Stream channel adjustments and persistence of change in response to beaver damming on a fluvial fan, Odell Creek, Montana

Rebekah Levine

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STREAM CHANNEL ADJUSTMENTS AND PERSISTENCE OF CHANGE IN RESPONSE TO BEAVER DAMMING ON A FLUVIAL FAN, ODELL CREEK, MONTANA

BY

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B.A., GEOSCIENCES AND AMERICAN STUDIES
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2007

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Earth and Planetary Science

The University of New Mexico
Albuquerque, New Mexico

May, 2011
DEDICATION

To the mountains and landscapes that continue to fascinate me and to the woods and rocky shores of Mere Point that nurtured my beginnings.
ACKNOWLEDGMENTS

I extend many thanks to my advisor Dr. Grant Meyer for believing in me and giving me the reigns to take charge of my own project. Your guidance has pushed me to become a clearer thinker and a keener observer of the Earth’s surface. I strongly value your commitment to excellence and your belief in your students’ abilities. Thanks also to Dr. David Gutzler and Dr. Gary Weissmann for support and encouragement throughout my time at UNM. Your thoughtful comments about my research and life as a graduate student are greatly appreciated.


I extend great appreciation to Felisha Yazzie for taking time away from her 2 year old daughter to come to the remote Montana wilderness to be part of this project. Your dedication to hard work is phenomenal. Thanks for being adventurous! A special thanks also to Michelle Gauthier for her incredible enthusiasm, without it I would have been scrounging for help in the field. Michelle’s hard work and excitement about geology made the mosquitoes almost disappear (almost!). Cheers to the rest of the hearty field helpers, Gina, Tim, Austin, Chad, Brendan, Erin, Della and Kyle. Kyle, thanks for your unfailing support. I also want to extend appreciation to my fellow students in EPS who have been great sounding boards and cheerleaders: Lyman Persico, Ben Swanson, Sarah Keller, Nina Lanza and many others.

Cheers to my family and all others who have encouraged and believed in me.
STREAM CHANNEL ADJUSTMENTS AND PERSISTENCE OF CHANGE IN RESPONSE TO BEAVER DAMMING ON A FLUVIAL FAN, ODELL CREEK, MONTANA

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M.S., Science Education, Montana State University, 2007
M.S., Earth and Planetary Sciences, University of New Mexico, 2011

ABSTRACT

Beaver damming in streams is thought to increase bed elevation through in-channel sediment storage, thus beaver reintroductions are used as a river restoration tool to repair incised stream channels. However, effects of beaver damming are dependent on specific stream hydrologic and geomorphic characteristics. Data on dam effects, especially the longevity of dam effects, are limited. To investigate whether damming promotes channel aggradation and creates persistent geomorphic change, 9 reaches containing 46 cross-sections were studied on Odell Creek at Red Rock Lakes National Wildlife Refuge, Centennial Valley, Montana. Odell Creek has a basin area of 46 km², a snowmelt-dominated hydrograph and peak flows between 2 - 10 m³/s. Odell Creek flows down a fan with a decreasing gradient (0.018–0.004), terminating in Lower Red Rock Lake as a mostly single-thread, variably sinuous
channel, except where beaver damming has caused overbank flooding, creating multi-thread channels. The study reaches represent downstream variability including non-dammed sites and beaver dams built and abandoned over the last decade. In-channel sediment characteristics and storage were investigated using pebble counts, fine sediment surveys, sediment mapping and one dam breach survey. Volumes of fine sediment (≤ 2 mm) stored behind beaver dams range from 40 – 463 m³. Deposition occurs from decreased water surface slope, shear stress and velocity upstream of dams. However, high flows do facilitate some transport of suspended sediment over dams. Observations of abandoned dam sites and a dam breach revealed that much of the sediment stored above beaver dams is evacuated downstream quickly following a breach, but that a patchwork of preserved sediment may remain for several years following a breach and may be stored for longer periods on the floodplain. Persistence of sediment within the main channel on Odell Creek is limited by frequent breaching (<1 – 5 years), so a long-term rise in bed elevation from beaver related channel filling is not likely if current processes continue. However, if beaver remain in the system, sites along the stream will be in different stages of beaver occupancy, promoting maintenance of habitat heterogeneity and invigorating riparian zones through overbank flow along the stream corridor.
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INTRODUCTION

North American beaver (*Castor canadensis*) and their dams are believed to have been a more significant component of fluvial systems prior to European colonization and extensive beaver trapping (Pollock et al., 2003; Wohl, 2006). The boggy, flooded landscapes and extensive riparian zones associated with beaver are likely to have influenced the fluvial landscape more significantly than they do today. Pre-colonization beaver populations are estimated at between 60 – 400 million animals (Seton, 1929; Naiman et al., 1988), compared with today’s estimates of 6 -12 million (Naiman et al., 1988). Like large woody debris (LWD), beaver dams increase low-velocity areas, adding cover for fish, and increasing habitat for emergent aquatic insects (Gurnell, 1998; Marcus et al., 2002). Emergent aquatic insects fuel both the aquatic and terrestrial food webs (Nakano and Murakami, 2001). The idea that beaver may promote a strong base for both food webs was supported in southwestern Wyoming where the introduction of beaver was associated with a 20% increase in avian species richness (Apple et al., 1984). Beaver damming has also been shown to increase riparian vegetation, raise water levels, attenuate flood peaks and alter sediment transport and storage patterns (McCullough et al., 2005).

It has been suggested that the cumulative effect of sediment stored upstream of beaver dams increases channel bed elevation (Pollock et al., 2007). Thus, the near eradication of beaver throughout the United States has been implicated for increased rates of stream incision with the loss of in-channel sediment storage promoted by their dams (e.g. Butler and Malanson, 1995; Pollock et al., 2007). In the western United States, and elsewhere, fluvial incision is cited as a cause for the loss of wet meadow habitat and a decline in aerial extent of riparian zones (Marston, 1994). Along with extirpation of beaver (e.g. Wohl, 2006), incision in the
intermountain west has alternatively been attributed to grazing, agricultural land use as well as shifts in climate (e.g. Meyer et al., 1995; Miller et al., 2004). Ecologists have suggested that incision is to blame for fish species decline (Shields et al., 2008) as well as for overall negative impacts on riparian health (Pollock et al., 2007). Riparian degradation and incision has also been specifically associated with the loss of beaver in Yellowstone National Park (Wolf et al., 2007). Additionally, the decline of riparian vegetation promotes a more xeric species assemblage which may exacerbate erosion problems by decreasing bank strength (Micheli and Kirschner, 2002).

With beaver loss being one of the suggested reasons for the incision of stream systems, a potential solution to counteract incising streams is re-introducing beaver and promoting beaver dam building at sites where riparian zones are limited by stream incision. Dam building should promote a rise in stream base levels and effectively increase floodplain-stream connectivity (McCullough et al., 2005; Pollock et al., 2007). Using beaver as river engineers is a more natural solution than the intensive and disruptive creation of an inset floodplain using heavy equipment (Pollock et al., 2007). The use of beaver for river and riparian rehabilitation has been implemented at some sites and met with successful re-colonization of beaver, local increase in water table elevation and reinvigoration of riparian vegetation (Apple et al., 1984; Albert et al., 2000; Demmer and Beschta, 2008). The success of these projects has been attributed to aggradation of sediment upstream of dams (Pollock et al., 2007).

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 m³) of total volume of sediment stored behind individual dams. In most of this work variations in hydrologic and geomorphic controls, such as stream size, have not been considered, so specific reasons for variations in effective sediment storage have not been investigated. There has also been a lack of data collected about the persistence of the sediment stored upstream of an individual dam. However, Westbrook et al. (2010) directly measured sediment accumulations on terraces following a dam breach and found that at their site, on the Upper Colorado River, the bulk of sediment accumulation occurred as overbank deposition at an elevation equivalent to a 200 year flood event. The dam breached in spring flows and no assessment of in-channel sediment volumes, either before or after the breach, was conducted.

Despite having a limited scope of understanding of sediment dynamics from studies of streams with active beaver dams, there has been interest in the longer term effects that beaver damming may have on alluvial valley formation. It has been hypothesized that beaver have the potential to form extensive meadows and aggrade alluvial valleys (Ruedemann and Schoonmaker, 1938; Ives, 1942; Butler and Malanson, 2005; Pollock et al., 2007). Significant quantitative data to support this hypothesis is lacking, but a recent study tested this hypothesis in the Northern Range of Yellowstone National Park by investigating the stratigraphy of Holocene fluvial deposits for evidence of long-term beaver aggradation and subsequent incision in channels following beaver abandonment (Persico and Meyer, 2009). The study found that beaver pond aggradation was limited, occurring over ~29% of the mainstem channel network with a maximum thickness of < 2 m.

In addition to the studies of beaver induced sedimentation, there has been extensive work done by ecologists investigating beaver dam effects on ecosystem function (e.g. Beier and
Barrett, 1987; Cooke and Zack, 2008), but only a limited number of studies directly address the geomorphic impact that beaver damming has on streams (Gurnell, 1998), particularly beyond the lifetime of an individual dam. 

We know that beaver dams interact with the fluvial system to alter geomorphic rates of change (Viles et al., 2008), but 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). In order for managers to make informed decisions about using beavers as a means to restore riparian habitat, a more geomorphically diverse and quantitatively intensive body of information needs to be obtained that is specifically related to river scale and attributes. The goal of this study is to add to the quantitative data on beaver damming as a geomorphic agent from a mountain stream setting on a low-gradient fluvial fan and to determine whether any of the in-channel effects of beaver damming persist beyond the existence of the dam in the channel. The specific focus is on sediment dynamics in the stream channel as influenced by beaver damming, but other geomorphic effects that were observed are also discussed.
STUDY AREA

The study area is located on Odell Creek in the Centennial Valley in southwest Montana, about 50 miles west of Yellowstone National Park (Figure 1). The Centennial Valley is an east-west trending, normal faulted basin. The active normal fault creates dramatic relief, with the Centennial Mountains rising 3000 m above the valley floor. The headwaters of Odell Creek originate in the mountains that are composed of a diverse lithology, with headwater streams draining Miocene volcanic and Cambrian-Permian sedimentary units, which include large limestone units. The springs and streams of the upper basin join to form Odell Creek’s main trunk in Odell Canyon (2180 m). 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. At the mouth of the canyon, where Odell Creek flows out onto the valley floor, the drainage basin area is ~45 km². The valley bottom portion of the creek flows over a low gradient Late Pleistocene-Holocene fluvial fan (Pierce, Unpublished data). Fan gradients range from 0.018 at the head of the fan, to 0.007 in the middle portion and 0.004 toward the toe. The fan section of the creek was the focus of the study and displays pool-riffle morphology with a sinuosity of 1.2 in the uppermost study reaches and 2.6 through the middle reaches where most beaver activity was observed while the lower reaches have a sinuosity of 2.3. The creek is variably incised within the fan surface. Along an incised portion of the fan, a layer of Mazama ash (6850 BP) was identified approximately 1 meter below the surface. Identification of the ash as Mazama climatic tephra was conducted using the electron microprobe microanalyzer at Washington State University (Foit, Unpublished data).
Centennial Valley experiences the majority of its precipitation in winter and spring from Pacific storms tracking along the jet stream, with May and June producing the highest precipitation amounts (Western Regional Climate Center, http://www.wrcc.dri.edu, 2011), and an annual mean precipitation of 550 mm. The valley experiences average mid-winter temperatures of -10°C and average mid summer temperatures of 13°C (www.wcc.nrcs.usda.gov/nwcc/site?sitenum=568&state=mt, 2011). This weather pattern means that Odell Creek has a snowmelt dominated hydrograph with high flows in spring that taper off to low base flows throughout the summer and into fall. From 1993-1998 the US
Geological Survey (USGS) maintained a stream gauge on Odell Creek (#06008000) near the mouth of Odell Canyon. Peak spring discharges during that period ranged from 2.2 m$^3$s$^{-1}$ – 9.9 m$^3$s$^{-1}$, with low base flows ranging from 0.2 m$^3$s$^{-1}$ – 0.3 m$^3$s$^{-1}$ (http://waterdata.usgs.gov/nwis/uv?06006000).

In the meandering reaches on the valley bottom, several different willow species (*Salix spp.*) dominate the banks the creek (O’Reilly, 2006). The middle portion of the creek (4.5 -12 km in channel distance from apex of fan) has the highest sinuosity as well as the greatest willow density and it is this section of the creek where most of the beaver activity is presently occurring. Overall, willow is the dominant riparian woody species on Odell Creek. The only area where willow co-exists with another woody species is at the mouth of Odell Canyon where there is a stand of cottonwoods (*Populus spp.*) that has been used by beaver. It is one of the few stands of cottonwoods in the entire valley. Aspen (*Populus spp.*) are also present in the valley, but not on Odell Creek, so willow is the primary building and food source material for beaver living on the creek. Odell Creek and its associated riparian zone is important habitat for migratory birds, moose, deer, elk, river otter and less frequently grizzly bears and wolves. Odell Creek’s aquatic habitat is an important 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 currently under review to be listed as an endangered population and the Westslope cutthroat trout is a species of concern in the state of Montana. The health of the fluvial and riparian systems in the valley is of crucial importance to local land managers (USFWS, 2009; Korb, 2008).
Red Rock Lakes National Wildlife Refuge (RRLNWR) manages much of the land on the valley bottom and the majority of the valley portion of Odell Creek on the Odell Creek fan flows through RRLNWR land. The majority of this is within the Red Rock Lakes Wilderness. For the most part, the creek has been protected from livestock grazing for the last several decades. Although humans have been utilizing the valley for centuries (Brower, 1897), agricultural land use by Euro-American settlers did not occur until after 1876 and information on land use since that period is relatively well documented (Bailey et al., 2006). Despite fairly limited impacts to riparian zones since RRLNWR took ownership, beaver have remained unpopular and trapping and moving of beaver has occurred at RRLNWR at various periods. Dam breaching to aid in fish movement has also been a component of fish management strategies and has continued into the present (RRLNWR files; G. Boltz personal communication; Vincent, 1962).
METHODS

I designated 9 study reaches on Odell Creek after reconnaissance of the creek from the uppermost portions of Odell Canyon to Lower Red Rock Lake (Figure 2). Reaches were selected to represent downstream variation in channel parameters. Reaches were also selected based on their beaver damming status, so that non-dammed reaches, currently dammed reaches and reaches with dams abandoned within the last decade are represented. The abandoned sites were identified and the time of beaver occupancy bracketed using air photos from RRLNWR archives and Google Earth Time Series images.

Figure 2. Selected study reaches on Odell Creek shown in red. Reach 1 is 3.3 km from the fan apex.
Table 1. Reach descriptions for Odell Creek.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Reach Type</th>
<th>Period of damming</th>
<th>Downstream Distance (m)</th>
<th>Mean Reach Slope</th>
<th>Sinuosity</th>
<th>No. of cross-sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>non-dammed</td>
<td>-</td>
<td>0</td>
<td>0.0123</td>
<td>1.2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>abandoned dam</td>
<td>~ 2004 - 2006</td>
<td>184</td>
<td>0.0073</td>
<td>1.2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>dam</td>
<td>2008 - 2010</td>
<td>1268</td>
<td>0.0075</td>
<td>2.3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>non-dammed</td>
<td>-</td>
<td>2501</td>
<td>0.0027</td>
<td>2.3</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>dam</td>
<td>2008 - 2010</td>
<td>3837</td>
<td>0.0037</td>
<td>2.7</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>abandoned dam</td>
<td>~ 2002 - 2004</td>
<td>4171</td>
<td>0.0016</td>
<td>2.7</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>non-dammed</td>
<td>-</td>
<td>5635</td>
<td>0.0012</td>
<td>2.6</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>abandoned dam</td>
<td>~ 2006 - 2007</td>
<td>8848</td>
<td>0.0007</td>
<td>3.1</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>non-dammed</td>
<td>-</td>
<td>10460</td>
<td>0.0004</td>
<td>2.5</td>
<td>4</td>
</tr>
</tbody>
</table>

In each reach, water surface profiles were surveyed along the channel edge and bed surface profiles were surveyed through the center of the channel. All surveying was conducted using a Sokkia total station. Water surface surveying was conducted 16 July – 20 July 2009 and water surface slopes for each reach were calculated. To supply reasonable slope values for each cross-section, reaches were divided into sections delineated by significant channel obstructions such as large woody debris, active beaver dams or abandoned beaver dams.

Detailed bed sediment mapping was done at low flow in 2009 and 2010. The bed sediment maps were later digitized in ArcMap, so that the percentage of channel bottom covered by a given sediment texture within a reach could be calculated. In reaches with intact dams and partially preserved relict dams, the height and width of each were measured. At currently dammed sites, depth of fine sediment accumulated upstream of each dam was surveyed at 2 m intervals and at 4 m intervals at sites > 50 m from the dam. At each interval a narrow fencing shovel was pushed through the fine sediment until coarser bed material was encountered. Surveying continued upstream until there was no longer a visible layer of fines covering coarser bed material. The measured depth was assumed to reflect mean fine
sediment accumulation with test measurements beyond the transect confirming that transect measurements were a reasonable estimate for mean sediment depth. Total volume of sediment was estimated from mean sediment depth measurements, distance between measurement points and channel widths at each sediment measurement location. At sites where fine sediment was not continuous across the channel the area of the sediment patch was measured and transects across the patches at 1-2 m intervals were used to estimate mean sediment depth and then calculate the volume for the patch. Non-continuous sediment patches mostly occurred adjacent and downstream of breached beaver dams.

Within each reach, cross-sections were delineated with distances between cross-sections determined by pool-riffle spacing, so that all hydrologic types were represented (pool, riffle, glide, run). Cross-sections were also placed 1-2 m above and below each active and abandoned dam site. At each cross-section detailed notes were made to aid in bankfull stage determination and high water surveys were done in May and June 2010 to further constrain estimates of bankfull stage. Pebble counts and measurements of b-axes of ≥100 pebbles (Wolman, 1954) in grids 2 m upstream and downstream of cross-section sites were also conducted. All sediment ≤0.5 mm (medium sand or smaller) was classified as fine sediment and coarse sand (2 – 0.5 mm) was recorded as a separate category.

Bankfull discharge was determined from detailed field notes collected during cross-section surveys along with flagging, observations, discharge measurements with a flow meter and photos during high water events. Attempts were also 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 mid to
late summer after peak runoff. Discharges during the survey period ranged from 0.8 m³s⁻¹ – 1.4 m³s⁻¹.

Cross-section, water surface slope and clast 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:

\[
\tau = \gamma Rs
\]

where \(\gamma\) is the specific weight of water and is assumed constant, \(R\) is hydraulic radius, in this case determined by width times mean depth, and \(s\) is slope from section water slopes surveyed in the field. We know that beaver dams increase \(R\) and decrease \(s\) upstream of dams (Pollock et al., 2007), so their presence should affect bed shear stress and the ability of a stream to transport sediment. The collected grain size data was used to calculate Shields critical shear stress, the bed shear stress required to move a given grain size, in this case the median grain size, and is determined by:

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

where \(\rho_s\) is the density of sediment, \(\rho_w\) is the density of water, \(g\) is acceleration due to gravity and \(D_{50}\) is the median grain size in meters. \(\tau^*\) is the dimensionless shear stress and a value of 0.045 was chosen 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 there is much uncertainty associated with these calculations from variability in studies used to calculate \(\tau^*\) and variation is stream attributes (e.g. Buffington and Montgomery, 1997). In calculations of \(\tau_c\) for Odell Creek, it is important to note that sediment mapping and pebble counts all occurred at low discharge
where the bed material may not be representative of what the stream can transport at high flows (Lisle et al., 2000). The ability of the channel to transport sediment at a given cross-section is essential for determining the effect that beaver dams have on sediment storage and transport compared to other locations along Odell Creek.
RESULTS

In-channel hydrologic effects

The primary hydraulic effect of beaver damming within the channel is adjustment of the water surface slope (Figure 3) which changes in-stream velocity and increases bankfull width. At dammed sites the water surface slope above the dam is very low relative to surrounding sites (Figure 4). Sites upstream of beaver dams are locations of water slope discontinuity which is more pronounced at sites higher on the fan, where water slopes are expected to be steepest. The change in slope caused by damming extended upstream 40 m in reach 3 and to at least 117 m in reach 5. However, sites below beaver dams have water surface slopes that are consistent with the down fan trend (Figure 4).

Figure 3. Long profile of reach 3, uppermost beaver dam reach (Figure 2). The bed surface is shown in red and water surface is shown in blue. Beaver dam locations are indicated by red stars. Note that water profile data was collected when the downstream dam was partially breached.
Figure 4. Log-normal plot of reach section water slopes as a function of stream distance from reach 1 for Odell Creek. Each point represents the slope of the water surface for a section within a reach. Reaches are identified by number and all section slopes for a given reach are within dotted line boxes. The exponential curve fit is for all section water surface slopes without an active beaver dam.

The change in water surface slope caused by damming affects stream velocity above dams. Stream velocities were measured on 22 May 2010 at a non-dammed site between reaches 2 and 3 and ~2 m above and below the second active dam in reach 3. The non-dammed and downstream-dam sites maintained similar mean velocities (Figure 5), but mean velocity at the upstream-dam site was reduced to 0.2 ms\(^{-1}\), about 50% of the velocity recorded below the dam where velocity was 0.4 ms\(^{-1}\).
Figure 5. Discharge and mean velocity measurements for 22 May 2010 to investigate the effect that overbank flow, caused by Dam 1 in reach 3. Measurements were taken at a site upstream of Reach 3, between dams 1 and 2, below dam 2 and after the diverted flow on the floodplain rejoined the main channel. The shaded polygon shows the approximate area affected by overbank flow with flow direction over the floodplain noted. Stream flow direction on Odell Creek is from south to north. The thick dotted black line shows the location of a cross-section above dam 1 that captured the morphology associated with overbank flow.

The presence of beaver dams increases wetted width at bankfull flows by backing up flow, and at sites where bank confinement is minimal the wetted width increase can be significant. At dammed sites the maximum wetted width, corresponding to bankfull discharge at non-dammed cross-sections, was 106.5 m in reach 3, compared to a maximum non-dammed bankfull width of 20.0 m (Figure 6). The uppermost beaver dam in reach 3 creates the greatest wetted width as flow is easily forced onto the floodplain to much higher than bankfull level at discharges equivalent to bankfull at non-dammed cross-sections. 50% of the
flow was recorded leaving the main channel above the dam in May discharge measurements. The diverted water flows over the floodplain, through a dense willow community, creating a complex wetland environment. The overbank flow was observed depositing some sediment around vegetation and in low velocity pond areas while in other areas the flow was actively eroding material and carving channels into the floodplain surface. The diverted flow rejoins the main channel with a slight loss in discharge (Figure 5). At other dam sites the effects of damming are less pronounced due to more confining banks, but the presence of dams increases the variability in cross-sectional bankfull widths represented within a reach to nearby non-dammed sites (Figure 6). The mean standard deviation in bankfull width for dammed reaches is 26.2 m while the mean standard deviation for non-dammed reaches is 3.06 m. The increase in width above dams can be maintained at lower flows with slight width reductions, but effectiveness of dams to flood surrounding areas is related to bank height and confinement of the dammed reach within terraces or valley walls (Figure 7).
Figure 6. bankfull width (a) and low flow width (b) with stream distance from reach 1. Each symbol records width at an individual cross section with different shapes indicating the hydrologic type. Reach numbers are noted and all cross-sections within a reach are contained within a box. The darker gray shows dammed reaches, lighter gray indicates formerly dammed reaches and open symbols are non-dammed reaches.
Figure 7. Cross-sections looking downstream for above active beaver dam sites in reaches 3 and 5 respectively. Shown are cross-section 3-1 (a.) and 5-1 (b.). The location of (a) is shown in figure 5. Elevations are above an arbitrary datum, solid blue line is surveyed water level at low flow while dashed line is estimated bankfull flow. Note that cross-sections are not at same scale.

Cross-section 3-1 (Figure 7a) has less confining stream banks than cross-section 5-1 (Figure 7b), 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 upstream of the dam site on river right where confinement by stream banks is limited. The flow creates a meander chute, with some erosion on the floodplain, eventually rejoining the main channel to the right of the pictured cross-section. At cross-section 5-1 (Figure 7a) the dam is less effective at covering a broad area at low flow where the surface on river right slopes upward continuously for 100+ m beyond the edge of the pictured cross-section, so even at bankfull stage wetted width is limited by valley geometry. However, although dam 1 in reach 5 is less effective at increasing wetted width compared to other sites, overbank flow is still augmented
by the existence of the dam. The mean width/depth ratios at both 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 (Table 2).

Table 2. Channel geometry data for active beaver dam reaches

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<th>reach</th>
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<th>bf depth (m)</th>
<th>bf w/d</th>
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US = upstream, DS = downstream, bf = bankfull, lf = lowflow, w/d = width to depth ratio

**In-channel adjustments to beaver damming**

Sediment storage at beaver dam sites reflects changes to the hydraulic parameters of slope, width, depth and velocity. Width and depth decrease in response to damming while slope
and velocity decrease. Calculations of bed shear stress show that competence at cross-sections above beaver dam sites is significantly reduced. However, cross-sections with $D_{50}$ values in the sand and silt category are likely to be mobile at these sites at bankfull discharge.

Slope is the variable that exerts the most control over $\tau$, so relatively small changes in slope can have a large effect on stream competence. At sites upstream of beaver dams $\tau_{bf}$ values are equivalent to values in reaches 7, 8 and 9 where low $\tau_{bf}$ values are expected (Figure 8). The opposite is true at sites downstream of dams where $\tau_{bf}$ is relatively high and larger grain sizes relative to surrounding cross-sections are represented. The adjustment in shear stress, both upstream and downstream of dams, increases variability in $D_{50}$ within dammed reaches relative to nearby non-dammed reaches (Figure 9 and Table 2). However, some of the grain sizes represented at each cross-section may have been transported at flows other than bankfull.
Figure 8. Bed shear stress at $Q_{bf}$ as a function of distance downstream. Colors indicate reach type while shapes indicate different cross-section hydrologic types.

Table 3. Estimated bed and critical shear stresses for dammed reaches on Odell Creek. Bolded cross-sections show where $\tau_{bf} > \tau_{crit}$ indicating competence to transport D50. Distance from first reach is also noted.

<table>
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<th>$\tau_{lf}$ (Nm$^{-2}$)</th>
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US = upstream, DS = downstream, bf = bankfull, lf = lowflow, $\tau$ = bed shear stress, $\tau_{crit}$ = Shields critical shear stress, D$_{50}$ = median grain size
Figure 9. (a) Median grain size ($D_{50}$) for each cross-section as a function of distance downstream from reach 1. Trend line is for non-dammed sites (black), dammed sites are shown in red and abandoned dams are green. Shapes indicate hydrologic type as per Figure 8. (b) same plot as (a), but filled symbols show cross-sections where $D_{50}$ is predicted to be mobile, $\tau_{bf} > \tau_{crit}$. Cross-sections are grouped and numbered by reach.
The discontinuities in sediment transport created by beaver dams are evidenced by sediment textures that are sand sized or smaller in reaches where they are anomalous based on downfan fining trends (Figure 10).

Figure 10. Percent sand and fines in each reach from bed sediment maps. The best fit line highlights the downstream trend based on the 4 non-dammed reaches.

Sites at downstream locations are expected to have finer grain sizes than those at upstream sites (Knighton, 1998). Odell Creek has base level control from Lower Red Rock Lake and as a stream on a fluvial fan its slope decreases dramatically downstream accentuating downstream fining trends. The downstream fining trend, for the most part, is even evident between the beaver dam sites as well. The greatest amount of fine sediment is stored at the first active dam in reach 5 (463 m$^3$) compared to the first active dam in reach 3 (68 m$^3$) (Figure 11 and Figure 12) which is 2.5 km upstream from reach 5. However, beavers often build dams in series, with the first dam of the series trapping the most sediment, thus leaving
less to be deposited in the ponds above dams just downstream. A look at the second dam in reach 3 displays this effect (Figure 11). The stored sediment is a coarser textured sand and gravely sand with a lower total volume, 40 m$^3$, compared to the 68 m$^3$ accumulated upstream of the first dam in the series. Sediment texture and volume variation was not only apparent from sediment maps, but is corroborated by bed shear stress values (Figure 8 and Figure 9). In reach 3, bed shear stress upstream of dam1 was 0.8 Nm$^{-2}$ while upstream of dam 2 that value was 7.8 Nm$^{-2}$ indicating greater competence above dam 2. Dam 2 in reach 3 was partly breached by spring flows in 2009, but was repaired by mid-summer. During the breach, slope and width adjusted toward non-dammed conditions and likely increased sediment removal and transport. However, sediment volume measurements were conducted in late August after at least a month and half with a fully functioning dam, so it appears that sedimentation is limited in the second dam in a sequence. A similar situation was also observed in reach 5 where the second dam in the sequence stored a limited amount of fine sediment (Figure 12).
Figure 11. Map showing surface sediment textures on channel bed in reach 3 (flooded width extends well beyond the channel above dam 1 in this reach (Figure 5)). Dams are indicated with black arrows and sediment volumes calculated from fine sediment depth surveys are displayed in the red boxes.
Attempts have been made to estimate rates of sediment accumulation behind beaver dams (e.g. Butler and Malanson, 1995; Pollock et al., 2007). Butler and Malanson (2005) recognize that much variability exists in pond sediment accumulation rates which they attribute to watershed-scale influences and longevity of a particular dam in the system. One of the confounding factors in predicting beaver pond sediment accumulation is the multiple dam complex described above. Another complicating effect is that sediment accumulation is not constant and ponds often have periods of sediment removal even while the dam remains intact. During spring snowmelt runoff events fine sediment was observed in transport over
This observation is further corroborated by bankfull bed shear stresses that are greater than Shields critical shear stresses suggesting that transport of the $D_{50}$, in this case fines, is occurring at the 4 sites upstream of dams during $Q_{bf}$ (Figure 9).

![Figure 13. High flow transporting suspended sediment over dam 1 in reach 5 in May 2009. Dam location in reach is shown in Figure 12.](image)

**Persistence of beaver dam effects**

In early June 2010 the second dam in reach 5 (Figure 12) was breached allowing an assessment of sediment storage and transport following a breach. The highest flow recorded during that period was $\sim 4 \ m^3 s^{-1}$ on June 6$^{th}$ which is $\sim 40\%$ of the maximum peak discharge recorded by the USGS gauge (1993-1998) on Odell Creek and was produced by rain and snowmelt. Flags put in to mark lower flows in May and late June (both at $\sim 1.1 \ m^3 s^{-1}$) allowed for comparison of the change in wetted width and evacuation and deposition of sediment before and after the dam breach (Figure 14). Water elevation declined by 0.5 m following the breach and width narrowed by a maximum of approximately 5 m.
Figure 14. (a.) Breach of dam 2 in reach 5 in June 2010, taken looking upstream with dam on left side of photo. Pre-breach (orange - May) and post-breach (green - June) survey flags marking stage at a discharge of 1.1 m$^3$/s are at the same elevation downstream of the dam. The star indicates location of (b.) upstream of the dam breach site. (b.) Photo at the same flow of 1.1 m$^3$/s shows that above the dam breach, post-breach (green - June) flags are 0.5 m lower than pre-breach (orange - May) flags and show a 5 m decrease in wetted width as well as storage of some fine sediment.

Bank failure was also associated with the dam breach, with flags from May still attached to the bank material that collapsed into the channel. The breach was only partial which caused flow to be concentrated into a narrower part of the channel and may have contributed to the bank collapse. An alternative hypothesis is that the bank collapse may have led to dam breaching. The flow pattern created by the partially breached dam created a below-dam eddy. Only 1 m$^3$ of fine sediment remained upstream of the dam following the breach. The rest was transported out of the former beaver pond and approximately 13 m$^3$ of sediment was deposited in the eddy downstream of the dam. Pre- and post- breach longitudinal surveys showed that bed elevation decreased upstream of the dam and increased below the dam, where a scour hole had existed prior to the breach (Figure 15). These adjustments are attributed to fine sediment evacuation and subsequent deposition.
Figure 15. Bed long profile of section of reach 5 near dam 2 from survey data collected before and after breaching. The green line represents the bed before dam breach in 2009 and the solid red line is the bed several weeks after the dam breach in 2010. Dam location and scour hole are also noted.

Observing the effects of a dam breach on the channel aided in interpreting channel conditions at older abandoned dam sites. On Odell Creek beaver dams are maintained ≤1 -5 years based on field observations of occupancy and analysis of airphotos. Although dams are active for a relatively short period, at all observed abandoned sites some effects of damming appear to persist for at least 2 years, but may persist much longer. The channel widening and bank collapse phenomenon observed during the dam breach in reach 5 may not be unusual, as similar bank morphology appears to be preserved in reach 8 (Figure 16) and possibly in reach 6 (Appendix I). Both reaches 6 and 8 show some preservation of fines just upstream and adjacent to the intact portion of the dam. It also appears that the below-dam eddy may play a transient role in maintaining fine sediment, with reaches 2 and 8 having moderately elevated levels of fines compared to the general downstream trend (Figure 10). In reaches with dam breaches, pockets of fines are stored below intact portions of breached dams and are clearly seen in detailed sediment mapping. An additional longer term impact of damming and breaching was seen in reach 6 where channel narrowing and deepening occurred in response to confinement by the remaining portion of the breached dam along with stored sediment.
(Figure 17). It is likely that the newly breached dam in reach 5, with intact portions of the dam remaining, will produce similar effects.

Figure 16. Sediment map detailing sediment volume from sediment depth transects in below-dam eddy (black circle) and site of bank collapse and channel widening in reach 8. The dam is the grey area and dark black arrows indicate flow direction.
Figure 17. Cross-section for abandoned dam in reach 6 looking upstream, showing sediment that has remained stored since the dam breached sometime in 2004 with person standing on stored sediment. Notice the narrowing of the still active parts of the channel. The star indicates the same location on the cross-section and photo.
DISCUSSION

*Sediment dynamics affected by active beaver damming*

Large volumes of sediment were stored upstream of beaver dams on Odell Creek (Figure 11 and Figure 12) in areas of decreased water surface slope (Figure 4), velocity (Figure 5) and competence as indicated by bed shear stress (Table 3 and Figure 8). Therefore, fine-grained material was stored in the channel at locations far upstream of where fine sediment would be expected given that the lowest slopes and smallest $D_{50}$ are usually the farthest downstream. That small grain sizes are found so far upstream results in a greater diversity of grain sizes represented in beaver-dammed reaches (Figure 9) compared to nearby non-dammed sites.

Habitat heterogeneity has been defined as the spatial variability of physical characteristics that can be utilized by organism or community of organisms (Lisle, 1995), so the variability in grain size provided near beaver dammed sites contributes to a greater diversity in channel habitat types. The finding that large volumes of sediment are found upstream of the first dam in a series is not surprising and is consistent with previous research (e.g. Butler and Malanson, 2005; Pollock, 2007). However, as on Odell Creek, much of this research has also shown that deposition behind dams is not uniform. I found large discrepancies in sediment storage between dams in the same reach where dams are built in series. The first dam effectively traps the most sediment leaving the second dam less potential material to trap (Figure 11). Each dam also has its own history of construction, destruction and repair which may limit the total sediment accumulated behind a dam despite its position in a dam series. Prior research has also shown that the first dam built (usually the uppermost dam near the beaver lodge) has the greatest longevity (Howard and Larson, 1985; Naiman et al., 1988).
Odell Creek provides further evidence that this is the case, with observed dam breaches only occurring at the second dam in the series. The second dam in reach 3 was partially breached and then repaired, but as slope increased in response to a failed section of the dam, bed shear stress would have increased, facilitating sediment transport.

Even without a dam breach fine suspended sediment was observed in transport over dams during periods of high flows (Figure 13). Although not measured, it is probable that there is also an increase in slope as water piles up behind a dam and flows over it, again resulting in an increase in sediment transport capacity. Values of bed shear stress indicate that transport of this fine material should occur at bankfull discharge (Figure 9).

Overbank flow may be an additional mechanism for sediment trapping as flow extends into stream bank vegetation. Vegetation increases roughness and decreases slope (Osterkamp and Hupp, 2010), both of which will effectively decrease sediment transport capacity and increase rates of sediment deposition. I observed deposition occurring in slower, deep water areas and in areas of dense vegetation in the flooded portions of reaches 3 and 5. However, erosion was also occurring as the diverted water carved new channels in the floodplain. No direct measurement of sediment dynamics was conducted outside of the main stream channel.

Research on the effects on sediment transport processes at sites just downstream of beaver dams is limited. My data consists of only two beaver dam reaches, so drawing broad conclusions about processes below dams is not possible. However, I did note that bed shear stress below the second dam in both reaches represented the reach maximum and this was also reflected in the $D_{50}$ values (Table 3). The area below the 1st dam in each reach had bed
shear stresses similar to riffles and runs in their respective reaches. The lower bed shear stresses are probably due to lower slopes at these sites from the backwater effects of the dam just downstream.

Additional morphologic change in response to beaver damming

In a fan setting, beaver damming may promote local avulsions at sites where the channel is relatively unconfined. On Odell Creek sites near the head of the fan are less likely to be incised within the fan surface. Overbank flow and flow splitting occurred in reach 2 from beaver damming and the channel has remained in a multi-thread form although beaver abandoned the site in 2007. In reach 3, 50% of the flow was diverted from the main channel and across the floodplain (Figure 5). New, smaller channels were observed in some locations eroding more permanent channels onto the floodplain surface. Whether total abandonment of the former channel will occur after dam abandonment is uncertain, but damming has had an effect on channel flow patterns and created a broad, complex riparian area.

Channel morphology as affected by dam breaching

A feature frequently preserved at dam breach sites on Odell Creek is the bank collapse and channel widening structure that was seen at the reach 5 dam breach that occurred in June 2010 (Figure 14). Similar bank collapse structures were also observed at two of the abandoned dam sites. Dam breaching that also eroded bank material near one end of a dam and widened the channel occurred at 61 of 161 dam failures at Bridge Creek, Oregon
(Demmer and Beschta, 2008). The observation of localized channel widening as a result of flow deflection has also been observed in many woody debris studies (Montgomery et al., 2003). Montgomery et al. (2003) suggest that forest channels have greater variability in width than do grassland channels. Odell Creek is not forested within my study reaches, but does exhibit width variability particularly within dammed reaches where mean standard deviation in bankfull width is 26.2m. Variable width may provide additional slow water habitat for fish fry rearing in Odell Creek (Levine, 2007). Increased habitat heterogeneity is provided by variations in boundary shear stress from dam remnants and bank protrusions that are large relative to channel size (Lisle, 2000).

*Sediment dynamics as affected by a beaver dam breach*

My analysis of the beaver dam breach in reach 5 in June 2010 shows that sediment evacuation from sites upstream of the dam can be rapid and accompanied by adjustments in bed morphology with scour pools filling below dams (Figure 15). Similar observations of fine sediment decline and pool shallowing were made by Lisle (1995) in a study of woody debris removal in a stream near Mount St. Helens. As mentioned previously, in-channel sediment deposited upstream of beaver dams is primarily of sand size (Figure 9 and Figure 11). With a slight increase in slope due to partial dam breaching, or high flows, the mean bed shear stress will increase and the first material to move will be medium sand (Knighton, 1998).

The sediment map in reach 5 was made after the dam breach. However, detailed notes of sediment texture were taken during bed profile surveying prior to the dam breach. Prior to
breaching, the area of fine sediment extended ~20 m upstream of the dam site and after the
dam breach only a very fine layer of sand covered gravel and pebbles at some locations
(Figure 12). However, some of that evacuated sediment was deposited just downstream
below the breached dam. 75% of the dam was still intact after the breach, so flow was forced
around the remaining portion and created an eddy downstream of the dam where fine
sediment could accumulate. Some filling of the scour hole is apparent by looking at the post-
breach bed profile (Figure 15). A similar pattern of sediment storage is observed to some
degree in all reaches with abandoned dams (Figure 16) and is reflected in the slightly
elevated percentage of sand and fines in reaches with abandoned dams (Figure 10). For
beaver dams to continue to have an effect for any significant period of time after they have
been abandoned, they must have an in-channel length and depth greater than half bankfull
width and depth as has been shown to be the case for large woody debris in channels < 50 m
wide (Abbe and Montgomery, 2003).

Although breached dam sites do promote some sediment storage they do not contain
anomalously high fine sediment levels compared to reaches with active dams (Figure 10).
This suggests that removal of the majority of fine sediment stored in the channel above dams
occurs rapidly. Butler and Malanson (2005), Pollock et al. (2007), Marston (1994) and
others have suggested that aggradation is occurring within channels dammed by beaver,
promoting reconnection of the stream with its floodplain, without reference to the differences
in discharge or slopes of streams, or the length of time that dams may be maintained in a
given system. However, many of the projections for the amount of aggradation that beavers
are able to accomplish require beaver occupation at a single site on the order of several
decades. The studies acknowledge that beavers will not continuously occupy a site, but they do not account for the sediment loss that may occur with each dam breach.

Pollock et al. (2007) suggested that continuous occupancy of a dam site was not unreasonable given that Johnston and Naiman (1990) had documented that any given dam site was occupied 80% of the time from 1940 -1986 on the Kabetogama Peninsula, Minnesota. However, on Odell Creek, site occupancy is ≤ 1 – 5 years, so dam breaches are a common occurrence. Breaching is also frequent on a variety of other streams. McCullough et al. (2004) observed dams regularly being damaged by ~2-year storm events in Eastern Nebraska. Many of these dams were later repaired, but it is probable that sediment moved downstream during the period of breaching. Beaver usually wait until periods of lower flow to repair breached dams and it uncommon for dams to be immediately rebuilt (Demmer and Beschta, 2008), so after breaching and before dam repair the water surface slope increases resulting in increased rates of sediment transport. Leidholt-Bruner et al. (1992) also noted that most dams in their study reaches in coastal Oregon failed during heavy spring run-off. On the Bill Williams River, Arizona, dams were breached at flows as low as 5 m$^3$s$^{-1}$, while some remained intact at flows approaching 65 m$^3$s$^{-1}$, but all dams were destroyed at 189 m$^3$s$^{-1}$ (Anderson and Shafroth, 2010). On Bridge Creek in Oregon 75% of dams in the 17 year study lasted ≤ 2 yrs, with some remaining as long as 7 years (Demmer and Beschta, 2008).

The wide variation in dam longevity is likely due to differences in magnitude and duration of flood events (Costa and O’Connor, 1995; Anderson and Shafroth, 2010) as well as reflecting differences in basin size and characteristics, channel geometry, and dam construction.

In addition to watershed characteristics contributing to dam failure, building materials available for dam construction 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). Therefore, at sites where building material may limit dam longevity, and thus aggradation of sediment, land managers are adding stabilization materials such as reinforcement posts or tires after beavers have built their dams, making the dams a more permanent feature (Apple et al., 1984; Bouwes et al., 2009). The idea is that dams that remain in place for longer periods will raise stream bed levels to help repair incised streams. It is possible, however, that these semi-permanent dam sites may have unintended consequences analogous to the effects of small mill dams in the Eastern United States (Walter and Merritts, 2008) where eventual dam failure led to downcutting through the finer pond sediments stored upstream of the dam. The downcutting created 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 unlikely.

Long-term Sediment Storage

Although dam breaches occur with great frequency on many streams, not all sediment is immediately evacuated from upstream sites, although the data show that significant volumes are removed (Figure 10 and Figure 15). The focus of the data in this study is on in-channel sediment dynamics, but evidence exists for longer-term sediment deposition and storage outside of the main channel. On the Upper Colorado River (mean snowmelt discharge 14.7 m³ s⁻¹) Westbrook et al. (2010) found that beaver dams cause overbank flow and influence the storage of sediment on the floodplain rather than in the main channel. The Odell Creek data
shows an increase in fines in the channel of an active beaver dam reach (Figure 10) along with an increase in bankfull width with damming (Figure 6 and Table 2). With the breaching of the dam, the stream will again narrow and abandon the outer edges of the pond leaving fine grained sediment behind (Figure 14). The finer-grained sediments will be incorporated onto the floodplain, upstream of areas where they would be expected, and will not be associated with large magnitude events that would normally be required to inundate the floodplain. The deposition of fine sediment on the floodplain by overbank flow in response to beaver damming was observed in the presently dammed reaches of Odell Creek and was clearly present following the June 2010 dam breach in reach 5 (Figure 14). In reach 2, where dams were abandoned in 2006, an overbank beaver deposit 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. Westbrook et al. (2010) have termed such sediment patches “beaver flood” deposits. At their study site sediment that had been deposited on a terrace 0.7 – 1.2 m above the active floodplain while the reach was dammed was abandoned on this surface after the dam breached. They estimated that it would take a flood with at least the magnitude of a 200 year recurrence interval event to flood that surface, but beaver damming promoted deposition there at average flows. Willow and aspen seedlings quickly established at the site and once successful they utilized groundwater to survive several years beyond the dam breach.

Although fine sediment storage on the floodplain after breaching is likely, Odell Creek also had areas within the main channel that were protected from total sediment removal. At abandoned dam sites, at least a small amount of sediment was stored just upstream and
adjacent to the intact portion of the dam as flow was directed toward the breached portion (Figure 14). In reach 6, where a partial breach occurred in 2004, the redirection of flow following the breach preserved pockets of sediment within the main channel both upstream and downstream of the intact portions of the dam (Figure 17). A similar, though less pronounced preservation scenario was also evident in reach 8 where 75% of the dam remained intact following a breach in 2007. It appears that the breach I observed in June 2010 in reach 5 will lead to a similar type of in-channel sediment storage. A complete removal of all dam material was not observed in this study, but on Bridge Creek, Oregon (peak $Q \leq 28 \text{ m}^3\text{s}^{-1}$) 19% of dams in 17 years suffered total washout, primarily during high flow periods (Demmer and Beschta, 2008). Total dam removal likely limits most preservation of fine sediment.

*Beaver damming and stream channel aggradation*

The work on Odell Creek shows some preservation of fine material at dam sites that remains several years after dam abandonment. However, long term channel filling in response to beaver damming is not observed to be occurring. In a 17 year study of 161 dams, Demmer and Beschta (2008) observed only 14 (9%) dams, filling completely with sediment. In each case, the stream eventually either cut through the center or around the end of these dams. The above examples suggest that either there are different stream environments where beaver-induced aggradation can be maintained as a more permanent feature, or dam breaching and its effects have not been fully explored. The data from Odell Creek does not support studies that claim beaver damming causes true valley-filling aggradation (e.g. Ives,
Instead, the present results are more consistent with work by Persico and Meyer (2009) showing the cumulative thickness of Holocene beaver pond deposits was < 2 m and patchy. Approximately 29% of the mainstem network in northern Yellowstone National Park showed the influence of beaver related aggradation with maximum aggradation of over 2 m occurring in glacial scour depressions where some aggradation would occur without the presence of beaver. The shallow and patchy Holocene deposits are consistent with sediment transport observed during high flows, the frequency of dam breaches, and the preservation potential of fine sediment on the dynamic Odell Creek system. That there is a limited influence of damming along the network in Yellowstone is not surprising given that optimal locations for damming are limited by stream power (Persico and Meyer, 2009), slope and food availability, so that not all sections of a stream are directly affected by beaver damming (Gurnell, 1998). It is also true that not all streams are affected in the same way by beaver damming, with stream scale controlling response.

Here I present a preliminary look at stream scale, so that the current work on Odell Creek can be understood in relation to other sites. More work needs to be done to put prior beaver work in the context of stream scale, so that meaningful conclusions and comparisons can be made about beaver dams across a variety of landscapes and stream sizes.

In many studies of beaver damming, stream scale has been ignored and inappropriate comparisons made between sites. Compared to other streams for which data are available, Odell Creek is of moderate size, having a maximum discharge of 10 m³ s⁻¹, a drainage area of 50 km² and dam longevity of < 1 – 5 years (Table 4). The characteristics of different sized streams impact the longevity of beaver dams on these systems which will alter sediment deposition and storage. Here, the large stream class is the limit of where beaver dam
construction is possible and I hypothesize that sediment storage within the channel is very limited in such streams. Alternatively, small scale streams may be sites where pond filling within the main channel may occur and be preserved.

Scale dependency was also investigated by Persico and Meyer (2009). They found that channel gradient and basin area exhibited a strong control over preservation of beaver related deposits in northern Yellowstone. With increasing basin area or increasing slope the likelihood of preservation declined. Improved attention to stream scale will yield a stronger understanding of beaver damming effects on the landscape and more meaningful management decisions for individual sites.
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Table 4. Comparisons of different scales of streams appropriate for beaver damming.
CONCLUSIONS

In-channel sediment storage on Odell Creek is limited by frequent dam breaches. Any sediment that remains in the channel following a breach is stored in small patches above and below the remaining portion of the dam and remains until the dam is completely removed. Given these observations, the potential for long-term beaver-induced aggradation of fine sediment appears limited on Odell Creek. Beaver can locally affect sediment dynamics and cause transient storage, but a long term reversal of incision is unlikely in Odell Creek unless other factors such as reduced discharge or increased sediment load also promote aggradation. Long-term effects of beaver damming likely depend on stream size. The most important effect of beavers building dams may not be their ability to stop or reverse incision, but their ability to raise water levels upstream of dams. Increased water elevation creates habitat heterogeneity by providing the channel with a variety of depths, velocities and shear stresses, creating a patchy and more diverse bed sediment texture where it would not exist otherwise. The presence of the dam also promotes overbank flow, while the dam is present, promoting a more connected river and floodplain. In some locations on Odell Creek overbank flow during damming deposited some fine sediment on the floodplain. This deposited sediment provides a moist, scoured seedbed that may facilitate establishment of riparian vegetation as observed in Reach 2. Breaching has also been shown to alter channel morphology as flow constricted by the remaining portion of the dam widens or deepens the channel creating additional morphological diversity. Beaver damming not only increases local habitat diversity, but provides habitat heterogeneity along the length of the stream corridor with dams in various states of construction, destruction and decay. Within a dynamic stream, dams, and their remnants, create a patchwork of habitats where the channel is alternately
connected and disconnected from terraces and floodplains and where the continuous presence of beaver in the system promotes riparian health and habitat diversity.
REFERENCES


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APPENDIX I:

Additional Sediment Maps
Sediment Type

- Coarse to Fine
  - Coarse gravel (64-256 mm)
  - Pebble gravel (2-64 mm)
  - Gravelly sand
  - Sand, unconsolidated
  - Veins very coarse sand (1-2 mm)
  - Very coarse sand (1.25-25 mm)
  - Medium sand (0.5-1 mm)
  - Fine sand (0.125-0.5 mm)
  - Very fine sand (0.0625-0.125 mm)
  - Clay (0.002-0.0625 mm)

Flow

Odell Sediment Map - Reach 1
APPENDIX II:

Odell Creek Cross-Sections
NOTES ON APPENDIX II

All surveyed cross-sections for each reach are depicted. Note that the scale for each cross-section varies, so pay attention to the axes. The black line shows surveyed data. The solid blue line is low-flow stage elevation and the dotted blue line is estimated bankfull stage elevation. A table is provided at the beginning of the appendix to place each cross-section in context with hydrologic type, and relevant stream distances provided. The cross-sections are organized from the most upstream locations to the farthest downstream locations in all cases.
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