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

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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 and 10 $m^3 s^{-1}$. 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 to 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.

1. 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 and 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.

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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.

2. Study area

Odell Creek is located in the Centennial Valley in southwestern Montana, about 50 miles west of Yellowstone National Park (Fig. 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 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.

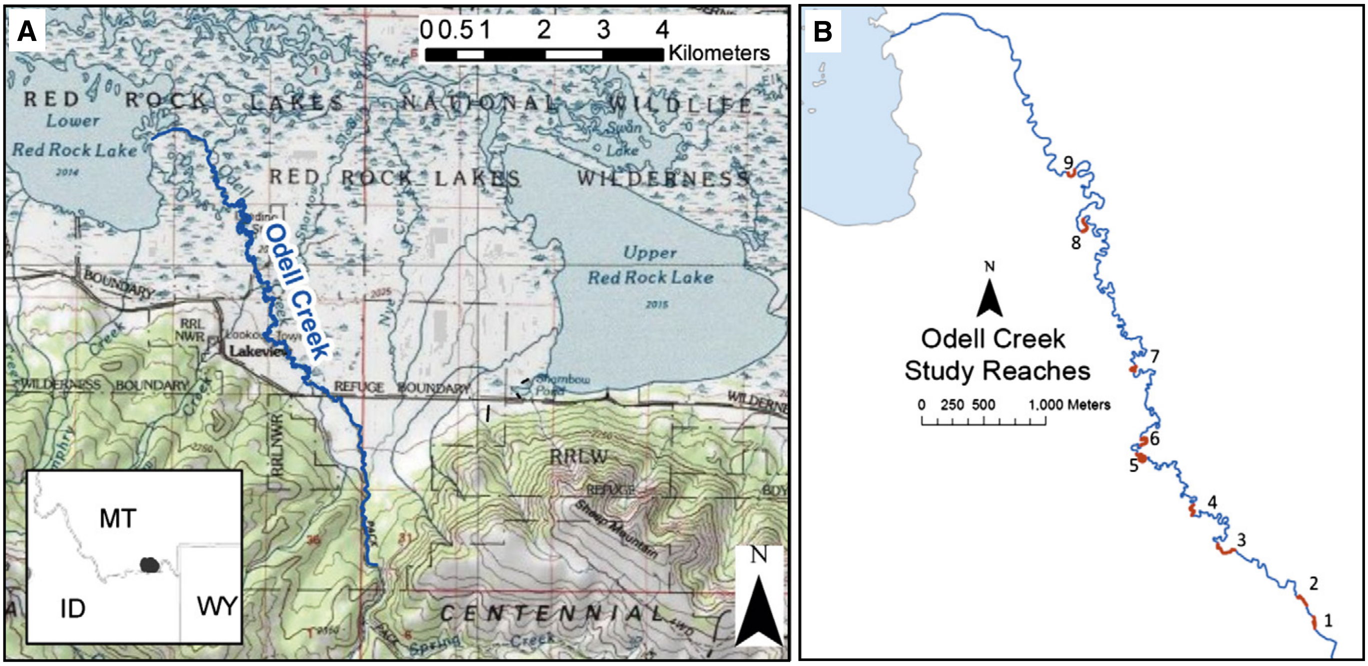

Fig. 1. (A) Odell Creek shown within Centennial Valley. Note the Odell Creek fan between the two lakes. Inset shows study area location within Montana in bold. (B) Study reaches on Odell Creek highlighted and labeled with reach number. Reach 1 is 3.3 km from the fan apex and represents the most upstream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

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 to 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} to 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.) has 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 is of crucial conservation importance to local land managers (Korb, 2008; USFWS, 2009).

3. Methods

We designated nine study reaches on Odell Creek between the fan apex and Lower Red Rock Lake (Fig. 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

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	–	10,460	33	0.0004	2.5	4

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 sediments of <2 mm in diameter ($\leq$coarse sand) were 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 m 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 $0.8\ \mathrm{m^3s^{-1}}$–$1.4\ \mathrm{m^3s^{-1}}$.

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).

4. Results

4.1. 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 to 0.6 m and downstream face heights ranging from 1.4 to 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.

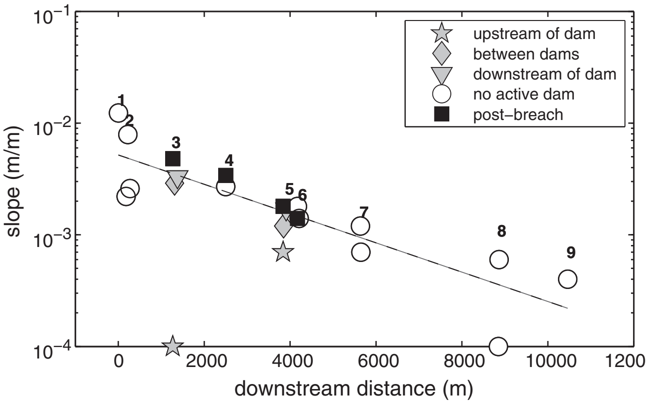

Fig. 2. Log-normal plot of water surface slope as a function of downstream distance from head of Reach 1 on Odell Creek. Reaches are identified by number above associated points. Reaches were broken into sections at significant channel obstructions (e.g., cross-channel wood and dams). The exponential 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.

4.2. 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 (Fig. 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 (Fig. 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.

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 (Fig. 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 (Fig. 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.

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 (Fig. 3B) has lower confining stream banks than cross-section 5-1 (Fig. 3C), 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

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%

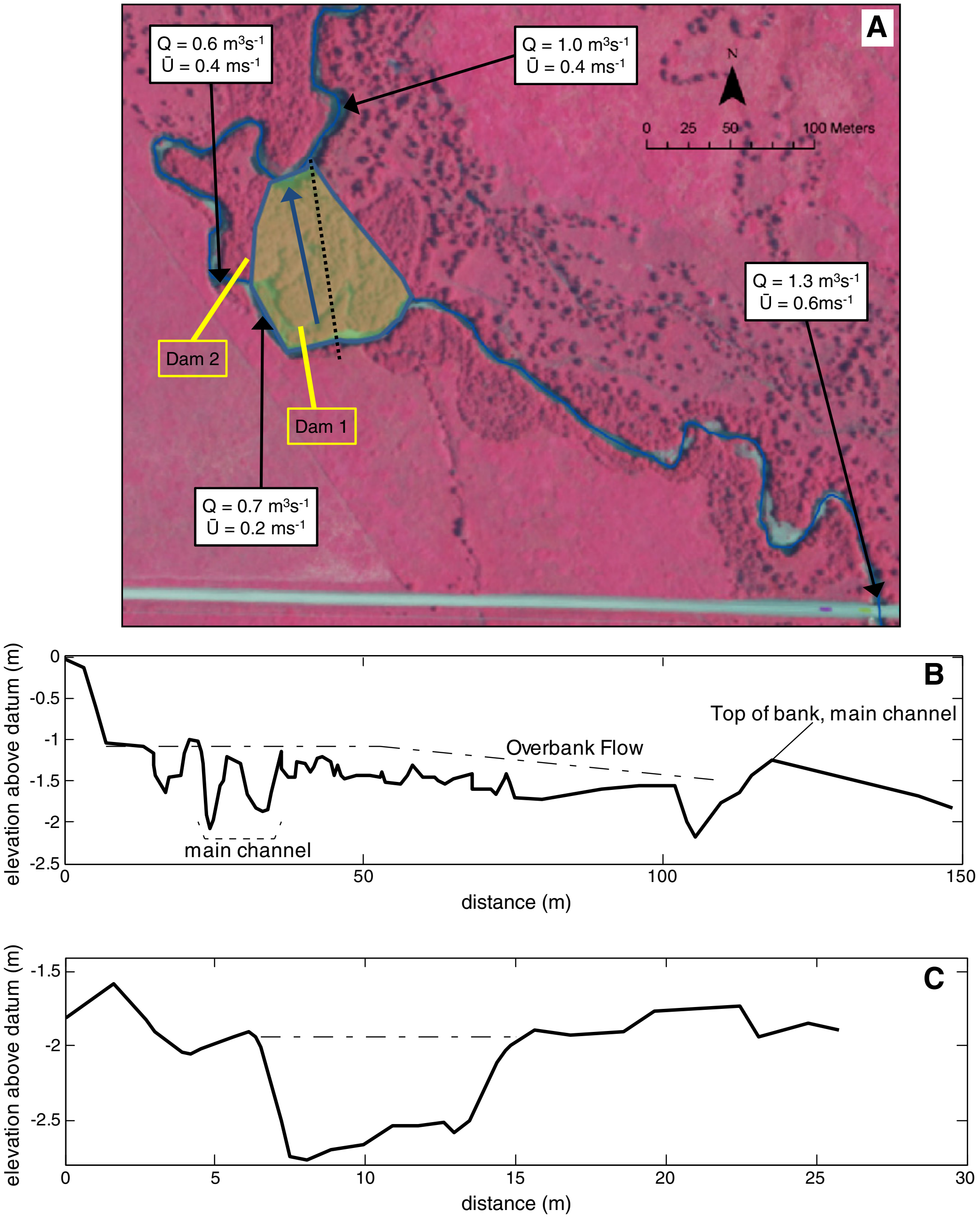

Fig. 3. (A) Discharge and mean velocity measurements on 22 May 2010 to investigate the effect of Dam 1 in Reach 3 (R3D1) on overbank flow. Black arrows indicate measurement sites with recorded discharge and velocity measurements. Main channel flow is from lower right to upper left. The shaded polygon 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 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.

4.3. 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 and 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 (Fig. 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 (Fig. 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 (Fig. 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.

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 (Fig. 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.

4.4. 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 $m^3\ s^{-1}$ 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 $m^3\ s^{-1}$ 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.

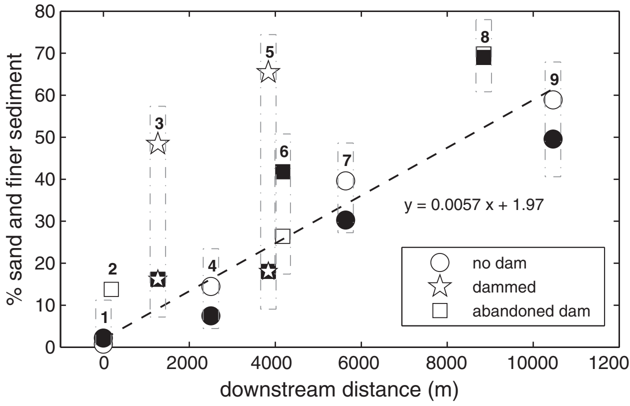

Fig. 4. Percent sand and finer sediment in each reach from pre-breach (white) and post-breach (black) bed sediment maps. Stars surrounded by black squares show post-breach values for previously dammed sites. Reaches are identified by number, and a dotted-line box is drawn around the data points associated 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.

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 (Fig. 8). Willow burial depth corresponded with surveyed elevation increases recorded in repeat cross-section surveys.

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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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

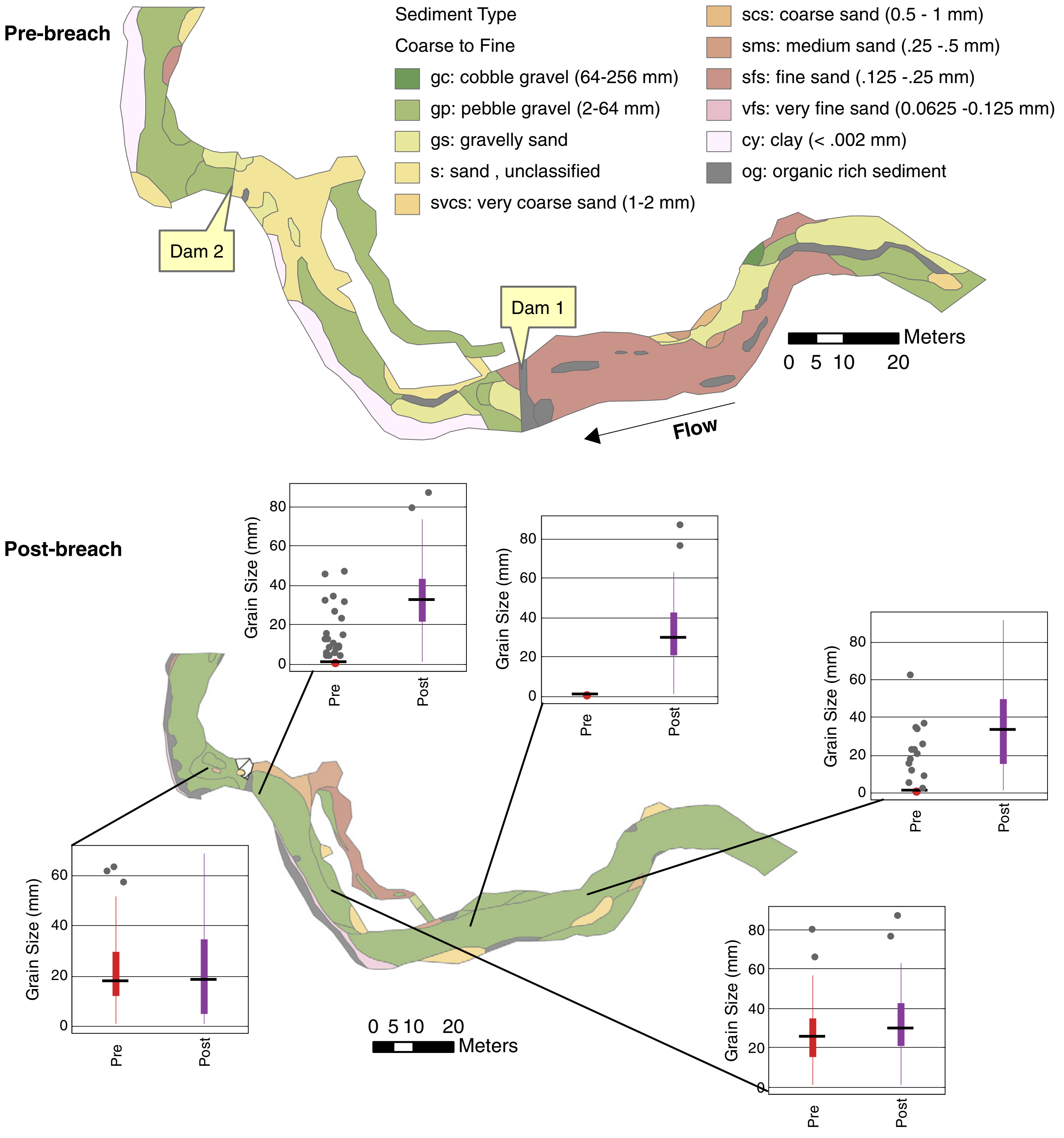

Fig. 5. Surface texture maps for pre- and post-breach bed sediment for Reach 3; colors show grain size categories. The post-breach map shows pre-breach (left plot) and post-breach (right plot) box plots of grain size distributions at cross-sections. For each box, the median value is shown by the horizontal 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.

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.

4.5. 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 $\leq$1–5 years based on field observations and analysis of air photos. 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

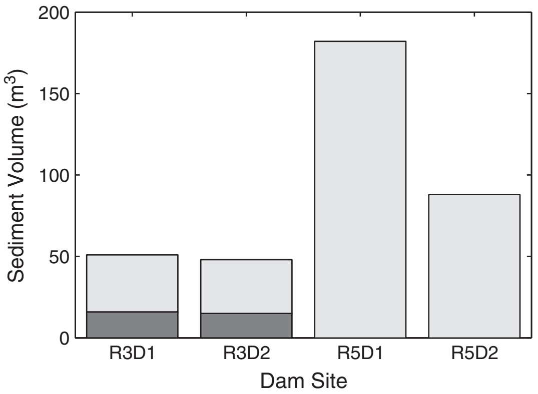

Fig. 6. Estimates of the volumes of sediment stored in the channel upstream of active beaver dams. Results are shown in downstream order with the most upstream site, Reach 3 dam 1 (R3D1), furthest left. The dark shading shows coarse sediment contribution to channel fill (>2 mm) while the light shading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

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 (Fig. 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 ≤2 mm sediment fraction compared to the downstream trend (Fig. 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 (Fig. 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.

5. Discussion

5.1. 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

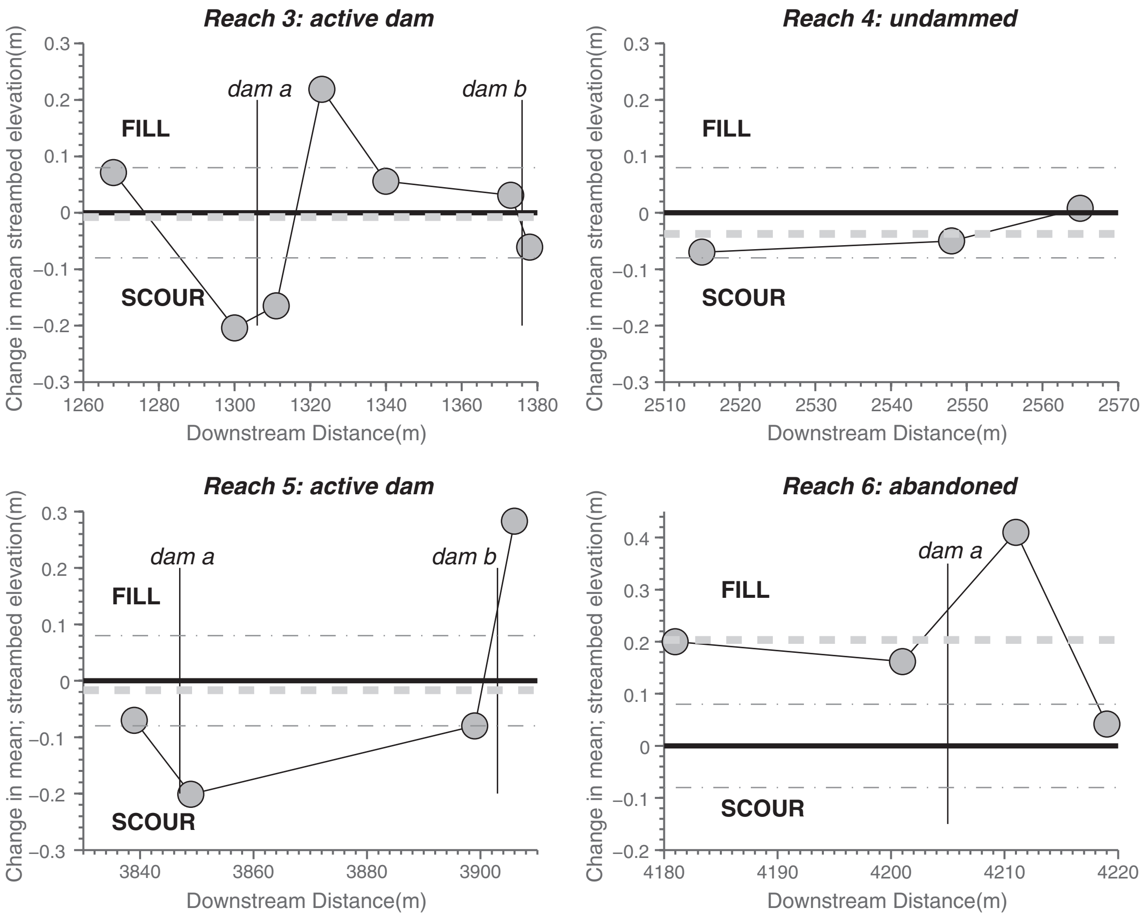

Fig. 7. Change in mean elevation of the streambed between repeat cross-section surveys in 2010 (pre-breach) and 2011 (post-breach). Reaches 3 and 5 contained dams in 2010 that were breached in 2011. Thick dotted line shows mean change in bed elevation for all cross-sections in the reach, and thin dash–dot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

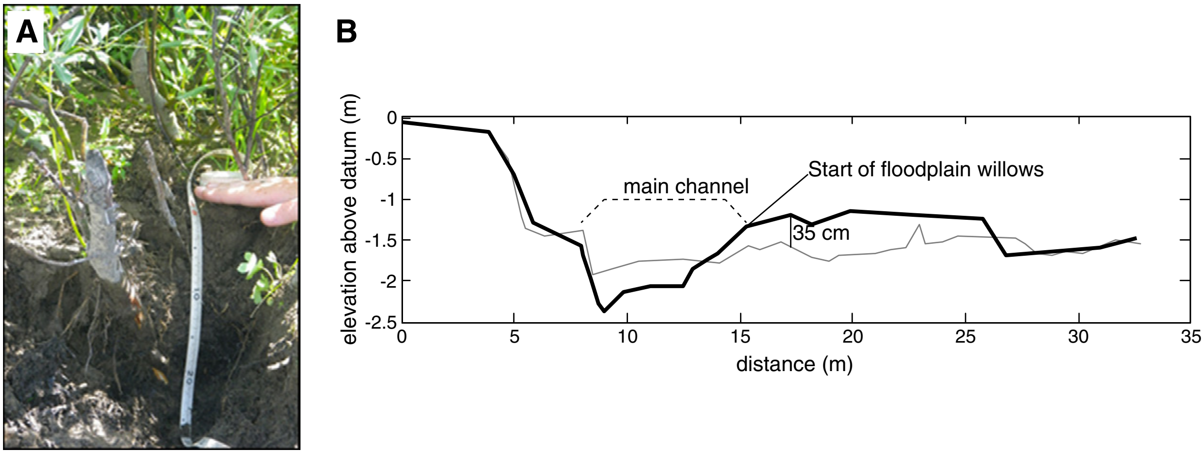

Fig. 8. (A) Photo showing at least 25 cm of sediment burying the base of live willows, about 4 m from the main channel along cross-section 3-2 in Reach 3. (B) Pre-breach (thin line) and post-breach (thick line) survey data for cross-section 3-2 showing widespread sediment accumulation of >20 cm depth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

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 (Fig. 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 $\tau_{bf} > \tau_c$ 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).

5.2. 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 (Fig. 7), with pre-dam slope conditions returning quickly after dam breaching (Fig. 2). The majority of the fine sediment is quickly moved out of the

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 Waddington (1990)	Ekwan Point	ON, Canada	0	–	9	0.02		–
Polvi and Wohl (2012)	Beaver Brook	CO, USA	0.01	188	15	–	–	–
Leidholt-Bruner et al. (1992)	Cummins Ck	OR, USA	0.03	30	21	0.28[a]		–
Jakes et al. (2007)	Upper Three Runs Ck, Lower Three Runs Ck, Meyers Branch, Fourmile Branch, Pen Branch, Steel Ck	SC, USA	0.01	209	30	–	–	–
Levine and Meyer–This Paper	Odell Creek	MT, USA	0	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	0.02	1000	103	–		–
Westbrook et al. (2010)	Colorado River	CO, USA	0.01	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)	Truckee River and Tributaries	CA, USA	0.01	33	–	–	–	–
Suzuki and McComb (1998)	Drift Creek Basin	OR, USA	0.02	33	–	–	–	–
John and Klein (2004)	Jossa	Central Germany	0.01	–	–	11.5	3	222
Hay (2010)	North Platte River	CO, USA	0.05	82	–	–	–	–

[a] Represents low flow Q.

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 (Fig. 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 (Fig. 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.

5.3. 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 (Fig. 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

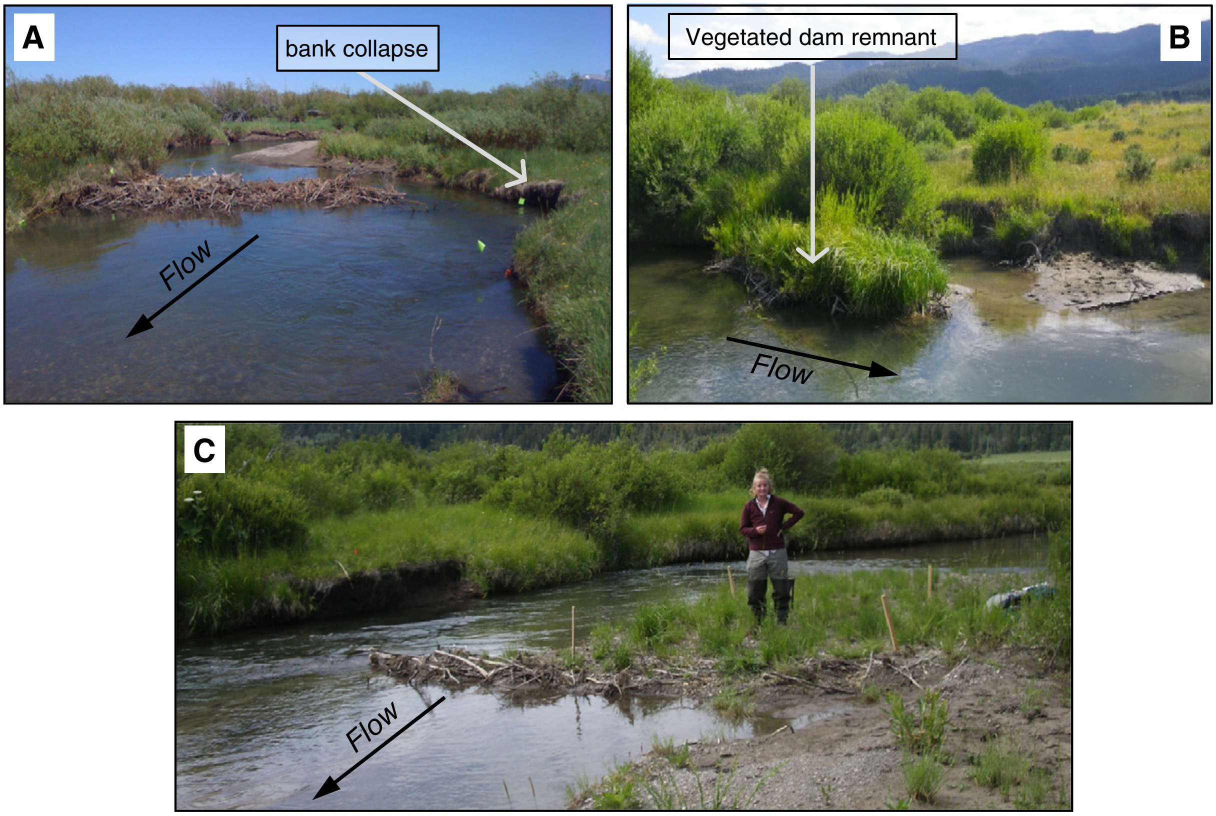

Fig. 9. (A) Partial side breach of beaver dam at R5D2. The photo was taken soon after the breach occurred and shows flow being redirected around the breached dam end. (B) Breached dam of unknown age between Reaches 7 and 8 on Odell Creek (not in a study reach). Dam remnant is stabilized by willow growth. 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 2004, 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.

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 (Fig. 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 $m^3\ s^{-1}$), 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).

5.3.1. 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).

5.4. 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 of <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 ≤1–5 years and a basin area of <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 $m^3\ s^{-1}$, whereas some remained intact at flows approaching 65 $m^3\ s^{-1}$, but all dams were destroyed at 189 $m^3\ s^{-1}$ (Andersen and Shafroth, 2010). On Bridge Creek in Oregon, 75% of dams in the 17-year study lasted ≤2 years, 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.

6. 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. Differences between dammed and undammed reaches 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 $\leq$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.

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