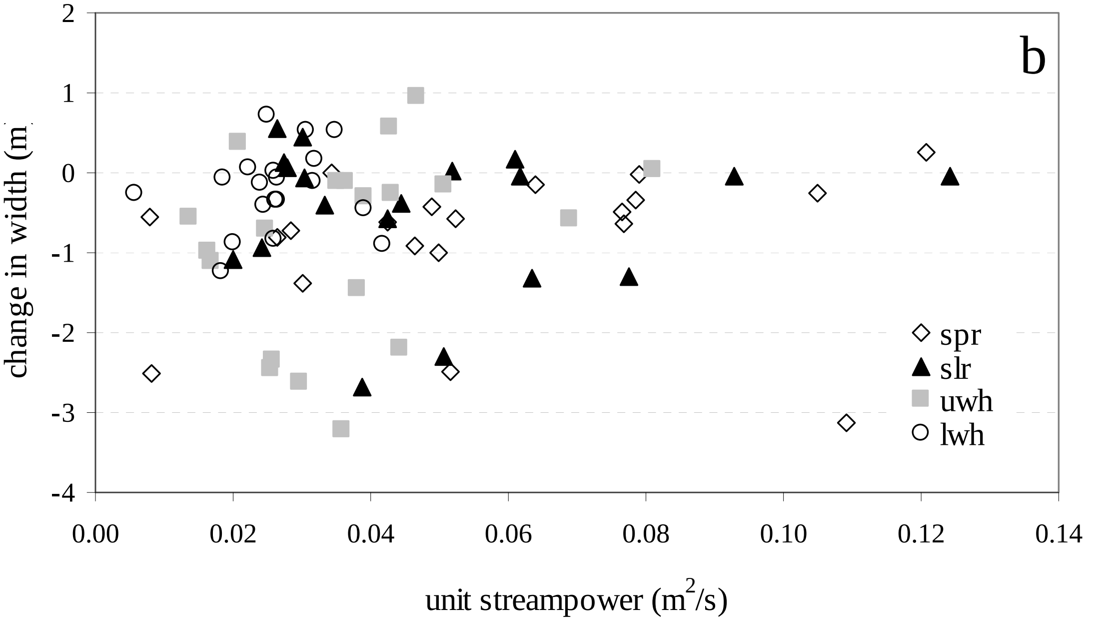
River	Area (km^2)	Q2 (m^3/s)	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)	Reference
North Fork Obion River, TN	963	279	552	700	810	919	Simon, 1989
South Fork Obion,TN	1103	300	595	755	875	993	Simon and Hupp, 1992; Simon, 1989
Homochitto River at Rosetta, MS	2040	1491	3538	4641	5490	6311	Wilson, 1979
South Fork Forked Deer, TN	2748	485	987	1264	1472	1679	Simon and Hupp, 1992; Simon, 1989
Homochitto River at Doloroso, MS	2953	1489	3113	4019	4698	5377	Wilson, 1979
Obion River, TN	4856	655	1353	1743	2037	2329	Simon, 1989
Southwest							
Gunshot Arroyo, NM	0.09	0.4	2	4	6	8	Gellis et al., 2005
Canada de la Cueva, NM	2.4	2	8	13	18	28	Malde and Scott, 1977
Arroyo de los Frijoles , NM	9.7	4	22	38	55	80	Gellis et al., 2005
Zuni River, NM	19	3	20	34	50	61	Balling and Wells, 1990
Pueblo Canon, NM	22	5	22	37	50	84	Malde and Scott, 1977
Chaco Wash at Pueblo del Arroyo, NM	261	27	87	155	173	217	Tuan, 1966; Bryan, 1925

River	Area (km^2)	Q2 (m^3/s)	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)	Reference
Rio Nutria, NM	294	14	83	141	219	297	Gellis, 1998
East Fork Virgin River, UT	648	75	272	476	566	721	Hereford et al., 1996
Douglas Creek, CO	1070	1	50	92	111	127	Womack and Schumm, 1977
Aravaipa Arroyo, AZ	1200	55	555	914	1242	3622	Cooke and Reeves, 1976
Puerco River (Little Colorado River), NM	1450	37	190	323	517	750	Leopold and Snyder, 1948
Whitewater Draw (Douglas Basin), AZ	2650	100	326	503	651	828	Cooke and Reeves, 1976
Santa Cruz River, AZ	5755	135	419	639	817	1028	Bentacourt and Turner, 1988
San Simon AZ	5957	137	424	645	825	1037	Cooke and Reeves, 1976
Chaco Wash, NM	11500	183	434	713	758	905	Gellis, 2002
San Pedro River, AZ	12225	178	526	792	1001	1244	Cooke and Reeves, 1976
Rio Puerco, NM	18892	207	786	1441	1937	3549	Bryan, 1928
Santa Cruz River, AZ	22224	219	624	929	1163	1431	Parker, 1995

APPENDIX C

Comparison of channel cross sectional geometry change and unit stream power


a
change in area (m^2)
unit streampower (m^2/s)
6
4
2
0
-2
-4
-6
-8
-10
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
◇ spr
▲ slr
■ uwh
○ lwh


b
change in width (m)
unit streampower (m^2/s)
2
1
0
-1
-2
-3
-4
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
◇ spr
▲ slr
■ uwh
○ lwh

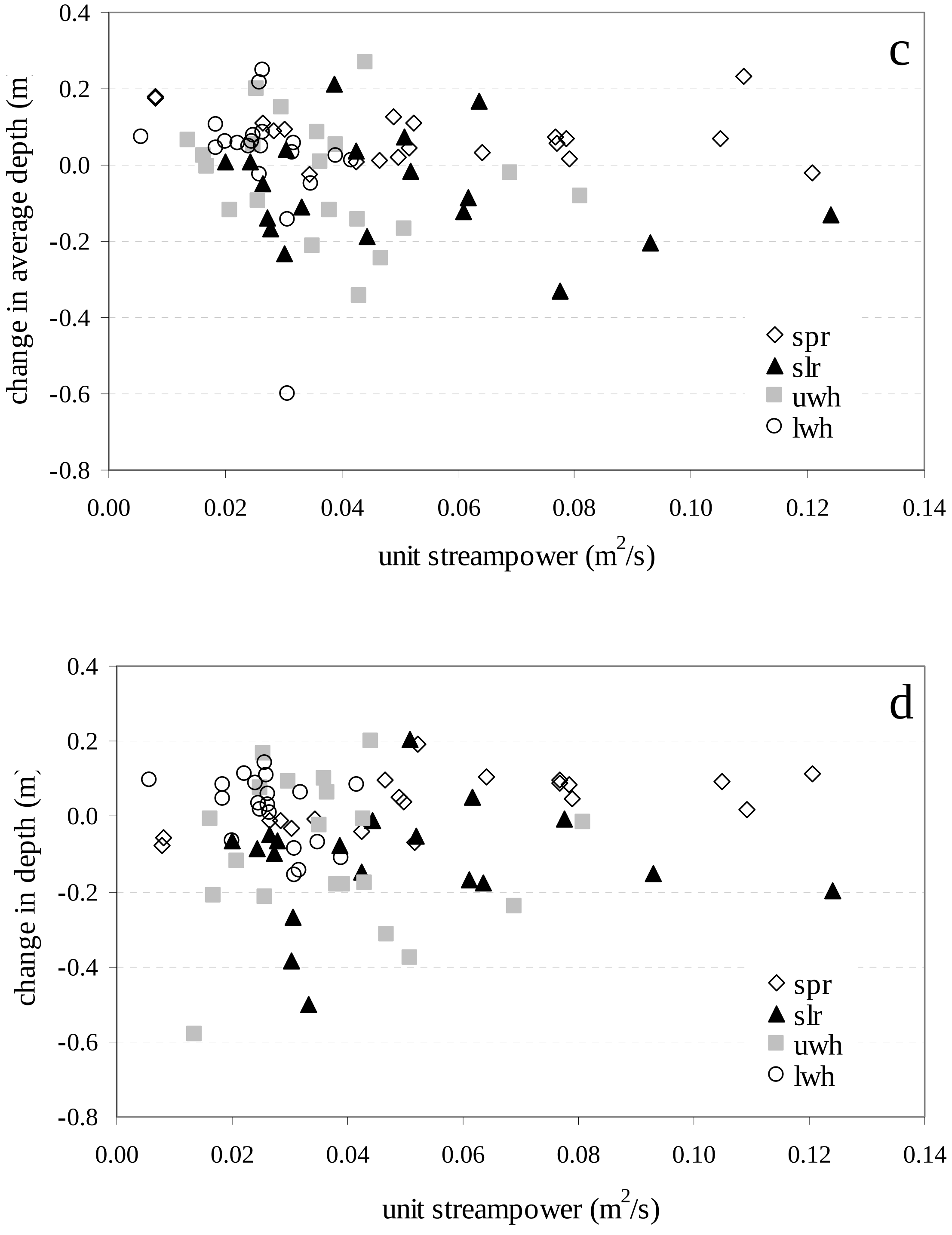
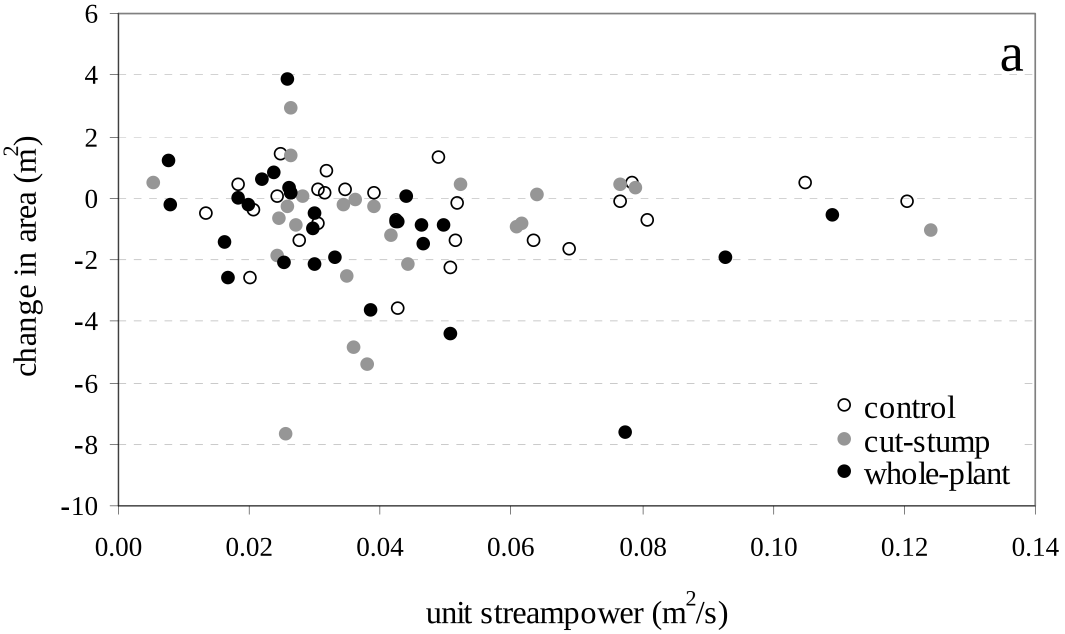
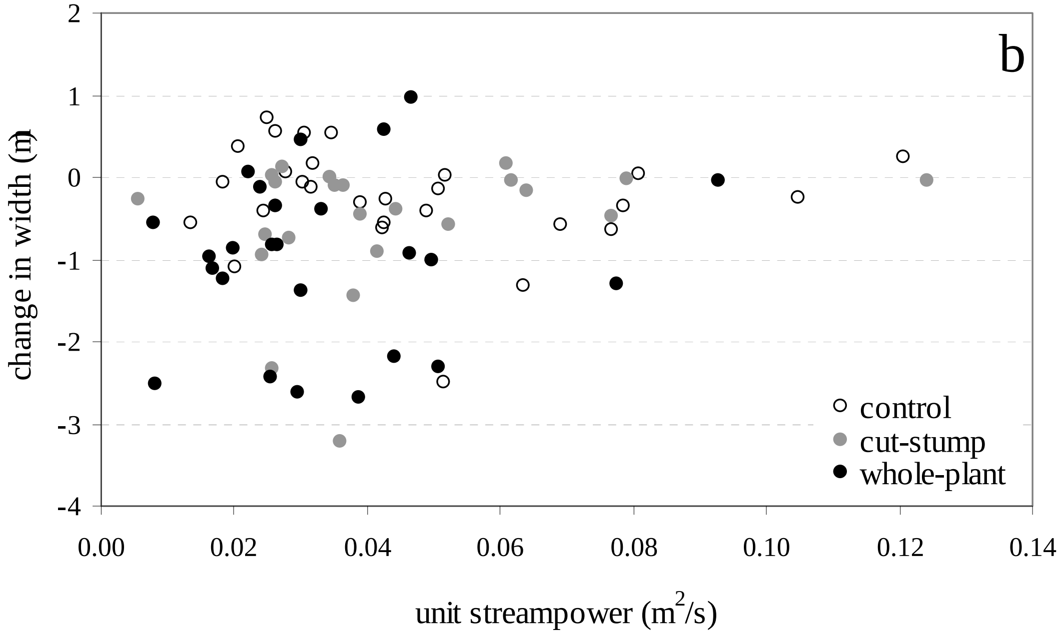
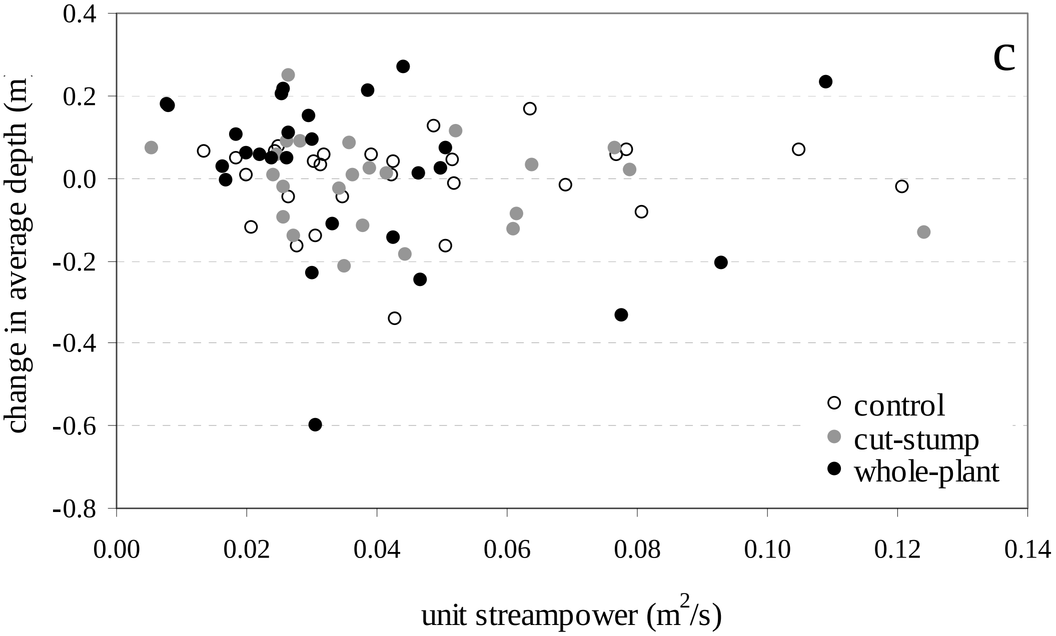


Figure C.1 Change in cross sectional geometry and unit stream calculated using toe width by study site, Spider Rock (spr) (open diamonds), Sliding Rock (slr) (black triangles), Upper White House (uwh) (grey square), and Lower White House (lwh) (open circles). Cross sectional geometry metrics include a. area, b. width, c. average depth, and d. depth (thalweg).


a
change in area (m^2)
6
4
2
0
-2
-4
-6
-8
-10
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
○ control
● cut-stump
● whole-plant


b
change in width (m)
2
1
0
-1
-2
-3
-4
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
○ control
● cut-stump
● whole-plant



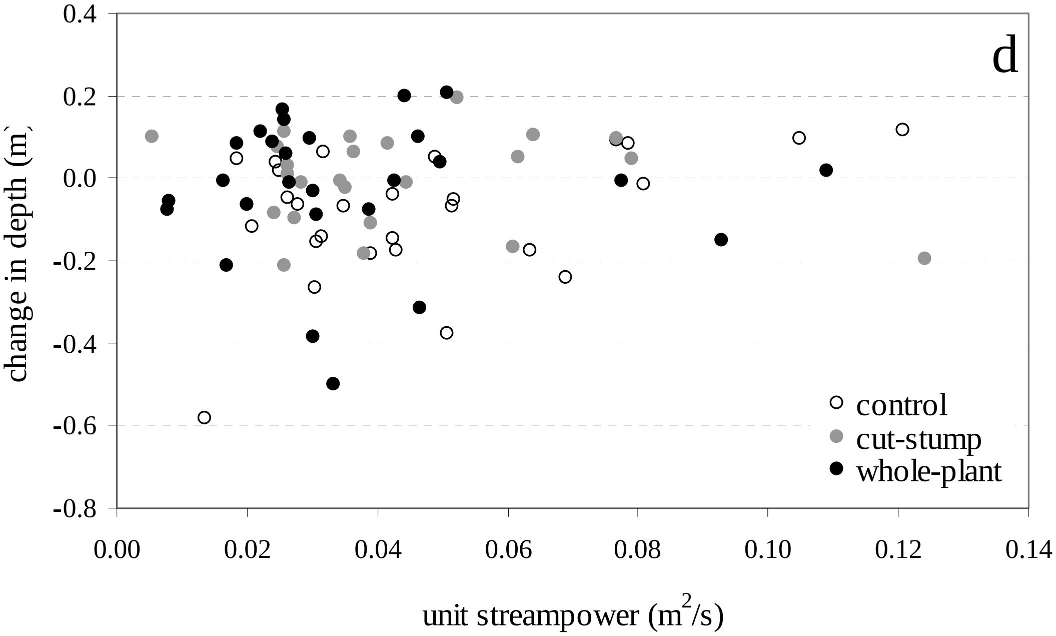
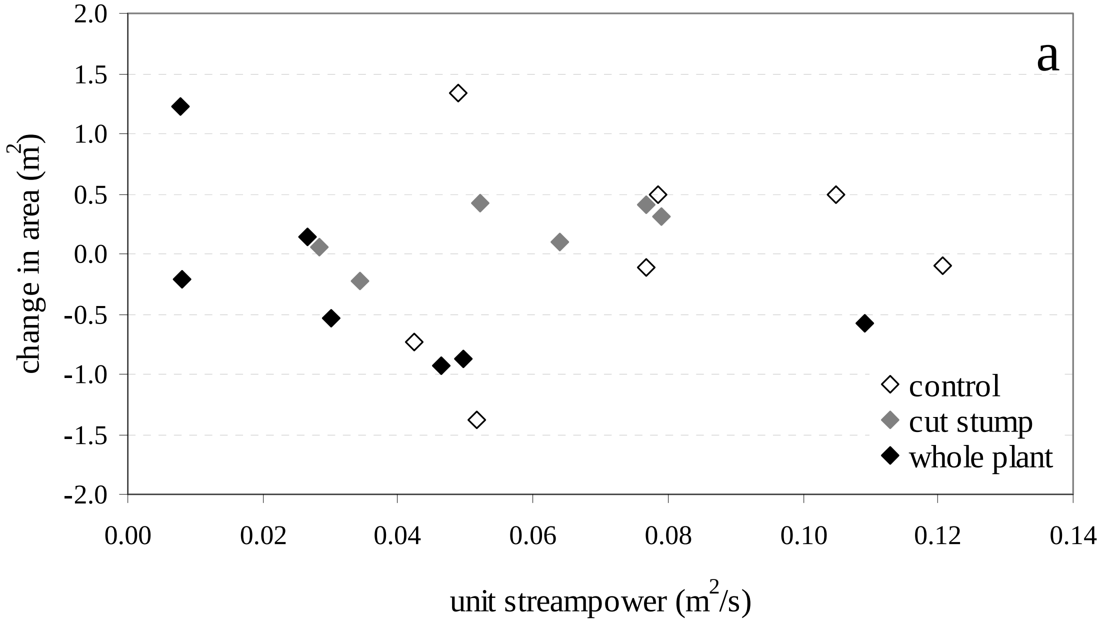
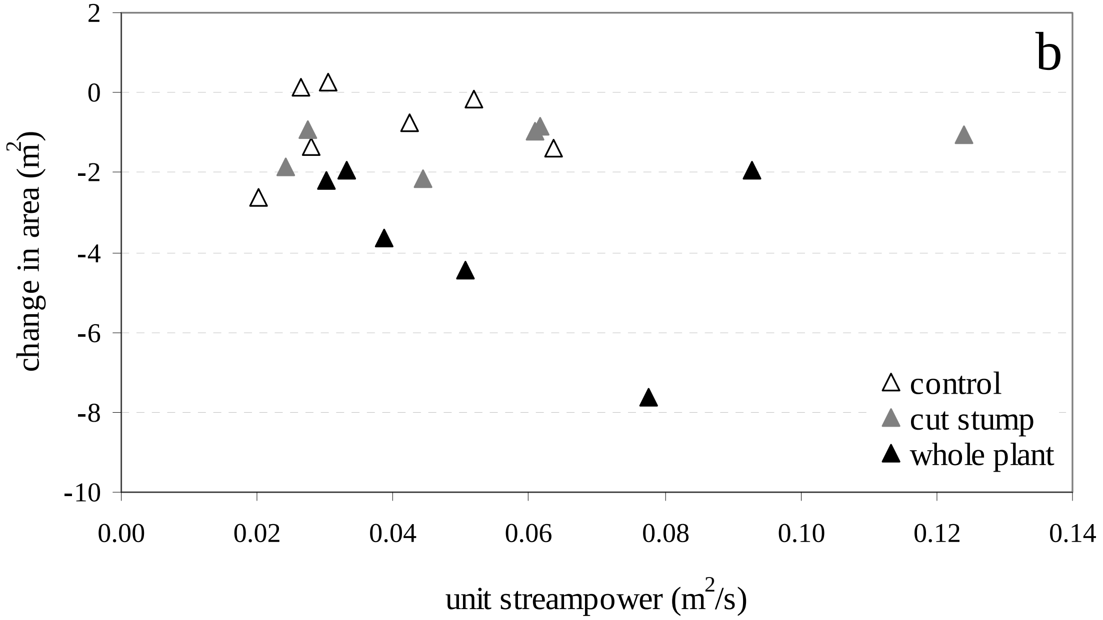


Figure C.2. Change in cross sectional geometry and unit stream calculated using toe width by reach, control (open circles), cut-stump removal method (grey circles), whole-plant removal method (black circles). Cross sectional geometry metrics include a. area, b. width, c. average depth, and d. depth (thalweg).


a
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
change in area (m^2)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
◇ control
◆ cut stump
◆ whole plant


b
2
0
-2
-4
-6
-8
-10
change in area (m^2)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
△ control
▲ cut stump
▲ whole plant

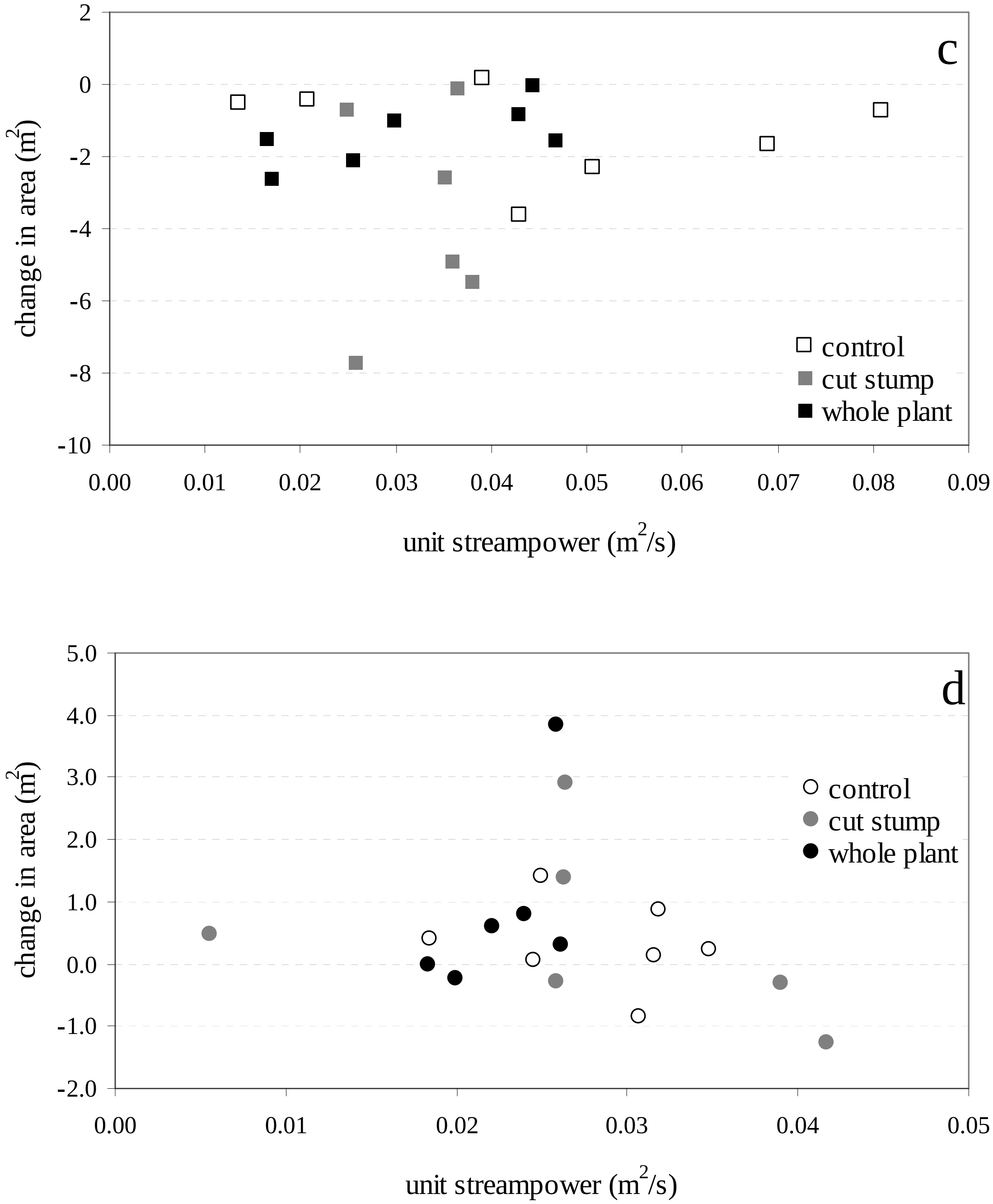
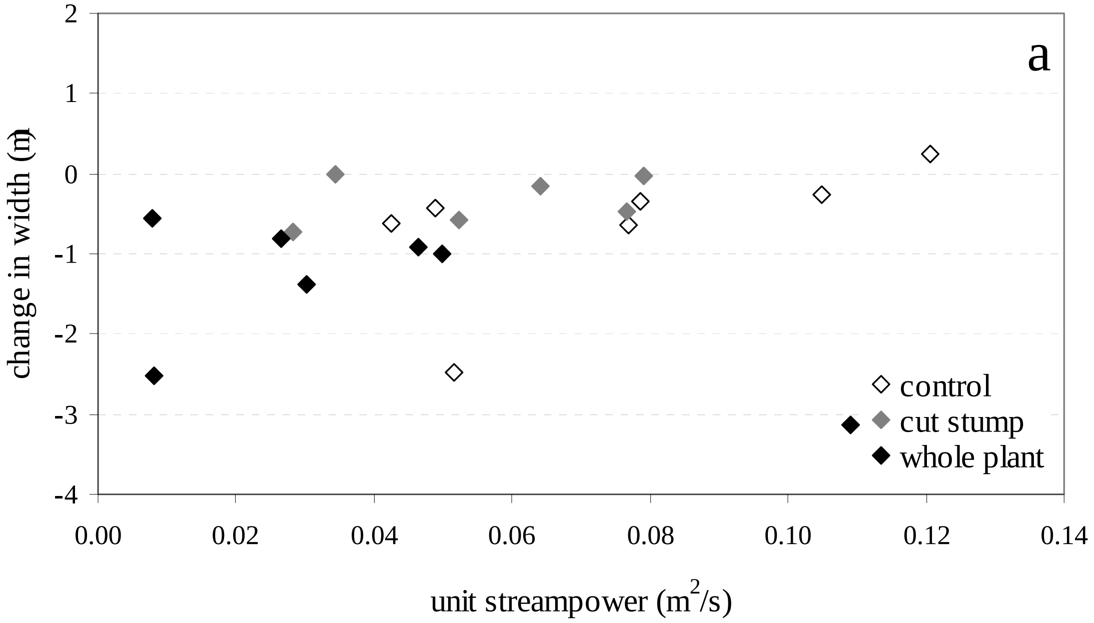
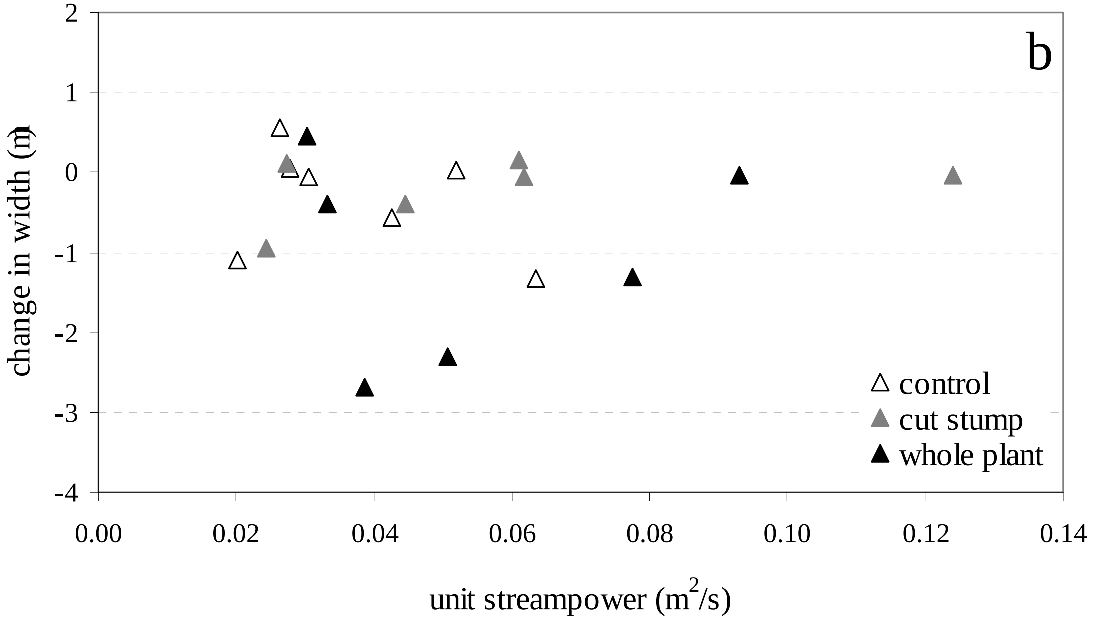
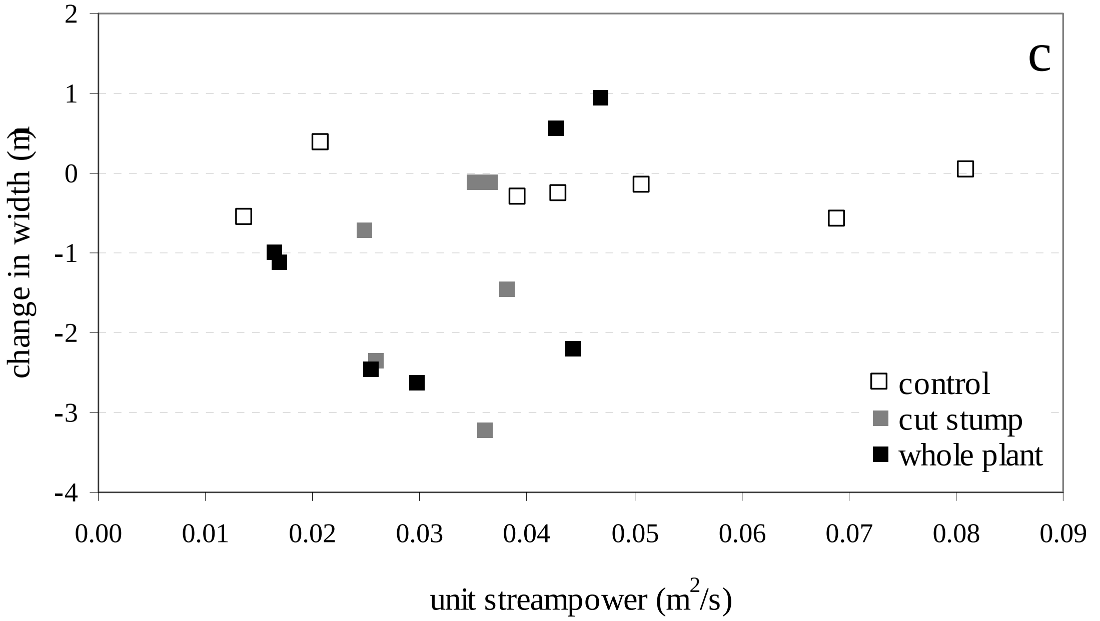


Figure C.3. Change in cross sectional area and unit stream calculated using toe width by reach, control (open shape), cut-stump removal method (grey shape), whole-plant removal method (black shape) within study sites a. Spider Rock (diamonds), b. Sliding Rock (triangles), c. Upper White House (squares), and d. Lower White House (circles).


a
change in width (m)
2
1
0
-1
-2
-3
-4
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
◇ control
◆ cut stump
◆ whole plant


b
change in width (m)
2
1
0
-1
-2
-3
-4
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
△ control
▲ cut stump
▲ whole plant



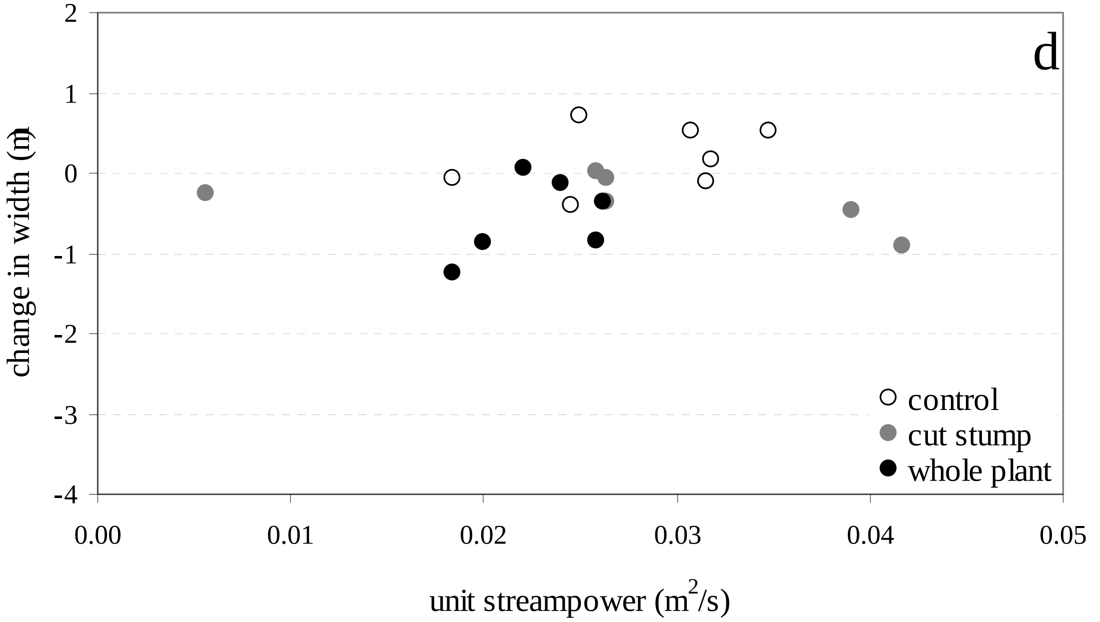
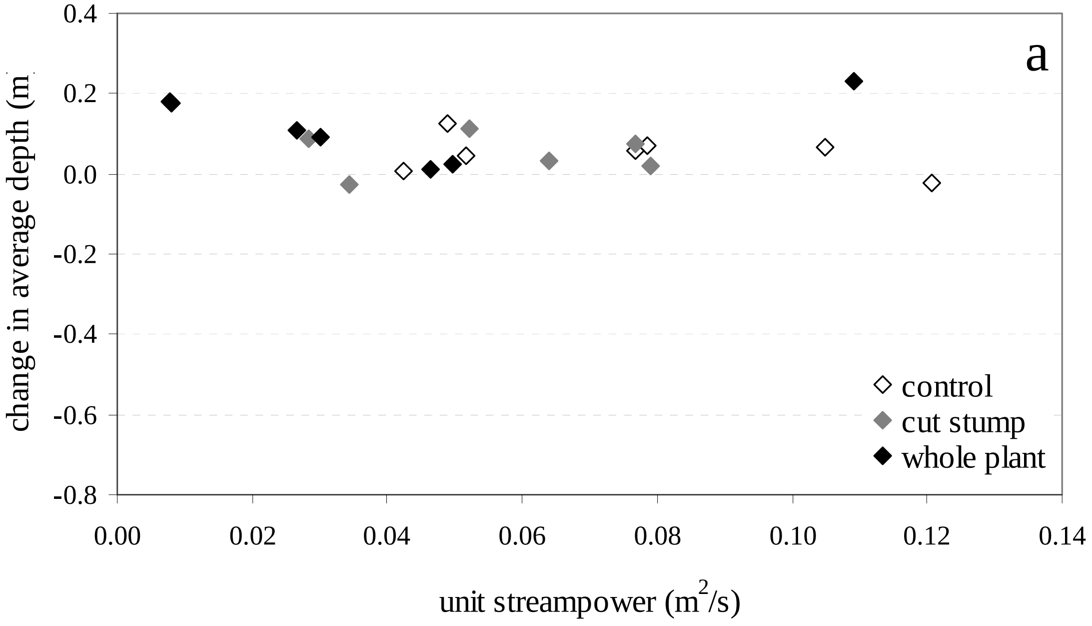
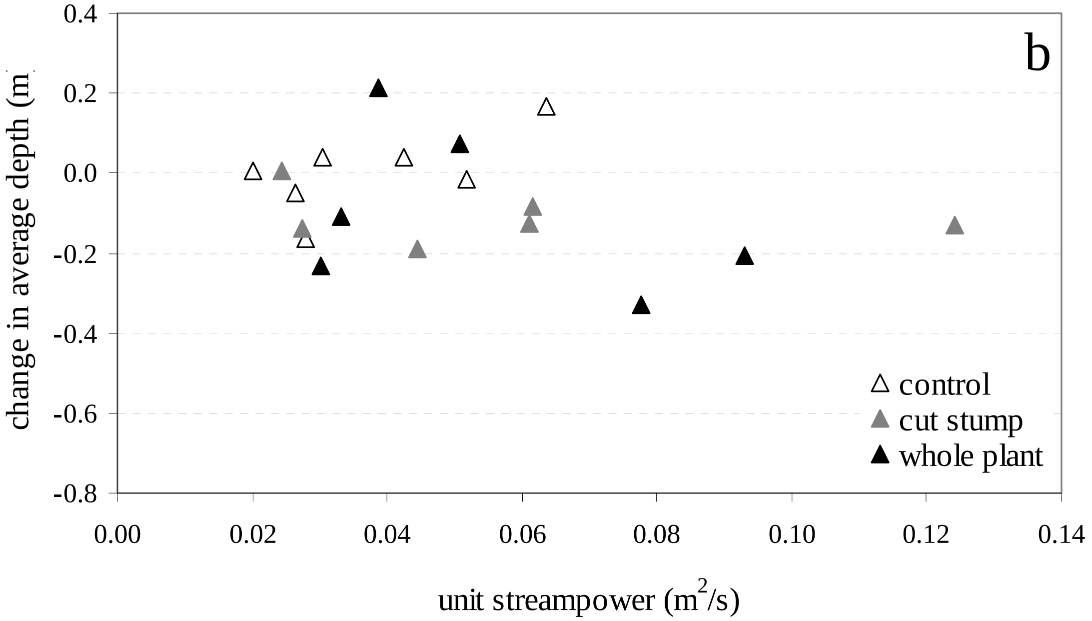


Figure C.4. Change in top width and unit stream calculated using toe width by reach, control (open shape), cut-stump removal method (grey shape), whole-plant removal method (black shape) within study sites a. Spider Rock (diamonds), b. Sliding Rock (triangles), c. Upper White House (squares), and d. Lower White House (circles).


a
change in average depth (m)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
◇ control
◆ cut stump
◆ whole plant


b
change in average depth (m)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
unit streampower (m^2/s)
△ control
▲ cut stump
▲ whole plant

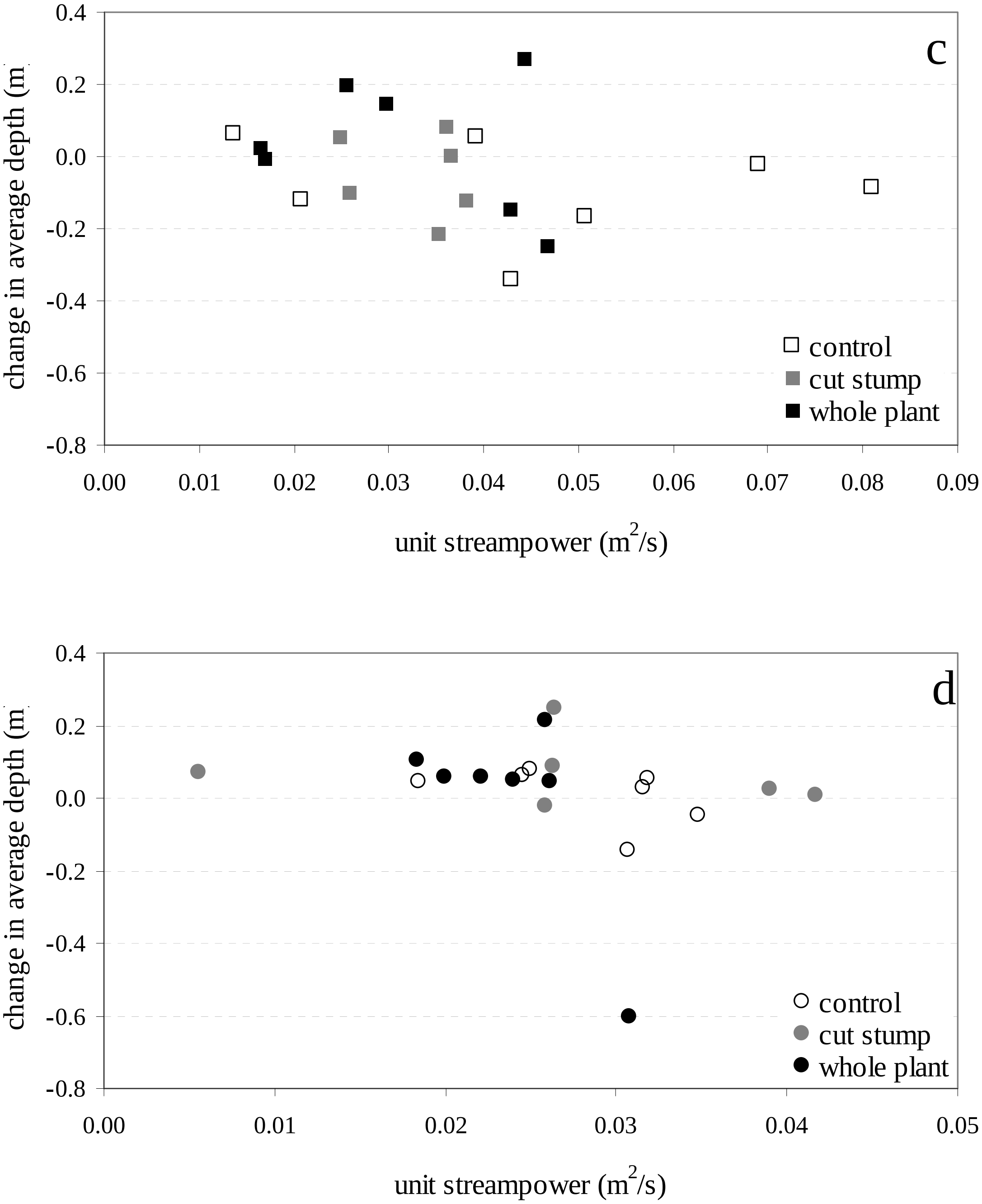
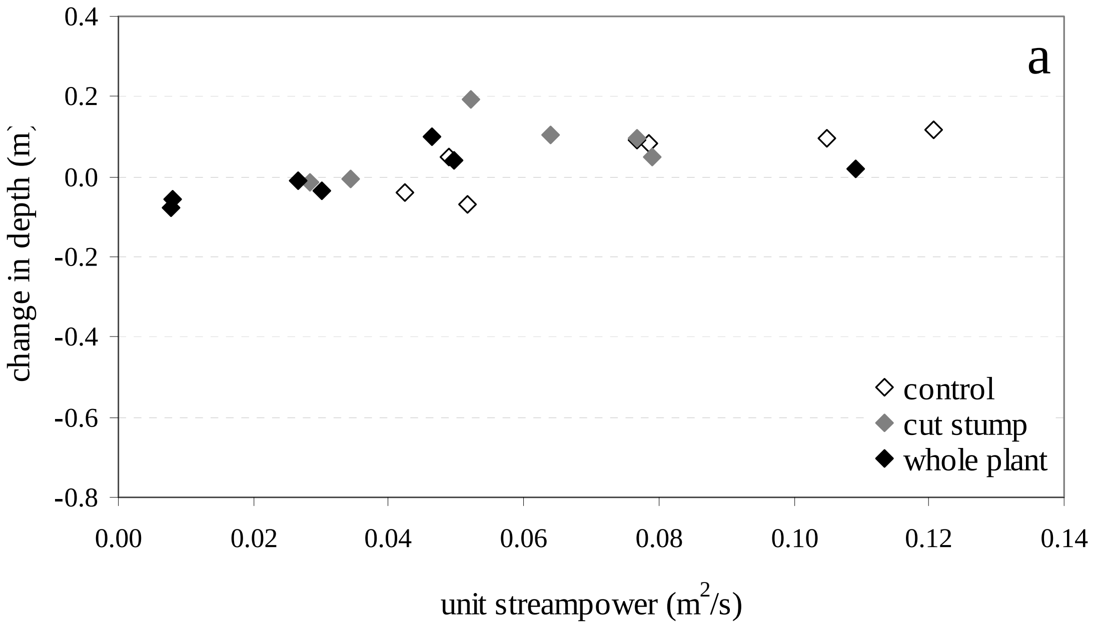
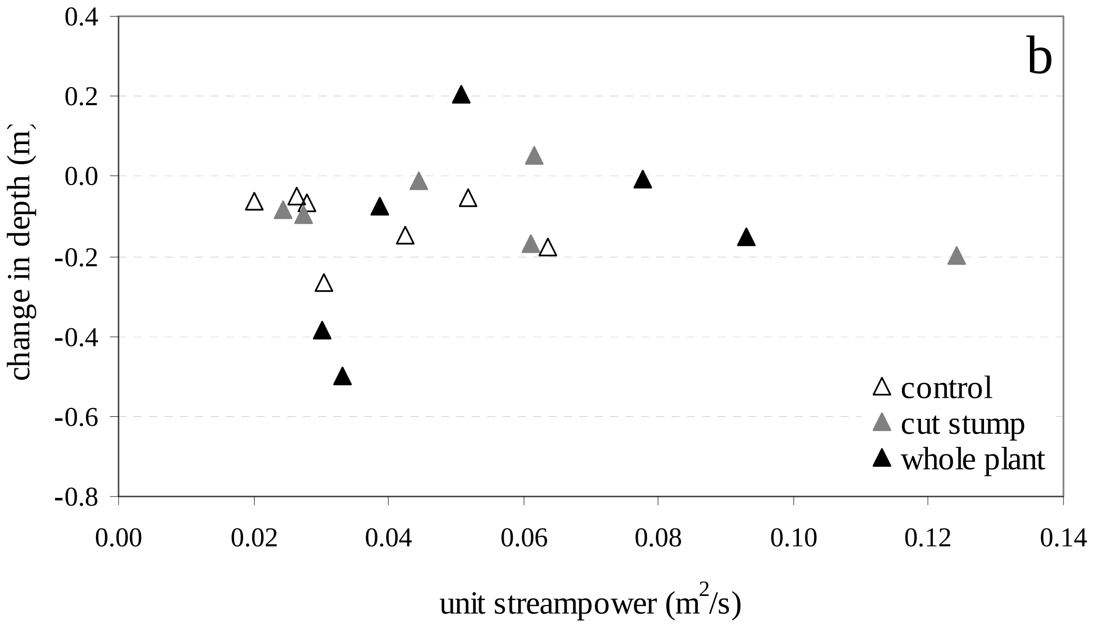
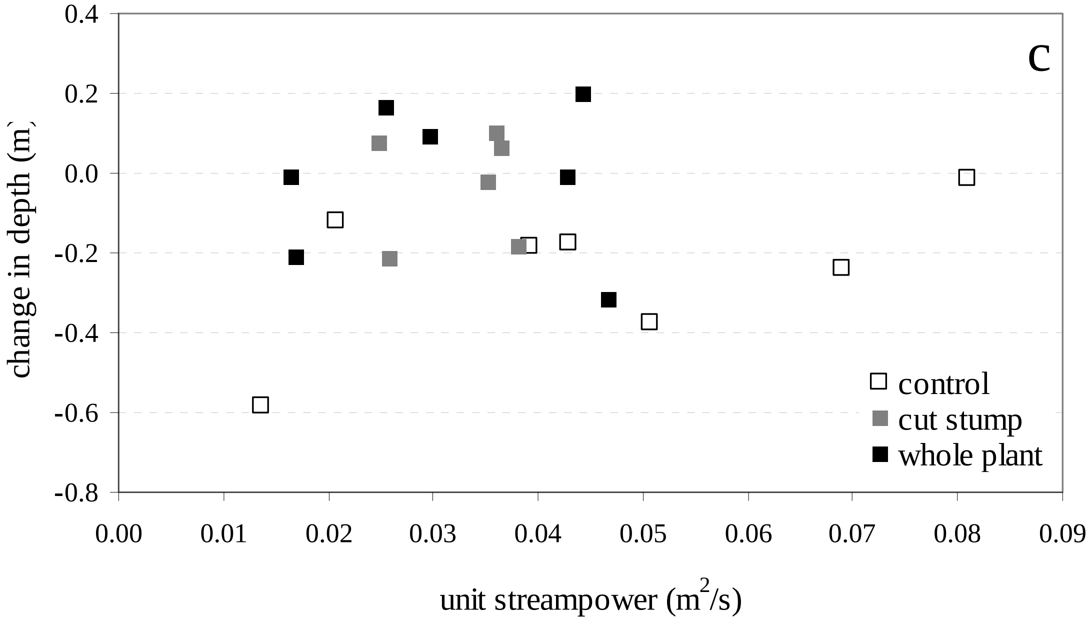


Figure C.5. Change in average depth and unit stream calculated using toe width by reach, control (open shape), cut-stump removal method (grey shape), whole-plant removal method (black shape) within study sites a. Spider Rock (diamonds), b. Sliding Rock (triangles), c. Upper White House (squares), and d. Lower White House (circles).


a
change in depth (m)
unit streampower (m²/s)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
◇ control
◆ cut stump
◆ whole plant


b
change in depth (m)
unit streampower (m²/s)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
△ control
▲ cut stump
▲ whole plant



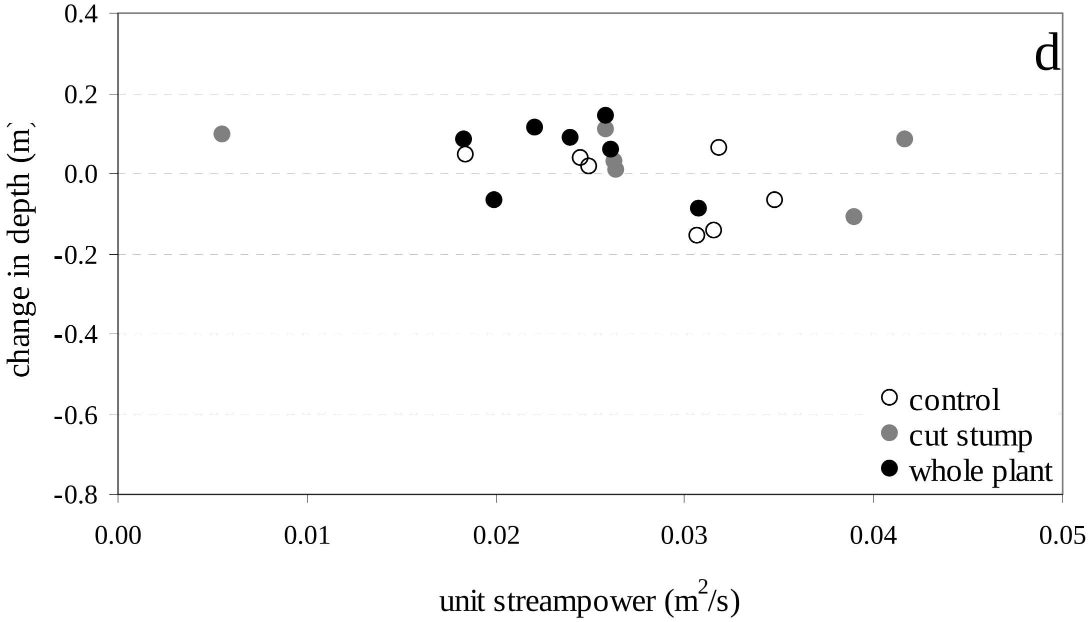


Figure C.6. Change in depth (thalweg) and unit stream calculated using toe width by reach, control (open shape), cut-stump removal method (grey shape), whole-plant removal method (black shape) within study sites a. Spider Rock (diamonds), b. Sliding Rock (triangles), c. Upper White House (squares), and d. Lower White House (circles).

APPENDIX D

CONCEPTS Calibration exercise using Canyon de Chelly discharge record

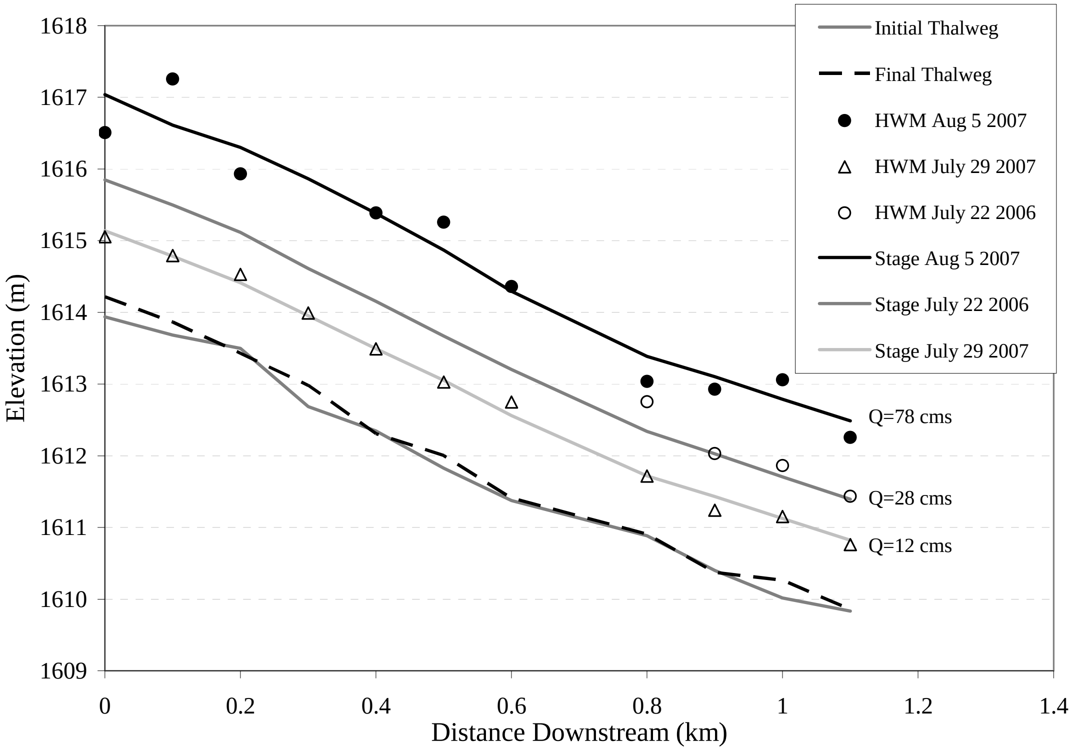
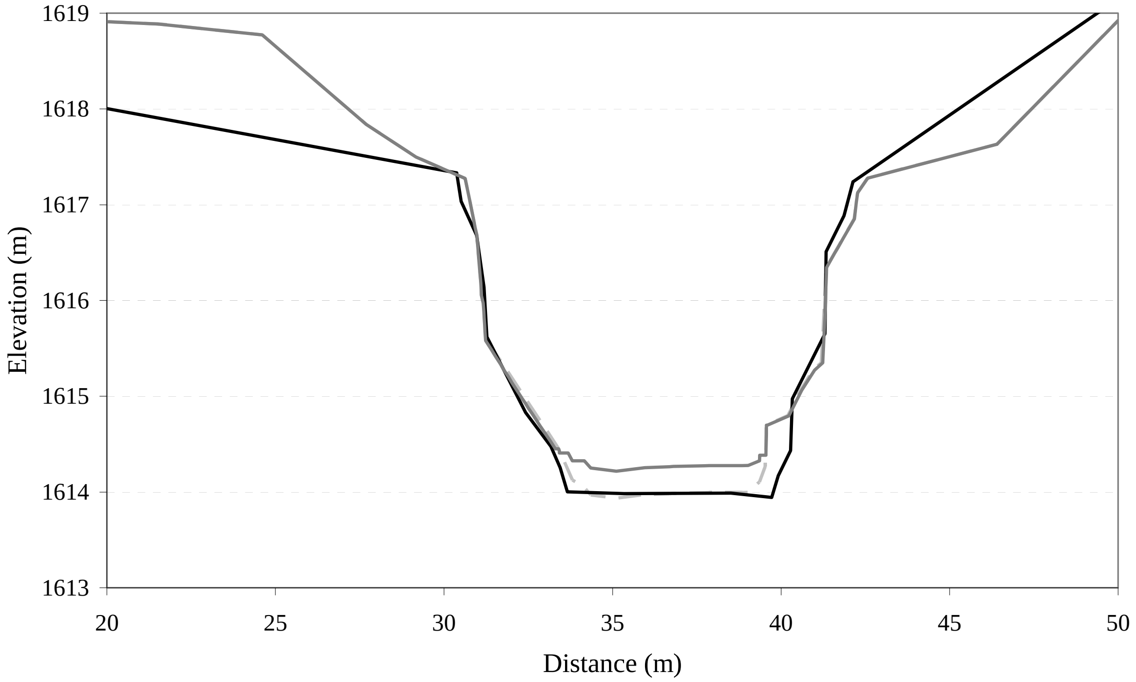
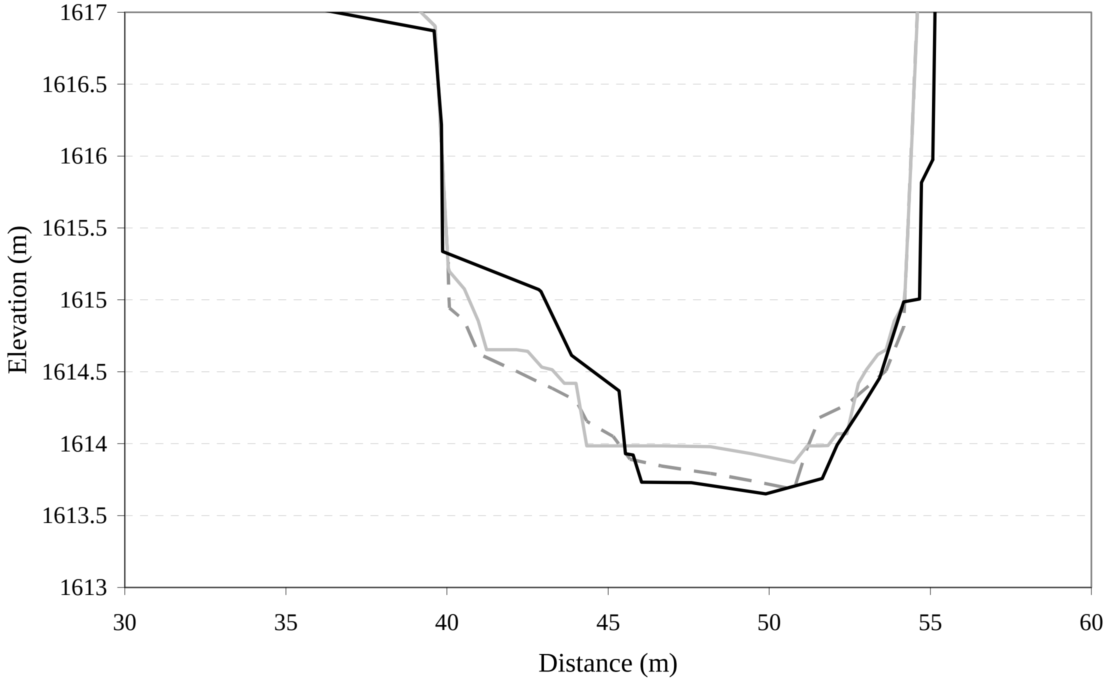


Figure D.1. CONCEPTS simulated peak stage profile and field-measured high water marks for three discharge events in UWH simulation reach.

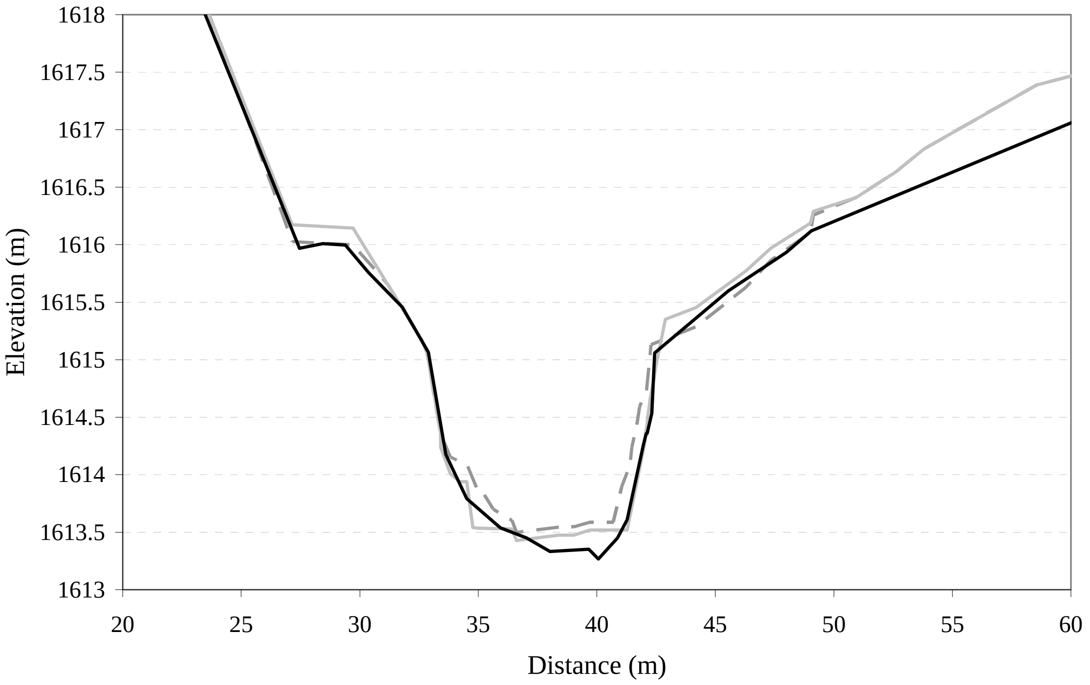
a.


1619
1618
1617
1616
1615
1614
1613
Elevation (m)
20
25
30
35
40
45
50
Distance (m)

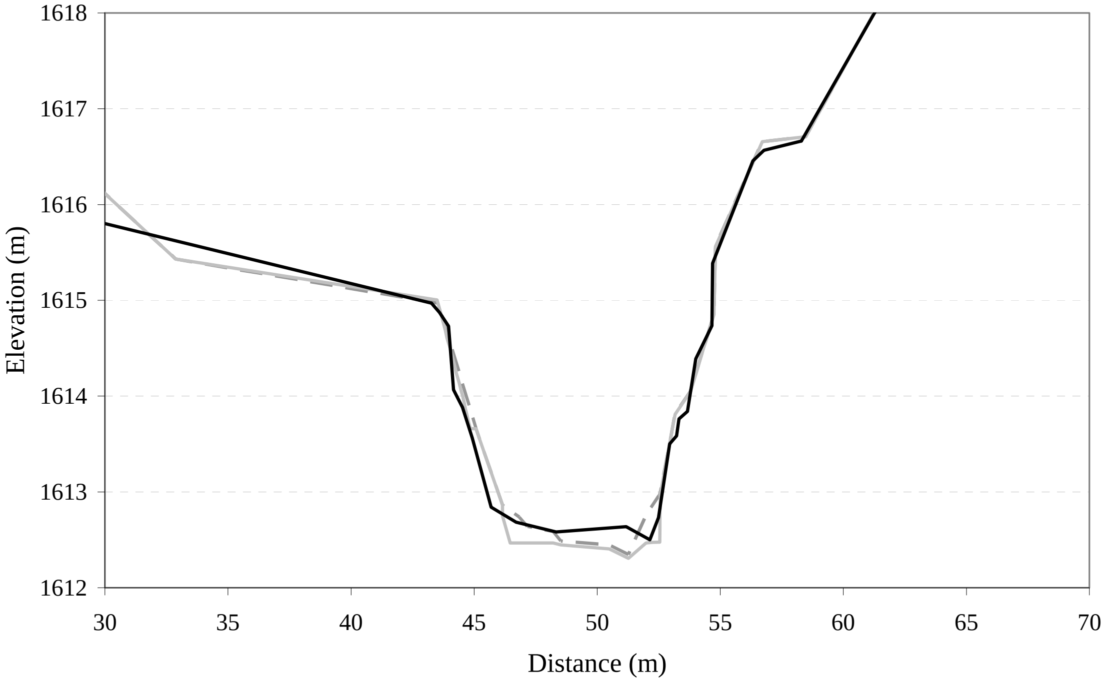
b.


1617
1616.5
1616
1615.5
1615
1614.5
1614
1613.5
1613
Elevation (m)
30
35
40
45
50
55
60
Distance (m)

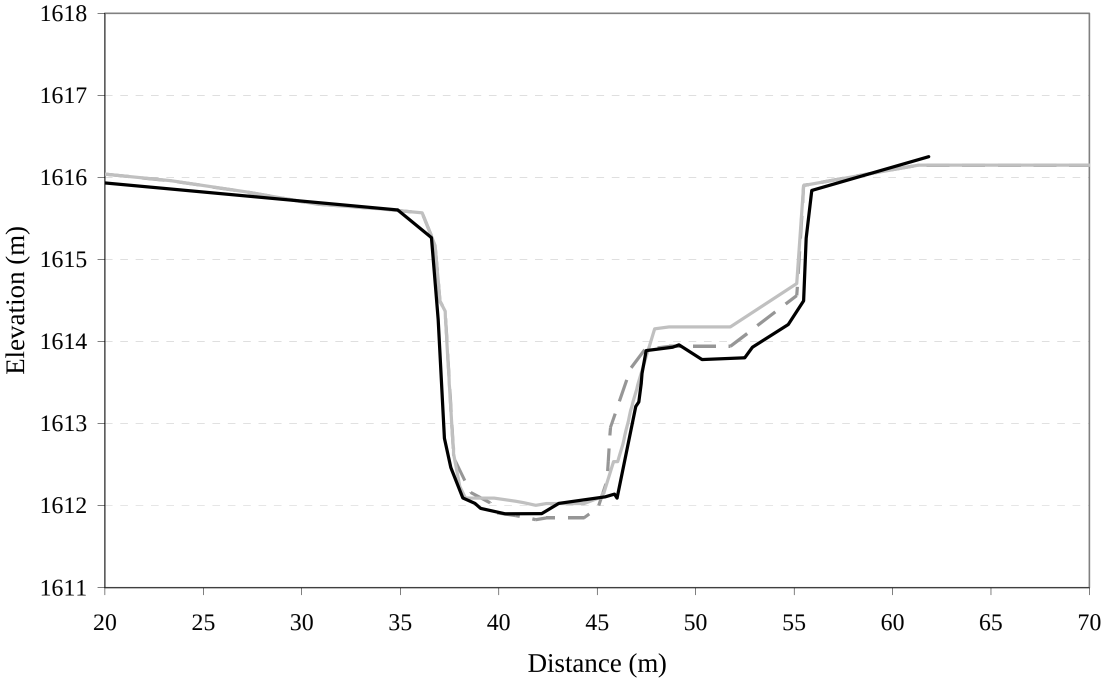
c.


1618
1617.5
1617
1616.5
1616
1615.5
1615
1614.5
1614
1613.5
1613
Elevation (m)
20
25
30
35
40
45
50
55
60
Distance (m)

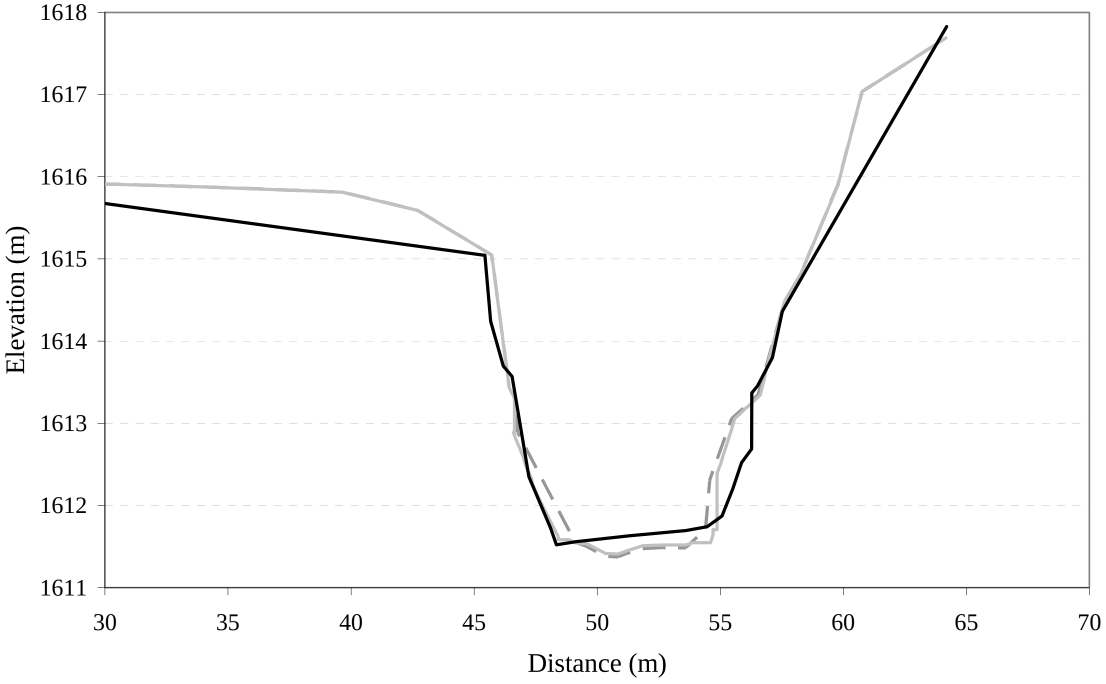
d.


1618
1617
1616
1615
1614
1613
1612
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)

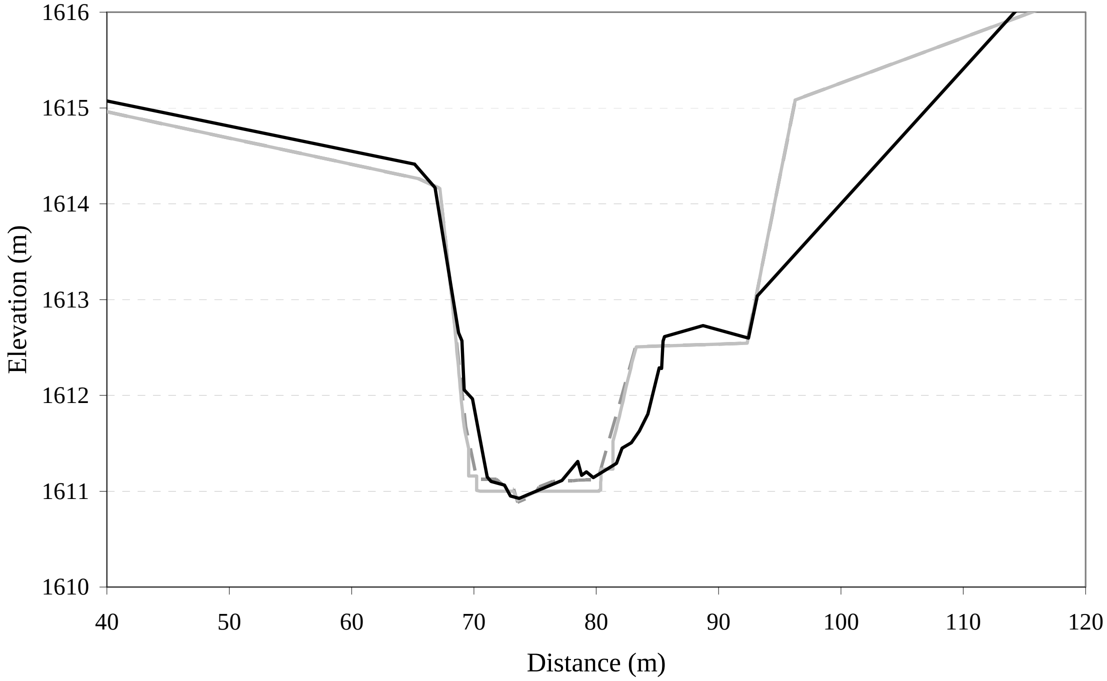
e.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
20
25
30
35
40
45
50
55
60
65
70
Distance (m)

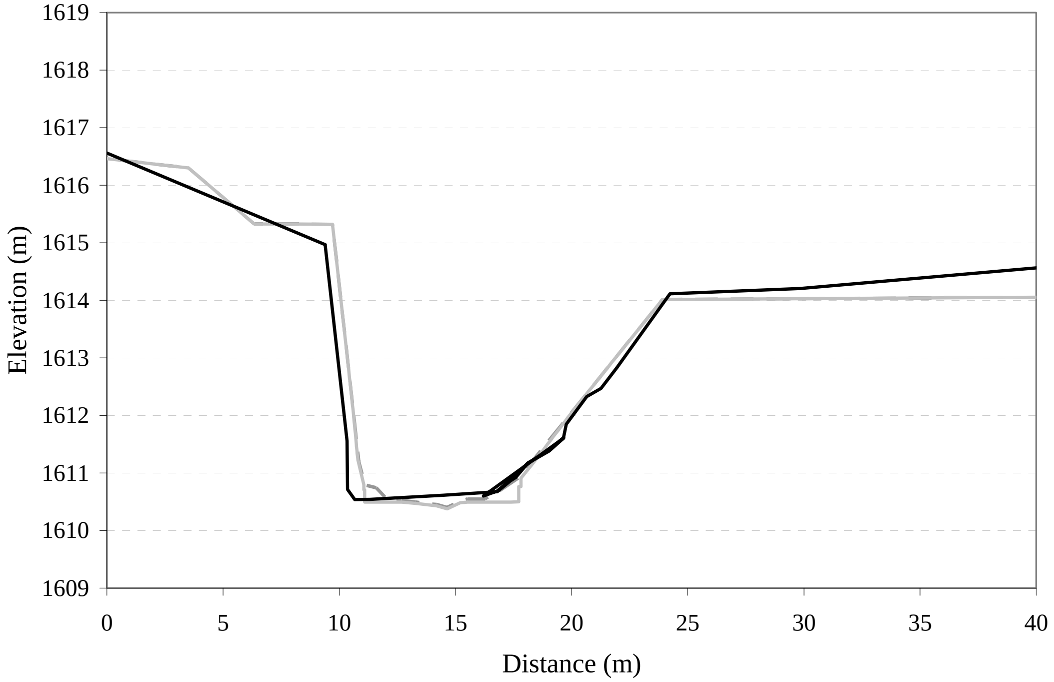
f.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)

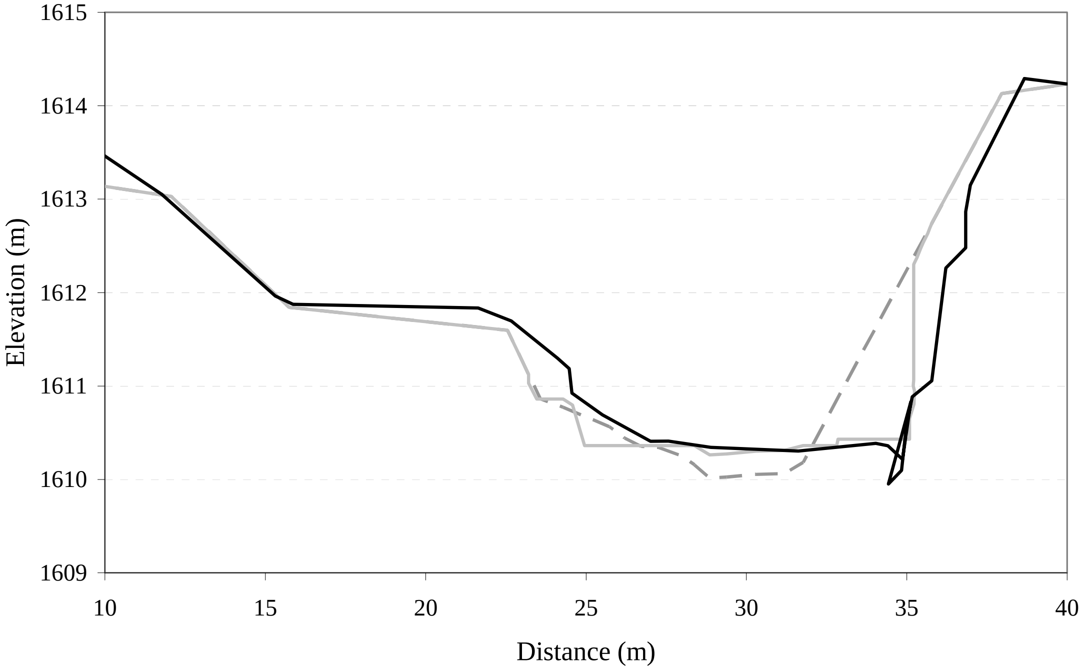
g.


1616
1615
1614
1613
1612
1611
1610
Elevation (m)
40
50
60
70
80
90
100
110
120
Distance (m)

h.


1619
1618
1617
1616
1615
1614
1613
1612
1611
1610
1609
Elevation (m)
0
5
10
15
20
25
30
35
40
Distance (m)

i.



j.

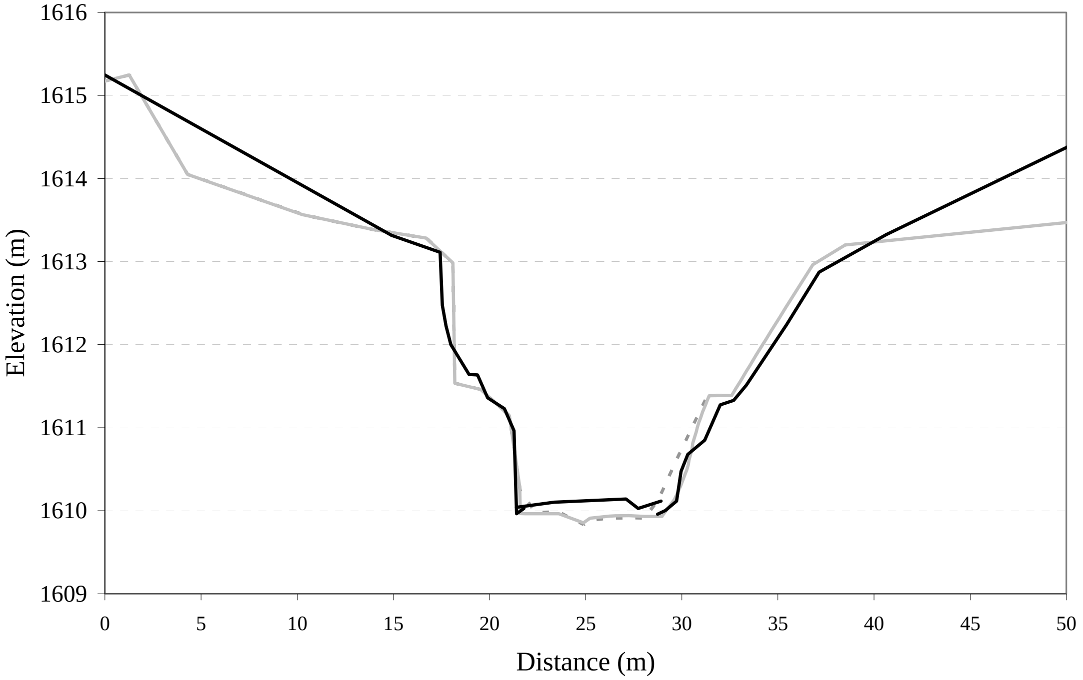
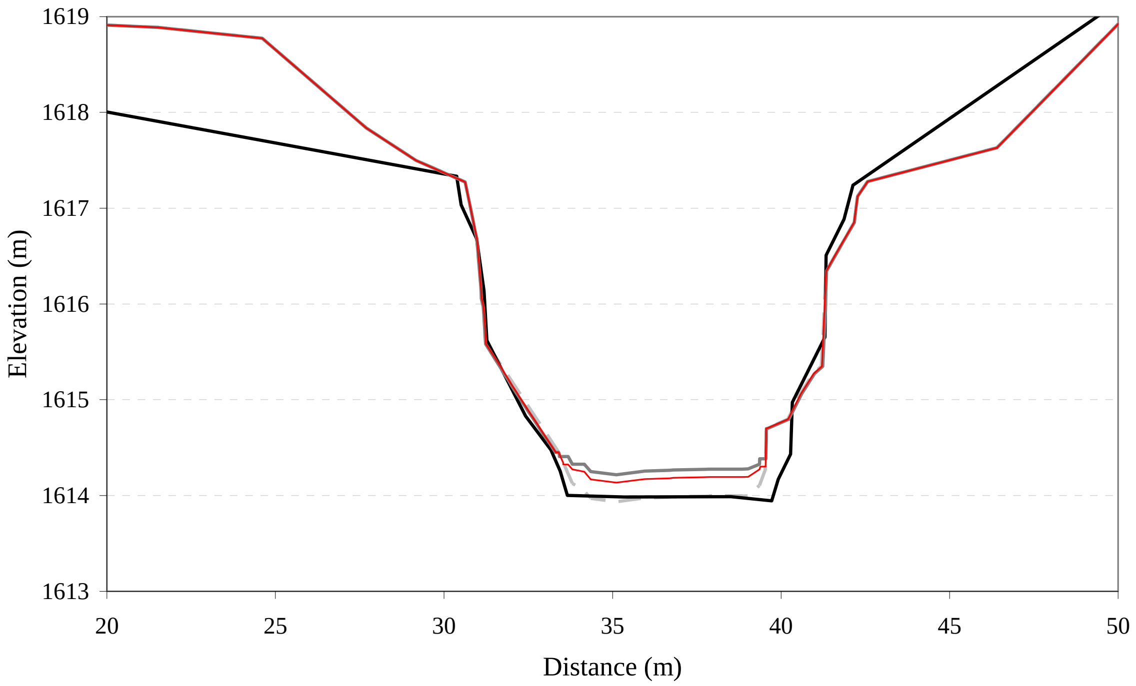


Figure D.2. Comparison of final field survey after August 5, 2007 discharge event and CONCEPTS simulation after the same event at cross sections along UWH simulation reach. Gray dotted line is initial survey, Gray solid line is CONCEPTS simulation, Black solid line is Field survey. a. Control Reach XS 0.0, b.Control Reach XS 1.0., c. Control Reach XS 2.0, d. Cut Stump Reach XS 4.0, e. Cut Stump Reach XS 5.0, f. Cut Stump Reach XS 6.0, g.Whole Plant Reach XS 8.0, h.Whole Plant Reach XS 9.0, i.Whole Plant Reach XS 10.0, j. Whole Plant Reach XS 11.0.

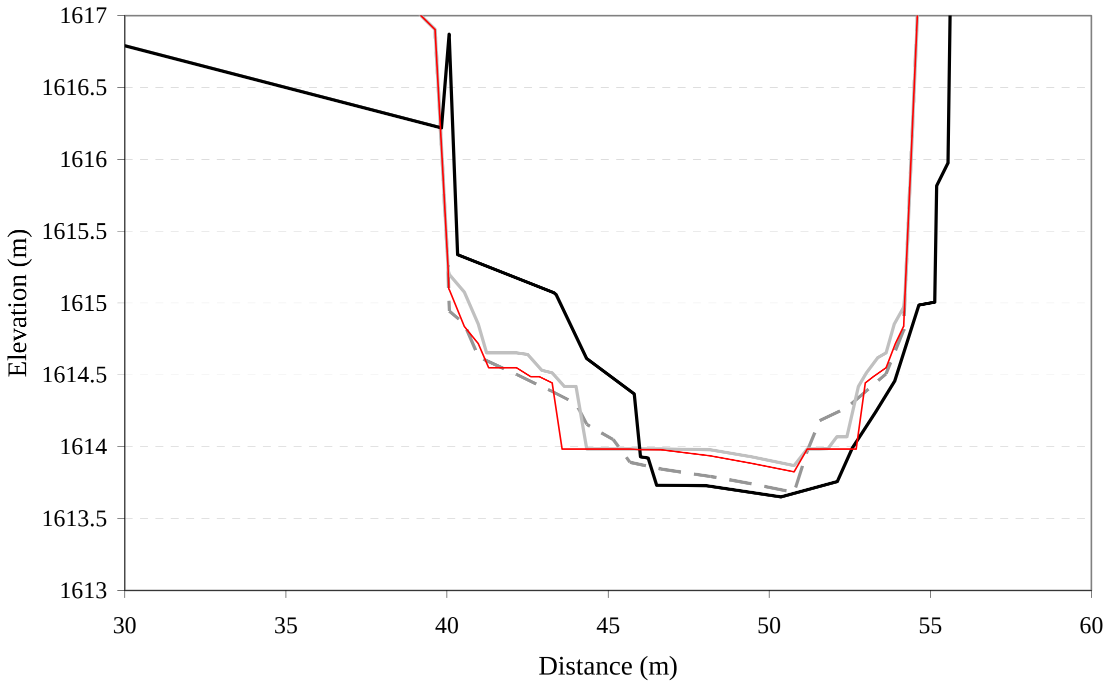
APPENDIX E

CONCEPTS Calibration exercise comparing estimated and maximum Manning *n* values using Canyon de Chelly discharge record

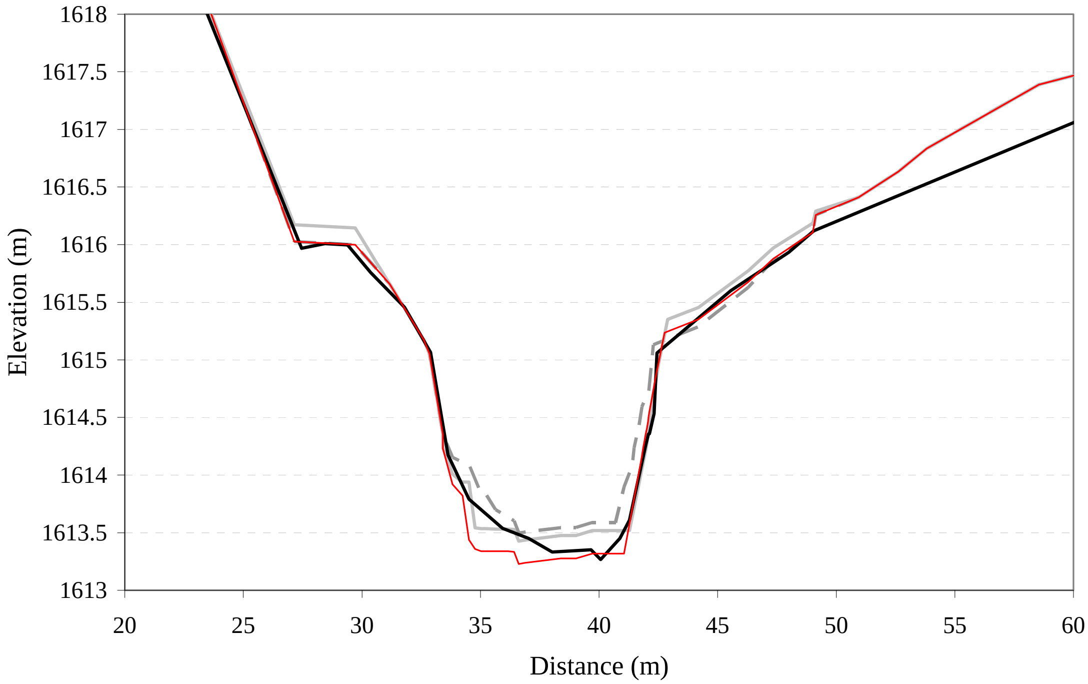
a.


1619
1618
1617
1616
1615
1614
1613
Elevation (m)
20
25
30
35
40
45
50
Distance (m)

b.

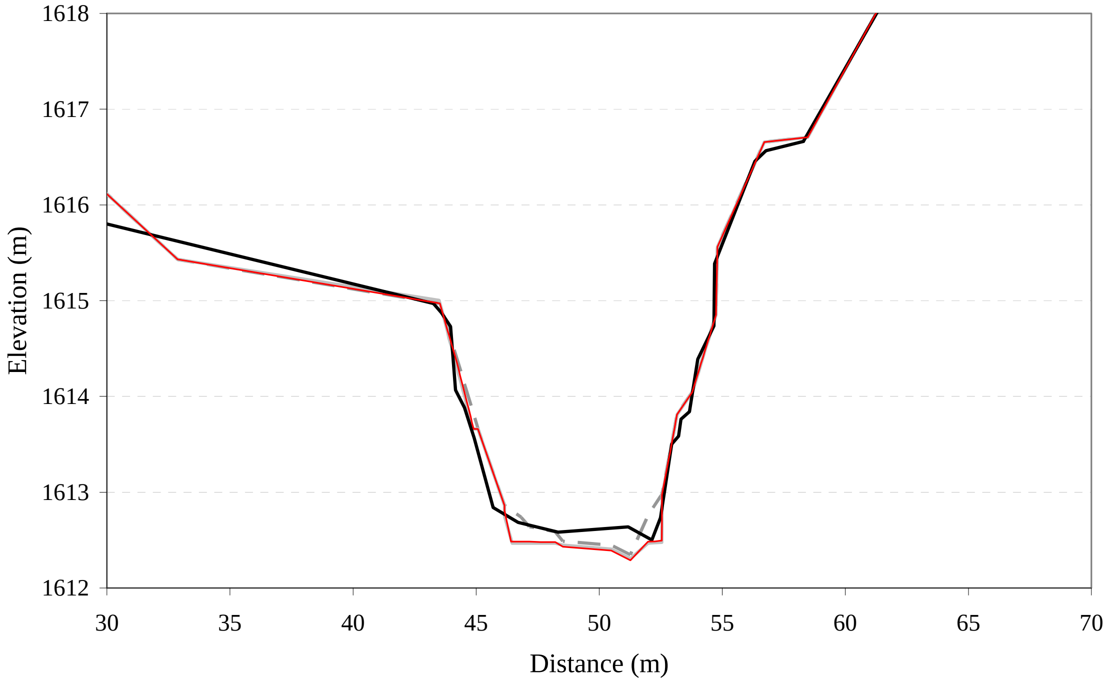

1617
1616.5
1616
1615.5
1615
1614.5
1614
1613.5
1613
Elevation (m)
30
35
40
45
50
55
60
Distance (m)

c.



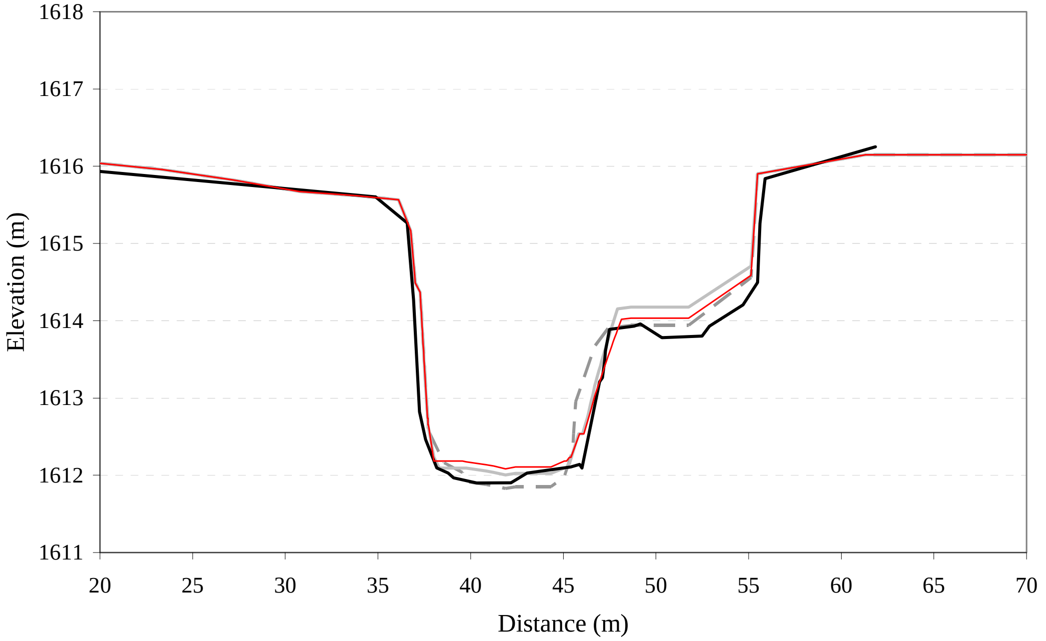
Elevation (m)
1618
1617.5
1617
1616.5
1616
1615.5
1615
1614.5
1614
1613.5
1613
20
25
30
35
40
45
50
55
60
Distance (m)

d.

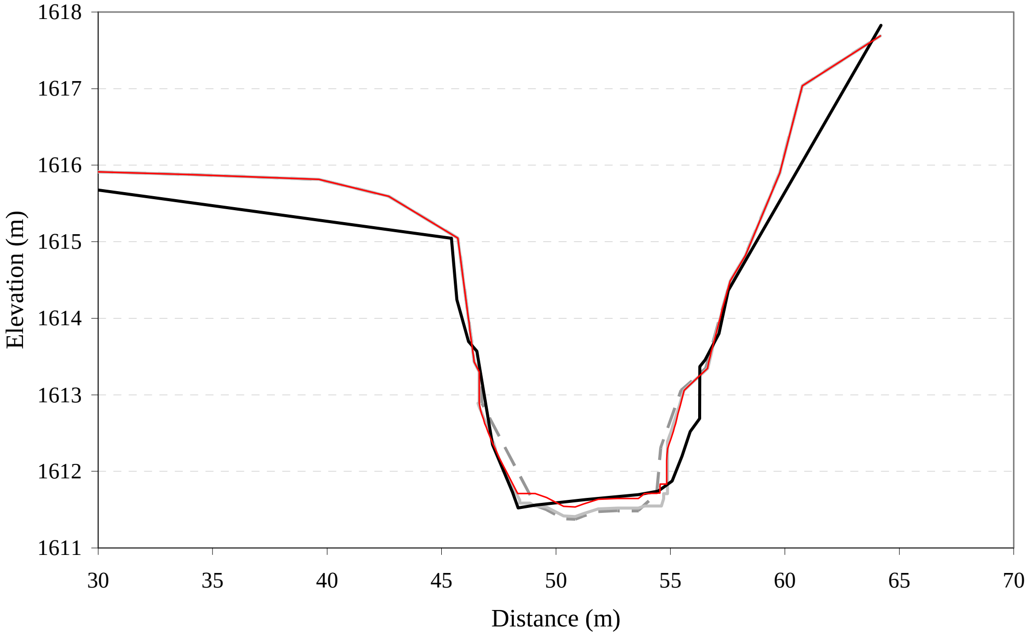


Elevation (m)
1618
1617
1616
1615
1614
1613
1612
30
35
40
45
50
55
60
65
70
Distance (m)

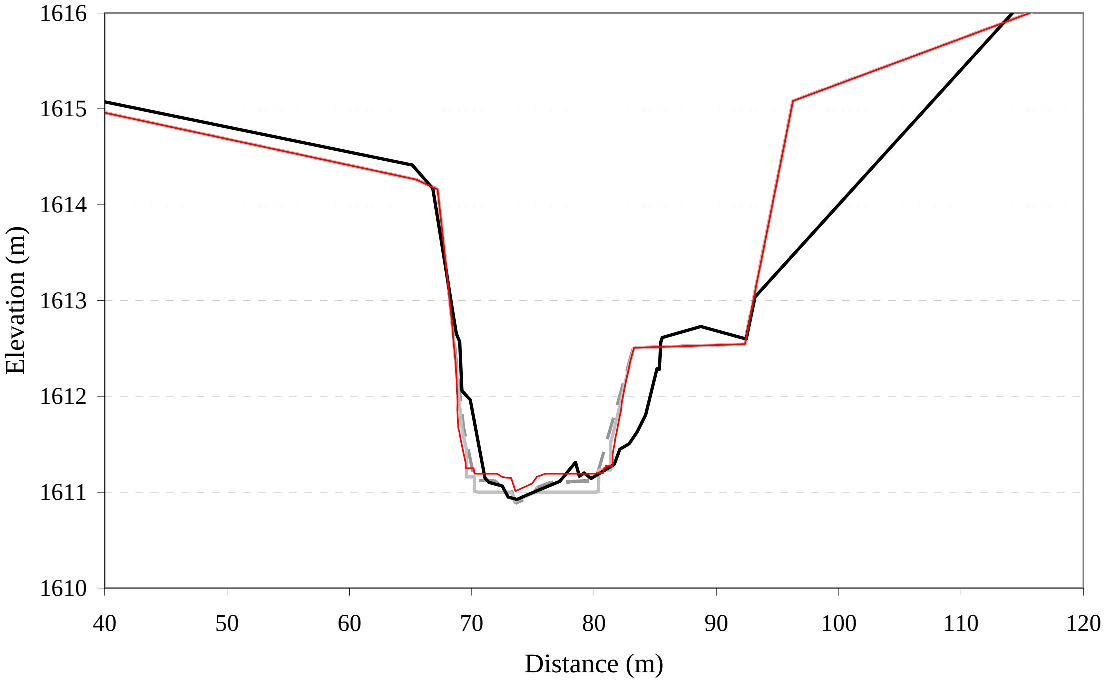
e.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
20
25
30
35
40
45
50
55
60
65
70
Distance (m)

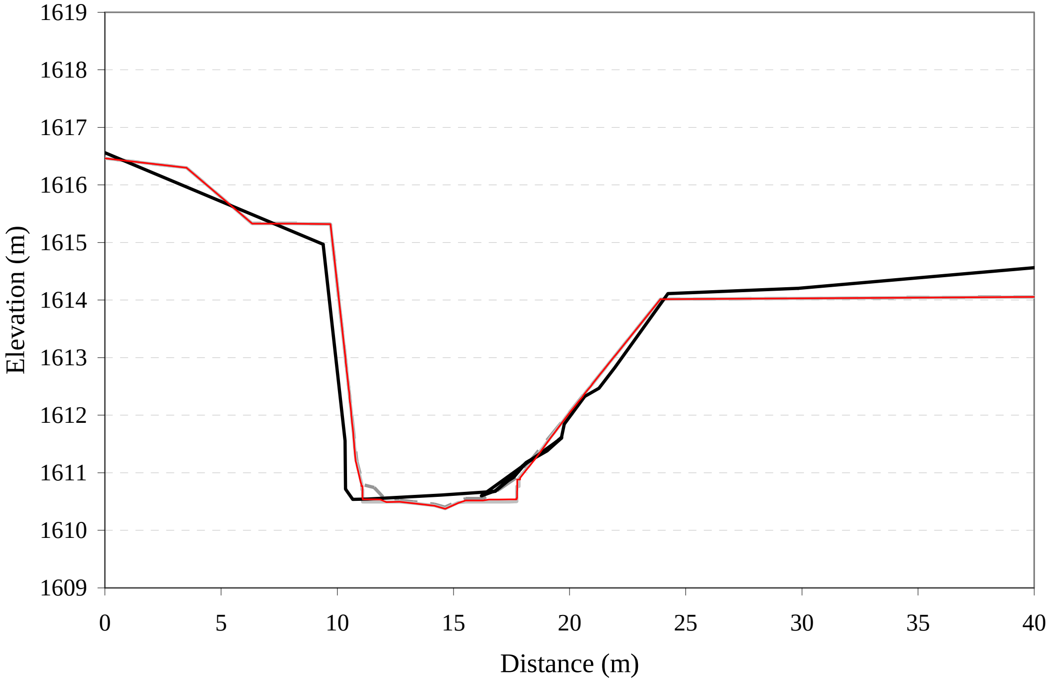
f.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)

g.


1616
1615
1614
1613
1612
1611
1610
Elevation (m)
40
50
60
70
80
90
100
110
120
Distance (m)

h.


1619
1618
1617
1616
1615
1614
1613
1612
1611
1610
1609
Elevation (m)
0
5
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15
20
25
30
35
40
Distance (m)

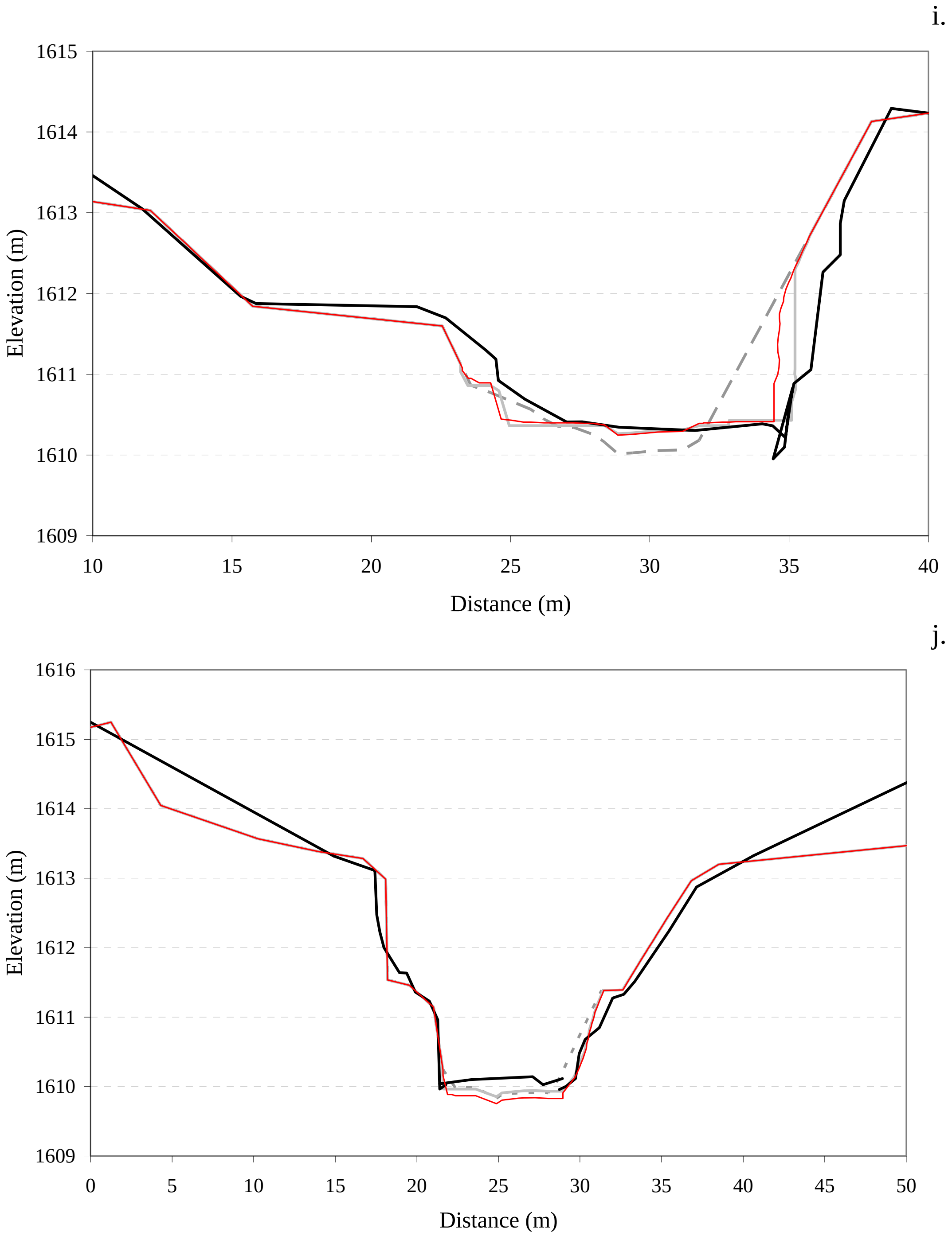
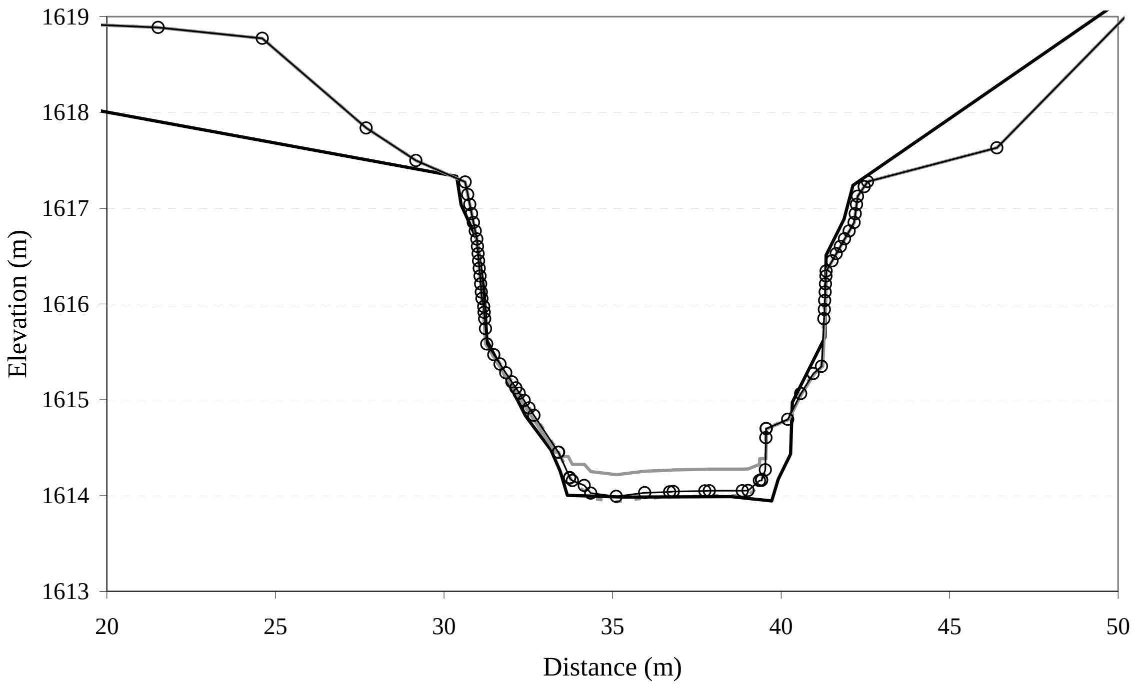


Figure E.1. Comparison of final field survey after August 5, 2007 discharge event and two CONCEPTS simulation after the same event at cross sections along UWH simulation reach. Gray dotted line is initial survey, Gray solid line is CONCEPTS simulation with field visually estimated Manning n values, Red solid line is CONCEPTS simulation with maximum Manning n values, Black solid line is Field survey. a. Control Reach XS 0.0, b.Control Reach XS 1.0., c. Control Reach XS 2.0, d. Cut Stump Reach XS 4.0, e. Cut Stump Reach XS 5.0, f. Cut Stump Reach XS 6.0, g.Whole Plant Reach XS 8.0, h.Whole Plant Reach XS 9.0, i.Whole Plant Reach XS 10.0, j. Whole Plant Reach XS 11.0.

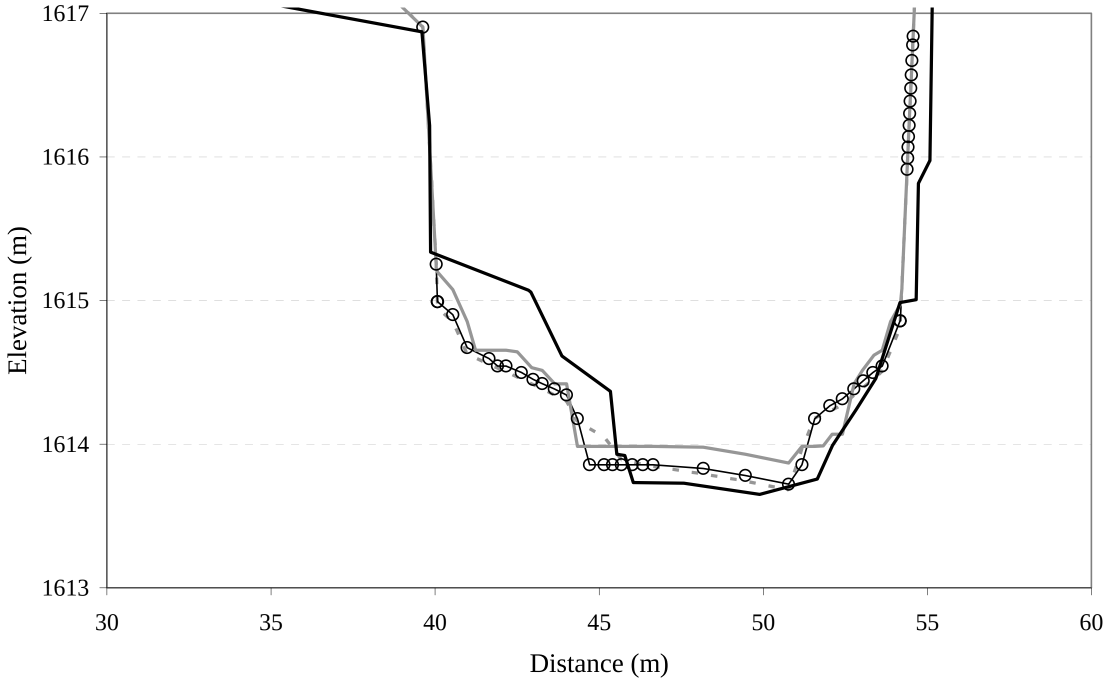
APPENDIX F

CONCEPTS Simulation exercise using surrogate discharge record from Zuni River, New Mexico

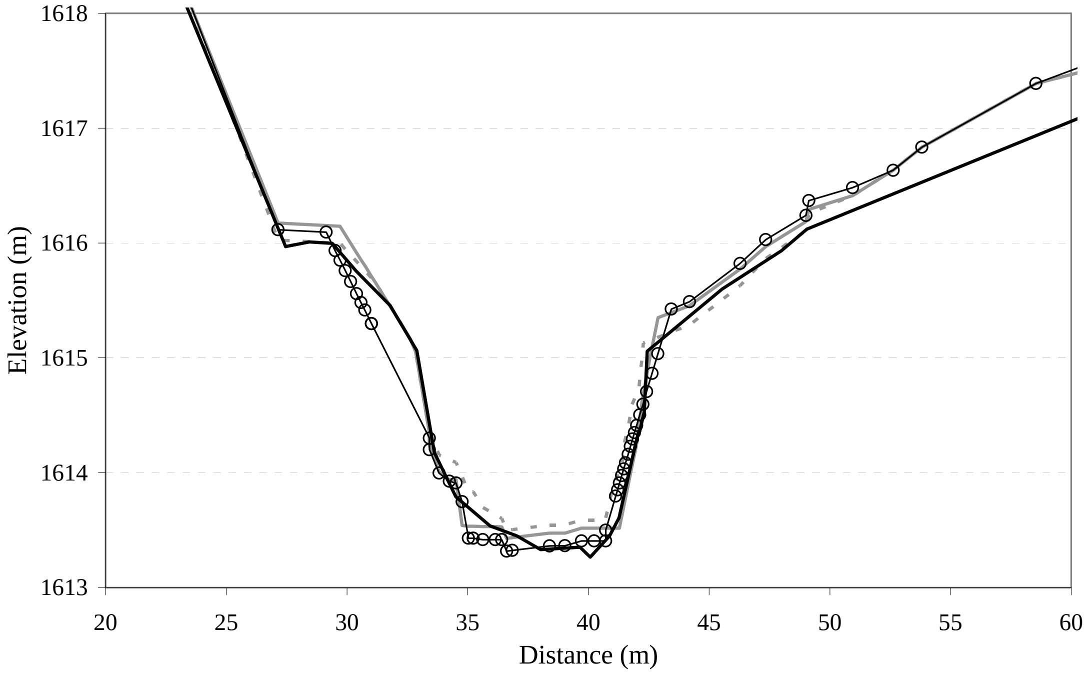
a.


1619
1618
1617
1616
1615
1614
1613
Elevation (m)
20
25
30
35
40
45
50
Distance (m)

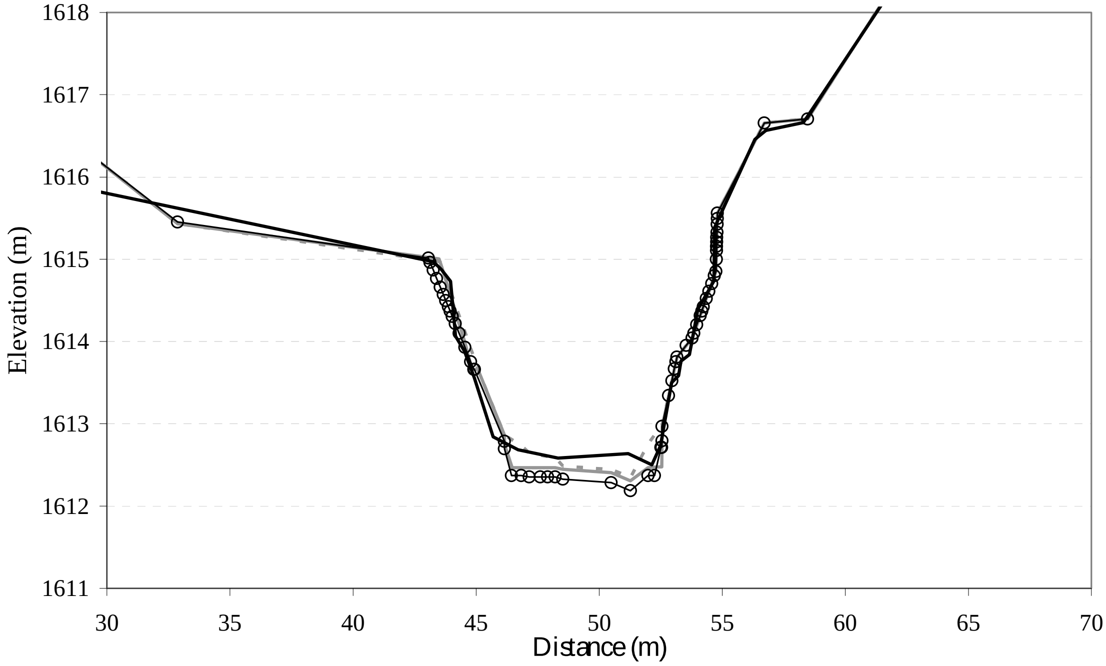
b.


1617
1616
1615
1614
1613
Elevation (m)
30
35
40
45
50
55
60
Distance (m)

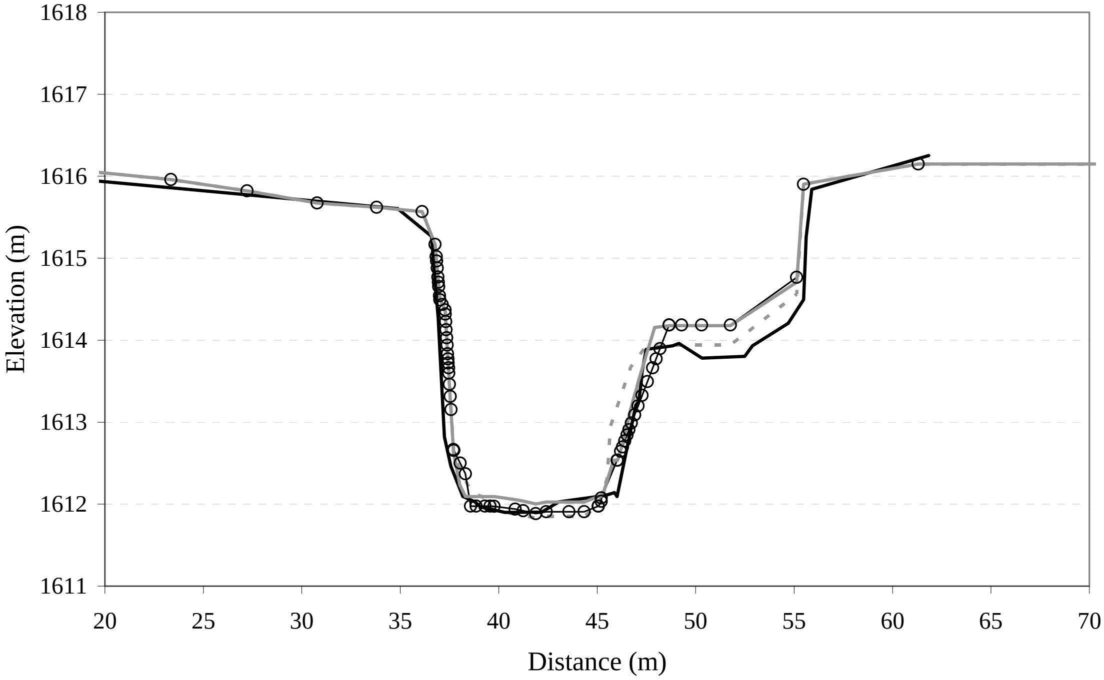
c.


1618
1617
1616
1615
1614
1613
Elevation (m)
20
25
30
35
40
45
50
55
60
Distance (m)

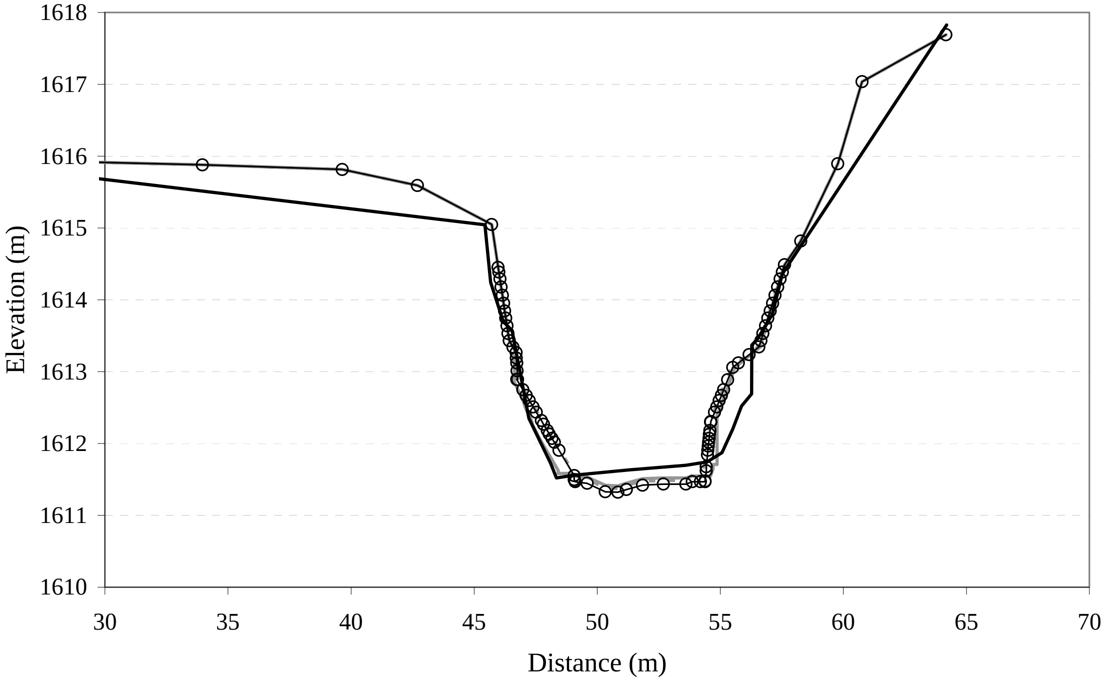
d.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)

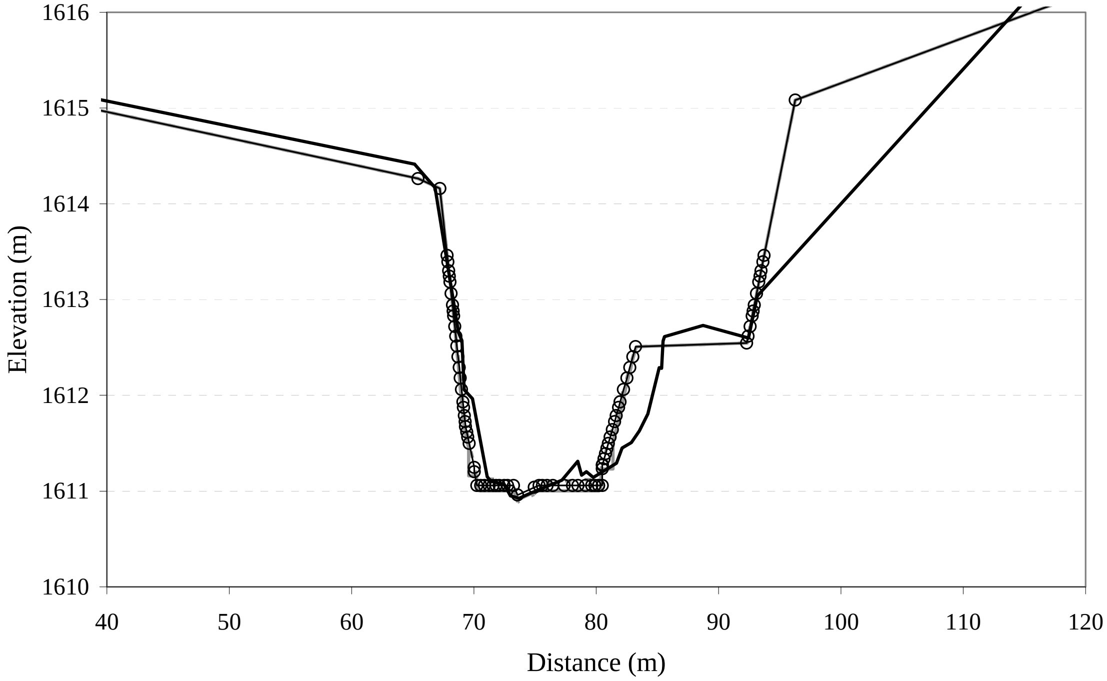
e.


1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
20
25
30
35
40
45
50
55
60
65
70
Distance (m)

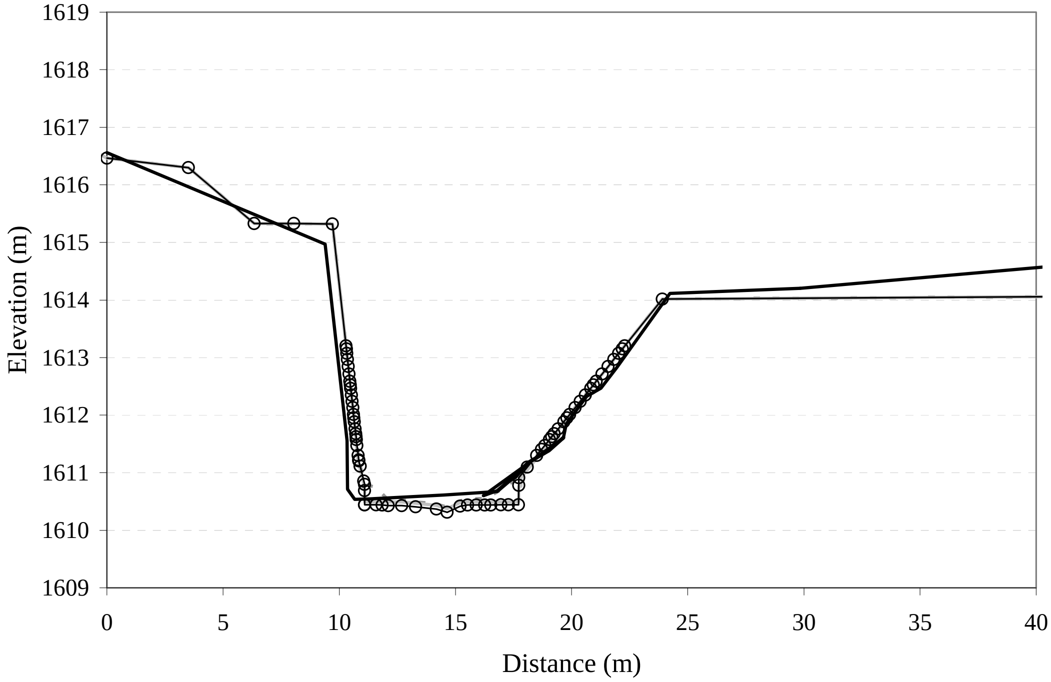
f.


1618
1617
1616
1615
1614
1613
1612
1611
1610
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)

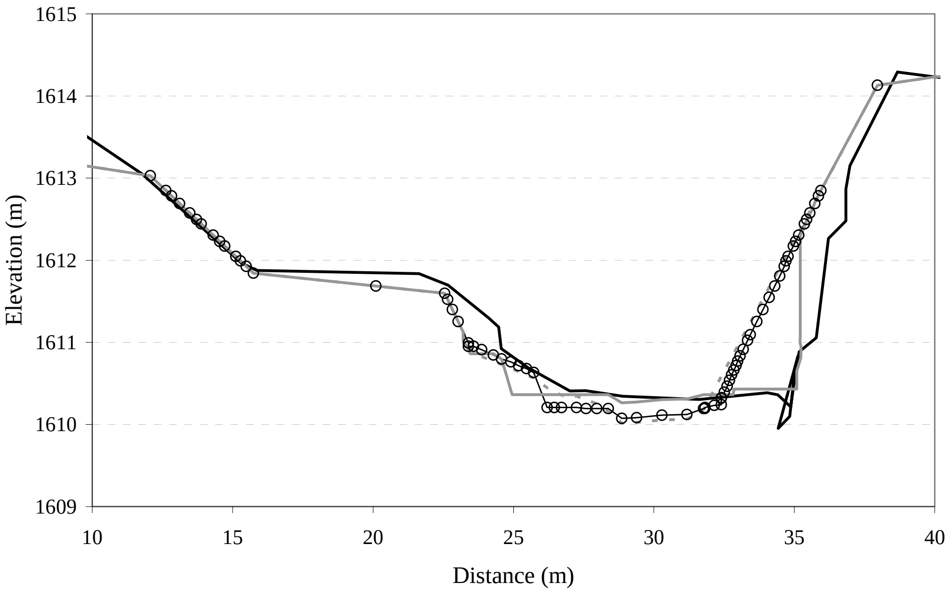
g.


1616
1615
1614
1613
1612
1611
1610
Elevation (m)
40
50
60
70
80
90
100
110
120
Distance (m)

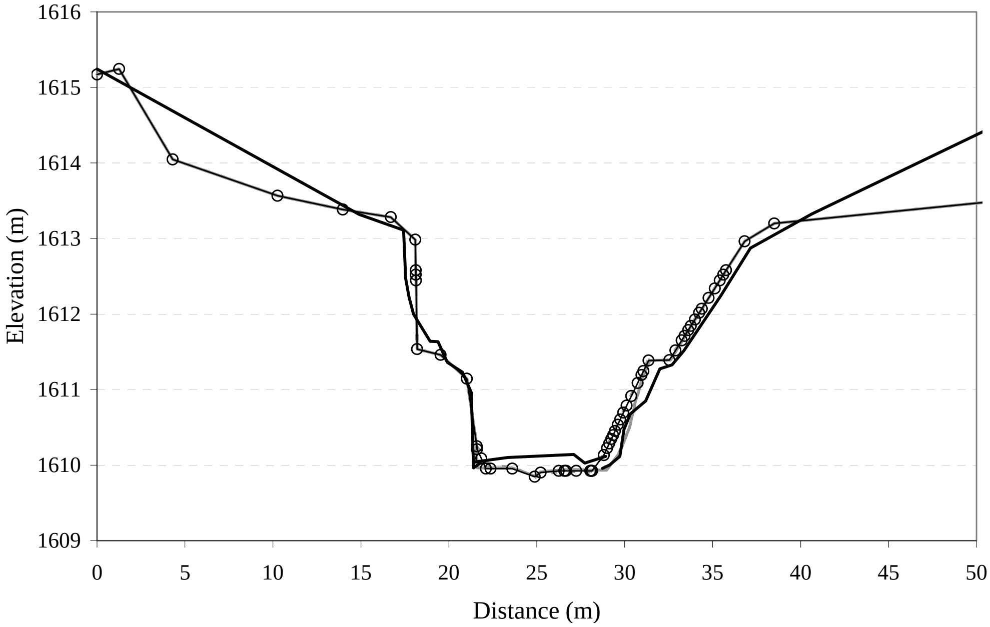
h.


1619
1618
1617
1616
1615
1614
1613
1612
1611
1610
1609
Elevation (m)
0
5
10
15
20
25
30
35
40
Distance (m)

i.



j.

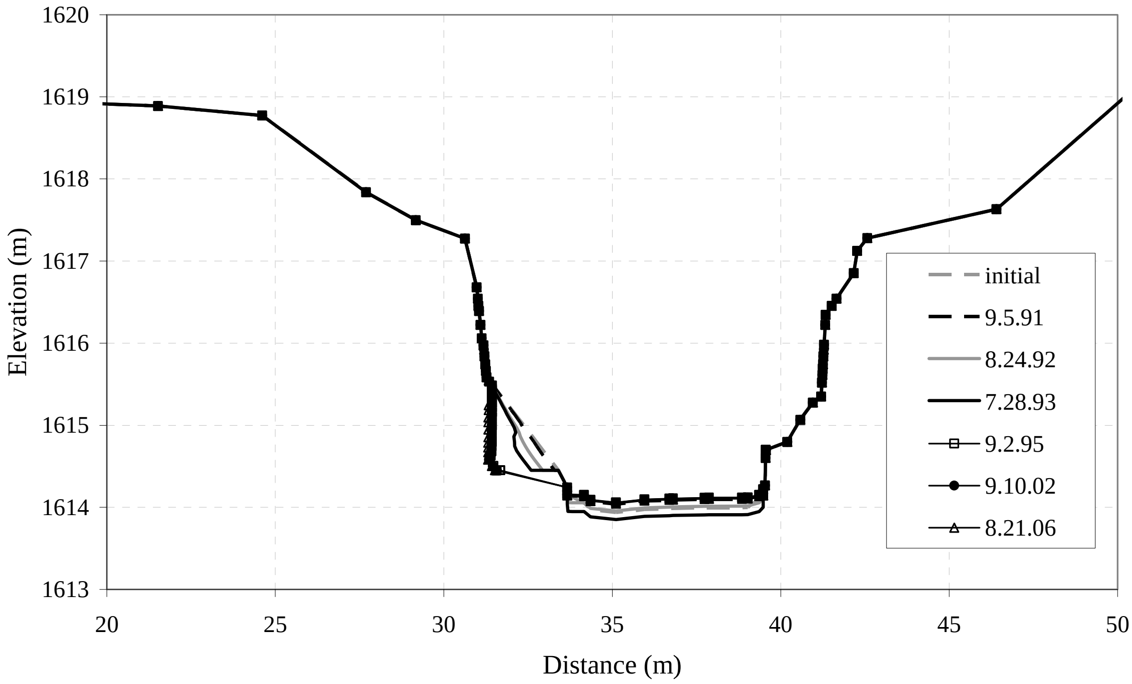


Appendix F.1. Comparison of final field survey after August 5, 2007 discharge event, CONCEPTS simulation of the August 5, 2007 discharge event with estimated peak discharge of 78 cms and a 5-day duration, and CONCEPTS simulation of the August 19, 2006 flood of record at the Zuni River adjusted for the UWH drainage area. The peak magnitude was 93 cms with a duration of less than 24 hours. Gray dotted line is initial survey, Gray solid line is CONCEPTS simulation with field visually estimated Manning n values, Black thin line with open circles is CONCEPTS simulation using the adjusted Zuni River flood of record, Black solid line is Field survey. a. Control Reach XS 0.0, b.Control Reach XS 1.0., c. Control Reach XS 2.0, d. Cut Stump Reach XS 4.0, e. Cut Stump Reach XS 5.0, f. Cut Stump Reach XS 6.0, g.Whole Plant Reach XS 8.0, h.Whole Plant Reach XS 9.0, i.Whole Plant Reach XS 10.0, j. Whole Plant Reach XS 11.0.

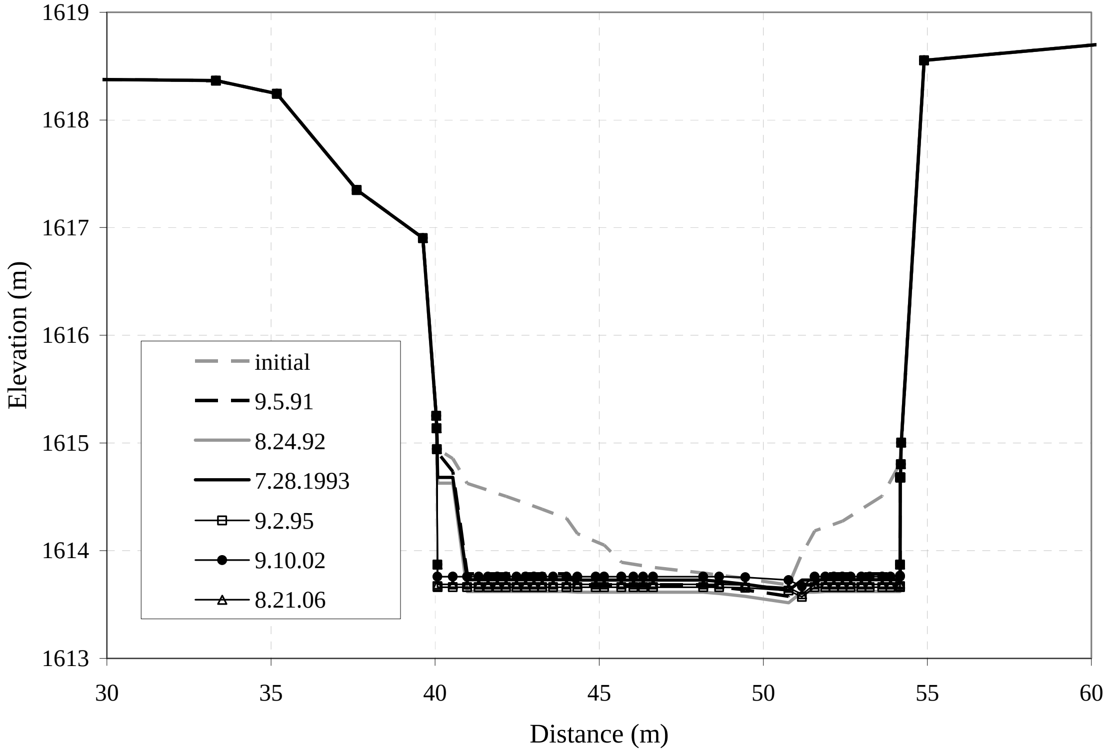
APPENDIX G

CONCEPTS Simulation exercise using surrogate discharge record from Jemez River, New Mexico

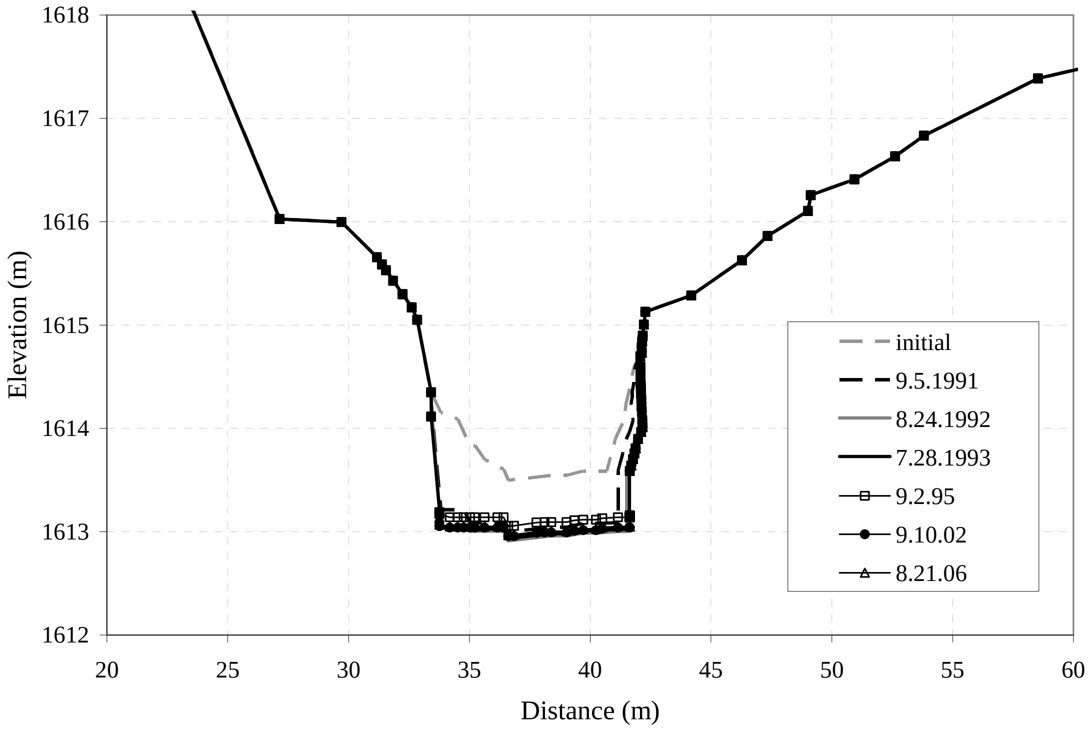
a.


1620
1619
1618
1617
1616
1615
1614
1613
Elevation (m)
20
25
30
35
40
45
50
Distance (m)
initial
9.5.91
8.24.92
7.28.93
9.2.95
9.10.02
8.21.06

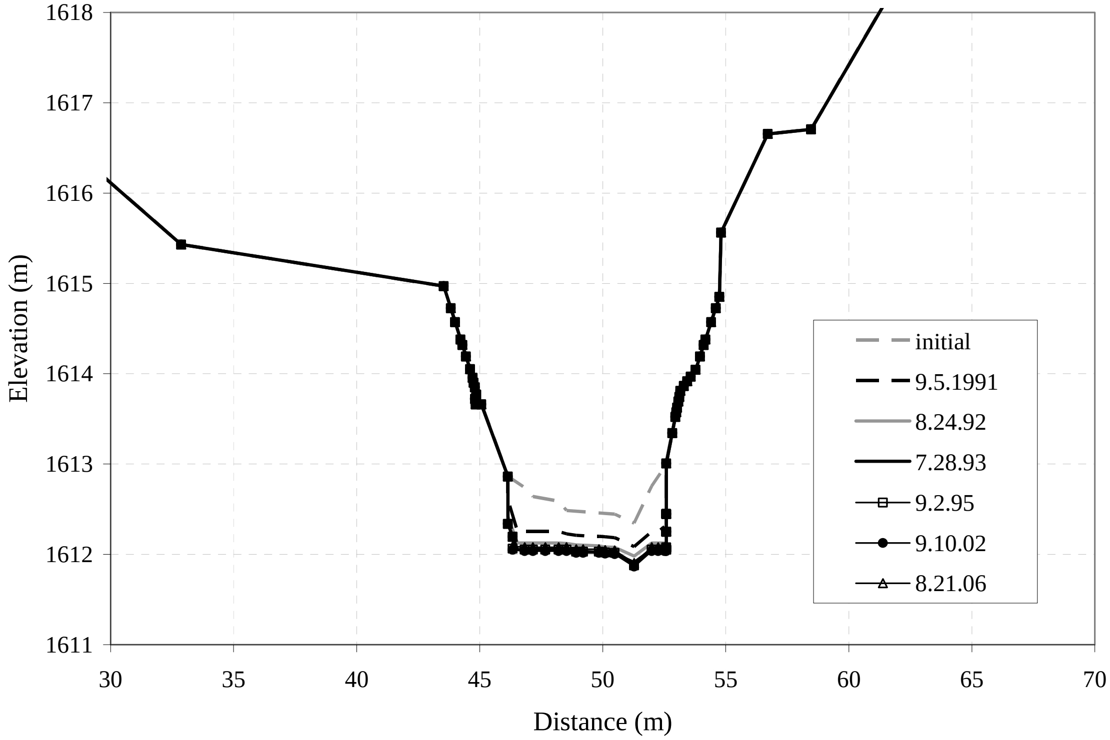
b.


1619
1618
1617
1616
1615
1614
1613
Elevation (m)
30
35
40
45
50
55
60
Distance (m)
initial
9.5.91
8.24.92
7.28.1993
9.2.95
9.10.02
8.21.06

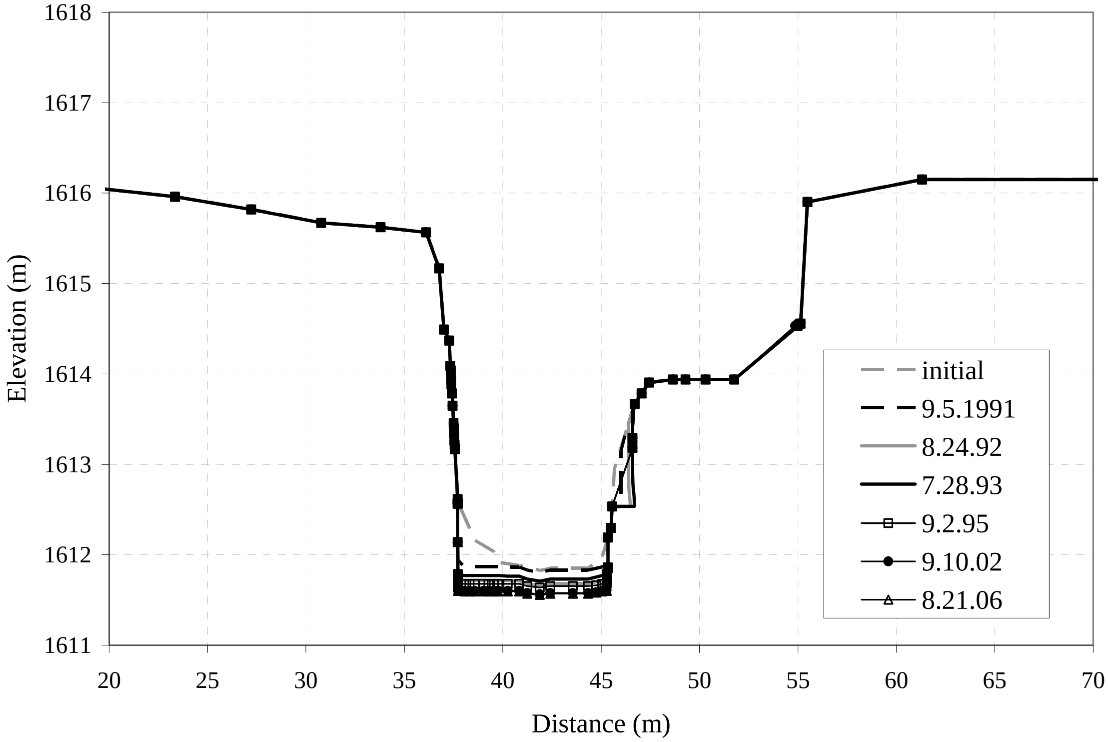
c.


1618
1617
1616
1615
1614
1613
1612
Elevation (m)
20
25
30
35
40
45
50
55
60
Distance (m)
initial
9.5.1991
8.24.1992
7.28.1993
9.2.95
9.10.02
8.21.06

d.

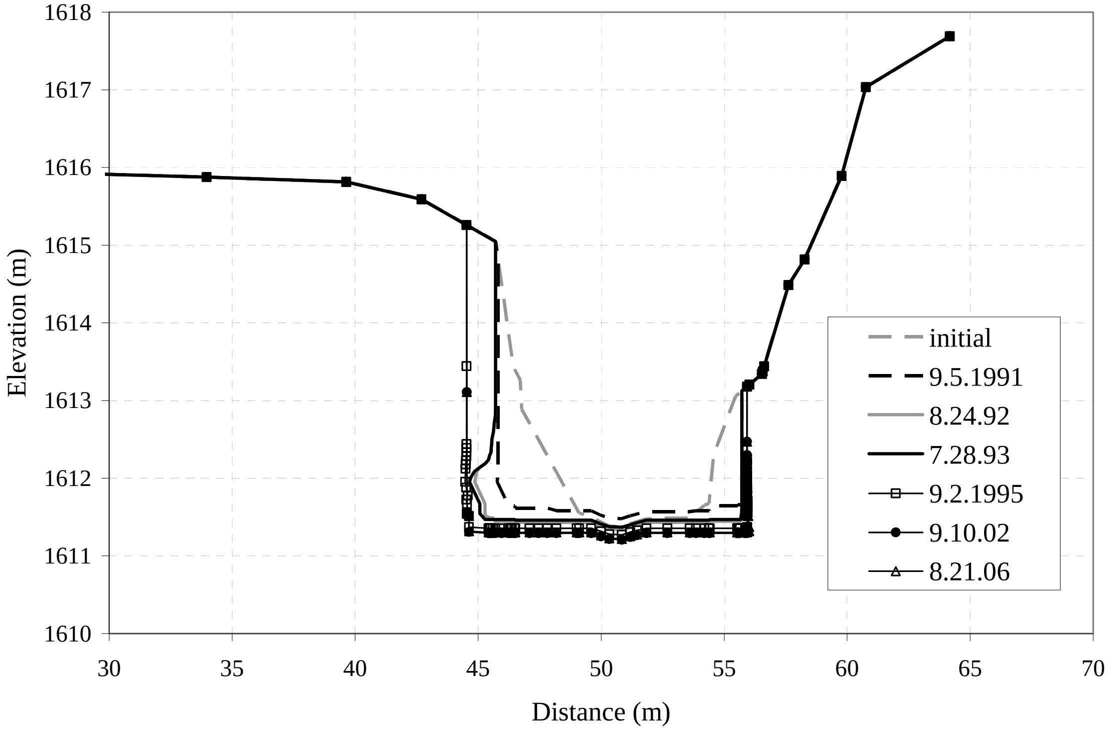

1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)
initial
9.5.1991
8.24.92
7.28.93
9.2.95
9.10.02
8.21.06

e.



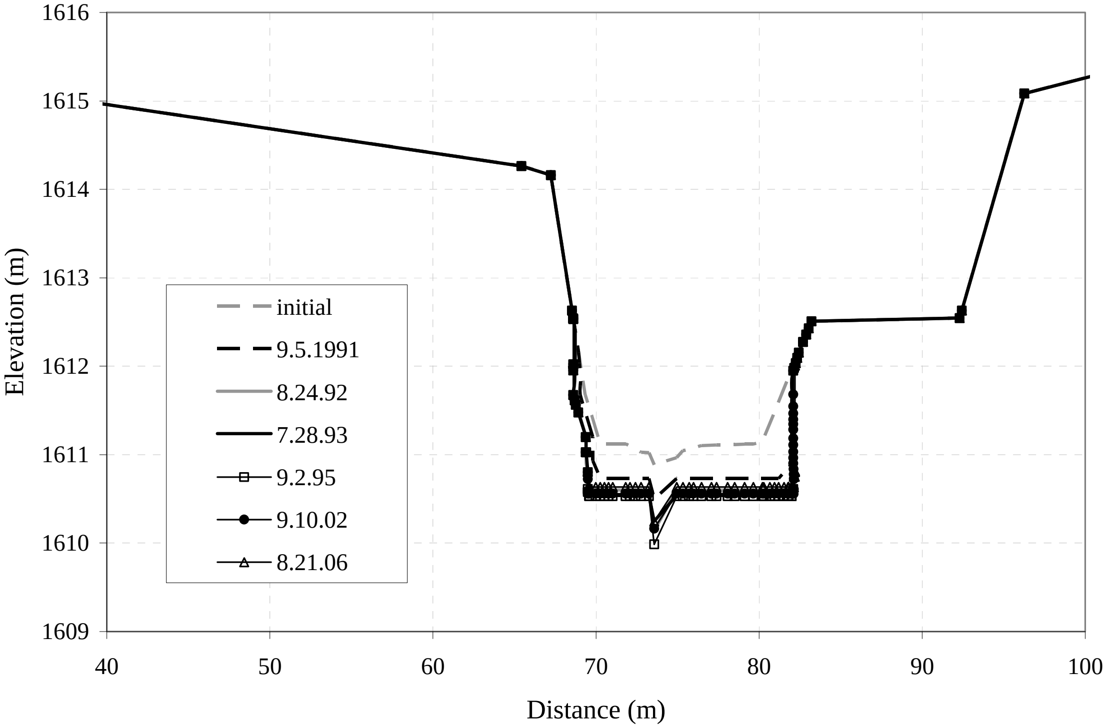
1618
1617
1616
1615
1614
1613
1612
1611
Elevation (m)
20
25
30
35
40
45
50
55
60
65
70
Distance (m)
initial
9.5.1991
8.24.92
7.28.93
9.2.95
9.10.02
8.21.06

f.

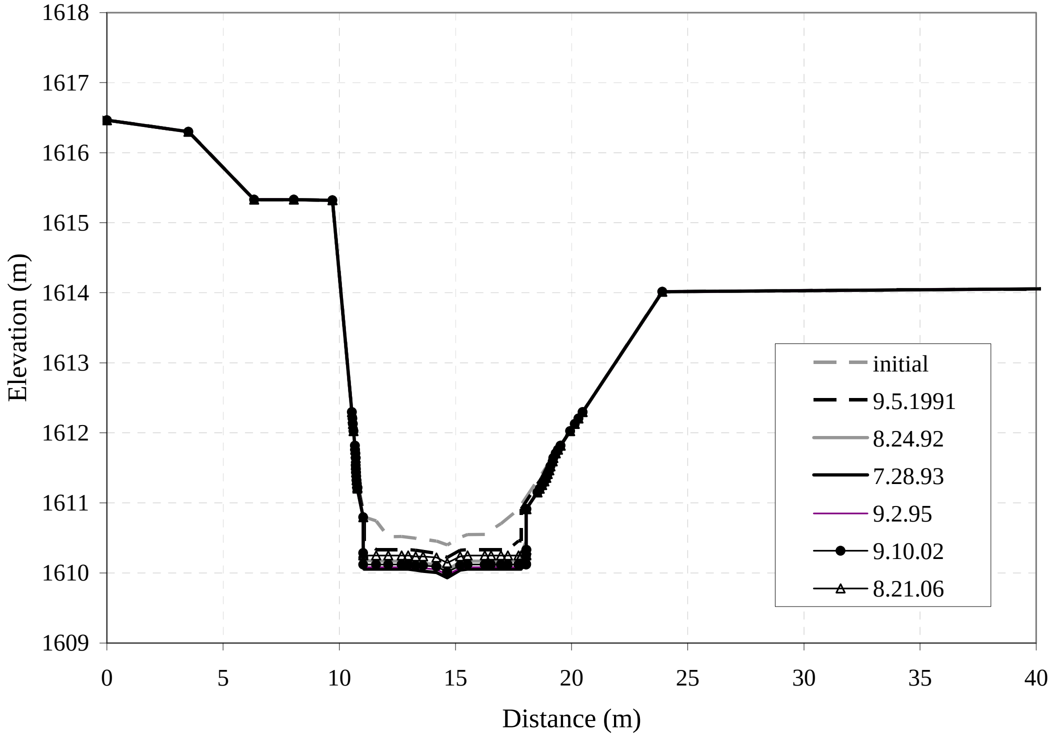


1618
1617
1616
1615
1614
1613
1612
1611
1610
Elevation (m)
30
35
40
45
50
55
60
65
70
Distance (m)
initial
9.5.1991
8.24.92
7.28.93
9.2.1995
9.10.02
8.21.06

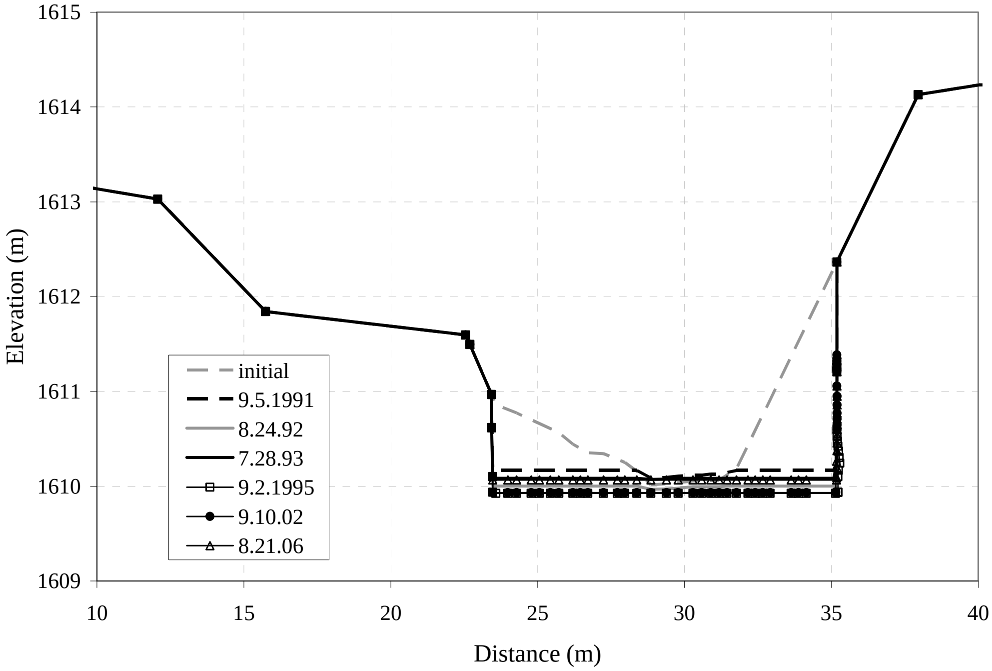
g.


1616
1615
1614
1613
1612
1611
1610
1609
Elevation (m)
40
50
60
70
80
90
100
Distance (m)
initial
9.5.1991
8.24.92
7.28.93
9.2.95
9.10.02
8.21.06

h.


1618
1617
1616
1615
1614
1613
1612
1611
1610
1609
Elevation (m)
0
5
10
15
20
25
30
35
40
Distance (m)
initial
9.5.1991
8.24.92
7.28.93
9.2.95
9.10.02
8.21.06

i.



j.

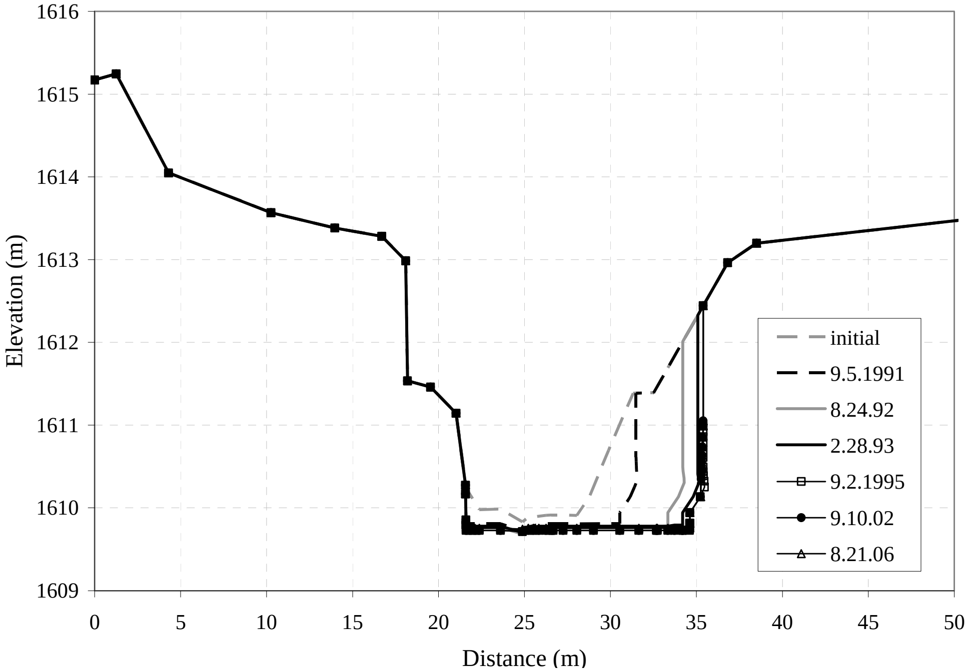


Figure G.1. Cross section geometry after 6 years of simulations in CONCEPTS using the Jemez River, New Mexico as a surrogate discharge. Individual lines in each plot represent the cumulative channel change at each cross section at the end of each water year used in the simulation. a. Control Reach XS 0.0, b.Control Reach XS 1.0., c. Control Reach XS 2.0, d. Cut Stump Reach XS 4.0, e. Cut Stump Reach XS 5.0, f. Cut Stump Reach XS 6.0, g.Whole Plant Reach XS 8.0, h.Whole Plant Reach XS 9.0, i.Whole Plant Reach XS 10.0, j. Whole Plant Reach XS 11.0.

APPENDIX H

Cross section locations in Upper White House for continued monitoring

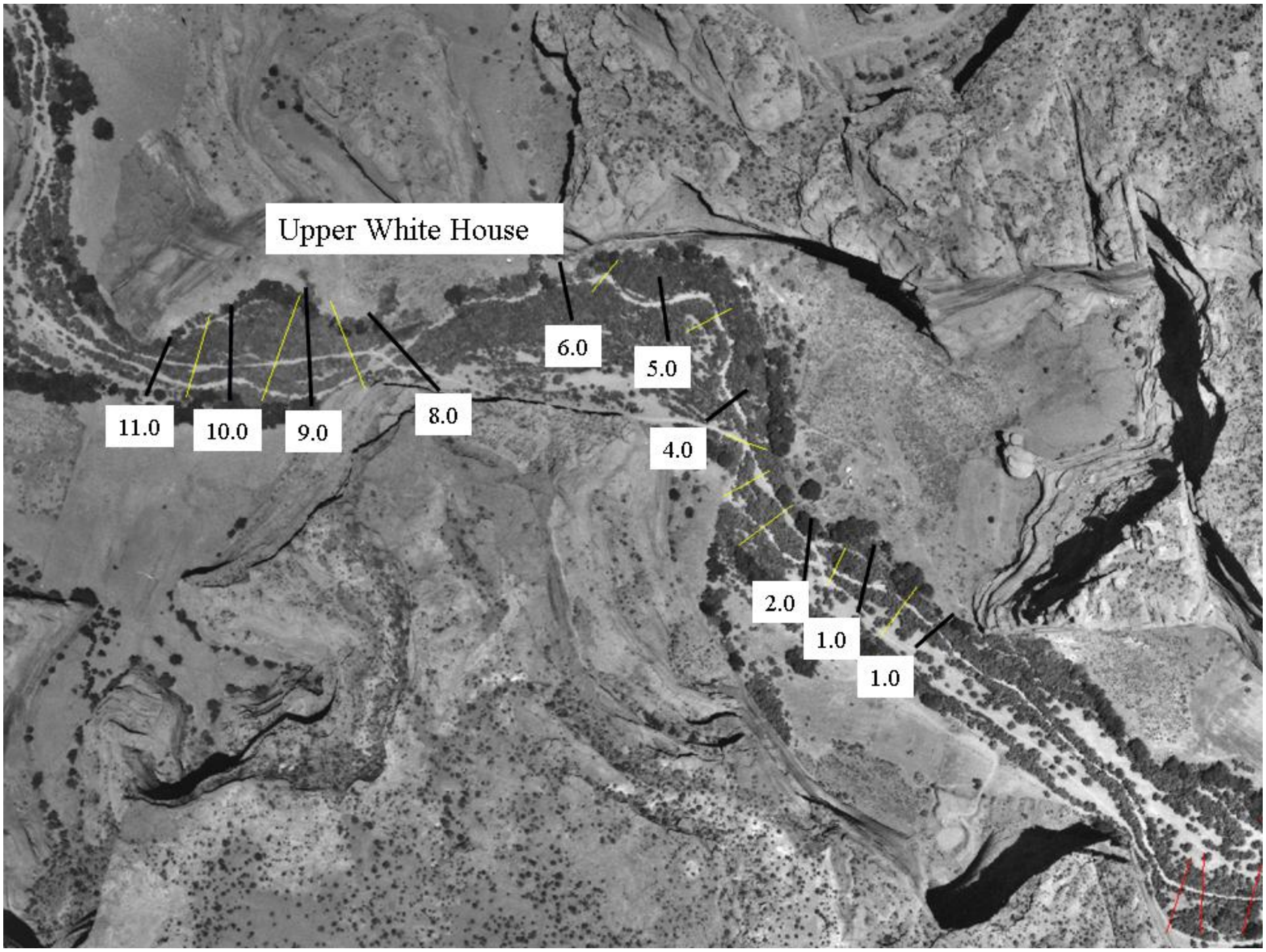


Figure H.1. Aerial view of select cross sections (thick black lines). Cross sections 0, 1, and 2 are the control reach, 4, 5, and 6 are the cut-stump, and 8, 9, 10, and 11 are the whole-plant removal. Selected cross sections are approximately 100 m apart and are every other cross section within the study site. Yellow lines represent non-selected cross sections.

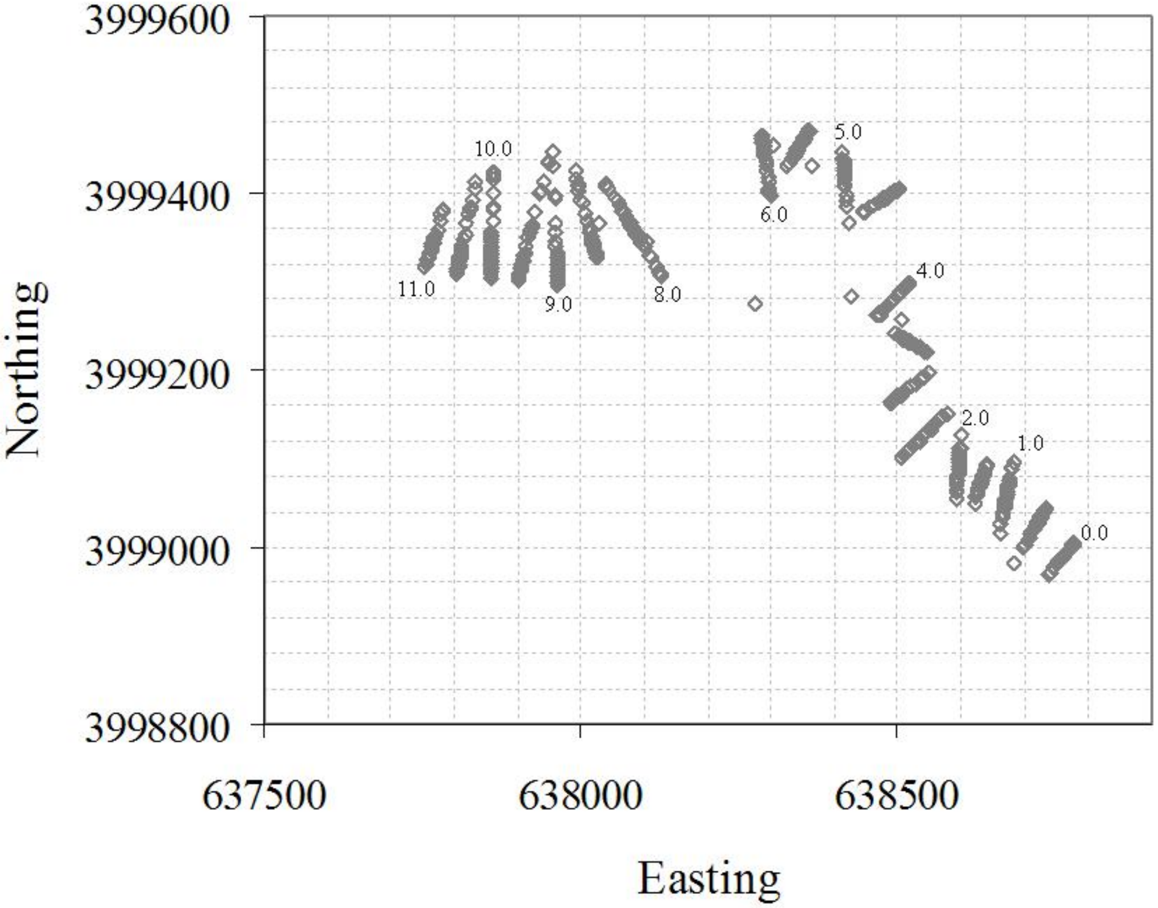


Figure H.2. Universal transverse mercator (UTM) units for select cross sections. Grey circles indicate locations where surface elevation data exist. Selected cross sections are numbered. Non-selected cross sections are not numbered.