7-1-2016

THE INFLUENCE OF BEAVER ACTIVITY ON MODERN AND HOLOCENE FLUVIAL LANDSCAPE DYNAMICS IN SOUTHWESTERN MONTANA

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by

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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy
Earth and Planetary Sciences

The University of New Mexico
Albuquerque, New Mexico

August, 2016

Acknowledgements

This dissertation is my own work, but the only way that I have been able to add my bit of science to the world is with the support of an army of others, so indirectly it is their work too. Many, many thanks to all of you for believing in me and providing your encouragement and support.

Major project funding, and laboratory and field support were provided by The National Science Foundation, The Earth and Planetary Sciences Department at The University of New Mexico, The Geological Society of America, Red Rock Lakes National Wildlife Refuge, The University of Montana Western and The AMS lab and staff at The University of Arizona.

Field assistance and companionship were provided by a great group of willing and cheerful undergraduates who braved the mosquito and willow jungle of the Centennial Valley creeks to help with all of the data collection. Thanks to Felisha Yazzie, Michelle Gauthier, Cory Burkett, Maria Dunleavy, Waheulla Barney and my Hydrology Class at The University of Montana Western. Additional field assistance was provided by US Fish and Wildlife Service volunteers.

I would also like to thank the supportive group of faculty, staff and students that is The University of New Mexico Earth and Planetary Sciences department. Thanks for all the great conversations about science and life and the encouragement that helped me believe that I could finish this dissertation and contribute to the understanding of riparian habitats. Special thanks to Cindy Jaramillo and Paula Pascetti for solving all of my administrative problems and being wonderful people to work with!

With the arrival of Alyce and Landon in May 2015 the finish line for this dissertation looked nearly impossible to reach, but a huge crew of family and friends and neighbors have provided the love, the hours and the care to make sure that the whole family was taken care of and that I was getting time to continue with research and writing. Special thanks to Maureen Levine, Kelsey Levine, Ellen Cutting, Gillian Hadley, Bill and Karen West, and Sue and Dan Levine. In particular, I need to thank Gina Pasini for the hours in the field, companionship and all of her energy for me and the babies!

Writing and research support from my committee Les McFadden, Peter Fawcett and Mark Stone has improved my work and research skills. Tim Levine provided additional support for writing, data management and project management, among many other things! My advisor, Grant Meyer has been a huge support throughout my time at UNM. He has been a companion in discussing field plans and an exceptional editor, always pushing me to do great work and pushing me toward the finish line even when it seemed elusive. He has also been patient and supportive during the last two years that have challenged me personally and professionally. Thanks for believing in me as a scientist and an individual.

Lastly, I want to thank my husband Kyle Cutting for supporting me in my scientific endeavors even while he pursues his own. This past winter while the blizzards swirled around outside, he took time to play with our children, taking precious time from his full time job and his own PhD work to give me the hours to complete mine. Thanks for your companionship in science, parenthood and life. Go team!

Science is indeed a collective effort. Cheers to all of you.

Rebekah Levine
June 2016
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ABSTRACT

Beaver dams effectively trap sediment in stream channels, leading to the hypothesis that persistent beaver damming on millennial timescales causes valley floor aggradation. The available field data, however, are inconclusive. I investigated modern and Holocene beaver-related deposition to understand beaver contributions to fluvial dynamics on multiple timescales in one stream system. Field investigations were conducted on Red Rock and Odell Creeks at Red Rock Lakes National Wildlife Refuge, Centennial Valley, Montana, documenting patterns of sediment storage at 4 stages of beaver damming in the modern channel (1) active; (2) transition from active to breached; (3) breached within the last decade; and (4) undammed. Ground surveys, airborne Lidar, stratigraphic analysis, soil surveys and 64 carbon-14 (^{14}C) ages, were used to investigate beaver impacts from the Early Holocene to present.

Upstream of active dams, fine (≤ 2 mm) sediment storage volumes ranged from 48 – 182 m^3 with additional storage on the floodplain from dam-induced overbank flows.

In-channel persistence of dam-induced sedimentation is limited by frequent breaching (<1 – 5 years). Dam breaching and subsequent downstream transport of willow cuttings from dams and beaver herbivory, however, extend beaver impacts beyond active dam sites, aiding colonization of willow, and adding roughness that promotes additional sedimentation. Major quantities of willow cuttings from beaver herbivory were observed on three streams in southwest Montana. Accumulations of beaver cuttings are also common in Holocene floodplain sediments on Odell Creek, with the majority of beaver-related deposits consistent with beaver-generated willow cutting accumulations on upper point bars and frequent dam breaching. Beaver-pond deposits exist, but rarely. Beaver-related deposition exists through most of the late Holocene when channel activity was dominated by lateral migration. Only ± 2 m of aggradation and incision occurred. The ages of beaver-related deposits overlap the severe droughts of the Medieval Climatic Anomaly, implying persistence of perennial flows in the large, north-facing basins of the studied drainages. Collectively, the modern and Holocene data show that basin attributes play important roles in how beaver influence fluvial systems, and that beaver contribute to both lateral and vertical deposition in the context of larger scale fluvial processes.

Preface

This dissertation investigates the role of beaver dam building activities on stream channel and valley floor morphology by investigating beaver-related deposition and morphological changes on stream systems in southwestern Montana. The dissertation is organized into three chapters, each dealing with a different aspect of beaver effects on fluvial systems and different time scales of inquiry, and written to be three standalone publications.

Chapter 1 builds on work begun as part of my M.S. thesis (Levine, 2011). This chapter adds significantly to my prior work by providing quantitative data about what happens when beaver dams breach and how patterns of sedimentation change in response to dam breaching. The data allowed me to make inferences about the likelihood of preservation for beaver-related deposits in studied stream systems and the likely longevity of beaver induced sediment patches. Findings from Chapter 1 were critical to understanding the beaver-related deposition that I observed in Holocene terrace deposits discussed in Chapter 3. Dr. Grant Meyer and Dr. Lyman Persico made contributions toward the development of my field techniques, but I devised the resulting field strategies. I conducted all of the field work with support from a team of undergraduate field assistants. I wrote the initial draft of the manuscript and my coauthor, Dr. Grant Meyer, provided helpful comments that tightened up interpretations and streamlined the writing for the final published manuscript. Chapter 1 was published in *Geomorphology* in 2014 (Levine and Meyer, 2014).

Chapter 2 is concerned with how beaver materials are incorporated into floodplain sediments. The impetus for this chapter came from observations that accumulations of beaver cuttings were common in the stratigraphy and also common on upper point bars in the modern stream. I developed field methods to document the prevalence of beaver cuttings along modern channels in consultation with Dr. Grant Meyer and biologist, Kyle Cutting. I performed all of the field work done in the Centennial Valley and developed a class project for the hydrology course at The University of Montana Western on the East Fork of Blacktail Deer Creek that contributed additional field data. Dr. Claire Gower at Montana, Fish Wildlife and Parks sponsored the work on the East Fork of Blacktail Deer Creek. I produced the first draft of the manuscript which was refined and improved with comments from my coauthor Dr. Grant Meyer. The manuscript is formatted for submission to *BioScience* in summer of 2016 where it will hopefully be read by an interdisciplinary audience of ecologists, geomorphologists and biologists to enhance understanding of the work beaver do in riparian corridors.

Chapter 3 focuses on beaver-related deposits found in Holocene sediments of Red Rock Creek and Odell Creek, Centennial Valley, Montana. The observations on modern processes in Chapters 1 and 2 are the building blocks for interpretation of the Holocene deposits. I conducted all the field work in Centennial Valley with support from undergraduate field assistants. Discussions in the field with Dr. Grant Meyer and Dr. Ken Pierce were helpful in interpreting fluvial terrace deposits. I prepared all the samples for radiocarbon dating and traveled to the University of Arizona AMS Lab where I worked with Todd Lange and Dr. Timothy Jull to complete the dating process on all but 3 samples that were run for radiocarbon. The remaining 3 samples were run by Beta Analytic Incorporated. I produced the initial draft of the chapter. Dr. Grant Meyer, along with dissertation committee members, provided helpful feedback on my interpretations and drafting of a few key figures. Editorial comments by Dr. Grant Meyer and Dr. Leslie McFadden on a draft of the chapter have been incorporated into the final dissertation, but the majority of the writing and interpretation are my own. A final journal article version of this chapter is in preparation for submission to *Geomorphology, Quaternary Research* or *Earth Surface Processes and Landforms*.

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Chapter 1

Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA

Abstract

Beaver dams in streams are generally considered to increase bed elevation through in-channel sediment storage, thus, reintroductions of beaver are increasingly employed as a restoration tool to repair incised stream channels. Here we consider hydrologic and geomorphic characteristics of the study stream in relation to in-channel sediment storage promoted by beaver dams. We also document the persistence of sediment in the channel following breaching of dams. Nine reaches, containing 46 cross-sections, were investigated on Odell Creek at Red Rock Lakes National Wildlife Refuge, Centennial Valley, Montana. Odell Creek has a snowmelt-dominated hydrograph and peak flows between 2 - 10 m^3s^{-1}. Odell Creek flows down a fluvial fan with a decreasing gradient (0.018–0.004), but is confined between terraces along most of its length, and displays a mostly single-thread, variably sinuous channel. The study reaches represent the overall downstream decrease in gradient and sediment size, and include three stages of beaver damming: (1) active; (2) built and breached in the last decade; and (3) undammed. In-channel sediment characteristics and storage were investigated using pebble counts, fine-sediment depth measurements, sediment mapping and surveys of dam breaches. Upstream of dams, deposition of fine ($\leq$ 2 mm) sediment is promoted by reduced water surface slope, shear stress and velocity, with volumes ranging from 48 – 182 m^3. High flows, however, can readily transport suspended sediment over active dams. Variations in bed-sediment texture and channel morphology associated with active dams create substantial discontinuities in downstream trends and add to overall channel heterogeneity. Observations of abandoned dam sites and dam breaches revealed that most sediment stored above beaver dams is quickly evacuated following a breach. Nonetheless, dam remnants trap some sediment, promote meandering and facilitate floodplain development. Persistence of beaver dam sediment within the main channel on Odell Creek is limited by frequent breaching (<1 – 5 years), so in-channel sediment storage because of damming has not caused measurable channel aggradation over the study period. Enhanced overbank flow by dams, however, likely increases fine-grained floodplain sedimentation and riparian habitat. Contrasts between beaver-damming impacts on Odell Creek and other stream systems of different scales suggest a high sensitivity to hydrologic, geomorphic, and environmental controls, complicating predictions of the longer-term effects of beaver restoration.

Introduction

Fluvial and riparian habitats are hubs of biodiversity and essential habitat at the land-water interface in the semi-arid western United States. Riverine and associated habitats are subject to disturbance by changing river flows (Beever et al., 2005) and because of relatively small area but high ecological significance, are areas of primary concern for land managers. Thus, the interaction between physical and biological components of river systems is an active area of research (e.g., Petts, 2009). Beaver damming is thought to be an effective mechanism for reconnecting incised streams to historic floodplains because of the propensity for sediment to be trapped upstream of dams in the beaver ponds (Beechie et al., 2008). Research on the in-channel dynamics of beaver dams and the effects on sediment transport, however, is limited, and few studies have attempted to quantify the persistence of sediment within the channel, the location of maximum storage, and the caliber of the sediment stored.

Historical accounts indicate that North American beaver (*Castor canadensis*) dams had much greater importance in fluvial systems prior to European colonization and extensive beaver trapping (Pollock et al., 2003; Wohl, 2006). Pre-colonization beaver populations are estimated at between 60 – 400 million (Seton, 1929; Naiman et al., 1988), compared with estimates today of 6 - 12 million (Naiman et al., 1988). Beaver damming has been shown to increase riparian vegetation, raise water levels, attenuate flood peaks and alter sediment transport and storage patterns (e.g., McCullough et al., 2005). Thus, the boggy, flooded landscapes and extensive riparian zones associated with beaver damming are likely reduced at present and represent one of the major human alterations to fluvial landscapes. Like large woody debris (LWD), beaver dams form low-velocity areas, add cover for fish, and increase habitat suitability for certain emergent aquatic insects (Gurnell, 1998; Marcus et al., 2002), linking streams and their adjacent riparian ecosystems (Nakano and Murakami, 2001). LWD and beaver dams are increasingly being looked at as natural alternatives in river restoration projects (e.g., Pollock et al., 2007), and beaver dams tend to more effectively and consistently increase water and sediment storage. Whereas beaver dams interact with the fluvial system to alter rates of geomorphic change (Viles et al., 2008), how much of an effect the dams will have on the system is likely dependent on the unique conditions of a specific river or stream (Lane and Richards, 1997; Persico and Meyer, 2009).

It has been suggested that the cumulative effect of sediment stored upstream of beaver dams increases the elevation of the channel bed (e.g., Pollock et al., 2007). Thus, the large reductions in beaver throughout the United States have been implicated for increased rates of stream incision with the loss of in-channel sediment storage (e.g., Butler and Malanson, 1995; Pollock et al., 2007). In mountain regions of the western United States and elsewhere, fluvial incision from loss of beaver damming has been hypothesized as a major cause of the loss of wet meadow habitat and a decline in the areal extent of riparian zones (Marston, 1994). Along with extirpation of beaver, incision in the mountain West has also been attributed to grazing and agricultural land use (e.g., Wohl, 2006), as well as shifts in climate and forest fire impacts (e.g., Meyer et al., 1995; Miller et al., 2004). Near our study site, in northern Yellowstone National Park, Wyoming, riparian habitat degradation has been specifically associated with the loss of beaver (Wolf et al., 2007), although reductions in streamflow from severe droughts are also a major factor in reductions to beaver and riparian areas (Persico and Meyer, 2012).

With beaver loss being one of the suggested reasons for the incision of stream systems, a potential solution is re-introducing beaver and promoting building of beaver dams at sites where the health and extent of riparian zones are limited by stream incision. Beaver have been used in some river and riparian rehabilitation projects that led to successful re-colonization of beaver, local increase in water table elevation and reinvigoration of riparian vegetation (Apple et al., 1984; Albert and Trimble, 2000; Demmer and Beschta, 2008). The success of these projects has been attributed, in part, to accumulation of sediment and a rise in bed level upstream of dams where fine sediment accumulation has been well documented (Pollock et al., 2007). Quantitative observations that clearly demonstrate that beaver dams promote a persistent, long-term change in stream bed level, however, are limited.

Sediment accumulation above dams has been directly measured at a variety of locations throughout North America (e.g., Butler and Malanson, 1995; Pollock et al., 2003; McCullough et al., 2005; Pollock et al., 2007; Green and Westbrook, 2009) revealing a wide range (9 – 6500 m^3) of total volume of sediment stored behind individual dams. Sediment stored upstream of an individual dam may be most strongly related to the persistence of the dam itself (Butler and Malanson, 1995). The longevity of a dam in a given fluvial system may be dependent on hydrologic and geomorphic controls, such as discharge, channel slope and valley width. The physical attributes of the fluvial systems where beaver dams are found and sediment is stored, however, are rarely reported in the literature, and specific reasons for variations in effective sediment storage have not been investigated in much detail. An additional limitation in the current data is the lack of quantitative assessments of sediment volumes that remain following a breach of a beaver dam. Observations of sediment volumes remaining in the channel following a dam breach have primarily been qualitative (Butler and Malanson, 2005), so assessing the longevity and effectiveness of beaver-induced channel sedimentation is difficult given existing data.

To facilitate beaver restoration as a means for restoring riparian habitat, a more diverse and quantitative body of information needs to be obtained that is specifically related to river scale and attributes. The major focus of our study of beaver dams on Odell Creek in southwestern Montana, is to understand some of the basic fluvial hydraulic changes created by beaver damming through comparison of beaver dammed reaches with undammed reaches within the same system. We seek to understand sedimentation patterns related to beaver dams by creating detailed maps of the sizes of bed sediments in the study reaches, and quantifying the sediment stored in the vicinity of beaver dams. An additional question is whether changes in channel morphology and upstream sediment storage persist following the breaching of beaver dams. Dams breached naturally during our study and in the decade preceding our study provide a way to investigate the persistence of change. If beaver damming does generate an increase in bed elevation that persists following a dam breach, then the increase in channel-floodplain connectivity may be a longer-term adjustment and not just related to the base-level and backwater effects of an active beaver dam. An alternate hypothesis, however, is that on larger streams, in particular, sediment storage does not persist once a dam has breached, and that an increase in floodplain connectivity is mainly improved while the dam is present. Although our study primarily focuses on sediment dynamics within the stream channel, additional observations of overbank processes and longer-term geomorphic change caused by beaver dams are also considered. We interpret our findings on Odell Creek in relation to previously studied streams affected by beaver dams.

Study Area

Odell Creek is located in the Centennial Valley in southwestern Montana, about 50 miles west of Yellowstone National Park (Figure 1-1). The Centennial Valley is an east-west trending, normal-faulted basin that holds the large, shallow lakes of the Red Rock Lakes National Wildlife Refuge (RRLNWR). The active normal fault creates dramatic relief, with the Centennial Mountains rising about 1000 m above the valley floor. The headwaters of Odell Creek lie in these mountains, which are composed of diverse rock types, including Miocene volcanic rocks, and thick limestone units within the Cambrian to Cretaceous sedimentary rock sequence. The springs and streams of the upper basin

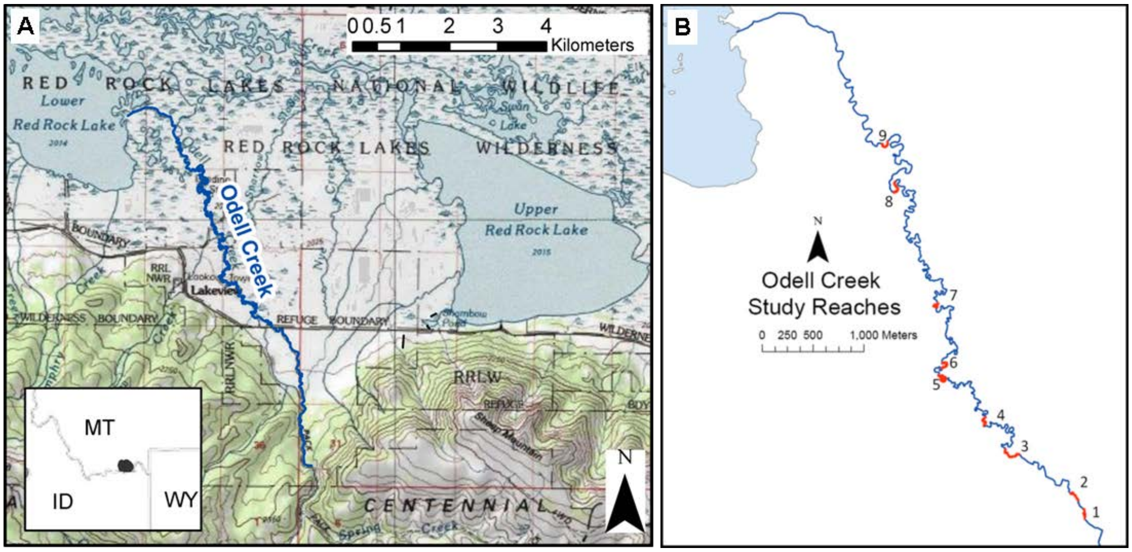

Figure 1-1. (A) Odell Creek shown within Centennial Valley. Note the Odell Creek fan between the two lakes. Inset shows study area location within Montana in bold. (B) Study reaches on Odell Creek highlighted and labeled with reach number. Reach 1 is 3.3 km from the fan apex and represents the most upstream site.

join to form the main trunk of Odell Creek in Odell Canyon. The reaches within the canyon can primarily be classified as plane-bed reaches (Montgomery and Buffington, 1997) and no beaver activity was noted in this area of the basin during our study. At the mouth of the canyon, where Odell Creek flows out onto the valley floor at ~2060 m elevation above sea level, the drainage basin area is ~45 km^2. The valley bottom section of the creek flows over a low-gradient fluvial fan of late Pleistocene-Holocene age (K.L. Pierce, personal communication, 2009). The channel does not have a distributary pattern at present. It is mostly incised within the fan surface and is confined by terraces up to several meters above the channel, with a well-developed inset modern floodplain of about 30 to 400 m width. Channel gradients range from ~0.018 at the fan head, to ~0.007 in the middle reaches and ~0.004 on the lowest reaches above where the creek flows into Lower Red Rock Lake. Thus, the main effect of the fan environment and downstream base-level control is the rapidly decreasing gradient downstream, which allows a variety of fluvial environments to be investigated with relatively constant discharge. Odell Creek displays pool-riffle morphology with a sinuosity of 1.2 in the uppermost study reaches; 2.6 through the middle reaches, where most beaver activity was observed; and 2.3 in lower reaches, declining to a nearly straight channel in the kilometer upstream of the lake. Despite the fan environment, the confined valley created by Holocene incision and moderate to low channel gradients make the site comparable to other streams where the geomorphic effects of beaver have been studied (Table 1).

Centennial Valley experiences the majority of its precipitation in winter and spring, with May and June producing the highest precipitation amounts (Western Regional Climate Center, http://www.wrcc.dri.edu, 2011). Annual mean precipitation is 550 mm. Average temperatures in mid-winter are -10°C and in mid-summer are 13°C (www.wcc.nrcs.usda.gov/nwcc/site?sitenum=568&state=mt, 2011). The local climate produces a snowmelt-dominated hydrograph on Odell Creek, with high flows in late spring and early summer that taper off to low base flows in August - October. From 1993-1998 the US Geological Survey (USGS) maintained a stream gauge on Odell Creek (USGS gauge 06008000) just above the fan head. Peak discharges during that period ranged from 2.2 m^3s^{-1} – 9.9 m^3s^{-1}, with base flows ranging from 0.2 m^3s^{-1} – 0.3 m^3s^{-1} (http://nwis.waterdata.usgs.gov/nwis/inventory/?site_no=06008000&agency_cd=USGS&).

The middle portion of the creek (4.5 -12 km channel distance from fan apex) has the highest sinuosity, the greatest willow density and the majority of the present beaver activity. Overall, willow of several different species (*Salix spp.*; O'Reilly, 2006) form the dominant woody riparian vegetation on Odell Creek, and provide the primary food and building material for beaver. Willow co-exists with another woody species only at the fan head, where cottonwood (*Populus spp.*) have been used by beaver. Odell Creek and its associated riparian zone provide important habitat for migratory birds, moose, deer, elk, river otter, and less frequently grizzly bears and wolves (USFWS, 2009). The aquatic habitat of Odell Creek is also a stronghold for the native Westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) and the southernmost endemic population of Arctic grayling (*Thymallus arcticus*). The Centennial Valley Arctic grayling population is a candidate species under the endangered species act and the Westslope cutthroat trout is a species of conservation concern in the state of Montana. The health of the fluvial and riparian systems in this remote valley are of crucial conservation importance to local land managers (USFWS, 2009; Korb, 2008).

Table 1. Odell Creek reach data

Reach	Reach Type	Period of damming	Downstream Distance (m)	Valley Width (m)	Mean Reach Slope	Sinuosity	No. of cross-sections
1	undammed	-	0	131	0.0123	1.2	3
2	abandoned dam	~ 2004 - 2006	184	292	0.0073	1.2	6
3	active dam	2008 - 2011	1268	408	0.0048	2.3	8
4	undammed	-	2501	292	0.0027	2.3	5
5	active dam	2009 - 2011	3837	339	0.0018	2.7	6
6	abandoned dam	~ 2002 - 2004	4171	189	0.0016	2.7	5
7	undammed	-	5635	254	0.0012	2.6	5
8	abandoned dam	~ 2006 - 2007	8848	236	0.0007	3.1	6
9	undammed	-	10460	33	0.0004	2.5	4

Methods

We designated nine study reaches on Odell Creek between the fan apex and Lower Red Rock Lake (Figure 1-1 and Table 1). Reaches were selected to represent downstream variation in channel parameters, and also to represent the effects of beaver damming on channel morphology and the persistence of beaver induced changes. Reaches were categorized as (1) undammed (no evidence of beaver damming during the period of air photos or during initial surveying); (2) active (dam sites active at the beginning of the study in 2009); or (3) beaver abandoned (dam sites abandoned ≤ 10 years ago). Sites that were previously occupied by beaver were identified in air photos from RRLNWR archives dating back to 1955 and Google Earth Time Series images. Structures spanning the width of the channel were considered intact dams. Field observations along with aerial imagery were used to bracket the period of beaver occupancy at a specific site. All nine reaches were surveyed in 2009 and 2010. In 2011, high flows from spring run-off breached all of the previously surveyed active dams, so active reaches (3 and 5) were resurveyed for all metrics to assess change, along with adjacent reaches without previously active dams (4 and 6).

Within each reach, cross-sections were delineated perpendicular to flow with distances between cross-sections determined by pool-riffle spacing and representing all morphologic types in the reach (e.g., pool, riffle, run). To capture channel adjustments caused by damming, cross-sections were also placed 1- 4 m above and below each active and abandoned dam site. Cross-sections were surveyed with a total station. Cross-sections in Reaches 3, 4, 5 and 6 were all resurveyed to assess change following snowmelt flooding and breaching of active dam sites. The 2010 bankfull waterline was chosen as the horizontal baseline for comparing change between pre- and post-breach cross-sectional areas.

To quantify the effects of the dams on water surface slope, and thus flow competence, water surface profiles were surveyed along the channel edge in each reach. Water surface surveying was conducted 16 July – 20 July 2009 (pre-breach) and 23 June – 29 June 2011 (post-breach). Where necessary, reaches were divided into sections delineated by significant channel obstructions, such as large woody debris, active beaver dams or abandoned beaver dam remnants. Profiles of the bed surface through the center of the channel were surveyed to assess adjustments of the bed slope from damming in all reaches and subsequent change caused by dam breaching in Reaches 3,4, 5 and 6. Water surface and bed profile surveying was conducted using a total station.

Dam dimensions were measured in active dam and beaver abandoned reaches. Length was measured using a meter tape while a stadia rod and level were used to measure the upstream and downstream dam face heights at 1 m intervals along the length of the dam. In reaches with breached dams or dams that breached during the study, dams were measured again to examine the disintegration of the structures.

Detailed mapping of bed surface sediments was done at low flow in 2009 and 2010 to evaluate the ability of dams to trap sediment and to assess the overall competence of each study reach. A second round of mapping the bed surface sediments was completed in all reaches following the high snowmelt flows and dam breaching in 2011. The maps of bed sediments were digitized in a GIS to calculate the percentage of channel bottom covered by a given sediment texture. Sediment mapping was based on the dominant sediment size class of the bed surface. Additional sediment texture and stream competence data were gleaned from measurements of b-axes of ≥ 100 pebbles (Wolman, 1954) in grids spanning 2 m upstream and downstream of cross- section sites. All sediment < 2 mm in diameter (≤ coarse sand) was classified as fine sediment. Pebble counts were done a second time in Reaches 3, 4 and 5 following dam breaching in 2011.

To assess the influence of dams on the volume of accumulated sediment, measurements of the depth and aerial extent of sediments were made in areas where significant amounts of fine sediment covered the channel bottom. Not surprisingly, channels upstream of active beaver dams featured the largest accumulations of fine sediment and were the most intensively investigated. Reaches containing abandoned dams also had significant patches of fine sediment. Upstream of active dam sites, the depth of accumulated fine sediment was surveyed at 2 m intervals. If the sediment patch extended > 50 m upstream of the dam, depth measurement continued every 4 m. At each measurement interval, a narrow fencing shovel was pushed through the fine sediment (predominantly sand and finer) until coarser bed material was encountered. Measurements were made in the middle of the channel with test measurements made 1 m to the left and right to assess mean depth of fine sediments. Surveying continued upstream until no visible layer of fines covered the coarser bed material. Total volume of fine sediment at a location was estimated using the average end-area method (Choi, 2004). The measured mean depth of sediment was applied to the nearest measured channel cross-section to calculate the approximate area of channel fill at each measurement interval. The volume of fine sediment was then calculated from the average of the areas of the two ends of a measurement interval multiplied by the distance between them. The volumes of the intervals were summed to yield the total volume of fine sediment stored in the channel. Overbank sedimentation was not accounted for in these calculations. At sites where fine sediment was not continuous across the channel, mostly adjacent and downstream of breached beaver dams, the area of the sediment patch was measured and transects across the patches with measurements at 1 - 2 m intervals were used to estimate the mean depth of sediment. Measurements of area and depth were then used to calculate the volume of sediment for the patch.

In addition to measurements of the volumes of fine sediment storage, coarse sediment storage in the channel above dams was estimated using pre- and post-breach bed and cross-section surveys. To estimate the area change between surveys, the pre- and post-surveys were laid over one another and the area between the two curves was calculated. To compare surveys, which were conducted using break points rather than even intervals, linear interpolation at 0.5 meter spacing was used. Elevation differences in pre- and post-breach bed surveys, in combination with the depth measurements of fine sediment, were used to estimate the volume of the channel fill from fine versus coarse sediment.

Bankfull discharge was estimated as part of an effort to understand sediment mobility at this commonly assumed effective discharge. Detailed field notes of vegetation breaks and geomorphic indicators collected during cross-section surveys were used to estimate bankfull stage. Surveys of high stages in May - June 2010 along with discharge measurements with a flow meter and photos helped to further develop estimates of bankfull stage. In locating bankfull elevation in each cross-section, attempts were made to maintain bankfull reach slopes that were internally consistent within the reach. Final picks for bankfull stage were based on channel morphology, vegetation and consistency of water surface elevations within each reach. Low-flow water elevations were those recorded during cross-section surveys in middle to late summer after peak runoff. Discharges were measured using an electromagnetic flow meter during the low-flow period of our study, and ranged from 0.8 m^3s^{-1} – 1.4 m^3s^{-1}.

Mobility of bed sediment is an important consideration in determining the effect that beaver dams have on sediment storage and transport, compared to undammed and breached dam locations. Cross-section, water surface slope and clast size data were used to calculate channel geometry, bed shear stress and Shields critical shear stress for each cross-section. Bed shear stress is the mean force per unit area exerted by a given flow and is determined by:

$$\tau = \gamma R s$$

where γ is the specific weight of water and is assumed constant, R is hydraulic radius, for wide natural channels approximated by mean depth, and s is slope from section water slopes surveyed in the field. Beaver dams typically increase R and decrease s upstream (Pollock et al., 2007), so their presence should affect bed shear stress and the ability of a stream to entrain sediment. The collected grain size data was used to calculate Shields critical shear stress (τ_c), the bed shear stress required to move a given grain size, in this case the median grain size. τ_c is calculated as:

$$\tau_c = \tau^* (\rho_s - \rho_w) g D_{50}$$

where ρ_s is the density of sediment, ρ_w is the density of water, g is acceleration due to gravity, D_{50} is the median grain size in meters and τ^* is the dimensionless shear stress. For this study a value of 0.045 was chosen for τ^* as reasonable value to predict movement of discrete textural patches along a gravel bed river (Buffington and Montgomery, 1997). Where $\tau > \tau_c$ the given discharge is capable of entraining the median grain size, although substantial uncertainty is associated with such competence estimates (e.g., Buffington and Montgomery, 1997). In calculations of τ_c for Odell Creek, clast measurements were made at low discharge, when the bed material may not be entirely representative of what the stream can transport at higher flows (Lisle et al., 2000).

Results

Physical properties of dams and dam sites

Four active dams were found in the middle reaches of Odell Creek in 2009. The dam heights were similar throughout the study reaches, with upstream face heights ranging from 0.4 – 0.6 m and downstream face heights ranging from 1.4 – 1.7 m (Table 2). All dams in the study were built entirely of willow. Dam lengths were highly variable, including the dam blocking the channel and extensions to some dams built across the floodplain. The longest active dam was R3D1 which was 36.0 m in 2011. The shortest active dam, R5D2 at 9.7 m, was built across the main channel only.

Table 2. Dam and dam breach data

Dam Name	Reach	Distance downstream (m)	Channel Width at Dam Site (m)	Upstream Extent of Backwater Area (m)	Breach Year	Breach Style	Intact Dam Face Ht (m)	Dam Top Width (m)	2010 Dam remnant length (m)	2011 Dam remnant Length (m)	Minimum % of stream width affected
R3D1	3	1306	10.7	25	2011	Full Breach	1	1	-	3	28%
R3D2	3	1376	7.4	23	2011	Full Breach	1	-	-	4	54%
R5D1	5	3847	14.4	88	2011	Partial Mid-channel breach	0.9	1.7	-	8	56%
R5D2	5	3903	9.7	40	2010	Partial side breach	0.9	1.9	7.3	4.7	48%
R6D1	6	4205	12.8	-	2004	Partial side breach	-	-	7	6.8	53%
R8D1	8	8862	10.7	-	2007	Partial side breach	-	-	7.8	-	73%

In-channel hydraulic effects of active beaver damming

The primary hydraulic effect of beaver damming within the channel is reduction of the water surface slope, which reduces velocity and increases bankfull width (Figure 1-2). The water slope discontinuity is more pronounced at sites higher on the fan, where ambient slopes are generally steeper. Backwater effects, however, are greater in areas with lower ambient slopes. The backwater effects of damming at the uppermost dam extended 40.0 m upstream in Reach 3 and to at least 117.0 m upstream in Reach 5. At sites downstream of beaver dams, water surface slopes are consistent with the downfan trend of progressively lower slopes with increasing distance from the fan head (Figure 1-2). All of the active dams were part of a series of closely spaced dams. The mean slope of the water surface between two dams in a series is affected by the backwater of the lower dam and the spillway of the upper dam, so that the slope is slightly lower than the downstream trend, but higher than upstream of the first dam in the series.

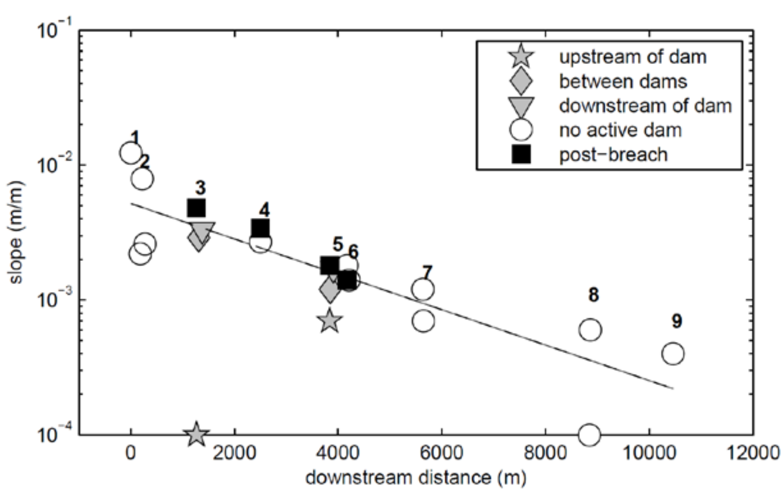

Figure 1-2. Log-normal plot of water surface slope as a function of downstream distance from head of Reach 1 on Odell Creek. Reaches are identified by number above associated points. Reaches were broken into sections at significant channel obstructions (e.g., cross-channel wood and dams). The exponential curve fit includes section water surface slopes in undammed and abandoned dam reaches and does not include reaches where dams breached in 2011. Black squares are water slopes surveyed following dam breaching in 2011.

Stream velocities reflect the slope changes promoted by beaver damming. Velocities were measured on 22 May 2010 at an undammed site between Reaches 2 and 3 as well as sites ~ 2 m above and below the second active dam in Reach 3. The undammed site and the site downstream of the dam maintained similar mean velocities, but mean velocity at the site upstream of the dam was about 50% of the velocities recorded at the other locations (Figure 1-3).

The presence of beaver dams increases wetted width at most discharges by ponding water upstream of the dam. At dammed sites, the maximum estimated wetted width, corresponding to bankfull stage at undammed cross-sections, was 106.5 m in Reach 3, compared to a maximum undammed bankfull width on Odell Creek of 20.0 m. The uppermost beaver dam in Reach 3, R3D1, was most effective at increasing wetted width. The backwater effects of the dam combined with floodplain geometry forced ~50% of the flow to leave the main channel above the dam in May discharge measurements. The diverted water flowed over the floodplain through a dense willow community. The overbank flow was observed depositing some sediment around vegetation and in low velocity ponded areas, whereas in other areas, the flow was actively eroding overbank sediment and carving shallow channels into the floodplain surface. The diverted flow rejoined the main channel with a measurable loss in discharge, presumably from infiltration into the floodplain surface (Figure 1-3). At other dam sites, the effects on wetted width and creation of cutoffs because of damming were less pronounced as a result of differences in channel and floodplain morphology.

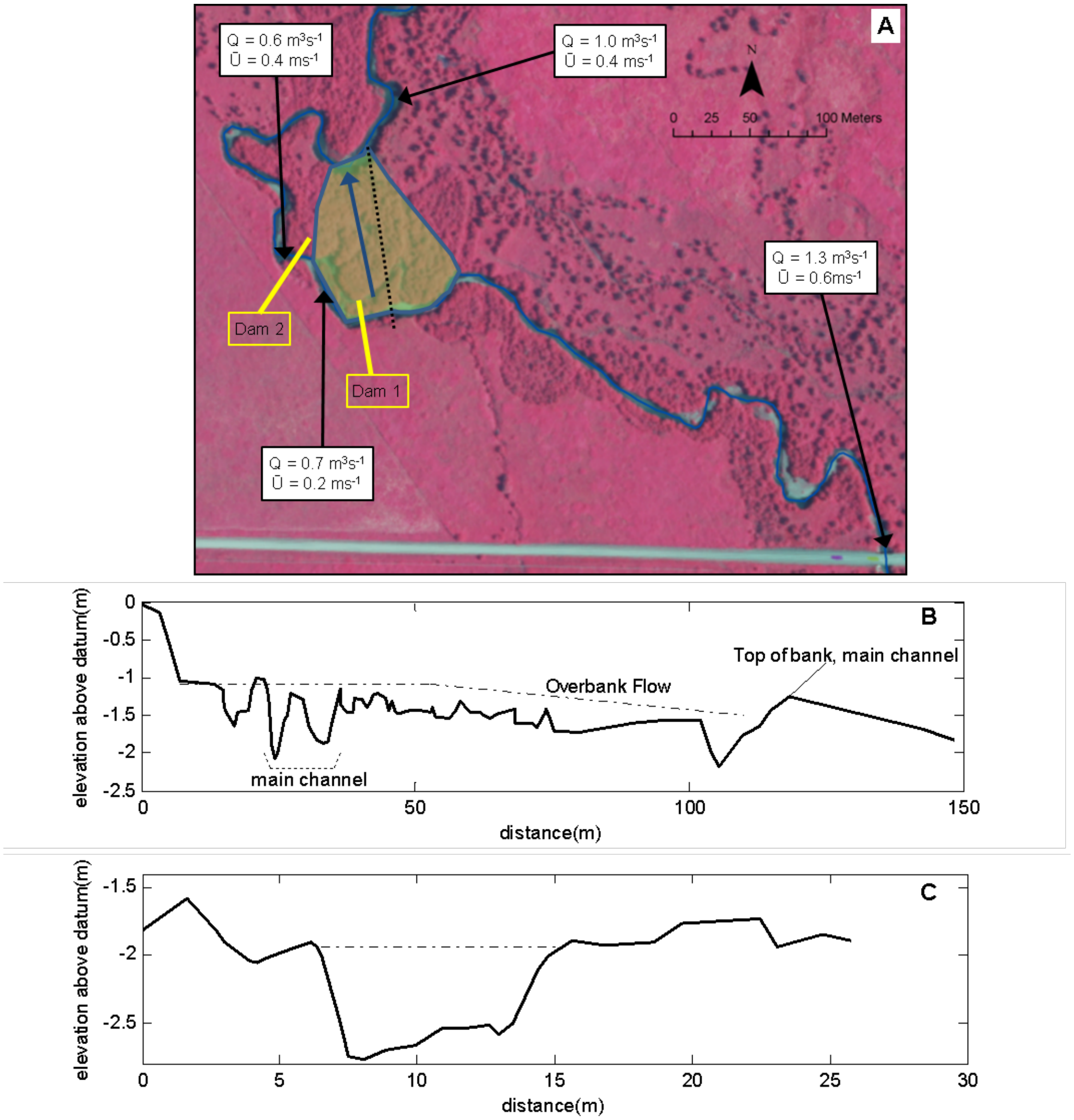

Figure 1-3. (A) Discharge and mean velocity measurements on 22 May 2010 to investigate the effect of Dam 1 in Reach 3 (R3D1) on overbank flow. Black arrows indicate measurement sites with recorded discharge and velocity measurements. Main channel flow is from lower right to upper left. The shaded polygon shows the approximate area affected by overbank flow, with flow direction over the floodplain noted. The dotted line shows the location of cross-section 3-1 above dam 1. (B) Cross-section 3-1 looking downstream. (C) Cross-section 5-1, just upstream of dam R5D1, showing a more confined channel morphology compared to (B), with less extensive overbank flow (note different scale). Elevations for cross-sections are above an arbitrary datum; dashed line is estimated bankfull flow.

The effectiveness of dams to flood surrounding areas is related to bank height and confinement of the dammed reach within terraces or valley walls. For example, cross-section 3-1 (Figure 1-3-B) has lower confining stream banks than cross-section 5-1

(Figure 1-3-C), so higher stream flows more easily inundate the floodplain and increase wetted width. At cross-section 3-1 water was continuous across the floodplain surface on river right, upstream of the dam site, where confinement by stream banks is limited. The flow creates a meander chute, with erosion and deposition occurring on the floodplain, eventually rejoining the main channel to the right of the pictured cross-section. At cross-section 5-1, wetted width is limited even at bankfull stage by the right bank, which continues to rise beyond the end of the cross-section shown. The mean width/depth (w/d) ratios at bankfull (bf) and low flows (lf) further demonstrate the different geometries of the two reaches, where mean w/d_{bf} are 155 and 35 for Reaches 3 (n = 8) and 5 (n = 6) respectively and where w/d_{lf} are 129 and 21. Although R5D1 is less effective at increasing wetted width compared to other sites, however, overbank flow is still augmented by the existence of the dam, increasing the variability in cross-sectional bankfull widths represented within a reach compared to nearby undammed sites. The mean standard deviation in bankfull width for active dam reaches is 26.2 m, whereas the mean standard deviation for undammed reaches is 3.06 m.

Channel response to hydraulic changes

Sediment storage at beaver dam sites occurs in response to changes in hydraulic parameters. Width and depth increase, whereas slope and velocity decrease. Slope is the variable that exerts the most control over τ, so relatively small changes in slope can have a large effect on stream competence. At sites upstream of beaver dams, τ_{bf} values are equivalent to values in low gradient reaches farthest downstream (Reaches 7,8 & 9) where low τ_{bf} values are expected. Mean τ_{bf} for cross-sections upstream of beaver dams is 1.3 N/m^2 which is similar to the mean τ_{bf} in Reaches 8 and 9 and less than shear stress values elsewhere on Odell Creek. The τ_c upstream of all beaver dams on Odell Creek is approximately 0.4 N/m^2. τ_{bf} just downstream of the last dam in a series is the greatest in the reach, with observed scour at these locations. Average τ_{bf} for dammed reaches, however, is lower than undammed reaches. Reaches 3 and 5, with active dams, have mean τ_{bf} values of 8.5 and 8.3 N/m^2, respectively, whereas the τ_{bf} for Reach 4 (between the two dammed reaches) is 15.0 N/m^2.

The reduced stream competence at cross-sections upstream of beaver dams creates abrupt discontinuities in the otherwise strong downstream fining trend observed on Odell Creek (Figure 1-4). The median grain size (D_{50}) at cross-sections upstream of dams is < 1 mm (sand or silt). Whereas Reach 3 with two dams exhibits reduced grain size, Reach 2 (950 m upstream) has a reach-averaged D_{50} of 23 mm. Reach 4, 1110 m downstream of Reach 3, also has a reach averaged D_{50} of 23 mm. The discontinuity in sediment deposition is further evidenced by the total area affected by each dam. Fine sediment covers most of the channel bed surface, extends at least 20 – 30 m upstream, and may extend > 100 m upstream (Figure 1-5). Therefore, as shown by the maps of surface sediments, dammed reaches disrupt the downstream trend of increasing fine sediment on the channel bed surface with increasing distance downstream (Figure 1-4). The r^2 value for the downstream trend for undammed reaches is 0.98, but including all reaches, r^2 is reduced to 0.53 because of greater variability in bed surface sediments in dammed reaches.

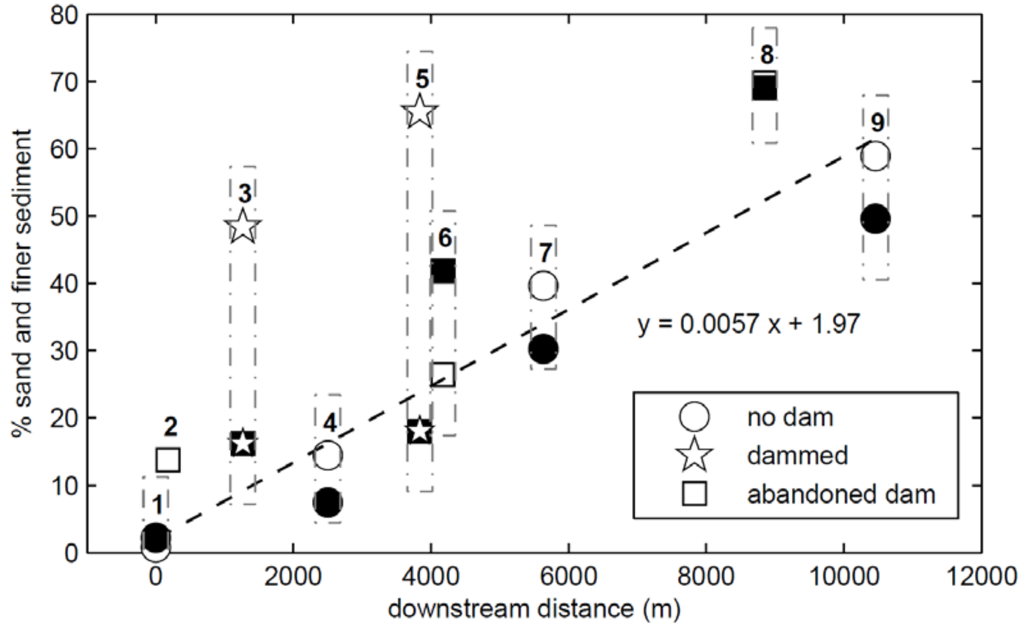

Figure 1-4. Percent sand and finer sediment in each reach from pre-breach (white) and post-breach (black) bed sediment maps. Stars surrounded by black squares show post-breach values for previously dammed sites. Reaches are identified by number, and a dotted-line box is drawn around the data points associated with each reach to compare pre- and post- breach conditions. The best fit line (r^2 = 0.98) highlights the strong downstream trend based on the 4 undammed reaches from the pre-breach period.

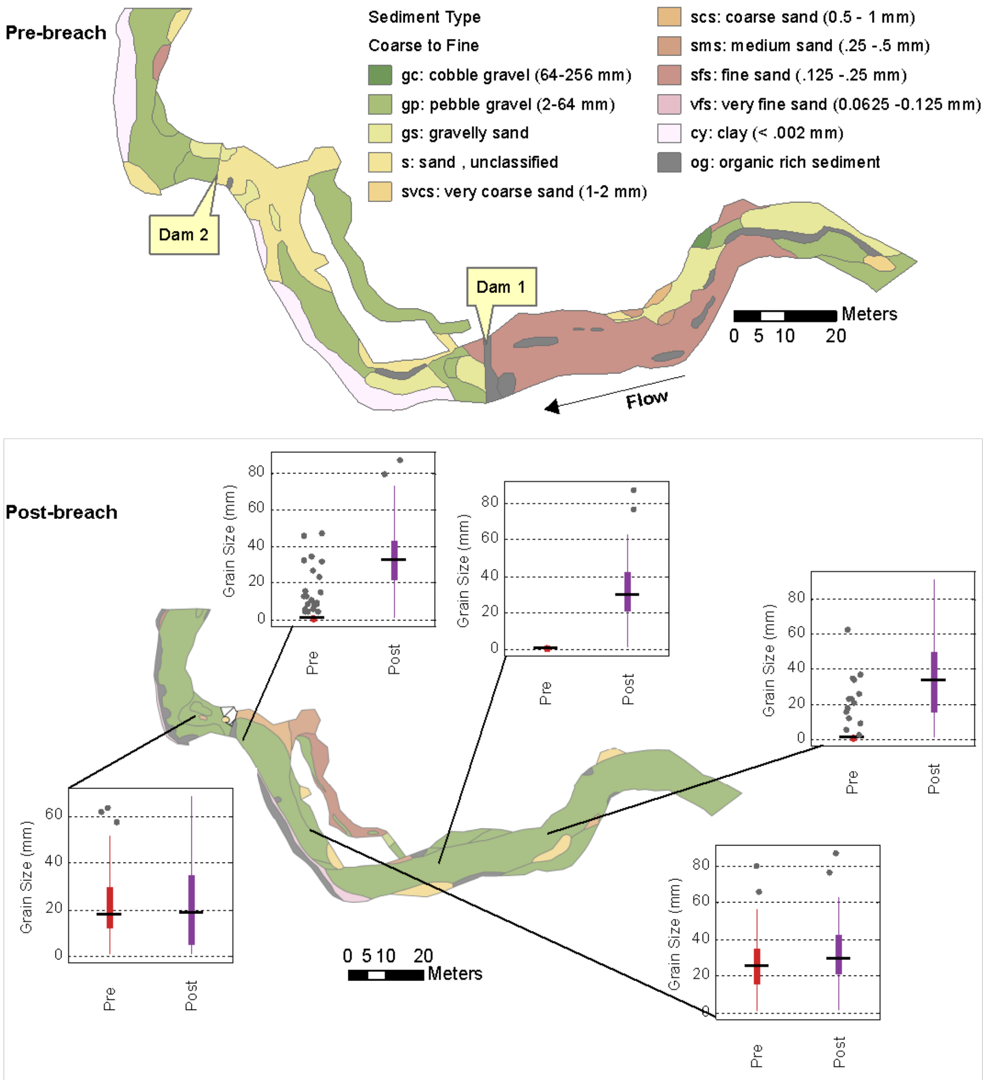

Figure 1-5. Surface texture maps for pre- and post-breach bed sediment for Reach 3; colors show grain size categories. The post-breach map shows pre-breach (left plot) and post-breach (right plot) box plots of grain size distributions at cross-sections. For each box, the median value is shown by the horizontal line; the top of the box is the upper quartile (q_3) and the bottom of the box is the lower quartile (q_1); whiskers are $q_3 + 1.5(q_3 - q_1)$ and $q_1 - 1.5(q_3 - q_1)$, approximately equivalent to $\pm 2.7\sigma$. Outliers are points outside this range and are plotted as gray dots.

Estimates of sediment volumes upstream of dams on Odell Creek range from 48 to 182 m^3; the bulk of the volume is from fine sediment (Figure 1-6). Total channel filling from active dams is 370 m^3. Although beaver dams are effective at trapping sediment, trapping efficiency for small reservoirs tends to be highest during low-discharge conditions when flows cannot fully overtop the dam (Merritts et al., 2011), such as in late summer on Odell Creek. During high snowmelt runoff discharges, fine sediment was observed in transport over dams. Estimates of bankfull bed shear stresses corroborate these observations. At the 4 sites upstream of dams, our estimates of τ_{bf} are greater than τ_c and suggest that transport of the D_{50}, in this case sand and finer sediment, is occurring during Q_{bf}. Sediment transport is also predicted downstream of dams where shear stress is elevated, particularly during high flows. Highly elevated shear stresses below the last dam in both reaches were reflected in reach maximum D_{50} values. Scour holes below the dams also formed in response to elevated bed shear stress.

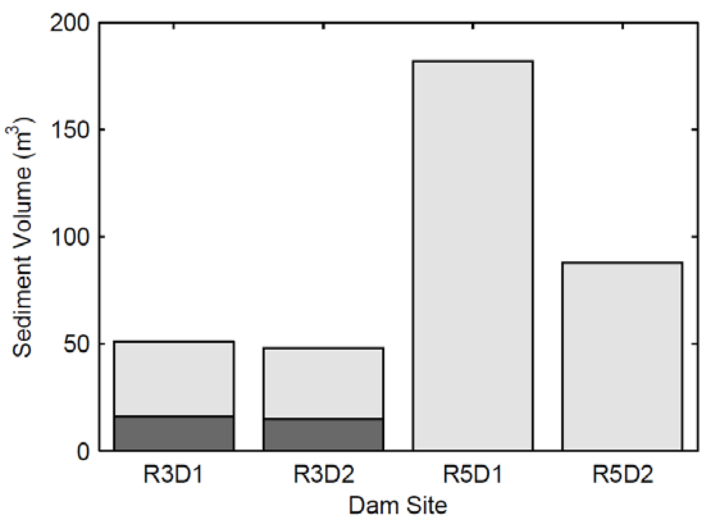

Figure 1-6. Estimates of the volumes of sediment stored in the channel upstream of active beaver dams. Results are shown in downstream order with the most upstream site, Reach 3 dam 1 (R3D1), furthest left. The dark shading shows coarse sediment contribution to channel fill (> 2 mm) while the light shading shows contributing volume from sand and finer sediment (≤ 2 mm).

Breaching of beaver dams and the immediate aftermath

Two breaching events occurred during our study. The first occurred in June 2010, breaching the second dam in Reach 5, R5D2 (Table 2). The highest flow we observed during that period was ~4 m^3s^{-1} on June 6, which is ~ 40% of the maximum peak discharge recorded by the USGS gauge (1993-1998) on Odell Creek and was produced by a combination of rain and snowmelt. The second breaching event occurred in June of

2011 and was responsible for breaching all three of the remaining dams in the study area. Estimated peak discharge for the event is 7 m^3s^{-1} based on direct flow measurements and comparison with the nearby Red Rock Creek USGS gauge (#06006000). The two breaching events presented an opportunity to observe the effects of dam failure on channel processes and sediment storage.

We observed three different styles of dam breaching: (1) full breaches where the entire in-channel portion of the dam was removed leaving only small dam remnants near the bank; (2) partial breaches where the dam was breached in mid-channel, leaving substantial parts of the dam intact on either side of the channel; and (3) partial side breaches where the dam is entirely removed on one side of the channel, while a large part remains intact on the opposing bank. Partial side breaching was most common on Odell Creek (Table 2). Partial side breaches appear to be associated with bank erosion, with 0.3 m of bank retreat measured at dam R5D2 where flags marking stage height had been placed prior to the dam breach. Similar patterns of bank erosion and dam breaching were also observed at R8D1 and R6D1.

Following the dam breaches, flooded width narrowed by 90% in Reach 3 upstream of R3D1, from an average width of 103.0 m down to 11.0 m. Changes were less pronounced in Reach 5, where upstream of R5D1 width narrowed by 20% from a dammed width of 40.2 m to an undammed width of 8.3 m. The rapid decrease in width left behind fine sediment that had accumulated outside of the bankfull channel from beaver ponding. Repeat cross-section surveys showed that during the period of damming, floodplain elevation increased, and fine sediment was observed burying floodplain willows (Figure 1-8). Willow burial depth corresponded with surveyed elevation increases recorded in repeat cross-section surveys.

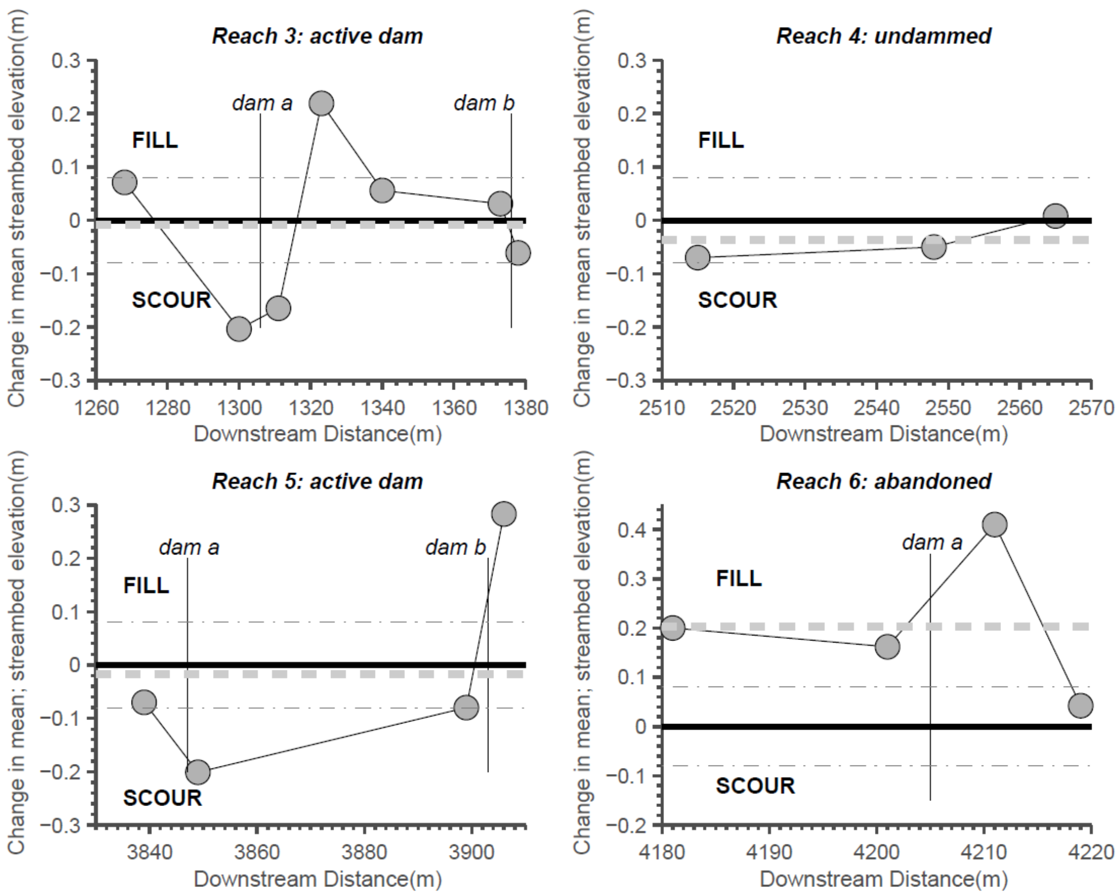

Figure 1-7. Change in mean elevation of the streambed between repeat cross-section surveys in 2010 (pre-breach) and 2011 (post-breach). Reaches 3 and 5 contained dams in 2010 that were breached in 2011. Thick dotted line shows mean change in bed elevation for all cross-sections in the reach, and thin dash-dot lines show the range of measurement error, above and below which scour and fill are considered to be significant.

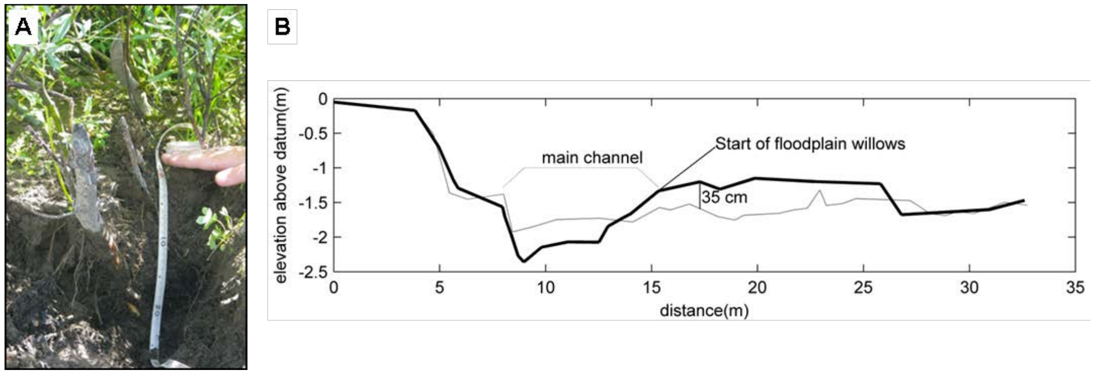

Figure 1-8. (A) Photo showing at least 25 cm of sediment burying the base of live willows, about 4 meters from the main channel along cross-section 3-2 in Reach 3. (B) Pre-breach (thin line) and post-breach (thick line) survey data for cross-section 3-2 showing widespread sediment accumulation of >20 cm depth across the floodplain surface. Note the increase in main channel depth in the post-breach cross-section survey.

Dam breaching quickly readjusts the channel slope to pre-dam conditions. Water surface slopes measured in July and early August 2011, 1 – 1.5 months after dam breaching, show a tight fit with Odell Creek downstream trends (Figure 1-2). The slope adjustment has clear effects on sediment movement as bed shear stress increases with increasing slope. Upstream of R3D1 the calculated τ_{bf} was 0.5 N/m^2 prior to breaching, whereas following the breach, shear stress increased to 23.0 N/m^2, capable of moving 32 mm pebble gravel. The increase in bed shear stress at breached dam sites is clearly reflected in pebble count data (Figure 1-5). Median grain size in all dammed reaches was ≤ 1 mm while dams were intact, but following breaching, median grain size for the same sites increased to 23 mm (n = 400 pebbles). Median grain size for all other cross-sections not directly upstream of dam sites changed from an average of 25 mm in 2010 to 19 mm in 2011, perhaps in part reflecting redistribution of fine sediment released from breached dams.

Remapping of bed surface sediment showed that most of the fine-grained in-channel sediment upstream of dam sites was removed following dam breaching (Figure 1-5). Within reaches where dams breached in 2010 and 2011, the percent of the bed surface covered by the ≤ 2 mm size fraction was reduced to levels consistent with the downstream fining trend on Odell Creek (Figure 1-4). The r^2 value for the trend line fitting all reaches increased to 0.77 after dam breaching, from 0.53 with dams intact. Although the majority of fine sediment is removed from sites upstream of dams, not all of the mobilized sediment is immediately evacuated out of the reach. Resurveys of post-breach cross-sections show that scour and bed lowering occur upstream of dams, whereas localized channel filling occurs immediately downstream of breached dam sites (Figure 1-7). Bed lowering upstream of breached dams appears to be compensated by deposition downstream, so that the net bed elevation change in the reach is within the range of survey measurement error. As indicated by sediment mapping, however, the areal coverage of the ≤ 2 mm size fraction is reduced following a dam breach, and the sediment volume retained downstream of the breach is significantly lower than the volume stored upstream of the intact dam. For example, in Reach 5 at R5D2, 75% of the dam was still intact after the breach, creating an eddy just downstream of the dam where some fine sediment evacuated from the former pond was trapped (Table 2). Additional storage space was provided by the scour hole below the former dam face. Prior to breaching, the volume of sediment stored upstream of the dam was 89 m^3; following the breach, storage downstream amounted to 13 m^3, indicating limited and localized retention of in-channel sediment.

Persistence of the effects of beaver dams

Direct observations of the effects of dam breaches aided in interpreting channel conditions in the older abandoned dam reaches (Table 2). On Odell Creek, beaver dams are maintained ≤1-5 years based on field observations and analysis of airphotos.

Although dams are active for a relatively short period, at all abandoned sites some effects of damming persisted at least a year; some may persist much longer. Breach style appears to play an important role in the longevity of dam effects, with partial breaches most commonly observed and apparently most effective at preserving dam effects. Partial side breaches, particularly where bank collapse occurred during breaching as observed at R5D2, cause flow to be forced around the outside end of the dam, creating eddies on the upstream and downstream sides of the preserved dam remnant. Sediment begins accumulating in both areas as the redirected flow effectively preserves the remaining portion of the dam, initiating a meander bend with the dam on the inside. In Reach 6, dam R6D1 breached in 2004, yet approximately half (6 m) of the in-channel length of the dam was maintained through 2011. Resurveys between 2009 and 2011 show that the cross-sections directly upstream and downstream of the dam remnant experienced net filling (Figure 1-7). In Reach 8, where the dam was breached in 2007 (Table 2), 73% of the original dam length still remained intact in August 2010. A volume of 3 m^3 of sediment was measured in storage upstream of the dam remnant, while 30 m^3 were stored downstream. Reaches 6 and 8 show elevated percentage of $\leq$ 2 mm sediment fraction compared to the downstream trend (Figure 1-4). Both reaches also display narrowing and deepening directly adjacent to the dam remnant in response to confinement by the dam remnant and associated stored sediment.

Despite dam-breaching and loss of much in-channel storage, some sediment storage may persist on the floodplain (Figure 1-8). In Reach 2, where dams were abandoned in 2006, a deposit formed by overbank flow forced by beaver damming was measured ~ 4 m beyond the edge of the active channel with a maximum fine sediment thickness of 0.43

m. Young willows were observed sprouting from an abandoned floodplain dam buried in these fine-grained deposits.

Discussion

Active dam sites – short term effects

Although Odell Creek displays clear trends of decreasing slope and bed sediment size downstream, discontinuities in slope created by active beaver dams promotes temporary storage of fine-grained material at locations much farther upstream than these trends would indicate. For intact dams, bed elevation increases upstream, with significant volumes of sediment stored (Figure 1-6). The elevated water surface and increased floodplain-channel connections can persist for the lifetime of the dam, which was ≤ 1 – 5 years over the study period.

Studies of beaver dams show that wide variability exists in the volumes of sediment retained in beaver ponds (Table 3). Dam sites on lower-gradient reaches of Odell Creek trapped the largest volumes of fine sediment. The backwater effect for dams depends on the ratio of dam height to river gradient (Csiki and Rhoads, 2010). The heights of beaver dams on Odell Creek are quite similar to each other (Table 2), so water surface slope has the greatest control on variability in the extent of backwater areas. With backwater areas increasing in length as slopes decrease down the system, greater areas for sediment accumulation are created. Also, dams built in series can affect trapping efficiency and sediment availability to downstream dams within the same reach. Dam R5D1 had the largest sediment volume; R5D2, the second dam in this series a short distance downstream, breached one year earlier than R5D1, so had less time to accumulate material. In addition, the first dam built (usually the uppermost dam near the beaver lodge) often has the greatest longevity (Howard and Larson, 1985; Naiman et al., 1988), increasing the total volume of sediment stored upstream of that dam (Merritts et al., 2011).

Even when a dam remains intact, a steady rate of sediment accumulation cannot be assumed. Although not observed directly on Odell Creek, leaky dams may allow some fine sediment to be transported at any discharge. More significantly, during periods of high flow, fine suspended sediment was observed in transport over dams on Odell Creek. Higher flows decrease the backwater area of a dam and increase the potential for sediment transport (Csiki and Rhoads, 2010). Calculations of bed shear stress for bankfull flows show that that $\tau_{bf} > \tau_c$ upstream of dams, indicating that removal of some fine material is likely at bankfull discharge. Variability in sediment volumes stored upstream of beaver dams on Odell Creek is consistent with that documented above low weirs and run-of-river dams, which create reservoirs with small storage capacity and do not alter the overall flow regime (Stanley and Doyle, 2002). The ability of run-of-river dams to slow river flow is dependent on water stage, thus, discharge variability is a strong control on the efficiency of trapping sediment (Csiki and Rhoads, 2010).

Table 3. Beaver stream study comparison table

Author	River/Stream	State/Province	Mean Slope (m/m)	Mean Valley Width (m)	Basin Area (km^2)	Mean Peak Q (m^3/s)	Mean Dam Longevity (yrs)	Mean Sediment Volume/Dam (m^3)
Woo and Wadington (1990)	Ekwan Point	ON, Canada	0.0009	-	9	0.022		-
Polvi and Wohl (2012)	Beaver Brook	CO, USA	0.005	188	15	-	-	-
Leidholt and Bruner (1992)	Cummins Ck	OR, USA	0.03	30	21	0.28^		-
Jakes et al. (2007)	Upper Three Runs Ck, Lower Three Runs Ck, Meyers Branch, Fourmile Branch, Pen Branch, Steel Ck	SC, USA	0.009	209	30	-	-	-
Levine and Meyer - This Paper	**Odell Creek**	**MT, USA**	**0.0042**	**241**	**45**	**6.05**	**3.5**	**92**
Green and Westbrook (2009)	Sandown Ck	BC, Canada	0.01	75	72	2.65	11.3	35
Polvi and Wohl (2012)	Big Thompson River	CO, USA	0.015	1000	103	-		-
Westbrook et al. (2010)	Colorado River	CO, USA	0.005	12	138	14.7	6.5	750
Demmer and Beschta (2008)	Bridge Creek	OR, USA	0.02	-	603	-	2	-
Pollock et al. (2007)	Bridge Creek	OR, USA	-	-	710	28	3	-
Beier and Barrett (1987)	Tuckee River and Tributaries	CA, USA	0.0116	33	-	-	-	-
Suzuki and McComb (1998)	Drift Creek Basin	OR, USA	0.022	33	-	-	-	-
John and Klein (2004)	Jossa	Central Germany	0.0057	-	-	11.5	3	222
Hay (2010)	North Platte River	CO, USA	0.045	82	-	-	-	-

^ represents low flow Q

Dam breaching – 5 to 10 year effects

Active beaver dams on Odell Creek were associated with elevated channel beds, but our data show that the rise is temporary (Figure 1-7), with pre-dam slope conditions returning quickly after dam breaching (Figure 1-2). The majority of the fine sediment is quickly moved out of the former beaver pond, the bed experiences scouring, and particle size returns to a state more consistent with the overall downstream trend. Sediment removal from sites upstream of a dam can be accompanied by adjustments in downstream bed morphology, with filling of scour pools below dams (Figure 1-7). Similar observations of fine sediment decline and pool shallowing were made by Lisle (1995) in a study of woody debris removal near Mount St. Helens, Washington. The sediment deposited upstream of beaver dams on Odell Creek is primarily sand sized. Sand is readily mobilized compared to finer, more cohesive sediment and more massive, coarser particles (e.g., Knighton, 1998). Similar rapid removal of fine sediment stored upstream of mill dams and run-of-river dams following breaching has also been reported (Csiki and Rhoads, 2010). Immediately following a breach, a small knickpoint quickly propagates upstream (Merritts et al., 2011). On Odell Creek, the sediment that does remain within a reach after dam breaching is primarily related to the degree of preservation of dam remnants (Table 2). Similarly, for large woody debris in channels < 50 m wide, effective trapping of sediment is accomplished by debris with an in-channel length and depth greater than half of bankfull width and depth (Abbe and Montgomery, 2003). Like woody debris jams, high flows may completely remove beaver dams; for example, on Bridge Creek, Oregon (peak $Q \leq 28\ m^3s^{-1}$), 19% of beaver dams in 17 years suffered total washout, primarily during high discharge periods (Demmer and Beschta, 2008). In Reach 3 where total dam removal occurred (Table 2), sediment storage may be short-lived compared to reaches where ≥ 50% of dam remnants persist, such as at R6D1 where some sediment accumulation is still occurring seven years after dam breaching. The persistence of the sediment stored near dam remnants is limited by the longevity of the dam remnant. Observations at Dam R5D2 show that these remnants can be slowly removed over time (Table 2), but at some locations the breached dam initiates a forced meander, where sediment accumulating around the remnant creates a new point bar preserved inside the bend (Figure 1-9). Willow stems, used by beaver in dam construction, often begin to sprout and grow roots, further strengthening the dam remnant, so that sediment at the dam site may be preserved for long periods as the meander evolves and the channel migrates away from the dam site.

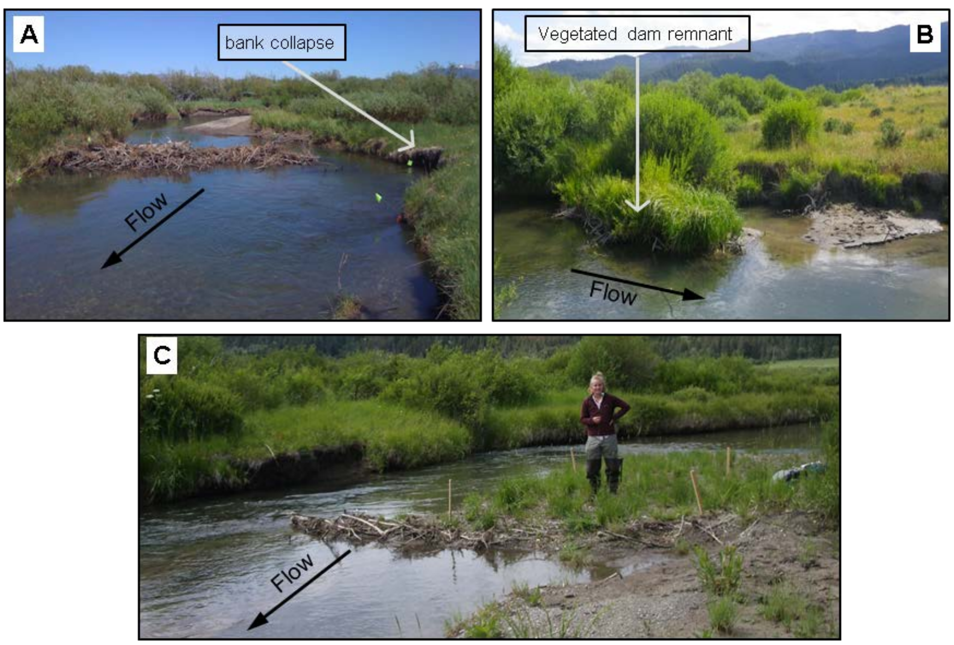

Figure 1-9. (A) Partial side breach of beaver dam at R5D2. The photo was taken soon after the breach occurred and shows flow being redirected around the breached dam end. (B) Breached dam of unknown age between Reaches 7 and 8 on Odell Creek (not in a study reach). Dam remnant is stabilized by willow growth. The site is in a relatively straight reach except where the dam remnant is forcing the creek to meander. Note sediment filling the channel downstream. (C) R6D1, breached in 2006, was still protruding across most of the channel in 2009. The person is standing on sediment deposited in the eddy upstream. The eddy downstream is also clearly visible Persistence of beaver dam impacts – multi-decadal

The observation that beaver dams influence channel form shows that although much sediment storage within the main channel may be short-lived, beaver dams can still induce longer-term adjustments to channel form and process. In addition to promoting meander development, beaver dams may also promote channel avulsions and meander cutoffs through facilitating overbank flow. In Reach 3, 50% of the flow was diverted from the main channel across the floodplain (Figure 1-3). While the dam was intact, we observed concentrated flow eroding new shallow channels across the floodplain. This beaver dam-induced overbank erosion may promote local avulsions where the channel is relatively unconfined (Field, 2001). Although cutoff and avulsion did not occur, the intact dam created a broad, complex riparian area. In the steeper Reach 2, however, a multi-thread channel pattern related to beaver damming was observed. Although the beaver dams breached in 2007, channels previously carved into the floodplain by beaver dam-forced overbank flow have remained active, becoming conduits for floodwater and sites of continued floodplain erosion. In 2011, the main channel in Reach 2 was abandoned by progressive avulsion into the overbank flow channels created during beaver occupancy. These observations support the inference that beaver damming increases channel complexity (e.g., Polvi and Wohl 2012) and can influence the frequency of avulsions and cutoffs on meandering streams.

In addition to localized floodplain erosion, the increase in bankfull width with damming promotes fine-grained sediment deposition on the floodplain after breaching (Figure 1-8), which can be retained at least several years following the breach as observed in Reach 2 (Section 4.5). Deposition occurred in the flooded parts of Reaches 3 and 5, in areas of slower, deeper flow and in dense vegetation, which increases roughness

(Osterkamp and Hupp, 2010). Along streams with high peak flows and frequent dam breaching, such overbank deposition may be the primary floodplain constructional process related to beaver damming, rather than in-channel aggradation. For example, on the relatively high-discharge Upper Colorado River (mean snowmelt discharge 14.7 m^3s^{-1}), Westbrook et al. (2010) found that beaver dams promote overbank flow and storage of sediment on the floodplain rather than within the main channel. They measured 750 m^3 of such "beaver flood" deposits on a terrace 0.7 – 1.2 m above the active floodplain, and estimated that it would take a 200-year flood to inundate the terrace, but that beaver damming allowed deposition there at average flows. Willow and aspen seedlings quickly established at the site and utilized groundwater to survive several years after the dam breach.

Similar to observations on Odell Creek, bank erosion focused near one end of a breached dam was reported for 61 of 161 beaver dam failures at Bridge Creek, Oregon (Demmer and Beschta, 2008). Localized channel widening as a result of flow deflection has also been observed in many woody debris studies in forested regions (e.g., Montgomery et al., 2003). Although Odell Creek is not forested and large woody debris is scarce within our study reaches, it does exhibit high width variability within beaver-dammed reaches, where mean standard deviation in bankfull width is 26.2 m. Variable width may provide additional slow-water habitat for fish fry rearing in Odell Creek (Levine, 2007). Greater habitat heterogeneity is likely provided by dam remnants and related variations in boundary shear stress that are large relative to channel size (Lisle et al., 2000).

Cumulative effects of beaver damming

Persistent elevation of the channel bed has not been documented at beaver dam sites along Odell Creek, as dam breaching results in removal of most stored sediment. The total volume of sediment stored by dams was only 370 m^3, and at least with current Odell Creek beaver populations, the total area of the channel bed that is affected by dams is relatively small. Nonetheless, it may be that with greater beaver populations and episodic occupation along most of the study stream length, that some aggradation or at least slowing of the long-term downcutting trend is possible.

Preliminary investigation of terraces along Odell Creek reveal that they are of Holocene age, as indicated by the presence of ~7630 cal yr BP Mazama ash (Zdanowicz et al., 1999) in a 2.5 m high terrace deposit, and show that net Holocene channel change on the fan has been incision of several meters. It appears that although beaver may store sediment locally along the stream system, other factors forcing net Holocene downcutting have dominated along Odell Creek. In contrast to the development of beaver meadows by the accumulation of stacked in-channel beaver-pond deposits (Ives, 1942; Polvi and Wohl, 2012), the dominant process of beaver-related floodplain development along Odell Creek appears to be overbank sedimentation forced by active beaver damming. This is consistent with the relatively thick, fine-grained floodplain deposits exposed in most cutbanks in the modern floodplain and Holocene terraces, which commonly contain beaver-cut willow stems, but rarely show sedimentary structures indicative of ponded water. Development of beaver meadows is also limited by the relatively high-gradient, gravelly channels of the upper Odell fan. Beaver select sites that are most favorable to dam construction and food availability, so that not all sections of a stream are equally affected by beaver damming (Gurnell, 1998). For example, only 29% of the small-stream network in northern Yellowstone National Park showed evidence for beaver-related aggradation, where locations suitable for damming are limited by stream power (Persico and Meyer, 2009).

Sediment dynamics and stream scale

The results of our study indicate that while fine overbank sediment storage and channel heterogeneity are enhanced by beaver damming, persistent net channel aggradation is unlikely to be promoted on Odell Creek. Some projections of the amount of aggradation that beavers are able to accomplish require beaver occupation at a single site on the order of several decades (Pollock et al., 2007; Beechie et al., 2008), or require that little sediment is removed following a dam breach (Butler and Malanson, 2005), neither of which is likely on Odell Creek. The contrasting effects of beaver damming in different stream systems indicates that the particular characteristics of a system are critically important to consider in projections of the effects of beaver damming. A preliminary look at beaver-fluvial study data, including drainage basin characteristics, supports this contention (Table 3). Beaver-occupied streams can be roughly divided into three scale classes: small, medium and large stream classes with contributing basin area and slope being important variables. Small-scale streams, with drainage basin < 30 km^2 and relatively low slopes, allow for the greatest longevity for beaver dams, and are locations where complete pond filling within the main channel may often occur and be preserved. Odell Creek falls within the moderate size classification with dam longevity of $\leq 1 - 5$ years and a basin area < 100 km^2. The large class represents the upper limit of where beaver damming is possible, where basin areas are > 100 km^2 (Table 2). We hypothesize that in-channel sediment storage is very limited in such streams, at least along main active channels, although beaver may still influence smaller side channels and floodplain spring creeks fed by hyporheic flow. Overall, small streams have greater dam longevity and potential for pond-sediment preservation.

Breach frequency is often related to basin size, but other factors can contribute as well. The breaching frequency of dams on Odell Creek is generally consistent with other studies reporting breach data. McCullough et al. (2005) observed dams regularly being damaged by ~2-year storms in eastern Nebraska. Many of these dams were later repaired, but beaver usually wait until periods of lower flow to repair breached dams and it is uncommon for dams to be immediately rebuilt (Demmer and Beschta, 2008), so sediment removal is likely in the interim. Leidholt-Bruner et al. (1992) also noted that most dams in their coastal Oregon study failed during heavy spring runoff. On the Bill Williams River, Arizona, dams were breached at flows as low as 5 m^3s^{-1}, whereas some remained intact at flows approaching 65 m^3s^{-1}, but all dams were destroyed at 189 m^3s^{-1} (Andersen and Shafroth, 2010). On Bridge Creek in Oregon, 75% of dams in the 17-year study lasted $\leq$ 2 yrs, with some remaining as long as 7 years (Demmer and Beschta, 2008). The wide variation in dam longevity likely results from differences in both magnitude and duration of floods (Costa and O'Connor, 1995 ; Andersen and Shafroth, 2010), as well as reflecting differences in basin size and characteristics, channel geometry, and dam construction. Where dam breaching occurs regularly, it is unlikely that net channel filling is occurring. A 17-year study of 161 dams shows limited support for long term channel filling with only 14 dams (9%) filling completely with sediment

(Demmer and Beschta, 2008). In each case, the stream eventually either cut through the center or around the end of these dams.

Building materials available for dam construction can also contribute to variations in the frequency of dam breaches. Dam failures are more common in areas where willow or other small diameter woody vegetation is used in dam construction as opposed to larger trees (Beedle, 1991). Where building material may limit beaver dam longevity, some land managers have added stabilizing materials, such as posts or tires (Apple et al., 1984; Bouwes et al., 2009). Although artificially reinforced dams that remain in place for longer periods may increase aggradation and help repair incised streams, it is possible that these local, semi-permanent dams may have unintended consequences, analogous to the 2 – 5 m high mill dams that have impacted many streams in the eastern United States (Walter and Merritts, 2008; Merritts et al., 2011). Eventual failure of mill dams led to incised channels with steep, highly erosive banks that were again disconnected from the floodplain. In a natural, unreinforced system, where breaching occurs regularly, this rapid return to deeply incised conditions is less likely.

Conclusions

On Odell Creek, active dams decrease water surface slope and promote short-term storage of fine sediment upstream of dams, increasing streambed elevation. At the same time, the channel is scoured downstream of dams during high flows, resulting in the highest D_{50} values in a given reach and a well-developed scour hole. These differences contribute substantially to greater channel and habitat heterogeneity within the study reaches. Total sediment volume stored in beaver ponds on Odell Creek during the study period was relatively small at 370 m^2. The majority of sediment stored upstream of dams was evacuated following dam breaching, which occurred on Odell Creek with a frequency of ≤ 1 -5 years over the study period. Sediment that remains within the channel is stored in small patches above and below preserved dam remnants, and persists until the dam is completely removed. Despite breaching, dam remnants continue to enhance channel heterogeneity and may commonly induce meandering. Beaver dam-enhanced overbank deposition is likely the most important way in which beaver activity aids in floodplain development along Odell Creek.

The potential long-term effects of beaver damming on fluvial systems are strongly affected by overall stream scale, along with the fundamental controlling factors of discharge, slope, bed shear stress, stream power, sediment load and caliber, and vegetation. We suggest that geomorphic, hydrologic, and overall environmental controls must be considered in detail when making system- and reach-specific management plans involving beaver.

Acknowledgements

My co-author, Grant Meyer and I would like to thank the National Science Foundation (grant EAR-0844293 to Meyer), the Earth and Planetary Science Department at the University of New Mexico, the Geological Society of America, Red Rock Lakes National Wildlife Refuge, and The Nature Conservancy of Montana for major project funding and support. Invaluable field assistance was provided by Felisha Yazzie, Michelle Gauthier, Corey Burkett, Maria Dunlavey and Waheulla Barney, with additional assistance from summer volunteers at RRLNWR. Comments by David Gutzler, Gary Weissmann, and two anonymous reviewers helped improve earlier drafts of this manuscript.

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Chapter 2

Beyond the dam: The far-reaching influence of beaver on stream and riparian dynamics

Abstract

Beaver are widely acknowledged as ecosystem engineers, primarily because of their hydrologic impacts and herbivory around dam sites. Our surveys on three streams in southwest Montana show that beaver affect channel processes and riparian plant recruitment well beyond intact dam sites and long after dams have breached. We documented major quantities of willow cuttings from beaver herbivory deposited along channel margins, aiding colonization of fresh deposits by sprouting, and adding roughness that promotes further sediment accumulation. Cuttings can also remain stored in sediments for thousands of years, highlighting the importance of beaver activity in floodplain carbon storage. We view beaver activity as a cycle, from the browsing of riparian plants through dam building, failure, and abandonment, where all parts of the cycle influence fluvial and riparian processes. In stream ecosystems largely predicated on disturbance, riparian plant recruitment and floodplain evolution are enhanced by frequent disturbance associated with the beaver cycle.

Introduction

Beaver have long been recognized for their ability to modify riverine and wetland habitats through constructing dams that alter hydrology, sediment storage, and channel morphology, with many potential benefits to riparian habitats (Levine and Meyer 2014, Pollock et al. 2007, Seton 1929). As riparian ecosystems across the globe have come under increasing stress, research on understanding and restoring natural processes is increasing. A focus on beaver as an important component of fluvial and riparian function has been part of this wave, and attention has centered on herbivory impacts (Johnston and Naiman 1990, Mouw et al. 2013) and the effects of intact dams (Westbrook et al. 2006, Woo and Waddington 1990). In this article we explore how secondary effects of beaver, including plant cuttings from herbivory and dam construction, remnants of breached dams, and associated sediment deposits work in combination with beaver dams and ponds to aid in regeneration of streamside vegetation and promote of diverse habitats in fluvial systems.

Beaver herbivory and dam building have rightly received much attention, but represent only part of the influences of beaver activity in stream systems. Riparian vegetation is dependent on access to shallow groundwater and relatively frequent disturbance by flooding and pulses of sediment, as caused directly by beaver damming. Most riparian plant reproductive strategies require establishment of seeds or other propagules (plant pieces capable of reproduction) on bare, moist sediment (Gurnell 2014). That also means that the riparian ecosystem is dependent on the interchange of water and sediment between the floodplain and the channel. In general, investigations of such fluvial system behavior have focused on physical processes, but biotic factors can play a major role in the development of channel forms and floodplains, particularly in meandering rivers (Murray and Paola 1994). Here we explore the potential that beaver have to affect channel processes and riparian vegetation development throughout the cycle of dam building, failure, and abandonment, including through downstream dispersion of fine woody debris generated in the beaver's abundant use of riparian willow. We present data from Odell Creek, Red Rock Creek and the East Fork of

Blacktail Deer Creek in southwestern Montana, along with observations from other streams in the region, exploring how secondary processes in the cycle of beaver activity enhance the reproductive and colonization potential of riparian vegetation on small streams and promote channel morphologic diversity.

The cycle of beaver activity and riparian plant regeneration

Riparian plants can regenerate through many pathways, including seed, vegetative propagules, and regeneration from the parent plant. These processes can be enhanced by disturbances such as floods, and beaver activity can accelerate disturbance rates.

In this paper we are primarily focused on how beaver impact the regeneration of willow species (*Salix* spp.) as they are the dominant streamside vegetation across our small study streams in southwestern Montana. Willows are a primary successional species and are able to regenerate sexually from seed as well as asexually from plant parts (Karrenberg et al. 2002). Along our streams in southwest Montana we observed both types of reproduction.

Summary of field investigations

As can be commonly observed along alluvial streams in the Rocky Mountain region, beaver-generated willow cuttings abound along the margins of the study area streams (Figure 2-1). Although seed dispersal may be the dominant and critical form of reproduction for riparian plants, sprouting from stem fragments that are cut or broken from the parent plant can also play an important role in riparian plant reproduction, particularly for species that are adapted to floodplain disturbance (Krasny et al. 1988). Our primary question was whether the accumulation of beaver willow cuttings along stream channels produced significant riparian willow regeneration. Our goals were thus to collect field data to (1) assess the dispersal and deposition of beaver cuttings and (2) determine if deposited cuttings led to the development of new plants. In addition, we considered the effects of willow cutting accumulations on sediment deposition. We focused on Odell Creek and collected preliminary data on two other streams, East Fork of Blacktail Deer Creek and Red Rock Creek, at the headwaters of the Missouri river system in southwestern Montana, USA. The study reaches on Odell Creek and Red Rock Creek are located within Red Rock Lakes National Wildlife Refuge and the study reaches on East Fork of Blacktail Deer Creek are located within the Gravelly-Blacktail Wildlife Management Area managed by Montana Fish, Wildlife and Parks. These streams have drainage areas of 83 - 158 km^2 and feature gravel-bed, pool-riffle meandering channels, with broad floodplains over most of the study reaches. All of the study reaches have experienced limited human impact, so provide a valuable reference for studying intact abiotic-biotic interactions. Hydrographs across the region are dominated by snowmelt, with peak flows occurring in May and June. Mean annual discharge on these streams ranges from 1.3 - 1.6 m^3s^{-1} and average maximum annual discharges range from 4.1 - 10.1 m^3s^{-1}.

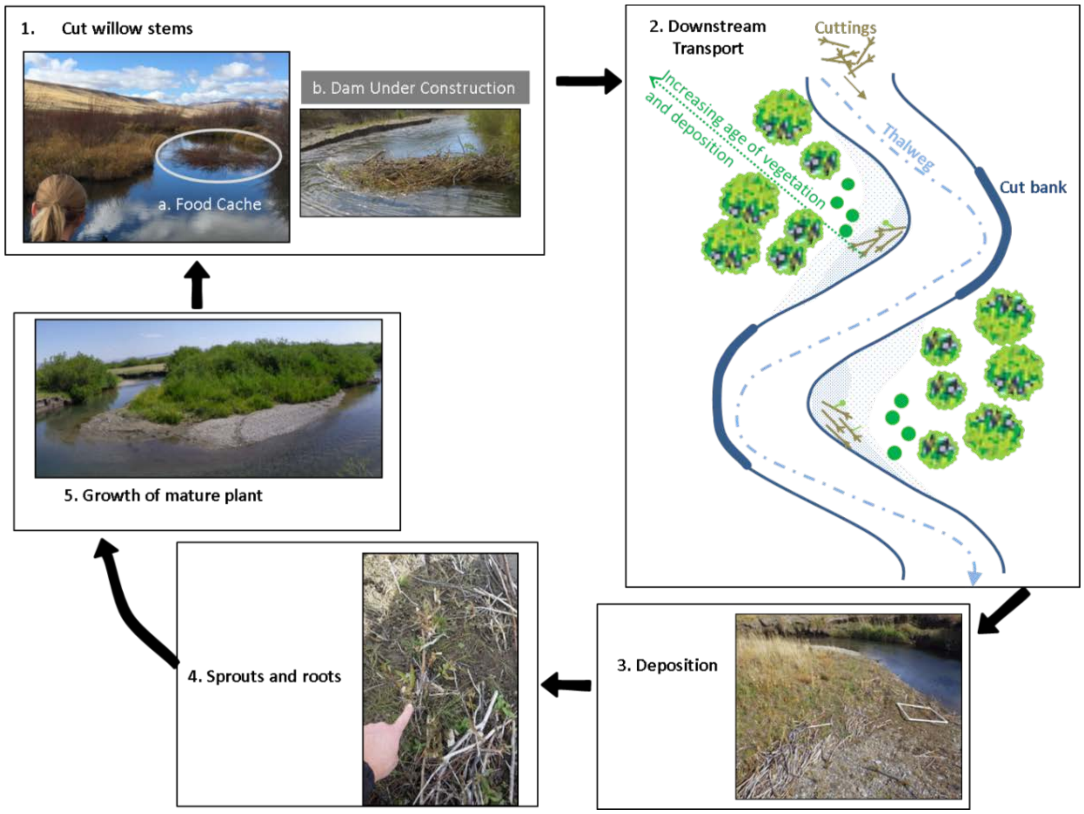

Figure 2-1. Beaver generation of willow cuttings (plant propagules) and distribution. 1. Beaver cut willow for dams on Odell Creek (1b), food cache on East Fork Blacktail Deer Creek (1a) and consumption. 2. Some cuttings—from loss or dam breaching—are transported downstream. The dashed line shows the thalweg, i.e. the deepest part of the channel. The cuttings are eventually deposited in areas of low velocity and shear stress, often on the downstream margin of point bars, along with fine sediment and willow seeds. 3. The cuttings add roughness contributing to further fine sediment accumulation. 4. Some of the cuttings develop adventitious roots and sprout on the wet substrate of bars. 5. Sprouted willows grow into mature plants, further adding roughness and promoting point-bar growth. All willows in this Odell Creek photograph are growing on point bars, whereas the cutbank in the background is formed in a higher grassy terrace. The youngest willows lie near the toe of the bar, coincident with the youngest sediment (see also (2) in this figure). The mature willows grown from both seed and beaver cuttings are ready for a new round of beaver herbivory.

Along Odell Creek we placed a 0.5 x 0.5 m quadrat and measured the total length of beaver cuttings within each quadrat at 90 sites, within three randomly selected 800 m stream reaches over 4 km. The sites were selected using a stratified random sample based on 3 channel morphologic classes: point bar, straight reach, or cutbank. Within each site, a quadrat was placed at the late summer flow stream edge, as well as at 1 m and 3 m from the active channel, to measure willow cutting accumulation as a function of distance from the channel and relative elevation above low-water stage, yielding a total of 270 quadrats.

Within each quadrat we summed the lengths of beaver-generated willow cuttings, as identified by clearly beaver chewed ends, and counted the number of sprouts growing on the willow cuttings. We also identified the surface sediment size that covered >50% of the quadrat from silt through cobble gravel using the Wentworth grain size classification (Wentworth 1922). Our results for cutting accumulations along Odell Creek showed that as depositional loci, point bars were significantly more important for storing cuttings (Figure 2-2), so we exclusively sampled point bars along three 800m reaches on Red Rock Creek and five 800m reaches on East Fork Blacktail Deer Creek.

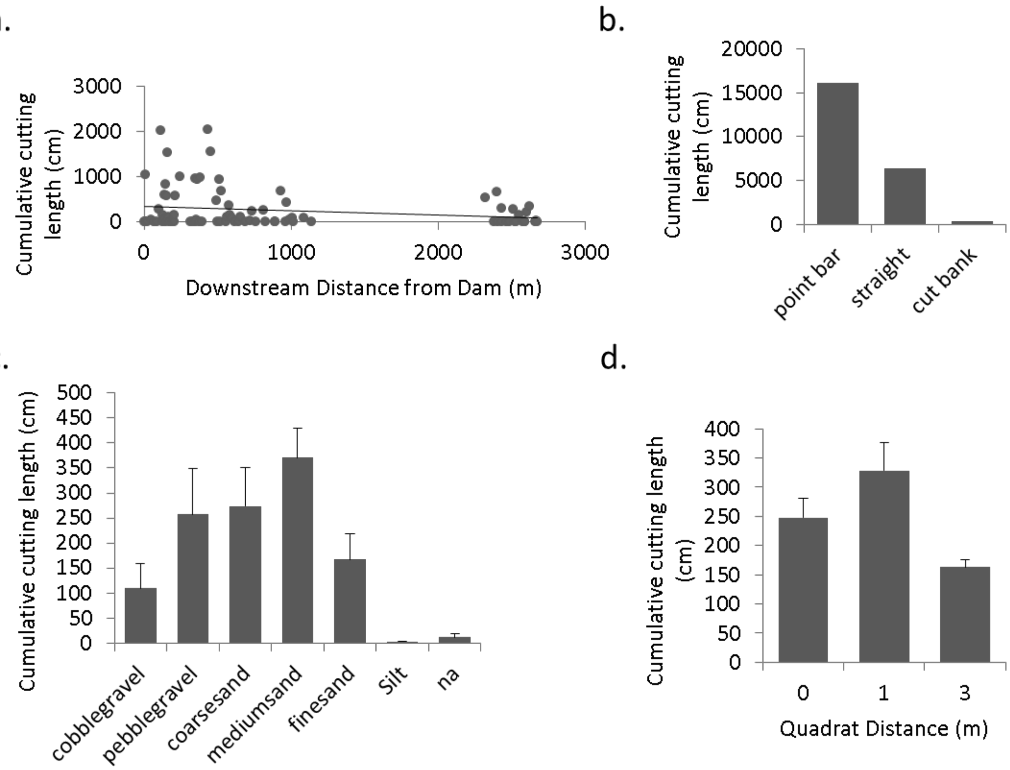

Figure 2-2. The cumulative length of willow cuttings produced by beaver herbivory relative to variables that may account for differences in accumulations of the cuttings along Odell Creek, Montana (a) Summed cutting lengths by site and plotted relative to site distances from the nearest upstream dam. All sites are shown; $r^2 = 0.04$. (b) Summed cutting lengths for each morphological class. (c) Cumulative cutting length averaged across quadrats in each sediment class; error bars show standard error. (d) Cumulative cutting length averaged across quadrats in each distance class (0, 1 and 3 m), where distances are from low-flow water edge; error bars show standard error.

Along Odell Creek we recorded 22,800 cm of beaver generated willow cuttings within our quadrats. Using the program R (R Core Development Team 2015) we performed linear mixed effects analysis (Bates et al. 2015) to assess parameters that we expected to have an effect on where and how beaver cuttings are deposited. To test how each parameter affected mean willow cutting length for a site, we used Chi-squared likelihood ratio tests where the full model, including the parameter of interest, was tested against the null model without the parameter of interest. We report the result as: χ^2 (degrees of freedom)= test statistic, p = p-value. Where appropriate, we also report the standard error of the mean (SE).

Active dam locations were assumed to be the most important parameter influencing cumulative willow cutting length because active dam sites provide a source for cuttings as beaver actively harvest willow for dam construction, food caches and immediate consumption. Our model results show that the distance downstream from a dam significantly explains variability in accumulated cutting length (χ^2 (1) = 4.487, p = 0.03415) (Figure 2-2). Based on the model, stick length will decrease by 0.06 cm/m (SE ± 0.03 cm/m) downstream of a dam site. We hypothesized that the total number of dams upstream of a site would be important in the total accumulated cutting length, but this proved not to be the case. The farthest downstream site, with 7 dams upstream, had a lower accumulated cutting length than all other reaches—including the most upstream reach, 3.6 km upstream, with only 2 dams upstream— suggesting that the travel distance between sources and depositional sites for cuttings is relatively low.

As noted above, channel morphology strongly controls deposition of willow cuttings, creating distinct populations of cutting accumulations among point bars, straight reaches, and cutbanks (χ^2 (2) = 6.412, p = 0.0405), where point bars accumulate the greatest cutting length (mean = 202.8 cm (SE±33.2))(Figure 2-2). Because point bars were dominant locations of accumulation, we subdivided point bar sampling sites by bar location: upstream, midpoint and downstream. Point bar location was important in explaining much of the variance in accumulated cutting length between sites (χ^2 (2) = 618.6, p< 0.001) with downstream sites accumulating the most cutting length (mean = 278.9 cm (SE ±59.1 cm)), followed by upstream (mean = 235.4 cm (SE ±65.1 cm)) and midpoint sites (mean = 126.7 cm (SE ±54.9 cm)). Greater cutting accumulations on the downstream edges of bars are consistent with the area of minimum boundary shear stress in meander-bend flow. Throughout a bend, the point of maximum shear stress moves from inside to outside of the bend. The shift in maximum shear stress is also reflected in grain size distributions, where the coarsest sediments are found in pools near the outside bank, just downstream of the point bar, while fine sediments are transported toward the downstream, inside bend, where shear stresses are lower (Dietrich and Smith 1984). Fine sand was the finest sediment texture observed at most sites and was more commonly found at downstream quadrats at the 1 m distance, which were also associated with the greatest cutting accumulations (Figure 2-3). Cutting length was also related to sediment texture within the quadrat (Figure 2-2).

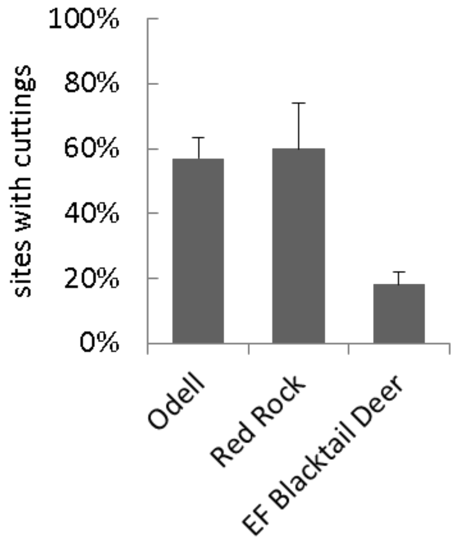

Figure 2-3. Mean percent of 0.5 x 0.5 m quadrats within each reach that contain willow cuttings produced by beaver herbivory along Odell Creek, Red Rock Creek and East Fork of Blacktail Deer Creek, Beaverhead County, Montana. Error bars report standard error.

Location relative to the active channel explains a significant amount of the variability in total length of cuttings between quadrats (χ^2 (2) = 618.6, p <0.001) (Figure 2-2), with 1 m quadrats accumulating the most (mean = 323.8 cm (SE ±55.62 cm)) followed by the quadrats adjacent to the low flow channel (0 m quadrats, mean = 247.3cm (SE ±51.1 cm)). The 3 m quadrats were the least likely to have accumulated cuttings (mean = 164.2 cm (SE ±70.9 cm)). In most cases, sites at 3 meters distance were on average 70 cm above the low-flow channel elevation, so only larger floods are likely to push cuttings this far onto the floodplain. Beaver are most active during the summer months, during the same period when the study streams have steadily decreasing discharges from snowmelt peaks in late May and early June. This should strand beaver-cut stems at various elevations, just as seeds are stranded by falling flows (Merritt and Wohl 2002). Our data indicate that moderate to low flows deposit most of the cuttings, which is consistent with periods of time when beaver are most actively harvesting willow.

Beaver cuttings and channel processes

The accumulation of beaver-generated willow cuttings is a common process along Odell Creek, where cuttings accumulated on 81% of point bar sites and 51% of all surveyed sites. Cuttings added to the stream channel by beaver activity are also likely act to alter sedimentation processes at these low-energy depositional sites. The beaver cut stems are small in diameter (1- 3 cm), with a mean length of 10.4 cm (SE ±0.22), but accumulate in clusters that cover large areas of the point bars. Also, the presence of some woody debris makes it more probable that additional wood will be trapped at the site (Millington and Sear 2007). Field experiments show that longer dowels are more likely to hang up on obstructions (Cordova et al. 2008), implying that shorter cutting lengths will be found farther from dams. Low-gradient streams also tend to transport small wood farther than in steep headwater streams, although mean dispersal distance for the dowel experiments in a low-gradient stream was 243 m. Even though the diameter is small, some roughness is added by accumulations of stems and as more stems are added, the effect will increase. The sediments that are covered by the wood, particularly if any pieces have become rooted, will act to protect underlying sediment, minimizing entrainment. Small roughness elements—including larger gravel (Fryirs et al. 2007), grass, and willow sprouts—can stabilize bar sediments and promote additional sedimentation (Parker et al. 2011). As sediment accumulates on the bar in response to the added roughness, more flow is directed toward the outer bank (Dietrich and Smith 1983) removing shear on the inside bend. In developing river bends, inner-bank deposition is the major process during frequent, small floods (Pizzuto 1994) and beaver cuttings add in some measure to the likelihood of deposition.

Not all streams will accumulate beaver cuttings in the ways we have observed. Even along Odell Creek, the upper, steeper gradient reaches did not have any major accumulation of beaver cuttings. Our field observations indicate that the lower gradient, meandering reaches of Odell and Red Rock Creeks accumulate more willow cuttings than the higher gradient, less sinuous reaches of East Fork Blacktail Deer Creek (Figure 2-3). All three streams, however, showed similar patterns of cutting accumulation on the downstream portions of point bars, and observations of large accumulations on point bars and in Holocene floodplain sediments of many other streams in the greater Yellowstone region indicate that fine woody debris accumulations from beaver herbivory are both common and persistent over long timescales (e.g. Persico and Meyer 2009, 2013).

Beaver cuttings and willow recruitment

Accumulations of beaver cuttings are certainly a common feature on the study streams, but do these sticks contribute to direct recruitment of willow? We counted sprouts from cuttings in each quadrat, which yielded a mean number of sprouts per quadrat of 0.5 (SE ± 0.1), with a total of 72 sprouts across all quadrats in the study area. Although this number is relatively low compared to the total length of cuttings, sprouts were present at 25% of all sites and appeared to be more numerous with a greater cumulative cutting length (Figure 2-4). Sprouts were most commonly associated with any sites having sand, in particular medium sand. Forty-five percent of medium sand quadrats had sprouts, with a mean of 1.2 sprouts per quadrat (SE±0.4), possibly because of significantly more cutting length available for sprouting (7616 cm). Coarse sand was associated with the highest mean sprout count (1.6 sprouts/quadrat (SE ± 1.4), and showed the greatest sprouting success per available cutting length (1018 cm).

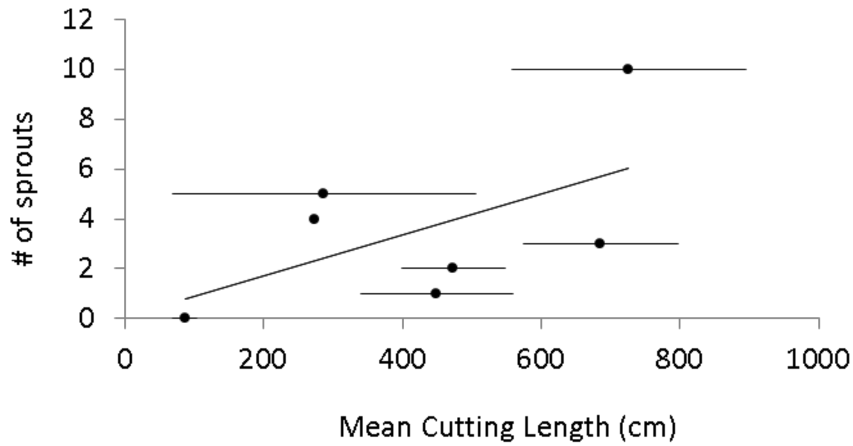

Figure 2-4. The number of sprouts counted within a 0.5 x 0.5 m quadrat as a function of mean cumulative cutting length at locations along Odell Creek. Error bars show standard error.

Overall, these data suggest that beaver herbivory results in deposition of a large number of cuttings on suitable substrates, making vegetative propagation a viable mechanism for recruitment. There is at least some relationship between cumulative cutting length and the number of sprouts produced (Figure 2-4), suggesting that a large number of stems and thus vigorous beaver populations are necessary to make vegetative propagation successful. Genetic data show that sexual reproduction likely dominates in Salicaceae, but that the ratio of asexual and sexual reproduction can vary greatly even between different populations of the same species, with variability attributable to local site factors (Karrenberg et al. 2002). Even if seed is the dominant mode of reproduction, the deposition and sprouting of cuttings should be considered an important secondary pathway to reproduction in streams occupied by beaver. The successful regeneration of floodplain willow cuttings under a wide range of moisture, sediment and burial regimes—particularly in comparison to non-floodplain willow (Radtke et al. 2012)—lends support to the importance of vegetative propagules in dynamic floodplain environments (Karrenberg et al. 2002). We hypothesize that the vegetative propagule mode of reproduction should increase in relation to the abundance of beaver, at least where population size is not strongly limited by food resources, but this remains to be tested.

Beaver dam dynamics and succession

Beavers build dams to alter aquatic habitats for optimal foraging of riparian vegetation, to maintain winter food caches and have water access to their lodges (Baker and Hill 2003). Like the addition of fine woody debris during construction and foraging, the completion and subsequent failure of the dam—all part of the cycle of beaver activity— play important roles in the development of riparian vegetation and river dynamics.

Beaver flooding

Beaver are strong swimmers, but less agile on land, so having access to their food source via water is important for minimizing predation risk. That means, however, that beaver herbivory of preferred trees and shrubs is concentrated around dam sites, generally within < 100 m of their pond (Donkor and Fryxell 1999, Johnston and Naiman 1987). The harvesting near dam sites is thorough, but decreases with distance from dam sites. Beaver herbivory opens up shrub and forest canopies which may allow other plants to gain a stronger foothold (Naiman et al. 1988), however, willow stem biomass is able to recover quickly from beaver cutting (Kindschy 1985), with biomass for willows returning or surpassing unbrowsed willows within two years (Baker et al. 2005).

By building dams, beaver change the hydrology of a river reach for their benefit, impacting both the properties of the flow and sediment regime (Levine and Meyer 2014), subsequently impacting the development of the riparian plant community that is driven by the climate and hydrological disturbance within a watershed (Gurnell 2014). Beaver dams alter the seasonal and longitudinal distribution of water and sediment, affecting plant communities that usually develop from primary succession on bare mineral substrate that is left behind by receding floodwater (Gage and Cooper 2005) or deposited as rivers and streams migrate laterally across their floodplains (Corenblit et al. 2007, Merritt and Cooper 2000).

Dam building initially occurs during low discharge when a flow is confined within the channel banks. Even where ponding is limited, dam construction reduces the water surface slope and flow velocity in the channel upstream of the dam, and in most cases, forces water overbank even within drier years and during times of year that usually do not see flooding. Beaver floods are usually of much longer duration than those caused by precipitation or snowmelt runoff, and dams remain in place anywhere from days to decades (Levine and Meyer 2014).

The commonly recognized benefit of flooding to riparian vegetation is to elevate of groundwater levels hundreds of meters downstream (Westbrook et al. 2006) with clear benefits to willow productivity (Marshall et al. 2013). In areas close to the dam site, however, the flooding can have deleterious effects on the vegetation; although flooding is part of life in the riparian zone, each species is adapted to a specific frequency, duration, magnitude and time period for flooding and may be impacted differently depending on life-stage (Poff et al. 1997). In areas subjected to prolonged inundation, the soils become anaerobic and willow establishment is inhibited (Johnston and Naiman 1987). Floodplain submergence also puts selective pressure on existing vegetation. In western North America, willows and cottonwood commonly occur together, but resident cottonwood species (e.g. *Populus deltoides, P. balsamifera, P. angustifolia)* demonstrate restricted root growth in response to inundation (Amlin and Rood 2001). If beaver-dam flooding persists, then the cottonwoods may die off, leaving behind the more flood tolerant willows, that are able to resprout more easily following inundation (Smith 2007), although in some cases even willow may succumb to inundation stress (Westbrook et al. 2010). Gaps created in the canopy by drowned plants allows secondary succession to occur (Mouw et al. 2013).

The presence of active beaver dams can also promote abandonment of a river reach (avulsion) (Polvi and Wohl 2012). The decrease in the water slope combined with the vertical changes in bed elevation and promotion of overbank flow may force the river to take a steeper path (Abbe and Montgomery 1996, Levine and Meyer 2014). Once the avulsion occurs, the abandoned channel can become an important site for willow establishment as it infills with sediment, if water table depth and soil water holding capacity are appropriate (Cooper et al. 2006, Gage and Cooper 2004). Beaver damming can also initiate channel abandonment by meander cutoff, as observed along Odell Creek (Figure 2-6). While the cutoff was imminent in the longer term, high water stages upstream of the dam caused overflow and cutoff at the meander neck. As on Odell Creek, the formation of a plug bar at the meander entrance can proceed rapidly, and the newly deposited sediment provides optimal habitat for riparian plant colonization (Toonen et al. 2012) through seed or vegetative propagules.

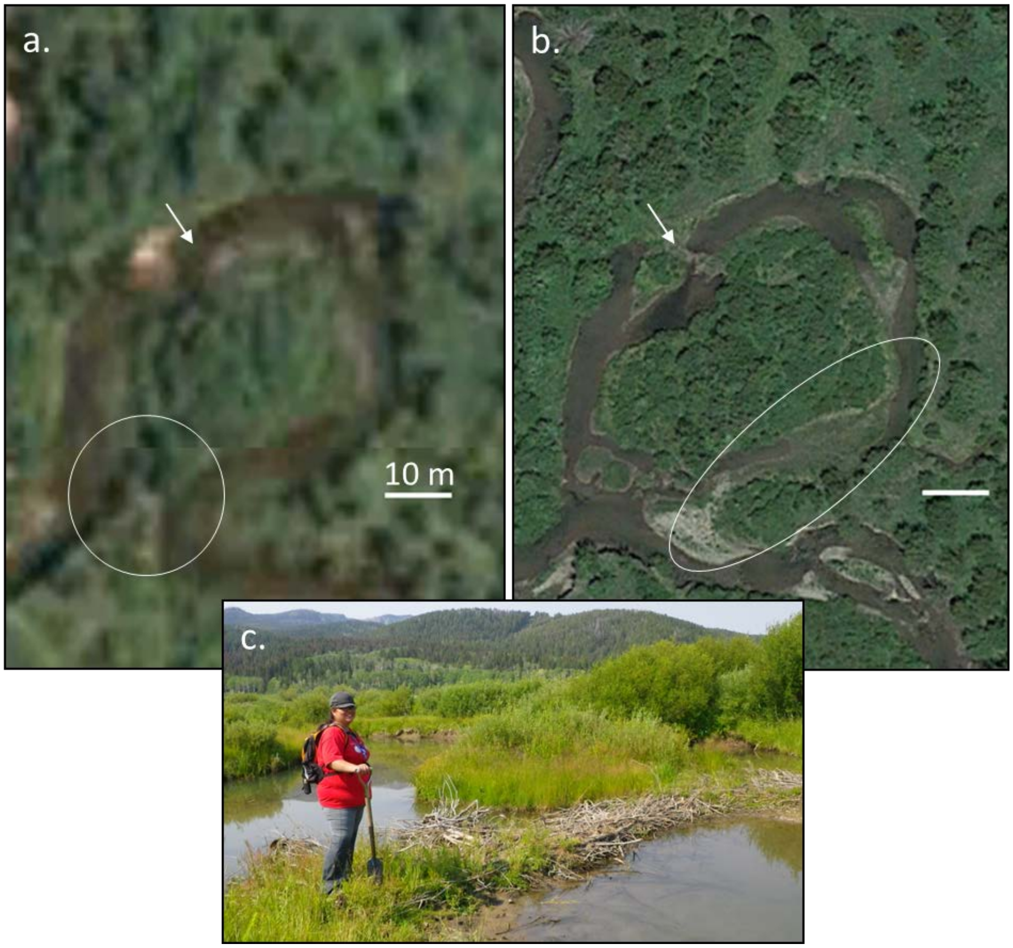

Figure 2-5. Development of meander cutoff promoted by a beaver dam on Odell Creek. a. Aerial view prior to cutoff with the neck of the meander circled. b. The same site three years after the neck cutoff, highlighting the development of the plug bar with vegetation growing on the bar. c. The dam site, also indicated by white arrows in a and b. Imagery is from Google Earth historical imagery 2009(a) and 2014 (b); flow in all images is from right to left.

The vegetation is directly affected by an intact dam because the dam elevates the groundwater, promotes die-offs to encourage succession and creates new habitat through avulsions, but the dam is also prepping the site for establishment of new vegetation following a breach. During a flood the water that is forced overbank also carries suspended sediment. Much of this sediment is eventually deposited on the floodplain as flow is dispersed across a greater area and interacts with the roughness of floodplain vegetation. Closely spaced willow stems reduce the boundary shear stress below the threshold for transport (Smith 2007), burying willow stems in fine sediment (Levine and

Meyer 2014), adding form drag that further reduces shear stress (Smith 2007). As flow is concentrated between plant stems, there may also be new secondary channels that develop on the floodplain surface leaving behind scoured sediment, lacking vegetation—areas that are ripe for recolonization following a breach.

Breached beaver dams

Beaver dams are under high stress during flood discharges, as during the snowmelt pulse in our Montana study area, and damage and breaching are common (Demmer and Beschta 2008, Levine and Meyer 2014). Dam breaching is a critical part of the beaver cycle in rivers—providing additional disturbance in the river corridor—and may be even more important for the maintenance of riparian forests. In the field of river restoration, a project is usually considered a failure when constructed elements "blow out" (Simon et al. 2007), but in the case of beaver dams, the "blowout" may be just as important as the initial structure. For some time, beaver have been seen as an important tool in stream restoration (e.g. Apple 1985), but the benefits are mostly recognized as stemming from intact dams (e.g. Beechie et al. 2008, Pollock et al. 2007). That perspective, however, is starting to shift toward consideration of beaver dams in their various states of repair (e.g. Levine and Meyer 2014, Pollock et al. 2014).

As a dam breaches, the water slope quickly returns to the ambient slope for the reach, with a resulting increase in sediment transport capacity, moving most of the fine sediment out of the main channel (Levine and Meyer 2014). After the dam is breached, the drained beaver pond leaves behind fresh sediment on the floodplain for plant colonization. The floodplain that had been variably scoured and filled during damming now provides numerous sites that are primed for colonization by seed or vegetative propagules.

Willows produce large quantities of short-lived, non-dormant seeds each year (Cottrell 1995, Densmore and Zasada 1983), with seed dispersal along the river corridor generally controlled by plant phenology and the flow regime of the river (Mouw et al. 2013). For Rocky Mountain species of willow, seed dispersal usually occurs as river stage begins to fall after the snowmelt runoff pulse in June and early July (Gage and Cooper 2005), usually coincident with the period when breached dam sites are prepped for plant colonization. Due to the short window of seed viability, willows are highly dependent on newly deposited moist sediment, which may occupy a very small percentage of the landscape (Gage and Cooper 2005). Recently breached dam sites increase the availability of this requisite habitat.

Vegetative propagules have a greater reserve of carbohydrates and water within the stem than do seeds, so are able to deal with more adverse conditions (Krasny et al. 1988, Thomas et al. 2012); however, they also require bare, moist sediments for successful reproduction. During the spring runoff, dams may breach throughout the river corridor, not only providing sites for colonization, but flushing some fresh beaver cuttings from the dams into the channel. In contrast to the seeds of willow, which appear to have a limited range of dispersal (Gage and Cooper 2005), the sticks are able to float downstream for long distances (Boedeltje et al. 2004), despite stranding of some on point bars and other depositional sites along the way.

Once the dam has breached and beaver have abandoned the site, established woody plants are able to contribute to regeneration following the beaver-induced flooding (Asaeda et al. 2011) by resprouting from the roots (Krasny et al. 1988). In a study of red willow in eastern Oregon, USA, the harvesting of stems in the fall (mimicking beaver harvest) was not detrimental to the plants, which sprouted more vigorously the following spring (Kindschy 1985).

The failed dam itself can also play an important role in the creation of new habitat for plant colonization. Osei et al. (2015) found that sites associated wood jams were related had the highest diversity in seedling development from plant propagules compared to bank, floodplain and bar sites without wood jams. The successful recruitment at jam sites was attributed to the retention of fine sediment, and breached beaver dams provide a similar environment. Commonly, a dam remnant extends partly across the channel from one bank following a breach, and controls flow patterns and deposition of sediment for a number of years (Levine and Meyer 2014). Because the dams are primarily made of cuttings from local riparian plants, the remaining dam portion is strengthened as the cuttings sprout and form a new stand, with plant stems providing additional roughness to the channel (Smith 2007).

The upper reaches of our southwestern Montana study streams are high-gradient, cascade, step-pool and plane-bed channels (Montgomery and Buffington 1997), and streamside vegetation is dominated by subalpine conifers. Large wood jams in these reaches act as discontinuities and can positively impact channel migration rates (Brummer et al. 2006), but large woody debris rarely makes it into the lower, meandering, pool-riffle reaches, the center of beaver activity, where low-stature willow is the main streamside vegetation, and uplands are dominated by grassland and sagebrush. The absence of large wood to create discontinuities make beaver dams and dam remnants even more important for trapping sediment and organic debris, including beaver cuttings. Like large woody debris, the remnants of breached beaver dams perturb water surface slope and add channel roughness, especially where cuttings have sprouted. Both adjustments promote sediment retention, raising bed elevations near the dam and creating a topographic high that begins to act like a point bar (Levine and Meyer 2014). Flow deflected toward the opposite bank by a stabilized dam remnant can initiate a new meander. Shear stress is concentrated at the outer bank, promoting erosion and deposition of coarse bed load, and fine sediment is deposited along the inner bank (Dietrich and Smith 1984) – in this case, the dam remnant, with deposition further enhanced by live plant stems. Thus the beaver dam remnant forces the channel to shift laterally over time, adding dynamism to the system and ultimately increasing the diversity of habitats (Levine and Meyer 2014).

Dynamic river systems are critical for maintaining riparian forests (Richards et al. 2002). Beaver predominantly build dams on low gradient (<3%) streams with abundant riparian vegetation (Scrafford 2011). Many of these streams feature meandering channels with floodplains on which roughness is mostly caused by riparian vegetation (Lazarus and Constantine 2013), and floodplain development is driven by the approximate balance between erosion on the outside bend and deposition on the inside bend (Parker et al. 2011). By adding roughness on point bars and channel discontinuities at breached dam sites, the cycle of beaver activity changes rates of deposition and erosion as it plays out over time throughout the system.

The beaver cycle and riparian patchiness

At any given time, a functioning beaver stream encompasses a mosaic of site types, including intact dams, recently breached or abandoned dams, long abandoned dams, and often, reaches unsuitable for beaver colonization. Beaver will relocate as resources are depleted at their dam site and move to where there are more available preferred food sources (Donkor and Fryxell 1999). Some sites can sustain a family of beaver for many years, while a less desirable site may be occupied for only a brief interval (Naiman et al. 1988). Site occupancy also depends on suitable geomorphic characteristics of a particular site, which varies between reaches and watersheds (Levine and Meyer 2014, Macfarlane et al. 2015, Persico and Meyer 2009). Shifting occupancy by beaver creates discrete and ever-changing areas of the stream corridor with fresh, moist sediment, or areas that are recovering from die-off from inundation. For riparian vegetation, this can generate variability in ages and even species distributions (Amlin and Rood 2001, Mouw et al. 2013, Naiman et al. 1988), which result in different properties of overbank flow on floodplains. For example, with their closely spaced stems and canopies near the ground, willows offer more protection from floodplain erosion than cottonwoods (Smith 2007) – thus the mosaic of species composition also produces differences in sediment transfer rates across floodplains.

The beaver cycle also acts along with other disturbance processes to generate heterogeneity. Riparian forests along streams that lack beaver or large wood are dependent on flood disturbance and channel migration to provide colonization sites on bare sediment (Johnson et al. 2012, Merritt and Cooper 2000), thus shrub and tree distribution is closely tied to flood occurrence, and flood levels that are fortuitously timed with seed dispersal (Rood et al. 2005). The result is vegetation in cohorts, with ages tied to flood intervals (Merritt and Cooper 2000). In beaver-occupied stream systems, however, beaver produce a steady supply of cuttings and substrates for regeneration, allowing plant recruitment to occur throughout the growing season (Asaeda et al. 2011) at sites in favorable parts of the beaver cycle. Overall, the variability in beaver occupancy over both space and time provides for riparian patchiness and habitat heterogeneity along the river corridor (Levine and Meyer 2014, Macfarlane et al. 2015, Polvi and Wohl 2012).

Long-term effects of the beaver cycle on floodplain dynamics

In addition to our data on modern accumulation of beaver cuttings, we have observed abundant beaver cuttings in older stream deposits along Odell and Red Rock Creek. Holocene terraces from 1.2 – 3 m above the low-flow channel represent former floodplains of these streams, and their deposits are commonly well-exposed in cutbanks. The older beaver cutting deposits appear as a distinct layer with high concentrations of beaver-chewed sticks, cut at a distinct angle (Figure 2-5). The cuttings have typically been preserved in the low oxygen environment of saturated sediments. The beaver cuttings are mostly contained within sandy sediment that overlies coarser sand, pebbles, or gravel. On top of the cuttings are fine sands grading to thick packages of sandy silt. Overall, these sequences show an upward-fining trend.

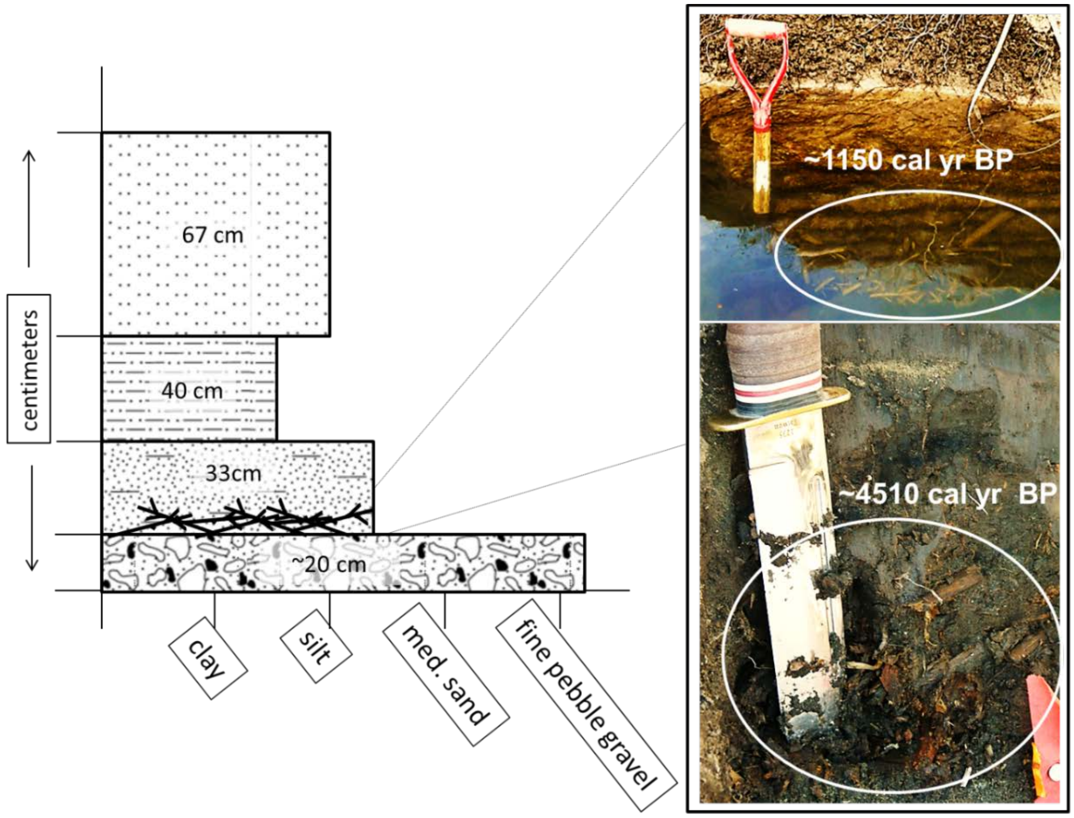

Figure 2-6. A composite stratigraphic column showing the typical occurrence of buried beaver willow cuttings in Holocene sediments along Odell Creek. The mean thickness for units represented at the majority of sites is shown. Cartoon sticks in the second unit from the bottom show the typical position of cuttings deposits. The photographs show examples of the cuttings in situ at 2 sites. In the top photograph the cuttings are below the water surface. White circles highlight the cuttings in each image and the median of the calibrated probability distribution for radiocarbon ages is reported from the INTCAL13 calibration curve (Reimer et al. 2013).

One interpretation might be that the cuttings-rich deposits represented Holocene beaver pond deposits, similar to those described by Persico and Meyer (2009) for smaller streams in northern Yellowstone National Park. However, the majority of Odell and Red Rock Creek deposits did not show the fine-scale layering, abundant fine organic matter, or gleying and redoximorphic features characteristic of beaver pond sediments deposited in still water (Persico and Meyer 2009, Persico and Meyer 2013, Polvi and Wohl 2012). In addition, true still-water conditions are relatively rare above beaver dams on the large Odell and Red Rock Creeks, and the observed longevity of dams along Odell Creek is 3-5 years (Levine and Meyer 2014). A channel abandonment that leaves the dam intact is a relatively rare event; three have been observed over a 10-year period. The cuttings deposit layers are also not consistent with the berm-like forms or localized woody debris accumulations that represent abandoned dams (Persico and Meyer 2009). The stratigraphy containing beaver cuttings, however, supports interpretation as point-bar deposits grading upward into finer overbank sediments composed primarily of suspended load (Nanson 1980). The abundance of beaver cuttings on modern point bars, including those being buried by sediment, lends additional support to this interpretation.

Persistence of beaver cuttings in floodplain sediments

Along Odell Creek, we found beaver cutting deposits to be well-distributed throughout the ~10 km of the meandering middle reaches, and they are common along Red Rock Creek as well. Thirty-four radiocarbon (^{14}C) ages show that beaver cuttings range in age from ~6200 – 360 cal yr BP. There are gaps in the record that may relate to periods of erosion or changes in climatic conditions (Persico and Meyer 2009, Persico and Meyer 2013), but deposition of beaver willow cuttings in point bars has been a common process over millennia. This is one mechanism by which beaver promote long-term burial and storage of organic carbon. Unconfined headwater streams with actively migrating channels and beaver activity, as on Odell Creek, can store ~75% of total carbon in the river network (Wohl et al. 2012). Wohl (2013) estimated that wet beaver meadows can account for 23% of the total carbon stored in the landscape, but this estimate is may be conservative because it does not include beaver-cut stems in point-bar deposits. Along unconfined meadow reaches of mountain streams, where large wood is rare, beaver activity can be the predominant mechanism for carbon storage. The multi-millennial preservation of beaver-chewed wood in point-bar sequences along Odell Creek attests to the importance of beavers in carbon storage well beyond the dam.

Management Implications

Across much of North America and Europe, beaver were once present in large numbers, but have been dramatically reduced by trapping, along with indirect causes of population decline (e.g. Naiman et al. 1988). Among many other impacts, increasing human pressure on river systems has caused riparian systems to begin unravelling, lacking the processes that maintain them—including beaver activity. By restoring the missing processes, rather than implementing hard engineering in place of a missing habitat attribute, a stream system is more likely to maintain its function (e.g. Beechie et al. 2010). Beaver activity and associated processes are notably lacking in many streams; in other river systems, beaver populations remain, but their dams are commonly removed to stop flooding or promote fish passage (e.g. Lokteff et al. 2013).

The loss of beaver removes important mechanisms for disturbance that are critical for the maintenance of riparian vegetation. Encouraging dynamic floodplains is essential to many of the goals of river restoration projects (Richards et al. 2002). Functioning stream corridors are predicated on disturbance, analogous to the way that forests are adapted to some frequency, magnitude, and severity of fires. As with fire, however, fluvial disturbances are often in opposition to human goals on the landscape, which is why management often limits disturbance. Allowing beaver to occupy a stream system, without removing their dams, aids in the restoration and maintenance of riparian vegetation and overall habitat diversity, where flooding and channel movement can reasonably be accommodated. It is important to recognize, however, that for beaver dams, failure is part of the success of these structures. Through failure, dams add woody debris to the system, produce bare moist sediment for colonization, and commonly induce meandering.

Reintroducing beaver is an alternative where site conditions and landowners or managers allow. Beaver, however, can be controversial, and restoration practitioners have been working on alternatives that have some of the functionality of beaver dams, but can be managed to alleviate concerns such as flooding and vegetation impacts. These beaver dam mimics—relatively deformable structures composed, at least partly, of local riparian vegetation—may also be used at locations where beaver populations cannot be sustained due to lack of food resources. At these locales, adding discontinuities is critical in creating sites for riparian plants to establish. Riparian plantings will likely also be necessary to establish vegetation, and willow cuttings can provide seed dispersal in areas that otherwise lack a seed source (Gage and Cooper 2005), mimicking dispersal of cuttings by beaver. Whether a river has beaver, or structures intended to provide the same benefits, a stream that has the ability to migrate will generate a more complex ecosystem, augmented by the effects of point bar deposition and meander development (Ward et al. 2002). Restoring the full cycle of beaver activity is an effective means to produce greater habitat heterogeneity for dependent organisms.

Conclusions

Beavers have received a lot of attention as keystone species and ecosystem engineers, primarily for their dam building effects, and for herbivory that mostly drives secondary succession. In addition, based on data and observations from southwestern Montana streams, we show that beavers promote multiple pathways for plant colonization (Figure

2-7). Riparian plants reproduce through seed, vegetative propagules and regeneration from damaged plant material, with each pathway augmented by or predicated on disturbance. Beaver activity, like other types of disturbance, resets succession, allowing pioneer species to gain a foothold. Through dam building, dam breaching and the addition of woody debris, beaver alter patterns and rates of sediment movement that create the wet, sandy substrate essential for the success of willow and most other riparian plants. Through the addition of woody debris from herbivory and the construction and failure of their dams, beaver provide additional reproductive material for plants and aid in carbon storage in floodplain sediments. In a world under increasing stress from shifting climate and rising demands for water and land by people, understanding the natural processes of the full beaver cycle can help to restore and maintain riparian habitat and stream ecosystems.

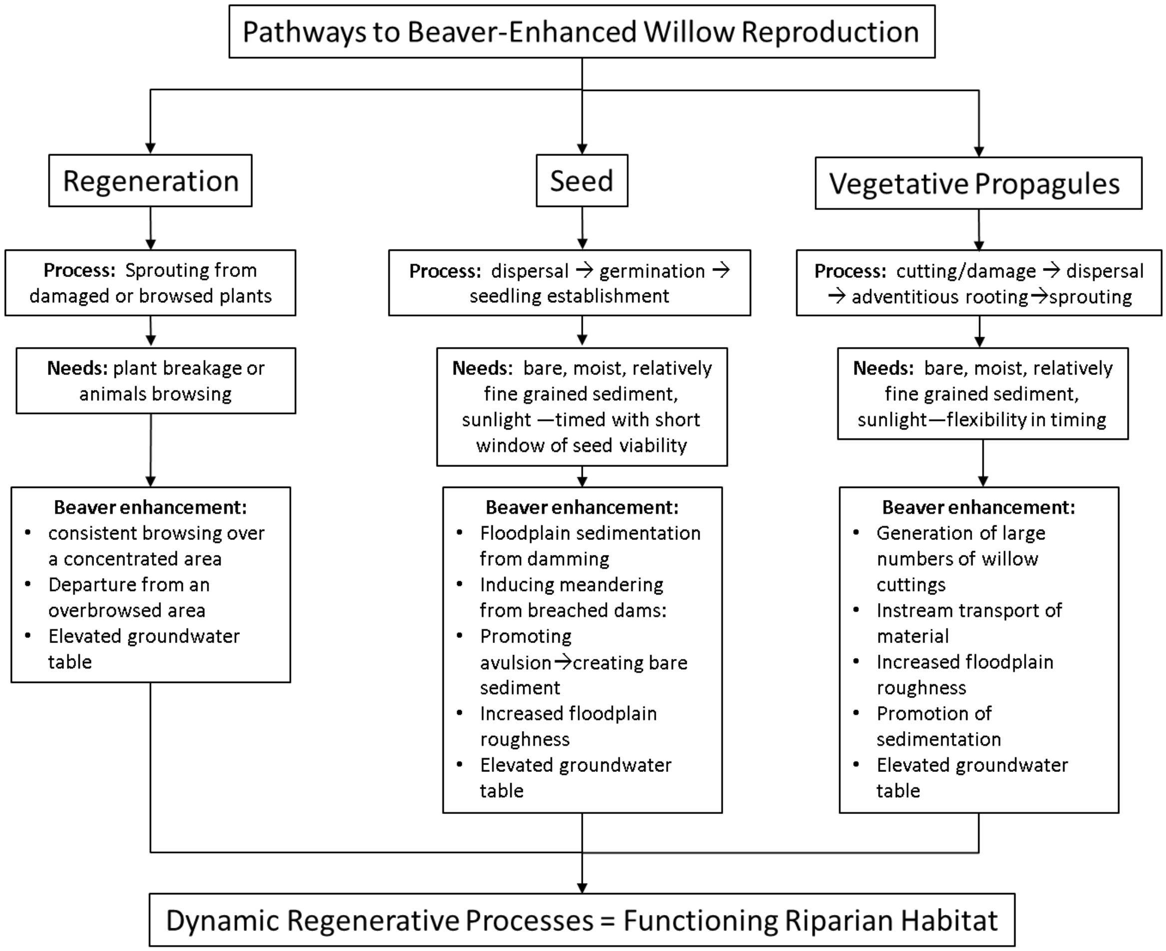

Figure 2-7. Overview of how beaver enhance willow reproduction through regeneration from the parent plant (asexual reproduction), seed (sexual reproduction) and vegetative propagules (asexual reproduction from plant pieces that have broken off the parent plant). Each process is briefly summarized, the basic requirements (needs) outlined and the beaver enhancements are listed.

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Chapter 3

The nature and persistence of beaver activity through Holocene climate change on an active meandering river in southwestern Montana

Abstract

Beaver dams effectively trap sediment in stream channels, leading to the hypothesis that persistent beaver damming on millennial timescales causes valley floor aggradation. If beaver activity promotes sedimentation, then long-term aggradation requires consistent occupation by beaver which depends on appropriate climatic conditions and—in the modern era— appropriate management actions. To address the role of beaver activity on valley floor aggradation and to document changes in beaver activity through time, we investigated the sedimentary sequences in alluvial fan and fluvial terrace exposures on Odell Creek and Red Rock Creek within the Centennial Valley, Montana where modern beaver still impact fluvial processes. Using ground surveys, airborne Lidar, stratigraphic analysis, soil surveys and 64 carbon-14 (^{14}C) ages, we developed a chronology of depositional episodes for the low gradient, meandering, Odell Creek. Four beaver pond deposits were identified, but most evidence of beaver activity consists of accumulations of beaver-cut willow stems, associated with upper point bar sedimentary sequences. Beaver-related deposition was identified within terrace deposits ranging in elevation from 0.8 to 1.8 m above the bankfull channel. This interpretation is consistent with observations of abundant beaver-cut stems and frequent beaver dam breaching ($\leq$ 5 years) in the modern channel of Odell Creek, suggesting that beaver contribute to both lateral

and vertical accretion (Chapter 2), but within larger scale fluvial processes. Incision has been the overall trend throughout the Holocene, but in the late Holocene lateral migration has dominated channel activity, with only minor aggradation and incision of ± 2 m, a range in which local base-level control by beaver dams may have had a significant influence. Evidence of beaver occupancy extends through most of the late Holocene, including during severe droughts of the Medieval Climatic Anomaly, implying persistence of perennial flows attributable to the large basin areas and general northerly aspect of Centennial Valley drainage basins. Understanding basin attributes that contribute to maintaining perennial flows during dry episodes has important implications for present and future climate change.

Introduction

It is estimated that over 70% of the riparian habitat in the Western United States has been impacted by human alterations to hydrology through ditching, draining, diverting, clearing and flooding (Gardner et al., 1999). In response to degradation of critical river corridor habitat (Baril et al., 2009), river and riparian restoration projects are becoming commonplace in the United States (Bernhardt et al., 2005). Many projects set restoration goals by designating a reference reach (Simon et al., 2007), yet even the reference reach may have experienced alteration. An example of such alteration is the extensive trapping of beaver in many headwater streams in North America during the 19th Century. The loss of beaver been cited as a factor in altering stream form and function (Wohl, 2006). In response, restoration practitioners have begun using beaver dams, and structures that mimic beaver activity, to bring some beaver induced functionality back to degraded streams. The restoration work is based on the premise that beaver activity causes channel aggradation (Pollock, 2007), yet limited quantitative work has been done to assess beaver dam impacts on long-term channel function (Levine, 2014).

A structurally intact and maintained beaver dam can trap large volumes of sediment, with sedimentation rates of up to 0.5 m per year (Pollock et al., 2007). However, sediment trapping effectiveness is variable, with reported volumes from selected studies ranging from 34 to 6353 m^3 of total accumulated sediment upstream of intact beaver dams(John and Klein, 2004; Westbrook et al., 2010; Levine, 2011; Butler, 2012). The observation that dams fill with sediment caused Ruedemann and Schoonmaker (1938), and later Ives (1942), to suggest that beaver may have the ability to form broad flat meadows from successive pond filling. Others have seized on the idea of increased sedimentation promoted by beaver damming as affecting landscape development (Bigler et al., 2001; Wells et al., 2000) and potentially improving incised river habitat (McCullough et al., 2005; Pollock et al., 2007). If beaver do have an effect on landscape evolution and large scale sedimentation of valley bottoms, then at least portions of that record should be preserved. The studies that suggest the development of large beaver meadows extrapolate data from modern observations (e.g. Bigler et al., 2001; Pollock et al., 2003; Pollock et al., 2007), but very few studies have attempted to look at the geologic record for evidence of beaver related aggradation (Persico and Meyer, 2009; Kramer et al.,2011; Polvi and Wohl, 2012; Persico and Meyer, 2013).

Persico and Meyer (2009) addressed the question of beaver related aggradation on high order streams —basin areas between 1 and 60 km^2 —in Yellowstone National Park’s Northern Range (Figure 3-1) and found that 29% of the length of their study streams provided suitable beaver habitat, and of this, beaver related deposits made up 58% of the Holocene sediment thickness, with maximum net beaver related Holocene filling of 2.5 m. However, in the rest of the studied stream network there was little evidence of Holocene filling by beaver damming. Beaver dam locations, and perhaps their preservation, appear to be limited by high stream power (Persico and Meyer, 2009) and so significant Holocene valley aggradation attributable to beaver was not evident along most of the stream network. Another study, conducted in Rocky Mountain National Park (RMNP), found that the total amount of postglacial valley filling ranges from 0.7 – 6 m and the percent of total valley fill attributed to very fine grained sedimentation in beaver ponds ranges from 28 – 64% (Kramer et al., 2011; Polvi and Wohl, 2012). At the RMNP site the total amount of alluvium, however, is small, so the significance of beaver related sedimentation is greater relative to sites with larger total volumes of valley fill such as in the Persico and Meyer (2009; 2013) study area in Northern Yellowstone and Grand Teton National Park.

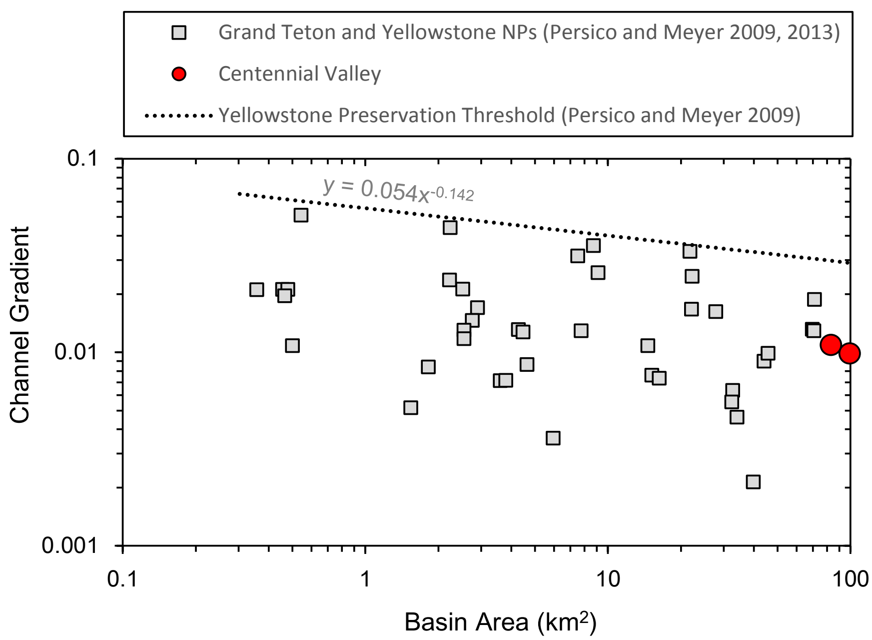

Figure 3-1. Channel gradient as a function of basin contributing area for stream reaches with Holocene beaver-pond sedimentation in Grand Teton National Park and Yellowstone National Park from Persico and Meyer (2009; 2013) with Odell Creek and Red Rock Creek plotted as circles for comparison. Both streams are below the threshold for preservation of pond sediments, but are larger basins than those studied by Persico and Meyer (2009; 2013).

Persico and Meyer (2009) were the first to tie changes in the relative amount of beaver activity to climate fluctuations using a large data set of beaver pond deposits. They showed that peaks in beaver abundance appear to correspond to wet periods in the Greater Yellowstone region. Additional work in Grand Teton National park indicates a similar pattern in clustering of beaver-related deposits during relatively wet periods (Persico and Meyer, 2013). They also noted a lack of beaver pond deposits during the Medieval Climatic Anomaly, a time of climatic variability and drought across the region (Carson et al., 2007; Cook et al., 2007; Huerta et al., 2009; Meyer et al., 1995) that lowered summer baseflows and may have caused small streams in the Greater Yellowstone Ecosystem to have intermittent flows in late summer (Persico, 2012). In light of their data, Persico and Meyer (2013) hypothesized that beaver may move to larger streams during dry episodes.

Our work seeks to test the stream scale hypothesis by focusing on two streams with basin areas of 83 km^2 and 99 km^2, at the upper end of those investigated by Persico and Meyer (2009; 2013) (Figure 3-1). We focus on two similar sized basins within the same mountain range. Rather than covering a large geographical area, most attention is focused on one stream, so that quantification of beaver related deposition is as complete as the stratigraphy allows. If our data show that beaver presence corresponds to the timing of that observed elsewhere in the Greater Yellowstone region, with corresponding gaps during dry periods, than even basins near 100km^2 did not have sufficient flows during drought prone periods to maintain riparian habitats. If there is evidence of beaver activity during drought prone periods then the study streams are above the threshold that allowed maintenenace of perennial stream flow during the drought prone periods of the mid – late Holocene.

Stream scale should also play a role in the preservation of beaver pond deposits, as increasing basin area increases stream power and limits preservation of beaver pond deposits (Persico and Meyer, 2009). If larger basins limit beaver pond deposition, then beaver deposits may be non-existant or beaver evidence may be preserved by different mechanisms within the larger streams of the Centennial Valley. To this end, descriptions of the nature of beaver-related deposits preserved in the Holocene stratigraphy are provided. Additionally, by placing beaver-related deposits within the context of the overall stratigraphy, the geological data can address the role beaver play in developing valley floor morphology, determining whether there is support for the hypothesis that beaver damming contributes significantly to valley floor aggradation.

Study area

Project work was conducted primarily on Odell Creek, Montana with some sampling and investigation along nearby Red Rock Creek. The study streams are located in the Centennial Valley, Montana, at the headwaters of the Missouri River System (Figure 3-2). Odell Creek and Red Rock Creek are relatively high-energy piedmont streams with snowmelt-dominated peak flows between 2-10 m^3s^{-1}. The Odell Creek watershed has a drainage basin area of ~83 km^2 and originates in the central part of the Centennial Mountain Range, draining a watershed composed primarily of Paleozoic and Mesozoic sedimentary rock in the east, and friable Tertiary volcanic rocks to the west (O'Neill and Christiansen, 2004). Where it exits the mountain front, Odell Creek is a relatively straight, plane-bed channel (Montgomery and Buffington, 1997) and then begins to meander through the middle reaches, the focus of this study, with an average valley floor sinuosity of 2.5 as it flows down a low-gradient (0.018 - 0.004) fluvial fan of Pleistocene age (Mumma et al., 2012). The creek has variably incised into this older fan surface. Incision began sometime after 11,000 years BP when Pleistocene Lake Centennial began draining out the western end of the Centennial Valley (Mumma et al., 2012). The incision has created stratigraphic exposures of alluvium of up to 3 m and, at the distal end of the fan, incision has exposed Pleistocene Lake Centennial sediments.

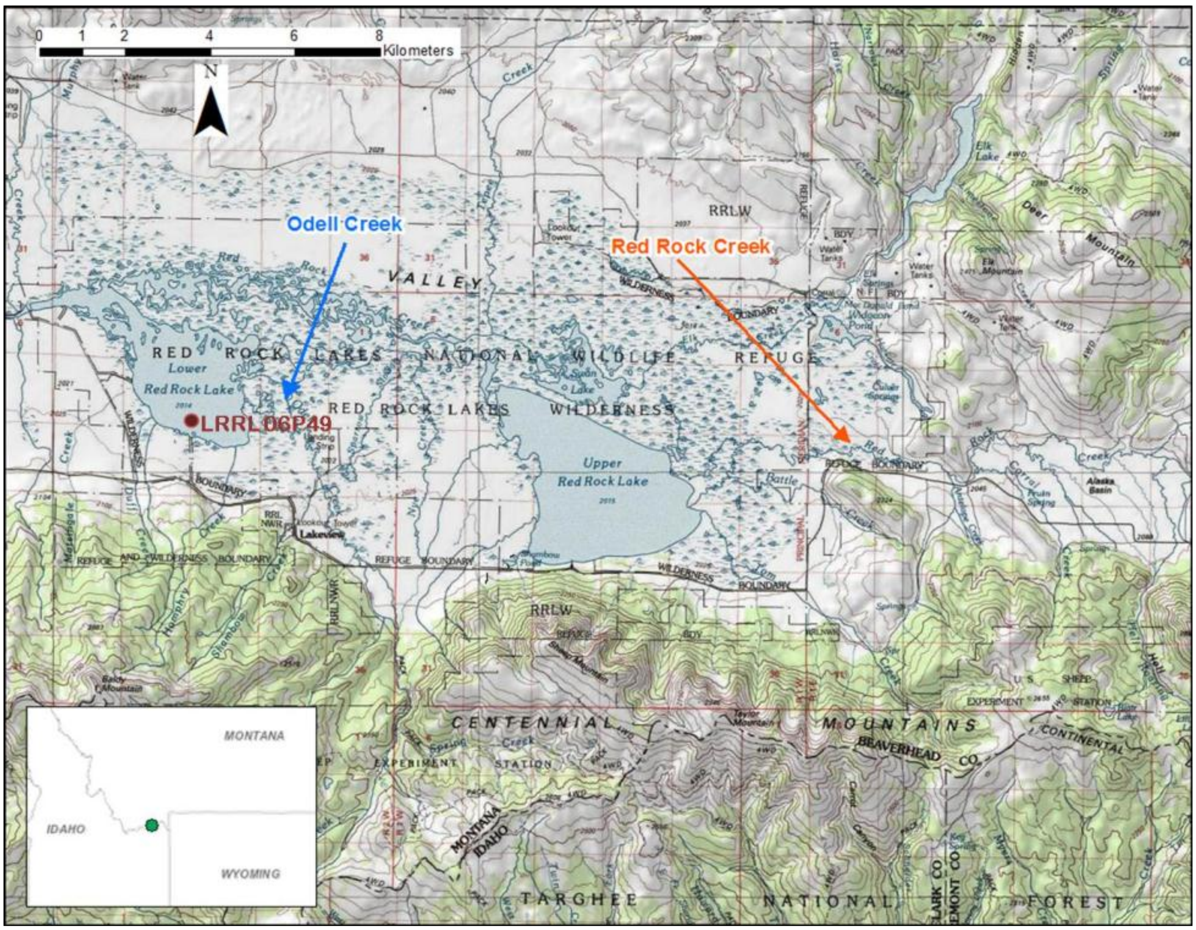

Figure 3-2. Centennial Valley study area. Inset shows site location in the region. Study creeks are indicated and core site LRRL 06P49 analyzed by Mumma et al. (2012) is shown.

Red Rock Creek has a watershed area of 99 km^2 and its major tributary, Hell Roaring Creek heads in the eastern Centennial Mountains and drains primarily calcareous rock of various ages and Absaroka Tertiary Volcanics (O'Neill and Christiansen, 2004). Hell Roaring Creek flows down an alluvial fan that slopes northwest before joining the main trunk channel of Red Rock Creek on the north side of the valley. Red Rock Creek is a low gradient meandering stream, so an excellent site for beaver occupation. Where damming has occurred, the dams succeed in flooding large areas of riparian habitat. Tertiary Huckleberry Ridge Tuff resists fluvial downcutting in the upper reaches of Red Rock Creek, so exposures of fluvial stratigraphy are more limited. Closer to Upper Red Rock Lake, at the mouth of the creek, bedrock no longer constrains downcutting, so stratigraphic exposures of up to 3.5 m exist, with incision into Pleistocene lake sediments in at least one exposure.

The streams are part of the largest wetland complex within the Greater Yellowstone Ecosystem, providing important habitat in a dry region (USFWS, 2009). Overall, willow (Salix spp.) is the dominant riparian woody species on Centennial Valley streams and is the primary food and building material for the Centennial Valley beaver population. Current beaver populations maintain a total of 12 – 20 dams on Odell Creek and Red Rock Creek. Average occupancy at any given dam site in a main channel is ≤ 5 years (Levine and Meyer, 2014). Like many locations across the western United States, although to a lesser degree, the Centennial Valley beaver population and associated riparian habitats have been affected by some human alterations, beginning with beaver trapping in the 1830's (Russell and Haines, 1965) and continuing through modern destruction of dams for fish passage and road maintenance. The majority of the study area is within Red Rock Lakes National Wildlife Refuge and has been under federal protection since the 1930’s, although abandoned irrigation ditches still crisscross the valley from a period of more intensive ranching.

Methods

Identification of beaver related deposition and sampling strategy

Stream incision along both creeks has exposed terrace deposits from a range of elevations. Terrace elevations were measured using Lidar (Light Detection and Ranging) data collected by The National Center for Airborne Laser Swath Mapping in August, 2010. Elevations were measured from the low-flow water surface as recorded in the Lidar data set and then recalibrated to the bankfull water surface based on field observations. The goal was to have a sampling of sites from a range of terrace elevations that should contain material from the range of time represented by the sediments, as well as a longitudinal distribution along the river corridor (Figure 3-3). Correlation and mapping of terraces from the Lidar data allowed for strategic site selection. The Lidar data were also used to locate preserved dams, by identifying berms perpendicular to paleochannel flow direction (Persico and Meyer, 2013), to select sites for augering into sediments.

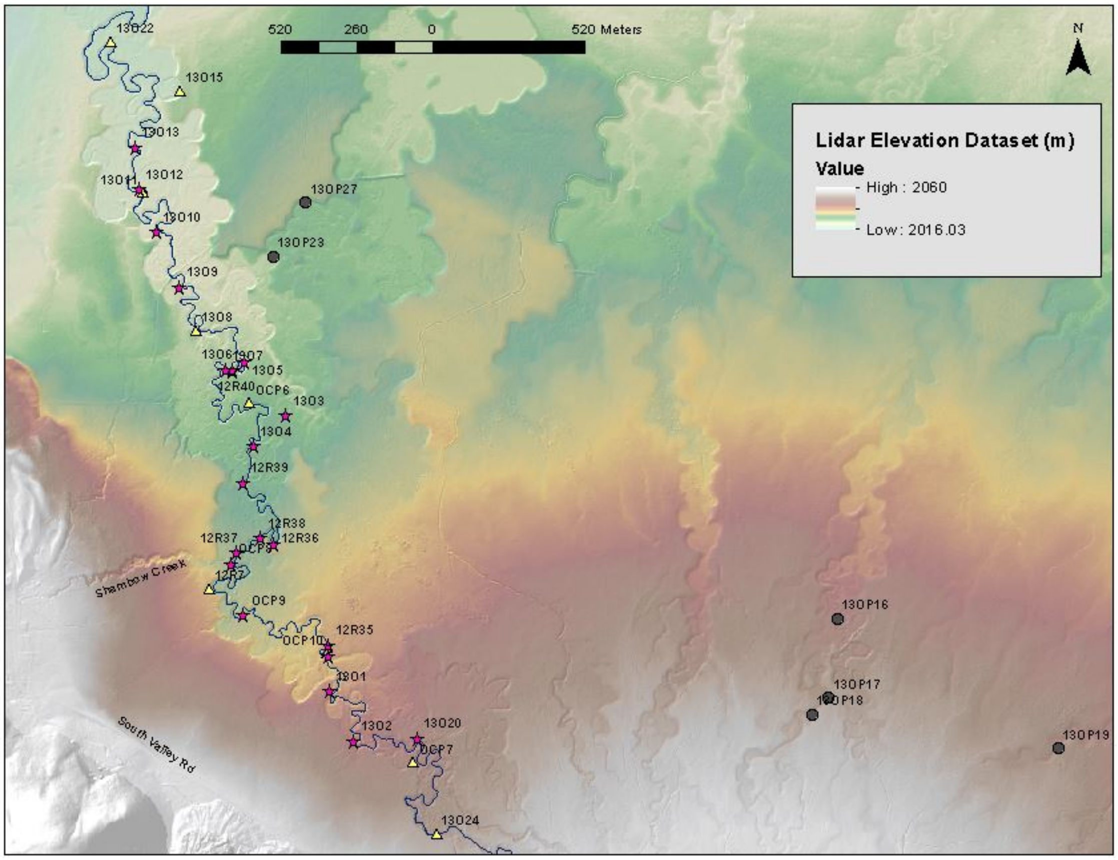

Figure 3-3. All site locations on Odell Creek and paleochannel auger locations with elevation data shown by gradational color. Exposures with beaver deposits are shown with a star, triangles are stratigraphic exposures without beaver, and grey circles are paleochannel augering locations. The Shambow Creek fan is a minor fan coming out of the Centennial Mountains on the southwest corner of the map while the proximal part of the large, low angle Odell fan is to the south of this map area, but the fan shape is visible in the elevation data. Beaver-related deposition was identified by locating exposures of beaver generated willow cuttings—distinct layers of clumped sticks, some sticks clearly showing beaver-chewed ends—within terrace sediments. Locations with good exposures through terrace sediments without beaver-related deposition were also identified to assess overall fluvial behavior and identify periods when deposition was occurring along the river corridor.

At sites selected for detailed investigation, changes in sediment texture, organic content, color, gravel content, soil texture, soil carbonate and clay content, and Munsell color were recorded. At sites without exposures, we augered through sediment until the water table or coarse gravel prevented further progress. At auger sites major shifts in sediment texture were noted along with depth of samples collected for potential dating.

Dating of beaver cuttings and sedimentary sequences

Samples of material were collected for radiocarbon dating during stratigraphic investigations. The beaver cuttings, generated in the stream corridor and probably buried quickly are unlikely to have been reworked from older deposits and thus should reflect the age of surrounding sediments, as well as the timing of beaver activity. Because one of the goals of the study is to investigate the timing of beaver activity, any wood—including reworked wood—that shows signs of beaver activity provides data on beaver presence. Any rounded charcoal, indicating significant transport, was avoided and annually produced material such as conifer cones and twigs were selected when possible to avoid inbuilt age error.

Rootlets were carefully removed from all wood and charcoal prior to dating. Standard pretreatment procedures (Brock et al., 2010) were used prior to analysis. 66 samples were ^{14}C dated using accelerator mass spectrometry (AMS) (Dickin, 2005) at the University of Arizona AMS facility. Three samples were sent to Beta Analytic Incorporated and were dated using radiometric methods requiring larger sample size. Radiocarbon ages were calibrated to calendar years before present (cal yr BP) using CALIB and the IntCal13 calibration curve (Reimer et al., 2013). For simplicity of discussion within the paper, individual ^{14}C ages are reported using the median probability of the age distribution, providing a central point estimate (Telford et al., 2004). For interpretation, however, the full probability distribution was used. A curve of cumulative probability distributions was generated for 64 dates to examine the timing of beaver activity throughout the Holocene. False probability spikes, caused by temporal variability in ^{14}C production, were reduced using methods described by Persico and Meyer (2013), allowing for comparison with their beaver pond deposit data sets from Grand Teton and Yellowstone National Parks.

Results

Nature of beaver-related deposits

Thorough reconnaissance along both Odell Creek and Red Rock Creek revealed that beaver-related deposits are a relatively common feature within bank exposures along both streams. Because of better constraints on terrace elevations from airborne Lidar data, detailed analysis of beaver-related stratigraphy was conducted primarily on Odell Creek. Stratigraphic data was collected for 40 sites, 26 with evidence of beaver, 8 without such evidence and 5 augering locations from paleochannels (Figure 3-3).

The deposits indicative of beaver activity are composed of beaver harvested willow cuttings where accumulations of cuttings are a dominant feature within the stratigraphy and commonly can be followed laterally for at least 2 meters. The average thickness of beaver deposits is 30 cm (standard deviation = ± 16 cm, n = 22) where unit thickness could be determined. The lower boundary could not be determined for 10 units containing beaver deposits. Average exposure thickness is 165 cm (± 35 cm), so approximately 18% of total aggradation within the exposures is associated with evidence of beaver. Beaver activity is certain when beaver chew marks, or a cleanly cut angled end on one of the cuttings, can be identified which was possible at the majority of sites. At > 50% of sites with beaver deposits, the beaver cuttings are contained within a unit composed of sand sized sediment commonly overlying gravel. The underlying material, however, is often difficult to identify because the beaver cutting deposits are located at the base of many of the exposures. The predominant overlying materials are fine sands grading to thick packages of silt. Overall, the beaver sections show an upward fining trend, with gravel or coarser sands near the base, with alternating fine sands and silts overlying the beaver cutting deposits. Silt dominates the upper portion of the stratigraphy. There are, however, three sites (12R39,13O2 and 13O4) where the beaver cuttings are contained within clay-rich units showing clear redoxomorphic features, lacking notable stratification, but still suggestive of a pond environment for deposition. A fourth site has beaver cuttings contained within a layer of peat (OCP10) that accumulated in a bog environment. We interpret these four sites as wetlands associated with abandoned meanders. Previously identified Holocene beaver deposits have primarily been interpreted as beaver pond sediments (Kramer et al., 2011; Persico and Meyer, 2009; Persico and Meyer, 2013; Polvi and Wohl, 2012), indicated by fine grained deposition, thin laminations, a greater percentage of clay, along with gleying and redoximorphic features, and high organic content.

The remaining 22 sites containing beaver deposits are not consistent with a pond environment for deposition. Most of these sites are composed of predominantly upward fining sequences with beaver cuttings contained within sand-sized sediments that did not show the characteristic darkening of sediments from high organic content observed by Persico and Meyer (2013). The fine and medium sand, however, are consistent with those associated with modern beaver cutting accumulations on upper point bars where fine and medium sand are most commonly associated with accumulation of beaver cuttings. Gravel and coarse sand were observed more rarely (Figure 2-2). Site 13O12 is located at a site with clearly identifiable ridge and swale surface morphology that develops from lateral accretion of point bar sediments and so provides a clear reference for sedimentation that should be associated with the depositional environment of a point bar. Sites 12R40 and 13O6 show preservation of a gravel bar within the stratigraphy and again is consistent with point bar stratigraphy where sands and gravels grade into finer, structureless sediments composed primarily of suspended load (Nanson, 1980).

Beaver chronology

Thirty-six beaver generated willow cuttings were ^{14}C-dated. Two of the ages were post-bomb dates (12R37S1 and 12R38S1), so are related to modern beaver deposition and are not included in the overall chronology. The remaining 34 ^{14}C ages from beaver deposits along with the 30 non-beaver ^{14}C ages were calibrated. The resulting calibrated probability distributions were summed to create an overall cumulative probability distribution (Figure 3-4). The beaver-related deposits serve as a proxy for beaver activity in the Centennial Valley, while the non-beaver ages show how beaver activity varies from the timing of overall sediment deposition over the Holocene within the study area. Two beaver cutting ages are notably out of stratigraphic order, but both are included in the results (Figure 3-5). Evidence of beaver chewed wood is evidence of beaver activity in the system even if it is less clear how it relates to deposition of the surrounding alluvium. Ages of beaver cuttings often overlap in time or are inverted within the range of 1σ analytical error. The cutting ages are within a few decades of each other and make up a significant thickness (10 – 30 cm) at many sites.

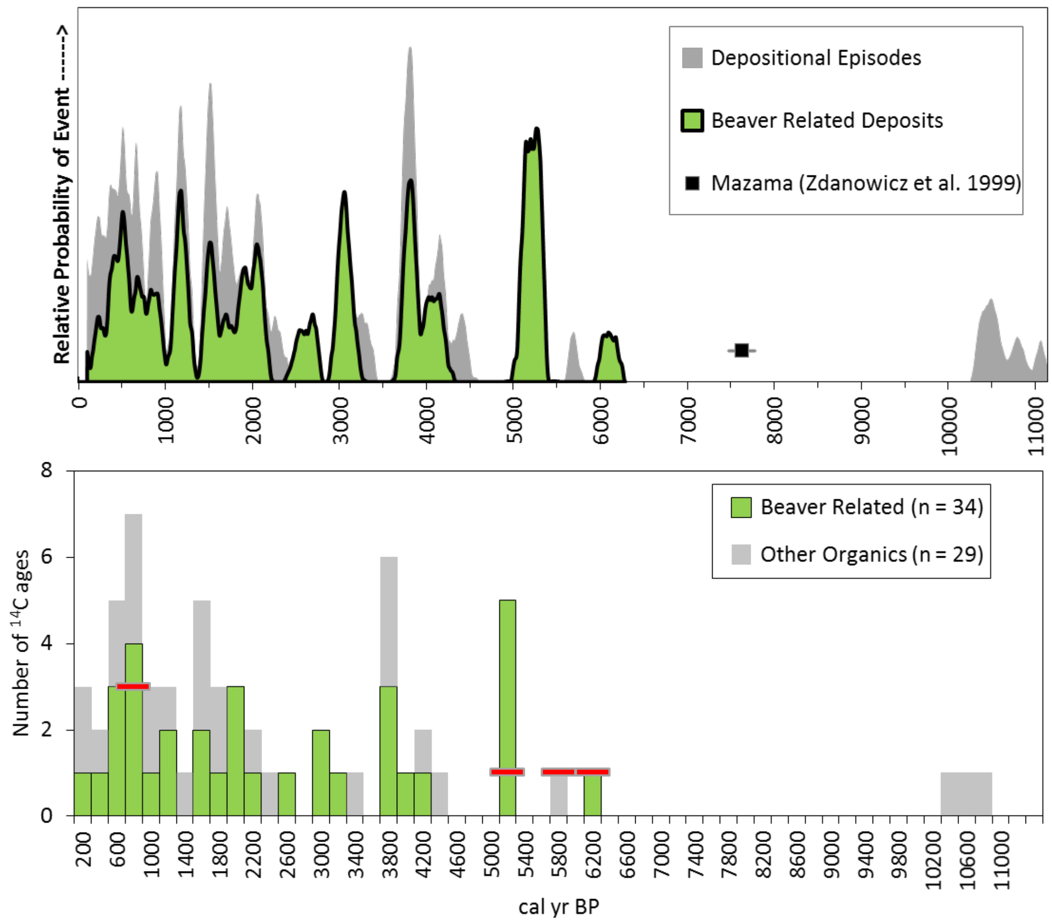

Figure 3-4. Cumulative probability distribution for all radiocarbon dates collected in Centennial Valley, Montana. Calibrated probability distributions for each sample ^{14}C age were summed and were smoothed using a 100-yr running mean. Depositional episodes includes all beaver and non-beaver samples while the beaver deposits only includes samples attributable to beaver. The Mazama tephra is found in Shambow Creek alluvial fan sediments exposed by Odell Creek incision. The most current date for the eruption of Mount Mazama is used here with error bars shown and is not assigned a range of probabilities in our data set. The histogram shows the number of ages from each type of sample contributing to the generation of the probability distributions by placing the calibrated median ages in 200-year age classes. The contributions of samples collected on Red Rock Creek is indicated by the height of the red bars on the histogram.

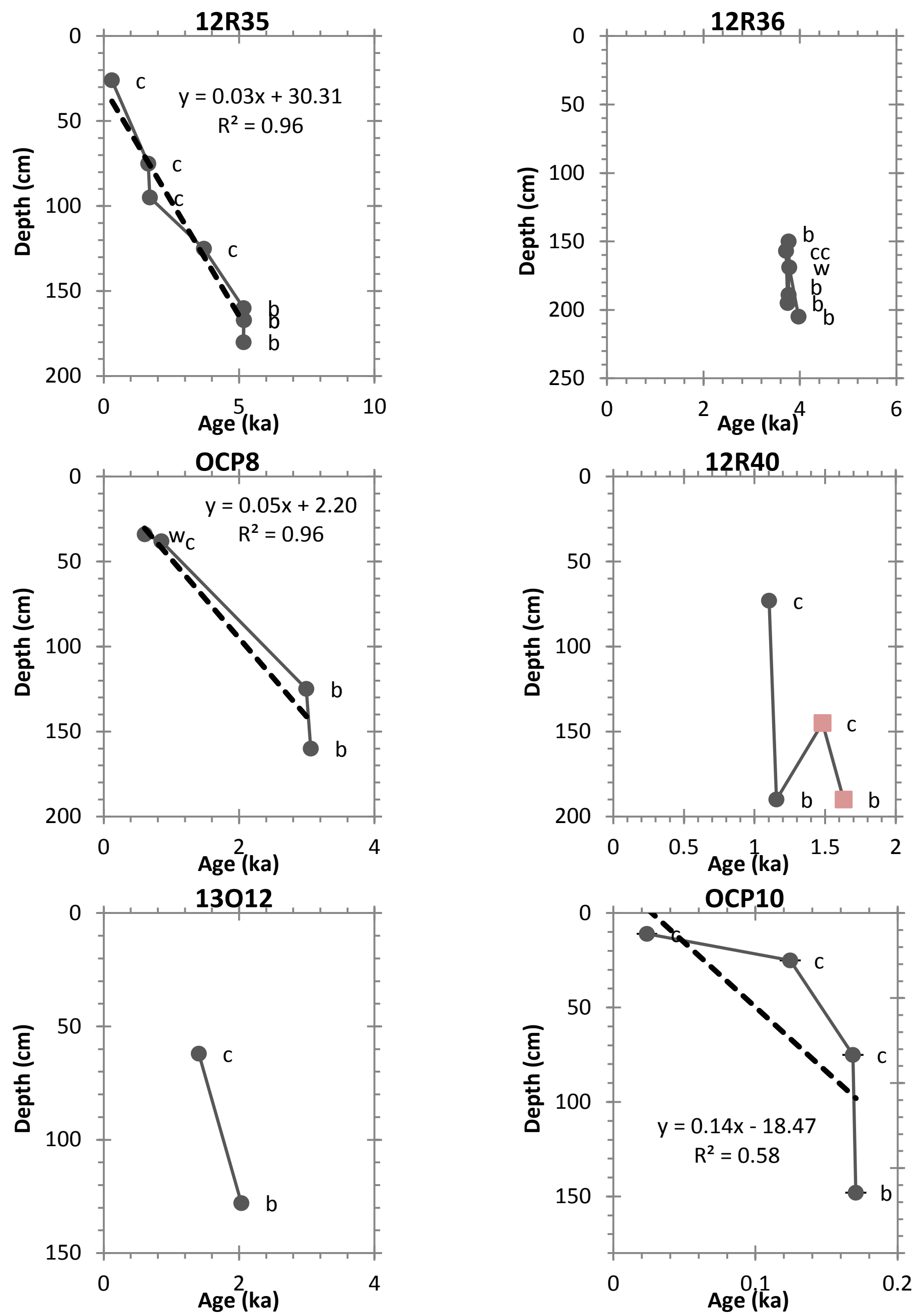

Figure 3-5. Plots of ages and depth of sampled material below terrace treads for all sites on Odell Creek with > 1 ^{14}C age. For sites with > 2 ages that are stratigraphically consistent, a line of best fit is shown, where the slope of the line provides an average vertical accretion rate and the R^2 value indicates the consistency of that rate over the time interval. Data points represented by red squares are ages that are out of stratigraphic order (n = 5). The 1σ analytical error is shown, but in most cases is less than the size of the plotted points. The letters next to each data point indicate the sampled material: b – beaver-chewed wood, c - charcoal, w – wood, cc – conifer cone, t - tephra

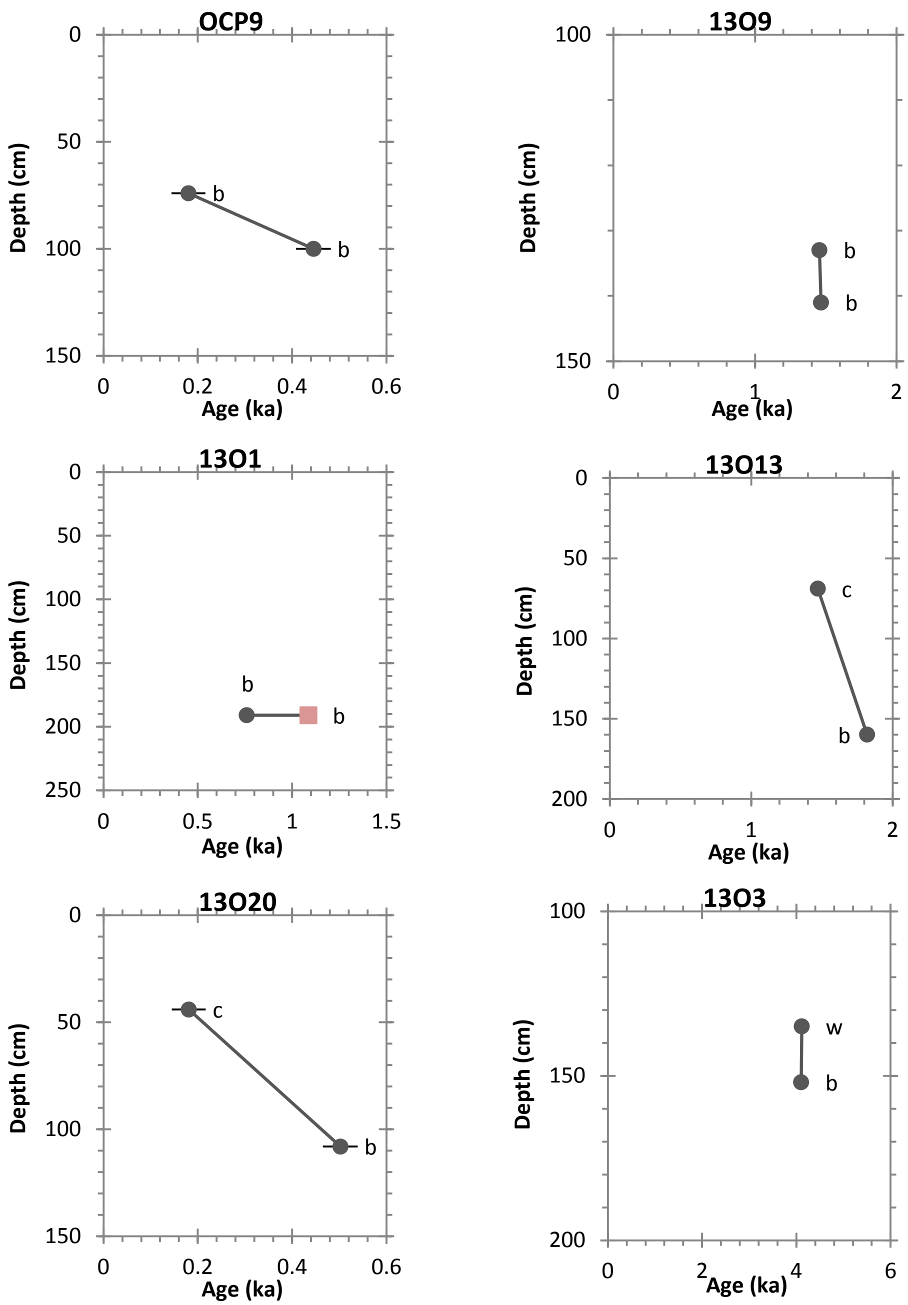

Figure 3-5 (continued). Plots of ages and depth of sampled material below terrace treads for all sites on Odell Creek with > 1 ^{14}C age.

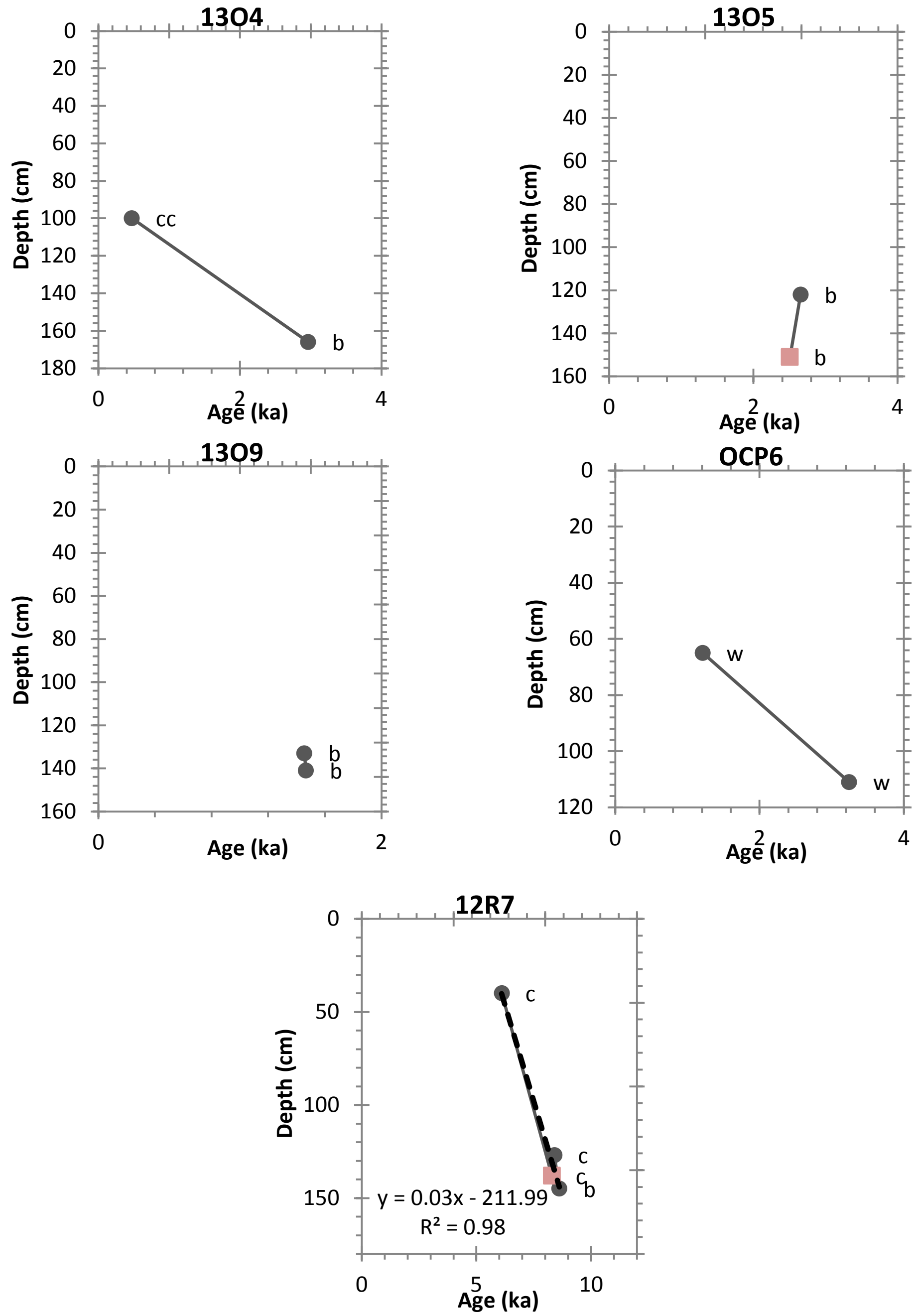

Figure 3-5 (continued). Plots of ages and depth of sampled material below terrace treads for all sites on Odell Creek with > 1 ^{14}C age.

The majority of beaver activity is clustered in the late Holocene with the only notable gap from 5000 cal yr BP – 4300 cal yr BP (Figure 3-4). During this episode, however, there is evidence of alluvial deposition. There is no evidence of any deposition along either Red Rock Creek or Odell Creek from 7600-6250 BP. Beaver deposits are, however, represented within all terrace deposit sequences. The oldest samples dated along Odell Creek are from the Shambow Creek alluvial fan sediments that show excellent preservation of organic material (Site 12R7), but no evidence of beaver.

In addition to the 36 ages collected on beaver cuttings 30 other samples of wood, charcoal and conifer cones were radiocarbon dated. One of the charcoal samples is out of stratigraphic order— dating to 8360 cal yr BP, but lying stratigraphically above two dates clustered around 4100 cal yr BP, and must have been reworked, so is not included in the results.

Odell Creek Paleochannels

The low-gradient fluvial fan of Odell Creek exhibits paleochannels across the surface that show a consistent meandering pattern (Figure 3-4). The modern channel occupies a channel belt, 150 – 700 m wide while paleochannel belts are on average 350 m wide with wider channel belts toward the west, closer to the modern channel. Paleochannel fills are inset below the upper level of the fan from < 1 m to 2.6 m below the surface. Five paleochannels were augered where it appeared that berms from beaver dams were present (3 sites) or sites that might help constrain the timing of incision of the modern channel belt (2 sites). Only one sample was able to be dated from the paleochannels. Site 13OP23S1, associated with the highest inset terrace of the modern channel, had a median age of 4365 cal yr BP at a depth of 90 cm below an approximately 25 cm thick A horizon. The water table was reached at 160 cm, preventing further augering. At sites on the fan surface, channel gravels were encountered between 111 and 186 cm depth, preventing deeper augering. Fine sediment dominates the paleochannel fills.

Odell Creek Terraces

The modern channel is incised to a maximum of 5.1 m below the Odell Creek fan surface. Odell Creek has also incised into the adjacent, and smaller, Shambow Creek tributary fan (Figure 3-3). The incision into the Shambow fan has exposed the oldest dated material within the investigated alluvial sequence. The longest period without any recorded deposition exists between the deposition of the 7627 ±150 BP Mazama tephra, 40 cm from the top of the Shambow fan exposure, and the oldest beaver deposit with a median age of 5170 cal yr BP near the base of an exposure of a high terrace (Figure 3-4).

Within the modern channel belt terrace elevations vary from 0.8 – 1.8 m above the bankfull channel. Terrace elevation does not clearly indicate the age of the underlying deposits, with large gaps in ages occurring between samples collected in the lower versus the upper part of terrace deposits. Additionally, there is significant overlap in the timing of deposition between terraces of different elevations (Figure 3-6).

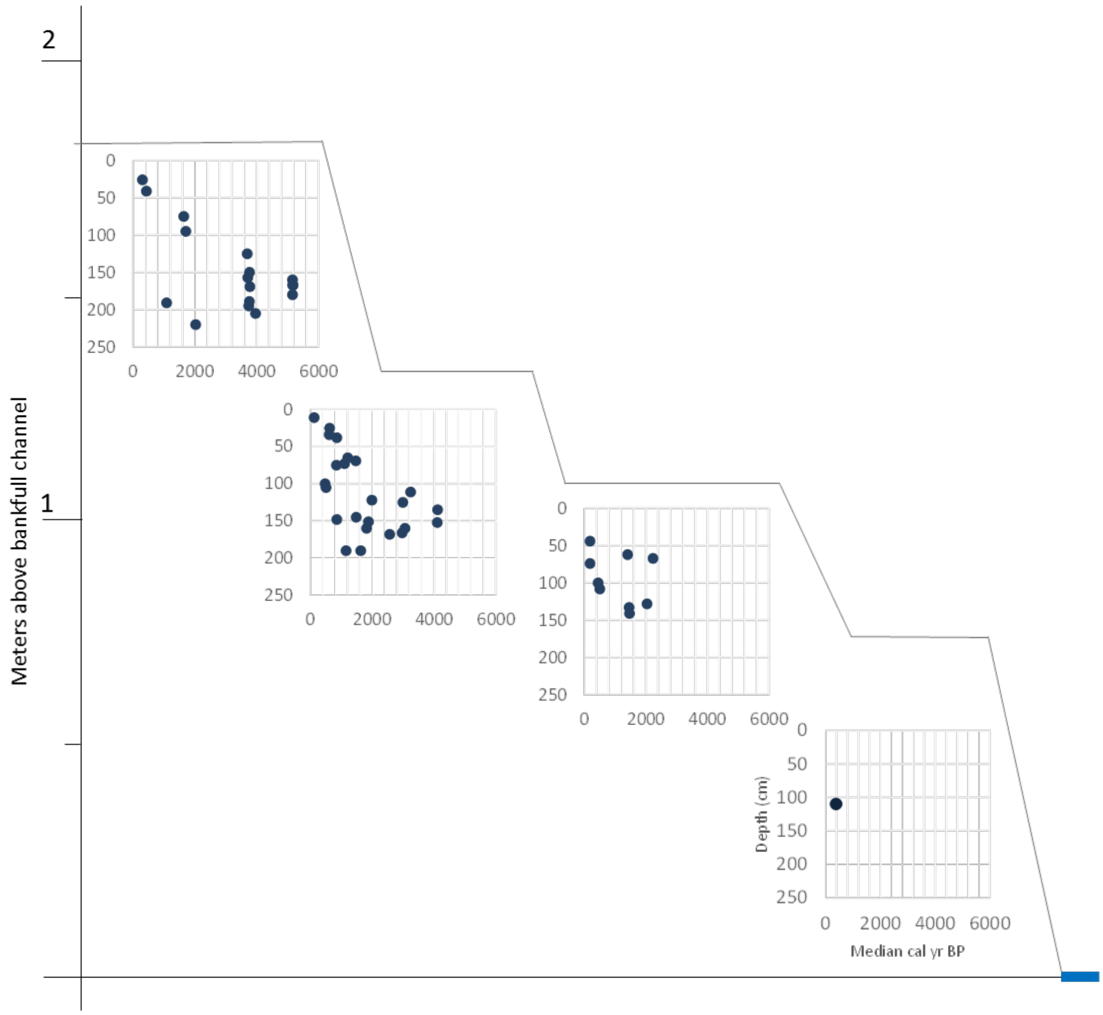

Figure 3-6. A diagrammatic view of terraces shown with elevation above bankfull water surface indicated by the level of the terrace tread. Differences in elevation are subtle, spanning only 1 m from the highest to lowest terrace tread, so relatively minor local adjustments in base level can cause overbank flooding on even the highest surfaces. The plots show ^{14}C median ages for material dated within the terrace deposits, plotted relative to the sample depth below the terrace tread. All plots are at the same scale so depth and ages across all sites can be compared. Forty-two ages from 13 individual sites are stratigraphically consistent (figure), so the scatter in the ages within terraces of the same elevation, show that terrace tread elevation is a poor predictor of underlying deposit age.

Linear estimates of sedimentation rates within terrace deposits with > 2 ^{14}C ages show a wide range of vertical accretion rates indicating variability in deposition rates within and between sites (Figure 3-5). The average across all sites is 1 mm/ yr (±0.7 mm/yr). The deposition within each individual terrace sequence, however, is not occurring at a constant rate. There are clear periods of rapid deposition and then gaps where the apparent deposition rate drops dramatically. If deposition is constant, then the slopes of deposition rate should be close to a straight line, but that is not the case where r^2 values are <0.96 (Figure 3-5). The apparent rate changes are likely from periods of non-aggradation or could represent periods of erosion that did not erode to the depths of the oldest sediments before another episode of deposition ensued.

When a site on a floodplain is not actively accumulating sediment, then soil development occurs, so buried A horizons should be evident within the stratigraphy (Bridge, 2003). 22 sites have at least one buried soil. The soils are usually thin (5 – 20 cm), dark and organic rich (moist Munsell colors: 10YR 2/1 and 10YR 3/2). Sites 12R35 and OCP8 show large time gaps of approximately 2000 years in their radiocarbon dates. OCP8 very clearly shows buried soil horizons between the time breaks. The soils are covered by fine sand lacking any soil development. At 12R35 soil units are covered by silt and diatomaceous pond deposits (Figure 3-7). Thin buried, organic rich A horizons are common in the exposure. The lower part of the exposure is dominated by gravel that grades to clayey sand. Based on the dated beaver cuttings that were collected over the span of 20 cm of section, deposition occurred relatively rapidly (20mm/yr). While 100 cm up the section, where deposition again appears continuous, the rate was much slower (3 mm/yr).

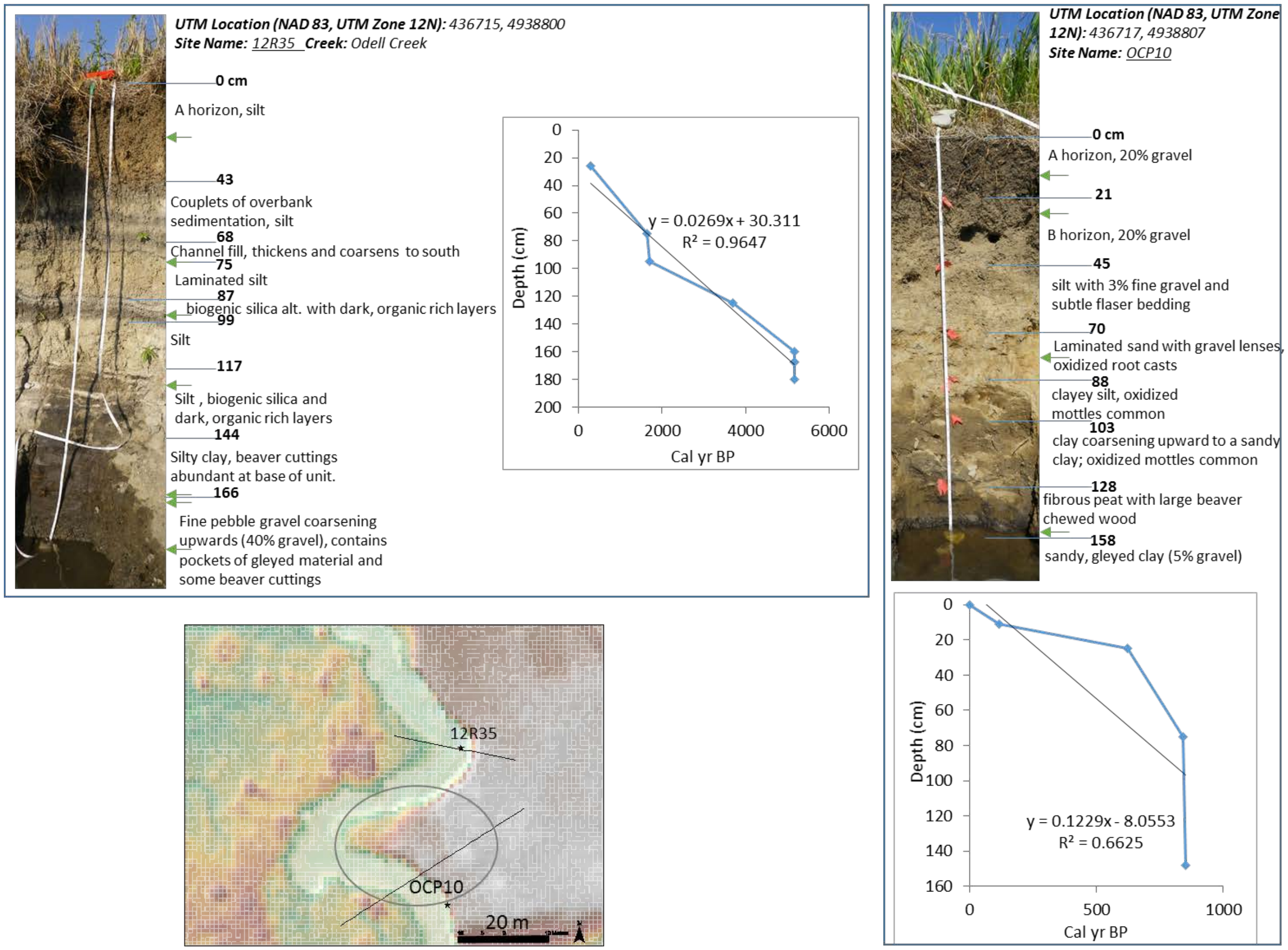

Figure 3-7. An example of a buttress unconformity along Odell Creek. The small map from Lidar elevation data shows the proximity of the two sites. There is a subtle erosional feature in the circle on the map representing the erosion and then refilling of the area with the much younger alluvium of OCP10. Age-depth plots of median calibrated ages are shown adjacent to the photo of each exposure. Linear trend lines are plotted to give an average depositional rate provided by

the slope of the line (equation), but note that there are periods of time when sedimentation proceeds rapidly such as at the base of the exposures with beaver cutting deposits, and when rates are much slower and large time gaps at 12R35. Name and locations of sites are noted at the top of each stratigraphic column. Depths of stratigraphic unit breaks are given in centimeters along with brief descriptions of the major features of each unit. Locations of samples collected for ^{14}C dating are marked with green arrows and correspond to the samples in the age-depth plot. Both of these sections have representation of ponding and high water tables, but note how different the stratigraphy and ages are between the two sites.

Gaps in deposition in terrace profiles on Odell Creek that are not represented by buried soils may represent erosional unconformities or be of short enough duration that no significant pedogenesis occurred during the interval. An example of such a relationship, a buttress unconformity, exists between sites OCP10 and 12R35. The two sites exhibit markedly different stratigraphy at adjacent sites with a difference in elevation of approximately 20 cm, yet the timing of deposition for the underlying alluvium varies by 4300 years (Figure 3-7).

The vertical stacking of deposits, particularly the dominance of silt and fine sand in the stratigraphy, show that accretion by overbank floodplain sedimentation is an important process in this beaver dominated stream. In most meandering systems, however, lateral accretion is the dominant depositional mode (Bridge, 2003). To estimate lateral accretion rates, two pairs of samples were collected along Odell Creek. At the first pair of sites, 13O6 and 12R40 (2565 BP and 1631 cal yr BP) there was a clear point bar sedimentary sequence exposed, suggesting the age relationship. The second pair, 13O11 and 13O12 (2230 and 1406 cal yr BP) were selected based on observed scroll bar morphology on the terrace surface allowing identification of the younging direction. The samples came from sites parallel to the channel migration direction. Accretion rates were consistent between the two pairs, lateral rates are faster than vertical rates, averaging 7mm/yr (±0.2 mm/yr) while vertical rates are 1 mm/ yr (±0.2 mm/yr). For comparison we calculated lateral migration rates for 12 meanders along modern Odell Creek using the erosional polygon method described by Micheli et al (2004). The channel centerlines were mapped using Google Earth Time Series imagery from 1995 and 2014 for our study area. Horizontal error in rectification between the images was accounted for using four control points with a mean error of 0.25 m/yr (standard deviation = 0.04 m/yr). Error in the measurement of the channel centerline has been previously reported as approximately 5% of the channel width (Micheli et al, 2004), so 0.02 m/yr for Odell Creek, contributing to total measurement error of 0.27 m/yr. Mean migration rates over the 19 year interval are 2.54 m/yr (standard deviation = 1.16 m/yr), so much greater than that recorded in the radiocarbon ages, but note that rates averaged over long time periods are biased toward lower rates (Knox, 2006).

A few sites have preserved evidence of long-lived oxbow ponds, persistent wetlands and low-lying floodplains indicated respectively by biogenic silica (e.g. Clarke, 2003), peat and cyclic A/C soil horizons (Bridge, 2003). Diatomaceous units were identified within the highest terrace at 12R35. The oldest unit containing the biogenic silica has a median age of 3700 BP (sample: 12R35S8) at a depth of 100 cm. Another, thinner unit containing biogenic silica, is found at 90 cm depth and dates to 1710 cal yr BP (sample: 12R35S9). At OCP10 the beaver cuttings were contained within a fibrous peat. The beaver cuttings found within the peat have a median age of 850 cal yr BP. Four sites contained thin, organic rich, buried soils alternating with layers of fine sand lacking any pedogenic properties. The cyclic A/C soil horizons are indicative of frequent flood events (Bridge, 2003). The flood cycles are seen in the Shambow Fan exposure (12R7), OCP10, 12R35 and within 4 other exposures representing various time periods. The evidence of oxbow ponds, wetlands and an inundated floodplain indicate that an active channel with a high water table has been common along Odell Creek at several periods in the past and is consistent with observations of the modern channel.

Consistency in fluvial response between Odell Creek and Red Rock Creek

Six samples along Red Rock Creek were dated. All 6 ^{14}C calibrated probability distributions are included in the curve of the summed probability distributions. Only 2 of the dates occur during a period when there is no evidence of deposition along Odell Creek (Figure 3-4). The rest of the dates correspond with periods of deposition along Odell Creek. The two older samples are found in the deposits of 1.5 m terraces, both sites exhibit at least 2 buried soils in the stratigraphy.

Discussion

Nature of beaver related deposits

We have identified three possible modes of preservation for the beaver deposits: (1) meander cut-off, (2) partial dam breaching and (3) accumulation of beaver cuttings on point bars. During the 10 year observation period, three sites avulsed away from a dam site, abandoning a portion of the channel and preserving an intact dam. The intact dams became buried in sediment as the abandoned channel filled with sediment. Although there is some stratigraphic evidence of ponding, this mode of preservation is relatively rare within our study area. In contrast, the majority of beaver-related deposits reported by Persico and Meyer (2009; 2013) are preserved pond deposits. Odell Creek, with a larger basin area than the streams studied by Persico and Meyer (2009; 2013), likely limits preservation of pond sediments (Levine and Meyer, 2014) (Figure 3-1).

The preservation of partially breached dams that remain attached to one bank is more common; during reconnaissance for this study in the spring of 2012 the creek contained 5 active dams and 6 partially breached dams. On average there are 6 active dams on Odell Creek at any given time with an average dam longevity of 3-5 years. Some of the dams are fully breached, but partially breached dams act to induce meandering and promote sediment deposition around the dam remnant (Levine and Meyer, 2014), so that eventually the dam remnant becomes incorporated into the floodplain, preserving the willow cuttings that compose the dam. The stratigraphy at partial breach sites should be relatively consistent with what would be expected at a point bar site since the dam remnant promotes meandering and point bar deposition. Incorporation of some clay from beaver pond deposition near the base of the deposit —associated with the willow cuttings composing the dam remnant—might be expected in this case.

Observations of the modern channel show that beaver cut willow cuttings commonly accumulate on upper point bars and are likely to be buried and preserved by point bar sedimentation. In the modern Odell Creek channel, 80% of 45 point bar locations over three 800 m reaches contained beaver harvested willow cuttings (see Chapter 2 for detailed methods). The stratigraphy shows that beaver cuttings are more common than can be explained by dam preservation, even from partially breached dam sites, and the stratigraphic data is consistent with point bar sedimentation suggesting that accumulations of beaver-chewed willow cuttings is a common process on Odell Creek from the Mid-Holocene to the present.

The few beaver cuttings that are out of stratigraphic order, likely represent transported cuttings. The fact that current erosion is remobilizing beaver cuttings is evidence that remobilization of older wood can occur. Just like contemporary cuttings, these older cuttings can accumulate on point bars and could be reburied with younger cuttings surrounding them. At site 12R40 younger and older ages are at the same depth, the younger age should be the age accepted for the deposit as the older one likely is a remobilized cutting.

Beaver related deposits within the overall stratigraphy and geomorphology

Beaver deposits are relatively widespread, and are preserved from the mid-Holocene to the present, suggesting the importance of beaver activity to the function of the study streams. The story of beaver contribution to valley floor morphology is more complex than stacked beaver pond deposits hypothesized by Ives (1942), granted Odell Creek and Red Rock Creek—although low gradient—are larger scale streams than those expected to accumulate beaver pond sediments (Figure 3-1). Approximately 18% of the deposition within terrace alluvium is associated with beaver activity and beaver-related deposits are represented in terraces of all elevations. Aggradation in the channel from beaver activity appears limited by frequent breaching where in-channel sediment is rapidly removed from the modern Odell channel following the breaching of beaver dams (Levine and Meyer, 2014). The only cases of permanent aggradation in the channel occur from channel abandonment. Sediment deposited on the floodplain by beaver dam induced flooding, however, remained stored on the floodplain, contributing to vertical aggradation (Westbrook et al., 2006; Levine and Meyer, 2014). Along modern Odell Creek, floodplain aggradation amounted to ~66 mm/ yr in a reach with an active dam (Chapter 1), a high rate of episodic accumulation. For comparison, Brandywine Creek, Pennsylvania with a drainage area of 743 km^2, and a long history of land clearing, has an aggradation rate of 23 mm/yr averaged over the period from 1912 – 1981 (Pizzuto, 1987). The presence of thick overbank deposits in the stratigraphy is indicative of aggradation

(Bridge, 2003), although in the case of beaver dams, that aggradation may occur episodically and for relatively short duration.

The long-term trend has been one of incision, with the modern channel incised up to 5 m below the fan surfaces. The majority of the incision occurred sometime after deposition of the Mazama ash (7627 ±150 BP). Lower Red Rock Lake, the terminus for Odell Creek, reached its present level around 10,500 BP (Mumma et al., 2012), so system wide base level has remained relatively consistent. The oldest terrace on Odell Creek shows beaver related deposition around 5200 cal yr BP. The lack of any beaver-related deposition in the early Holocene exposure does not necessarily mean that beaver were not present. The existence of beaver deposits in Red Rock Creek during the latter part of this interval suggests that beaver were likely present in Odell Creek as well. In a laterally migrating river system, destruction of older deposits is probable (Clevis et al., 2006; Lewin and Macklin, 2003). The early Holocene incision into the fan surface probably produced a narrow channel belt initially, making preservation of alluvium unlikely.

Once the major period of incision occurred, Odell Creek has had minor episodes of deposition and erosion throughout the rest of the Holocene, broadly coincident with episodes of lateral migration of stream channels in northern Yellowstone National Park (Meyer et al., 1995). Maximum cutting and filling, based on terrace elevations, only amounts to ± 2 m. Beaver evidence exists throughout the various filling cycles from the mid-Holocene to the present and may have existed in more of the alluvial sequences than we have accounted for because wood will be preserved for only a short time if water tables drop and wood is exposed to air (e.g. Wohl et al., 2012). There are several sites that show this could be the case, sites where beaver cuttings appear abundant, but the wood itself has been oxidized. Overall, vertical change within the channel belt is relatively minor and the long time spans represented within individual terrace deposits show that deposition is episodic and that the deposition rate may also be related to the shifting location of the channel relative to a given site (Bown and Kraus, 1987, Figure 3-5, Figure 3-6). Point bar sedimentation occurs rapidly, but as the channel migrates away from the site it may only be impacted by occasional overbank flows with very low sedimentation rates.

Our interpretation that the majority of beaver deposits represent point bar deposition suggests that beaver activity may impact lateral accretion as well as vertical filling. The evidence of persistent ponding and wetlands at sites OCP10 and 12R35 are a fundamental indicator of mobile river channels (Hooke, 1995). The beaver presence should enhance flooding in abandoned oxbows by elevating groundwater levels (Westbrook et al., 2006) and may even accelerate the channel migration that generates floodplain wetlands (Chapter 2).

Other stratigraphic information also shows the importance of lateral accretion to floodplain development. Terraces that contain the oldest basal ages are commonly covered by much younger deposits, indicating that the older, higher elevation terraces often accumulate sediment from adjacent younger floodplains (Figure 3-6). Similar stratigraphic relationships have been observed on other meandering rivers (e.g. Brakenridge, 1984; Lewin and Macklin, 2003). The existence of buttress unconformities (Figure 3-7) and large gaps in time in the stratigraphy are also consistent with migrating rivers, where upper portions of the stratigraphy may be removed and replaced by younger alluvial units (Lewin and Macklin, 2003). Our measurements of lateral deposition are limited, but on Odell Creek lateral deposition on centennial time scales is ~7 times the vertical rate. The interpretation that beaver-related deposits on Odell Creek are mostly from beaver cuttings floating downstream and accumulating on upper point bars, or represent breached dam remnants, means that at least some of the lateral deposition may be enhanced by beaver activity. The additional indirect effects of beaver enhancement of riparian plant recruitment, with subsequent changes in floodplain and channel roughness, is even more difficult to quantify, but should also alter sedimentation and channel migration rates (Chapter 2). The magnitude of beaver related impacts on channel migration rates, however, remains to be tested.

Beaver chronology and climatic influence

The lack of any significant gaps in the record of beaver related sedimentation in the late Holocene, particularly from ~4200 cal yr BP to the present, indicates that the Centennial Valley stream systems had enough water to support vigorous willow communities even during relatively dry periods. Higher stream power did not preclude beaver from the system during pluvial periods (Figure 3-8). Most notably, beaver-related deposits exist during the Medieval Climatic Anomaly, a period of warming and drying that occurred in western North America between ~900 and 1300 AD (Cook et al., 2007). The period corresponds with a peak in fire related sedimentation in Yellowstone National Park (Meyer et al., 1995). During this same period, there is a notable lack of beaver-related deposition in northern Yellowstone National Park and in Grand Teton National Park (Persico and Meyer, 2013). Persico and Meyer (2013) hypothesized that larger streams may become refugia for beaver during warmer climate episodes. Our Centennial Valley study streams support this hypothesis. The Centennial Valley streams have basin sizes that must be greater than some critical value, where perennial flows were maintained even during drought periods (Figure 3-1). Additionally, both the Odell Creek and Red Rock Creek watersheds are high elevation; > 50% of the watersheds are over 2100 meters and contain large areas of north facing slopes that have low incoming solar radiation values. In a region where summer stream flow is dependent on the accumulated winter snowpack (e.g. Huerta et al., 2009), we hypothesize that basin orientation that retards snowmelt and reduces evapotranspiration may be an important factor for maintaining perennial flows throughout the year.

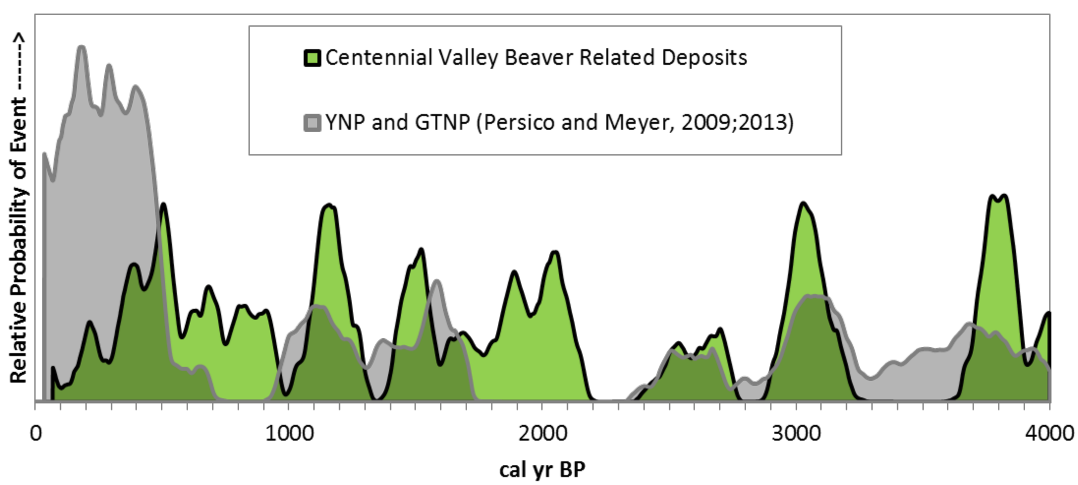

Figure 3-8. A comparison of the chronology for Centennial Valley beaver related deposits (n = 28) in streams of Yellowstone National Park (YNP) (n = 34) and Grand Teton National Park (GTNP) (n = 60). Calibrated probability distributions for each sample ^{14}C age were summed and were smoothed using a 70-yr running mean. The minima in beaver deposits in YNP and GTNP streams centered around 850 and 2100 cal yr BP, associated with several paleoclimatic proxies suggesting periods of drought, are not observed in the Centennial Valley where beaver deposits exist during these intervals

Conclusions

Beaver-pond deposits exist, but are an uncommon feature in the stratigraphy of Centennial Valley streams. Stacked pond sequences, suggesting valley filling by beaver, were not observed. The modern and Holocene beaver-related deposition indicate that preservation of beaver generated willow cuttings is associated with burial during upper point bar sedimentation within a laterally mobile stream system. The accumulation of cuttings may be generated by either downstream transport—and subsequent accumulation of cuttings on existing point bars—or a bank-attached breached dam portion that has promoted development of a point bar.

Through dam building and herbivory, beaver do affect, at least to some degree, vertical and lateral sedimentation rates. The presence or absence of beaver activity, however, is not responsible for valley-wide aggradation and degradation. Our data indicate that, at least on our larger Centennial Valley streams, beaver activity is acting within larger scale autogenic and allogenic processes that control meandering river behavior and valley morphology.

Our results also show that beaver and associated riparian habitats were able to persist during warm and dry times in the late Holocene within the larger, north facing basins of the Centennial Valley. Understanding the variables that contributed to maintenance of perennial flows in Odell Creek and Red Rock Creek, along with developing beaver chronologies elsewhere, could aid in understanding thresholds for riparian persistence. This knowledge may prove useful in the coming decades as management agencies and human water needs come up against changing climatic conditions.

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