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Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon

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Abstract

Channel incision is a widespread phenomenon throughout the dry interior Columbia River basin and other semi-arid regions of the world, which degrades stream habitat by fundamentally altering natural ecological, geomorphological and hydrological processes. We examined the extent of localized aggradation behind beaver dams on an incised stream in the interior Columbia River basin to assess the potential for using beaver, *Castor canadensis*, dams to restore such channels, and the effect of the aggradation on riparian habitat. We estimated aggradation rates behind 13 beaver dams between 1 and 6 years old on Bridge Creek, a tributary to the John Day River in eastern Oregon. Vertical aggradation rates are initially rapid, as high as 0·47 m yr^{-1}, as the entrenched channel fills, then level off to 0·075 m yr^{-1} by year six, as the sediment begins accumulating on adjacent terraces. We found that a 0·5 m elevation contour above the stream channel approximately coincided with the extent of new riparian vegetation establishment. Therefore, we compared the area surrounding reaches upstream of beaver dams that were within 0·5 m elevation of the stream channel with adjacent reaches where no dams existed. We found that there was five times more area within 0·5 m elevation of the channel upstream of beaver dams, presumably because sediment accumulation had aggraded the channel. Our results suggest that restoration strategies that encourage the recolonization of streams by beaver can rapidly expand riparian habitat along incised streams. **Copyright © 2007 John Wiley & Sons, Ltd.**

Keywords: incision; aggradation; *Castor canadensis*; riparian; Oregon

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Introduction

Channel incision is a common occurrence in stream channels throughout the semi-arid regions of the interior Columbia River basin, where a fragile balance between climate, vegetation and geology makes the vertical stability of channels highly vulnerable to changes in hillslope erosion, stream discharge and loss of instream retention elements (Cooke and Reeves, 1976; Welcher, 1993; Peacock, 1994). We define incision as a rapid downcutting and lowering of the stream bed such that it reduces the frequency and duration of flooding onto the adjacent floodplain (*sensu* Leopold *et al.*, 1964). Incision is a common response of streams to land use changes throughout much of the semi-arid regions of the American West and in other regions of North America, Africa, Australia, Europe, Asia, the Middle East and South America (Cooke and Reeves, 1976; Schumm *et al.*, 1984; Nagle, 1993; Prosser *et al.*, 1994; Simon *et al.*, 1995; Vandekerckhove *et al.*, 2000).

Incision has degraded instream and riparian habitat throughout the Columbia River basin, suggesting that restoration of such streams would benefit numerous species. Of particular interest is improving habitat for salmonids, because many of the Columbia River stocks are listed under the United States Endangered Species Act. Many streams in the Columbia River basin that historically supported salmon no longer do so, and habitat conditions are severely degraded in these incised streams (Nehlsen *et al.*, 1991; Elmore *et al.*, 1994; Wissmar, 1994). Incision can dramatically affect stream habitat for salmon and other fishes by the lowering of stream-adjacent water tables and the subsequent loss of riparian vegetation. The loss of above-ground vegetation reduces shading and organic inputs to the stream (Brown and Krygiier, 1970; Kiffney *et al.*, 2000), while the loss of below-ground roots increases the erodibility

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of stream banks (Smith, 1976). The lowered water tables also directly impact the stream by reducing groundwater inputs to the stream. This is a significant concern in semi-arid regions such as in our study area because many streams have incised to bedrock and therefore the water table is at or near the bedrock and there is little opportunity for water to be stored in the alluvium. As a result, many incised streams cease flowing or have substantially reduced flows in the summer because there is no baseflow provided by the alluvial aquifer (Elmore and Beschta, 1987). The loss of cool groundwater inputs also leads to increased summer stream temperatures (Poole and Berman, 2001). Further, incised streams rarely access their floodplains, high flows are concentrated within the incised channel, and fish have no access to slow-water refugia during floods (Harvey and Watson, 1986; Elmore and Beschta, 1987; Shields *et al.*, 1995). In contrast, numerous studies suggest that when local water tables of incised streams are raised, usually through the construction of beaver dams or small human-made dams, flows increase and intermittent streams become perennial (reviewed by Ponce and Lindquist, 1990; Pollock *et al.*, 2003).

The historical record suggests that numerous streams in the semi-arid region of the interior Columbia River basin once contained narrow, deep and gently meandering channels lined with dense riparian forests of cottonwoods, *Populus*, willows, *Salix*, and/or sedges, *Carex*, numerous beaver, *Castor Canadensis*, dams (which are generally constructed out of numerous pieces of small diameter (1–4 cm) wood and mud), abundant and easily accessible off-channel habitat on the floodplain and good flow and cool temperatures throughout most of the year (Buckley, 1992; Wissmar *et al.*, 1994). Today many of these same streams are incised and contain little or no riparian vegetation or beaver dams. Stream temperatures are high and flow is ephemeral (Elmore and Beschta, 1987; Buckley, 1992; Peacock, 1994; CBMRC, 2005).

Land use change, climate change or localized high intensity rainfall can cause channel incision, either by increasing the tractive force of water or by decreasing the resistance of the stream bed (Cooke and Reeves, 1976). Within the Columbia River basin, the exact mechanism that caused widespread channel incision remains uncertain, although its timing almost invariably followed the widespread trapping of beaver and the onset of intensive sheep and cattle grazing in the mid 19th and early 20th centuries (Russell, 1905; Buckley, 1992; Peacock, 1994). In other semi-arid regions, aggradation (recovery from incision) has been observed when grazing practices and riparian land uses are altered to allow the re-establishment of riparian vegetation (Zierholz *et al.*, 2001). Aggradation has also been observed to occur where beavers are able to build dams on streams (Scheffer, 1938; Butler and Malanson, 1995; McCullough *et al.*, 2005). This suggests that recovery will occur when natural processes are allowed to operate. However, the time frames for recovery may range from decades to centuries. Recovery rates are related to both the quantity of sediment entering a channel and the ability of the channel to retain this sediment.

Recovery of incised streams has both a physical and a biological component, though the two are interdependent. Physical recovery includes both the geomorphic and hydrologic changes that occur as a channel aggrades, while biological recovery includes the changes in riparian vegetation and instream biota that can either initiate or result from physical recovery. Much of the literature examining incised streams has focused on the changing geomorphic characteristics of such streams as they cycle through stable, incising and aggrading states (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Darby and Simon, 1999). A general conceptual model has emerged regarding the channel evolution of incising streams (Figure 1). The model has numerous variants, but most include (a) a sequence of relative stability followed by (b) rapid downcutting such that the stream is isolated from its floodplain, (c) an increased stream width-to-depth ratio, a decrease in stream sinuosity and extensive widening of the incised trench, which eventually leads to (d) a stream at a lower base level and a lower longitudinal slope, with a new inset floodplain that develops a more sinuous planform and lower width-to-depth ratio, then (e) slow, long-term aggradation of the streambed and inset floodplain that (f) may or may not reach the level and the longitudinal gradient of the former floodplain before a new cycle of incision begins. Because the incision phase is rapid and causes dramatic physical and ecological changes, research efforts have focused on understanding causes of incision, to what extent they are the result of land use practices versus a natural phenomenon and how future incision can be prevented (Schumm *et al.*, 1984; Darby and Simon, 1999). Less attention has been focused on factors influencing the post-incision phases and in particular the factors that might influence aggradation rates (but see Shields *et al.*, 1999). Generally, it has been assumed that aggradation of incised streams is a slow process that operates on a multi-century timeframe, and that extensive widening of the incision trench must occur prior to aggradation (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Rosgen, 1996). However, such assumptions are based almost entirely on the physical principles of sediment transport in fluvial systems, and do not include the effects of large wood, beaver dams (i.e. small wood) or riparian vegetation on sediment transport and deposition and the modification of fluvial landforms. Nonetheless, the channel evolution model illustrated in Figure 1 provides a framework for understanding the sequence of geomorphic changes that might be expected to occur following incision and how aggradation rates might be altered by large wood, live vegetation or beaver dams.

Live vegetation, particularly dense, emergent graminoids such as sedges, has been shown to effectively remove suspended sediment from water columns, primarily by creating a low velocity zone near the stream bed, which allows

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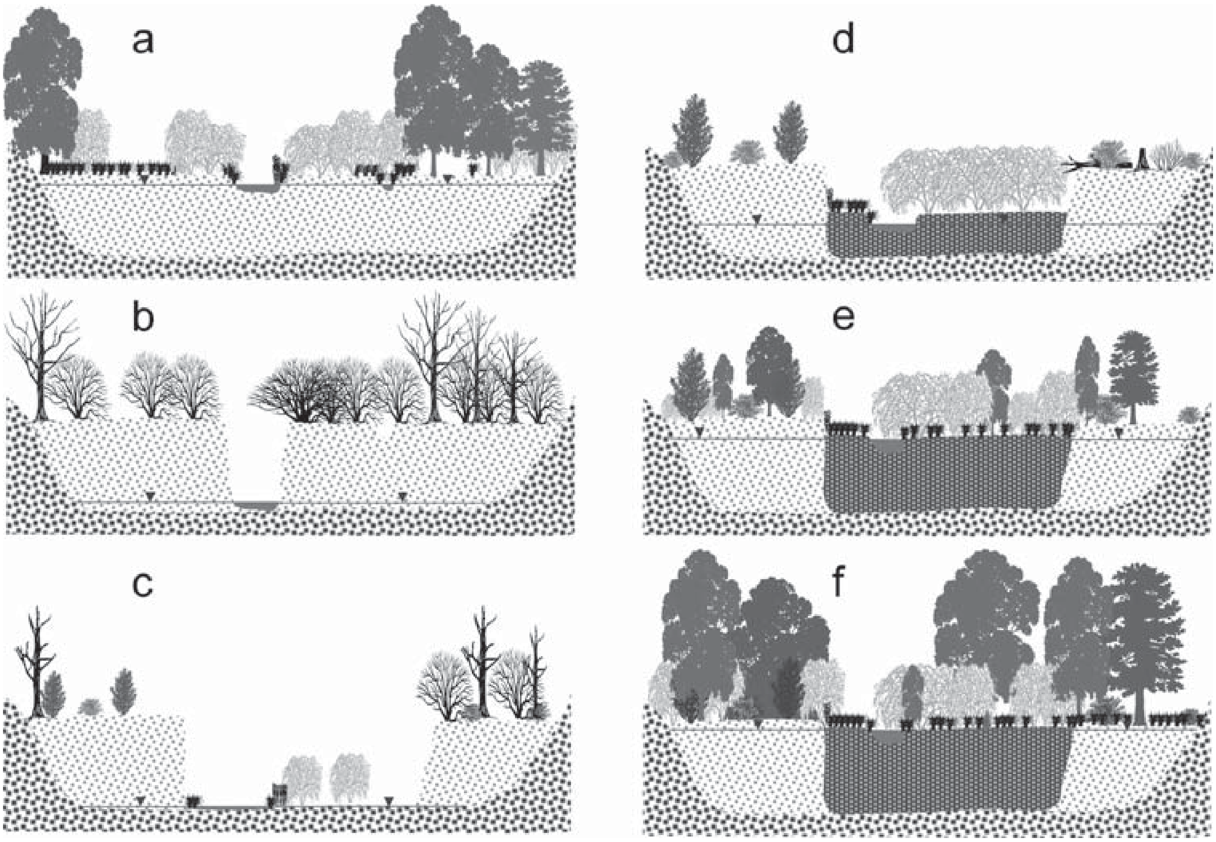

Figure 1. Conceptual diagram of incision and filling cycle in a semi-arid environment such as the interior Columbia River basin. (a) A fully aggraded stream connected to its floodplain and a water table near the floodplain surface. (b) Incision is triggered, usually by a change in land use practices that result in increased stream power. The water table lowers, resulting in the death of riparian vegetation. The channel is confined to a narrow trench. (c) Eventually, the incision trench widens as the channel develops meanders, and a narrow floodplain establishes with a greatly diminished riparian area. Xeric plant communities dominated by juniper and sagebrush develop on the former floodplain. (d) Floodplain vegetation such as sedges and willows trap sediment during high flows, and the developing meandering pattern of the stream lowers the stream gradient. Within the incised trench, aggradation begins to occur and the water table rises. (e) Over time, continued aggradation begins to reconnect the stream to its former floodplain, and the water tables continue to rise. During this period, plant diversity is high because both xeric and riparian species are present. (f) As conditions become more favorable to riparian species, the xeric species die out and riparian plant biomass continues to increase. The stream and riparian forest return to the pre-incision state.

fine-grained material to settle out of suspension (Elliot, 2000; Braskerud, 2001; Carollo *et al.*, 2002). Establishment of emergent vegetation following the cessation of cattle grazing has been implicated as an important prerequisite for aggradation of incised streams in the semi-arid regions of Australia (Zierholz *et al.*, 2001). Similarly, beavers affect sediment transport when they dam small streams by weaving together numerous small pieces of wood and packing the interstices with mud (Morgan, 1986). The dams create low velocity stream reaches where sediment can drop from suspension. Additionally, they often raise the water level such that it permanently floods the adjacent floodplain or low terrace, thus creating a large shallow littoral zone suitable for the establishment of emergent and other riparian vegetation (Pastor *et al.*, 1993). Thus beaver dams should affect sediment transport by directly influencing stream velocities, and indirectly by creating an environment conducive to the establishment of emergent vegetation that traps sediment. The geomorphic effects of beaver dams has been documented (reviewed by Gurnell, 1998; Pollock *et al.*, 2003), though few studies have examined aggradation rates and only one has done so in an incised stream (McCullough *et al.*, 2005). Butler and Malanson (1995) estimated sedimentation rates of 0·02–0·28 m yr^{-1} above four beaver dams in Glacier National Park, MT, while Meentemeyer and Butler (1999) observed average sediment depth of 0·28 m in five ponds 5 yrs old or less (i.e. a minimum aggradation rate of 0·06 m yr^{-1}), in Glacier National Park, MT, while Scheffer (1938) observed aggradation of 0·55 m over a two year period on a small tributary to the Columbia River in eastern Washington. Naiman *et al.*

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(1986) estimated that 3.2×10^6 m^3 of sediment were stored behind all the beaver dams in second-fourth order streams in their study area in Quebec. They calculated that if this sediment were distributed evenly across all the streambeds, it would raise them by 42 cm. McCullough *et al.* (2005) studied beaver colonization of an incised stream in Nebraska and found that in a reach where beaver had been established for 12 years stream bed aggradation averaged 0·65 m.

Field observations of small incised streams within the Columbia River basin suggest that incision depths typically range from 1 to 2 m, less frequently up to 5 m and in some extreme cases may incise as much as 20 m (see, e.g., Peacock, 1994). The aggradation rates behind beaver dams reported in the literature suggest that where beaver dams are present in incised streams aggradation may occur at a rate sufficient to reconnect a stream to its former floodplain on decadal timescales, thus increasing projected rates of recovery by an order of magnitude or greater over recovery estimates when it is assumed no beaver dams are present (see, e.g., Rosgen, 1994).

Because we know that historically beaver were abundant throughout the semi-arid regions of the Columbia River basin (Johnson and Chance, 1974; Buckley, 1992), we hypothesized that their reestablishment in incised streams could greatly increase aggradation rates and accelerate the recovery of stream and riparian habitat. The purpose of this study was to assess volumetric and vertical aggradation rates of beaver ponds in an incised stream and to estimate the projected time to accumulate the sediment necessary to reconnect the stream to abandoned floodplain terraces.

Site Description

The Bridge Creek watershed is a 710 km^2 watershed draining directly into the lower John Day River in eastern Oregon (Figure 2). Elevation ranges from 499 m at the mouth to 2078 m at the summit of Mt. Pisgah. The basin is dominated by sagebrush-steppe, *Artemisia*, and juniper-steppe, *Juniperous occidentalis*, in the lower elevations, with the vegetation changing progressively to forests dominated by Ponderosa pine, *Pinus ponderosa*, Douglas-fir, *Pseudotsuga menziesii*, and then spruce, *Picea englemannii*, with increasing elevation. Most of the mainstem and lower tributary reaches of Bridge Creek are incised and thus the riparian vegetation is limited to a very narrow band along the stream. Riparian vegetation is dominated by willows, but cottonwood is present in some areas, as are a variety of shrubs. High flows in Bridge Creek occur during the spring, when runoff from the melting snowpack raises water levels to near bankfull height for weeks at a time. Peak flows also occur during this time, typically when localized storm cells provide high amounts of precipitation that add to the existing high water levels. Maximum

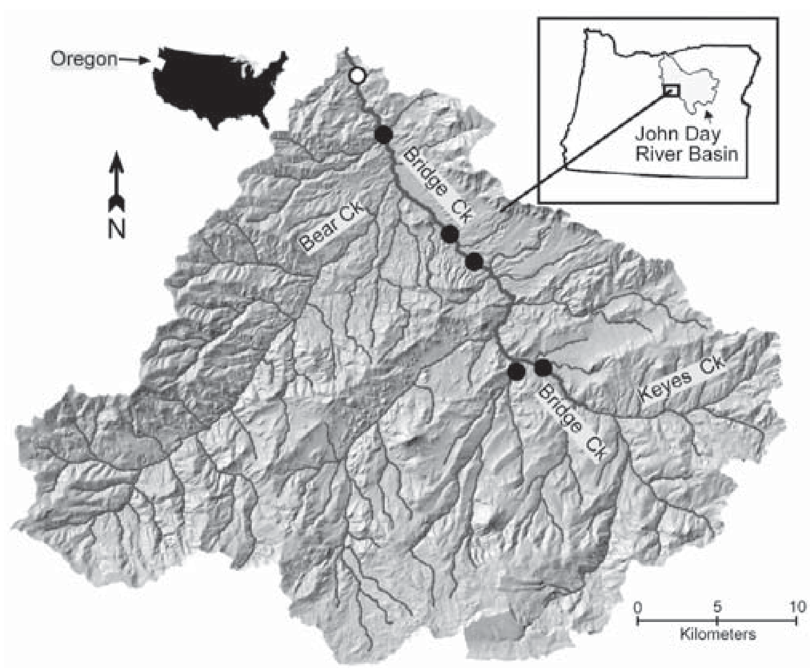

Figure 2. Bridge Creek drains a 710 km^2 basin into the lower John Day River in eastern Oregon. The John Day is a major tributary to the Columbia River. The black dots on the map of Bridge Creek are the general areas where beaver ponds are located. The white dot is the location of the gauging station.

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estimated peak flow in Bridge Creek near the mouth is 28 $m^3 s^{-1}$, while late-summer low flows have been measured as low as 0·15 $m^3 s^{-1}$ (Anna Smith, BLM, Prineville, OR, personal communication).

The surficial geology of Bridge Creek is dominated by thick layers of basalt and andesite that originated from numerous lava flows of the Eocene and Oligocene period. There are also substantial areas of highly erosive volcanic ash known as the John Day Formation that also originated from a series of volcanic eruptions in the Oligocene and Miocene. The lower main valley of Bridge Creek is surrounded by cohesive, fine-grained quaternary alluvium, much of which is derived from the ashes of the John Day formation.

Bridge Creek and its tributaries are utilized by an anadromous run of Middle Columbia steelhead, *Oncorhynchus mykiss*, that are part of the ecologically distinct Lower John Day population, which occupies the lower, drier Columbia Plateau ecoregion within the John Day Subbasin, and are listed under the Endangered Species Act (CBMRC, 2005). Bridge Creek is a priority watershed for restoration because its salmonid production and abundance potential is high (CBMRC, 2005). Chinook salmon have also been recently documented in Bridge Creek (M. Pollock, personal observation, June 2007). Habitat quantity, temperature, sediment load, habitat diversity and flow have been identified as limiting factors in Bridge Creek. Summer stream temperatures in Bridge Creek frequently exceed 27 °C when stream flows are at a minimum. Not surprisingly, Bridge Creek is on the 303(d) list of temperature impaired streams (CBMRC, 2005). Due to the erosive nature of some of the geologies, and in particular the large number of incised, failing stream banks, sediment loads are high in Bridge Creek, especially during peak flow events.

Methods

Sediment accumulation behind 13 beaver dams was estimated by establishing a grid of points upstream of the dam. Transects were spaced every 10 m upstream and sediment depth measurements were made every 5 m along each transect. Sediment depth was estimated by pushing a sediment corer through the surface layer of fine-grained unconsolidated sediment until a more compact layer was reached, which often contained larger clasts such as gravels. A clear boundary between loose, fine-grained surface material underlain by more compact, coarser-grained material existed at almost every point. The aggradation of unconsolidated fine-grained material was assumed to be recently deposited and to result from the construction of the beaver dam downstream. This was a reasonable assumption because sites that had no beaver dam downstream had no layer of fine-grained unconsolidated sediment, while all sites we examined upstream of beaver dams contained such a layer.

The age of the 13 beaver dams was determined from a database provided by the Bureau of Land Management, Prineville office. The BLM has been surveying for beaver dams along the mainstem of Bridge Creek for over a decade and has a GIS layer identifying the location of each beaver dam and each year that it has been present.

Digital orthophotographs for the mainstem of Bridge Creek were obtained from a three-band color imagery and light detection and ranging (LIDAR) survey of Bridge Creek from the mouth to approximately 28 km upstream to the town of Mitchell that was flown in September 2005 by Watershed Sciences, Portland, OR. The area within 0·5 vertical elevation of the stream channel was estimated by using the LIDAR coverage to develop 0·5 m contour bands above the existing stream, which were then verified in the field. Field observations and analysis of the orthophotos indicated that most recently established riparian vegetation was found within 0·5 m of the current stream bed. Thus the 0·5 m elevation contour above the streambed is a reasonable approximation of where riparian vegetation is at present or might be expected to establish in the near future.

The bed slope above 18 beaver dams (another 5 in addition to the 13 where sediment accumulations were measured) and reaches above and below the area of aggradation above the dam were estimated using a DEM grid generated from the LIDAR coverage. The vertical accuracy of the LIDAR is 4–7 cm, and the DEM grid cells are 0·5 m^2. Slope measurements were also made in the field to verify the accuracy of the remote sensing measurements.

Results

The aggradation rate decreased with age and was described by the power equation

$$AR = 0{\cdot}3835\ \text{Age}^{-0{\cdot}9093} \quad (1)$$

where AR is the aggradation rate, measured in m yr^{-1}, and Age is the dam age, measured in years ($r^2 = 0{\cdot}72$, $n = 13$; Figure 3). The data indicate initially high rates of aggradation, as much as 0·45 m in the first year, followed by a rapid decline and leveling off towards 0·075 m yr^{-1} by year six (Figure 3). Volumetric sediment accumulation rates among the 13 sites were variable, averaging 171 $m^3 yr^{-1}$, with a minimum of 17 $m^3 yr^{-1}$ and a maximum of 522 $m^3 yr^{-1}$. A

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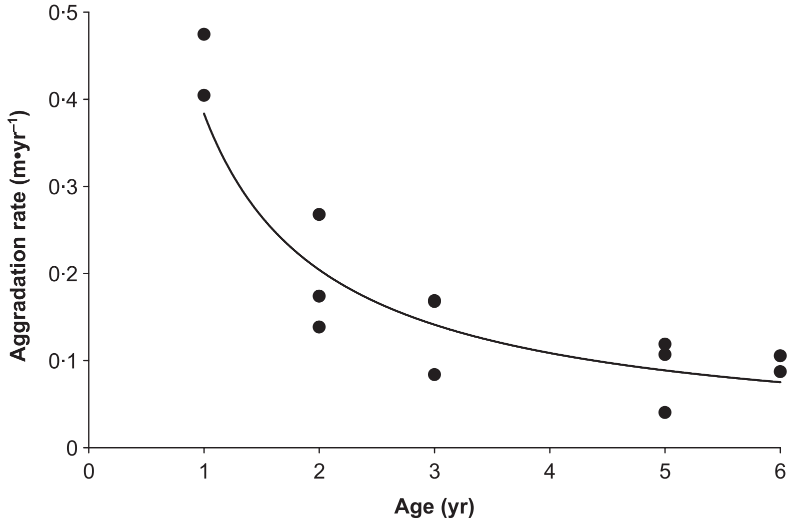

Figure 3. The relationship between beaver dam age and the aggradation rate (AR) upstream of the dam is described by the power equation Age = 0·3835 $AR^{-0·9093}$ (r^2 = 0·72, *n* = 13, *p* < 0·001).

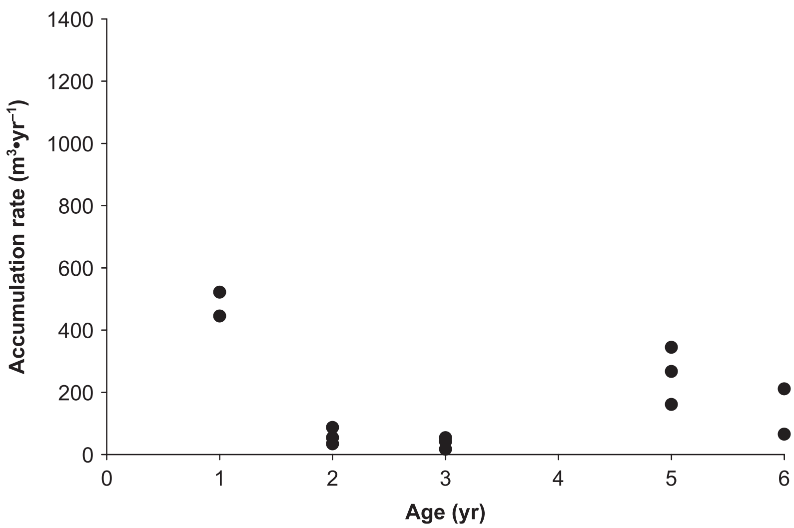

Figure 4. There was no significant overall trend between annual volumetric sediment accumulation rates and beaver dam age (linear regression: *p* = 0·6, r^2 = 0·02, *n* = 13), though both one-year-old dams did have the highest annual rate of volumetric sediment accumulation.

linear regression indicated no significant trend in the volumetric accumulation rate with age ($p = 0·6$, $r^2 = 0·02$, $n = 13$, Figure 4).

Sediment accumulations behind the beaver dams changed the bed slope. Upstream of beaver dams, bed slopes ranged between 0·001 and 0·014, averaging 0·004 (Figure 5). The underlying bed slopes ranged between 0·008 and 0·028, averaging 0·018. On average, the sediment accumulations reduced slopes by a factor of 4.5 or an average reduction in slope of 1.3%. In no instances did sediment accumulation behind beaver dams increase the slope of the stream.

Immediately upstream and downstream of the channel reaches where sediment accumulation occurred, the width of the area within 0·5 m elevation of the stream channel was remarkably consistent, averaging 8.6 m, with a range of 7.5–12.0 m. In contrast, where aggradation had occurred, the width of area within 0·5 m elevation increased and also became more variable, ranging from 16 m to 105 m, and averaging 44 m. The difference in widths between where aggradation had occurred and the average of the adjacent upstream and downstream reaches where aggradation had not occurred was significant (paired *t*-test, $p < 0·001$, $n = 18$).

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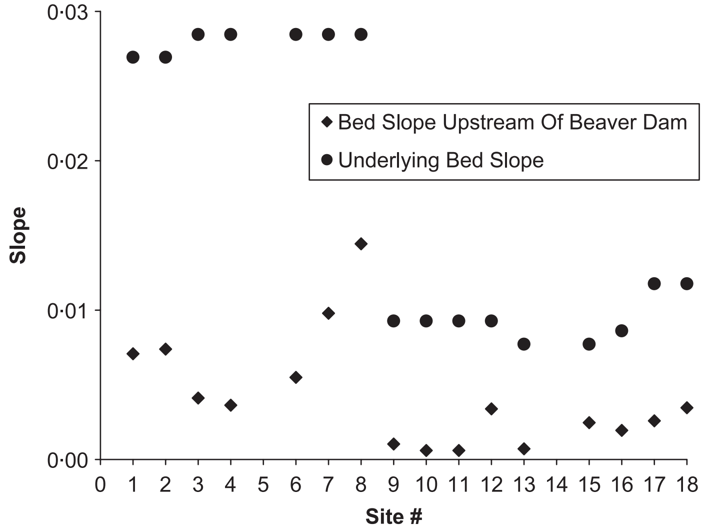

Figure 5. The accumulation of sediment behind beaver dams consistently lowered the slope of the stream bed. Upstream of beaver dams, bed slopes averaged 0·004, while the underlying bed slopes averaged 0·018. Circles mark the underlying bed slope; diamonds mark the bed slope immediately upstream of the beaver dam.

Based on the observed relationship between aggradation rates and dam age (Equation (1)) as well as other published literature on sediment accumulation rates (Scheffer, 1938; Butler and Malanson, 1995; McCullough *et al.*, 2005), we conservatively assumed a long-term (decadal) aggradation rate of 0·05 m yr^{-1} above intact beaver dams. We used this rate to estimate the increase in the area within 0·5 m vertical elevation of the channel that will occur over the next 90 years for which there are active beaver dams in a reach. We made this estimate for five aggrading reaches where beaver dams currently exist to illustrate how different geomorphic conditions will affect recovery rates (Figure 6). Because beavers do not continuously occupy a site, the actual time it will actually take for this aggradation to occur

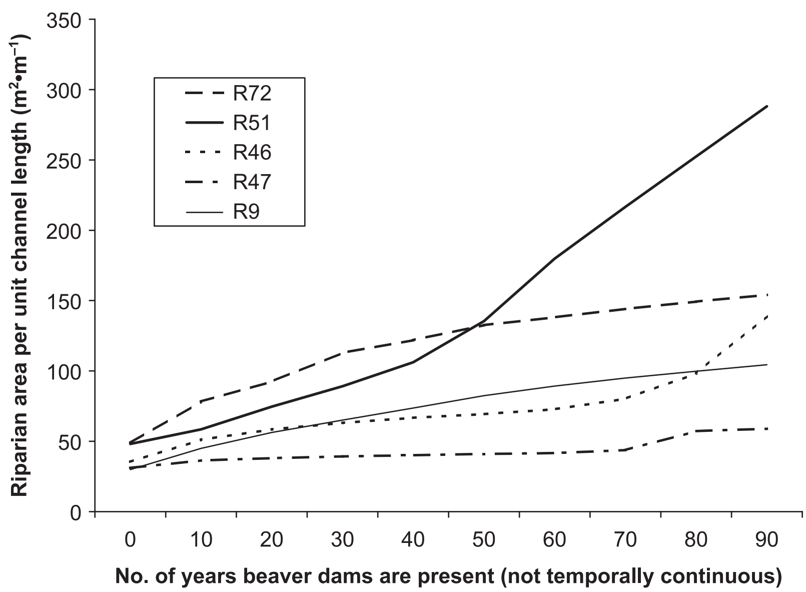

Figure 6. Estimated increase in stream-adjacent area within 0·5 m of the channel bed (i.e. the riparian area) as a function of the number of years for which the reach has active beaver dams, for five reaches on Bridge Creek that currently contain beaver dams. An aggradation rate of 0·05 m for each year for which beaver dams are present is assumed. The rate of increase of riparian area varies as a result of different degrees of incision and post-incision channel widening.

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will be dependent on the relative amount of time for which beavers are maintaining active dams in the reach. Thus the temporal scale on the *x*-axis is 'number of years with beaver dams' rather than 'years'.

For these five reaches, the average amount of riparian area per unit of channel length initially was between 25 and 50 $m^2 m^{-1}$. After a cumulative 90 years of beaver dams at each of the sites, the projected amount of riparian area increase ranged from a less than twofold to a more than sixfold increase (Figure 6). This variation was a function of the depth of incision, the location of abandoned terraces and the width of the valley floor.

Discussion

Our results demonstrate that within incised stream trenches beaver dams create an environment favorable for the deposition of suspended sediment. The beaver dams in our study area have already trapped enough sediment to raise the stream bed and reconnect the stream to low-lying terraces such that there was a fivefold increase in stream-adjacent area within 0·5 m elevation of the streambed. We observed that most areas within 0·5 m elevation of the streambed were being rapidly recolonized by emergent and woody riparian vegetation, particularly at the older sites. In some instances, sedimentation behind existing beaver dams has aggraded streams sufficiently to reconnect them to abandoned terraces, thus greatly expanding the areal extent of riparian vegetation (see, e.g., Figure 7).

Most models of the channel evolution of incised or inciseable streams concur that after a period of rapid incision the incision trench widens and a new inset floodplain is formed. Then the long process of aggradation begins as sediment accumulates on the inset floodplain during floods (see Figure 1). Our results suggest that the presence of beaver dams substantially alters this basic model. Beavers used small-diameter wood and mud to build small (generally <1·5 m high) dams on incised streams that had not yet widened. The dams created a slow-water environment that allowed sediment to drop out of suspension. At some (but not all) of our study sites, the incised streams had not yet gone through the widening phase, and the incision trench was able to rapidly fill with sediment, so the stream bed quickly aggraded. In several instances, the aggradation had already raised the stream bed sufficiently to connect the stream to formerly abandoned terraces (see, e.g., Figure 7), demonstrating that under proper conditions recovery of incised streams can occur over very short time frames. This is a significant finding, because a current scientific paradigm in

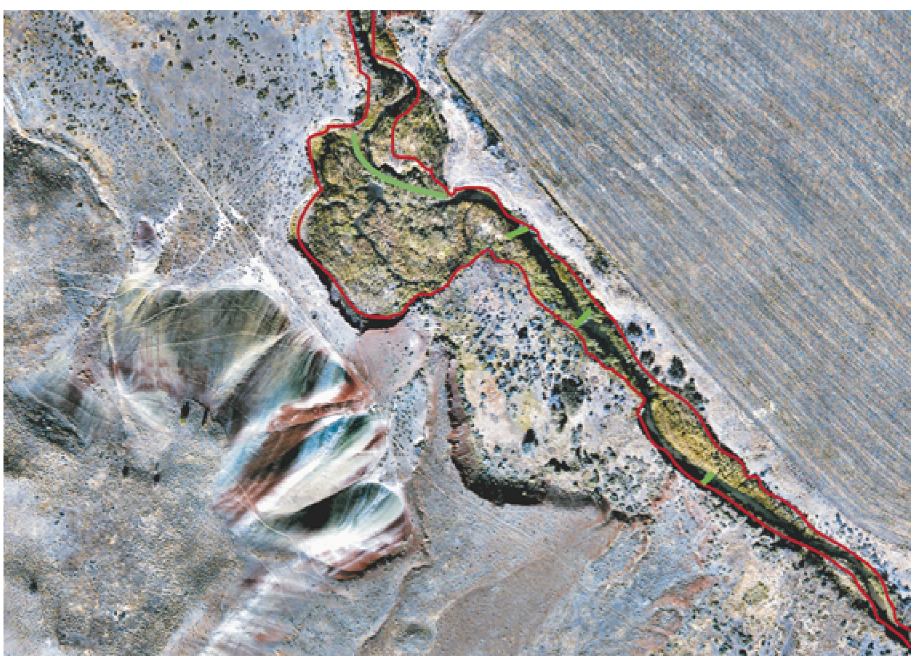

Figure 7. An aerial orthophotograph of beaver dams (green lines) and riparian vegetation adjacent to Painted Hills National Monument. The red line outlines the stream-adjacent area within 0·5 m elevation of the existing stream channel. The large, downstream beaver dam has aggraded the stream bed over 1 m in the past 6 years, raising the water table and allowing riparian vegetation to rapidly expand onto a formerly abandoned terrace such as the one immediately upstream.

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regard to the restoration of incised streams in the western United States assumes that the most practical way to accelerate the restoration of incised streams is to assist in the creation of a new inset floodplain and to create a new sinuous channel within the new floodplain (Rosgen, 1996). Needless to say, this approach requires the extensive use of heavy machinery and involves a tremendous amount of work and expense. As Figure 1 suggests, it also delays the full recovery of some of the hydrologic functions of the stream by delaying the rise of the water table within the stream-adjacent alluvium. In contrast, a number of examples exist where the construction of beaver dams or small check dams allowed streams to aggrade and water tables to rise, and formerly seasonal streams developed perennial flow (Stabler, 1985; DeBano and Heede, 1987; Ponce and Lindquist, 1990; Pollock *et al.*, 2003). Thus restoration strategies that widen the incision trench to construct an inset floodplain can actually delay recovery of an important hydrologic function and cause long-term damage to the system as a whole.

We did not observe any degradation of ecosystem function caused by the presence of beaver dams within incised streams. Rather than creating an inset floodplain, the dams often simply created conditions such that the stream could rapidly aggrade to the level of the former floodplain. In addition to the expansion of riparian vegetation observed at some of our sites, we also noted in late summer that below the dams were pockets of cool water that averaged 4·1 °C lower than the ambient stream temperature (Figure 8), presumably a result of upwelling from beneath the dam (see, e.g., White, 1990). Additionally, we also observed considerably higher abundances of juvenile steelhead in the aggrading reaches (Pollock *et al.*, in review). Collectively, these observations suggest that a number of stream ecosystem attributes are responding favorably to aggrading reaches and the corresponding rise in alluvial water tables, though cause and effect relations have not been determined.

Not all reaches dammed by beavers have created large areas suitable for colonization by riparian vegetation. Some dams have been constructed in narrow, deeply incised reaches that will require several meters of aggradation before they will be reconnected to any abandoned terraces. Figure 6 illustrates the differences in projected future riparian areas as aggradation occurs behind beaver dams for five different reaches where beaver dams currently exist. Reach 51 has aggraded substantially and has already reconnected to several abandoned terraces. When beavers have maintained dams there for a total of 50 years, it will reconnect to several other low terraces, widening the riparian area to about 100 m, until it reaches the valley floor, whereupon there will be rapid expansion of the width of the riparian area across the valley floor to a width of 300 m or more. In contrast, Reach 9 is in a fairly confined valley that has gently sloping colluvial fans on either side. Even with extensive aggradation, the area within 0·5 m vertical elevation of the stream bed remains limited, and the riparian width is unlikely to ever be much greater than 100 m. Reach 72 is similar to Reach 9 in that it has alluvial fan on one side, so there is a limited area of valley floor for the channel to climb up onto, but there are several large, low-lying abandoned terraces that it can access as it aggrades. Ultimately, however, rapid riparian expansion is limited to about 150 m by the colluvial fan. Reach 46 is deeply incised and has a small

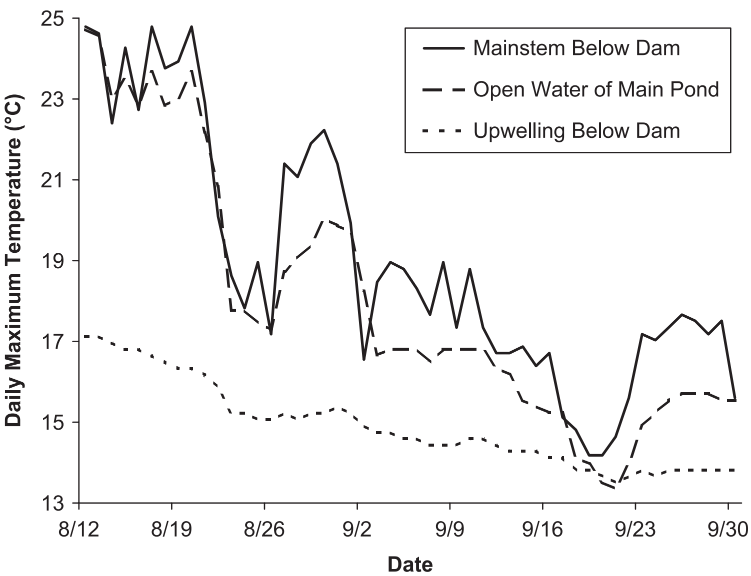

Figure 8. Temperature profiles of lower Bridge Creek in late summer 2005, showing that relatively cool pockets of water with mild temperature fluctuations exist below beaver dams, presumably the result of accumulated pond water above the dams downwelling through the alluvium and then upwelling below the dam (see White, 1990).

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inset terrace that has been abandoned as more incision occurred, but is close to being reconnected to the channel as aggradation behind beaver dams continues. However, once this occurs, there will be little riparian area expansion until beaver dams have been in the reach for about 7 decades, when enough aggradation will have occurred to reconnect the stream to the abandoned terrace approximately 3·5 m above the current stream channel.

Because it is unlikely that beaver will occupy any site continuously for a duration long enough to reconnect the stream to an abandoned terrace, the axis of Figure 6 refers to the number of years for which beaver dams are present, rather than years. We use this metric because beavers do not continually occupy a site. However, several studies of beaver pond occupation and abandonment under natural conditions suggest relatively high occupancy rates once a site is colonized. Data from Johnston and Naiman (1990a, 1990b), who studied the patch dynamics of beaver pond creation and abandonment over a 46 year period across the 294 km^2 Kabetogama Peninsula in Voyageurs National Park, MN, suggests a pond turnover rate of less than 20% per decade, and a slow but ongoing increase in the total area occupied by beavers at the end of the study period. The total area affected by the beaver dams was about 13% of the total Peninsula area, and many streams were impounded to such an extent that they formed a continuous series of ponds and had occupied almost all of the reaches that could be dammed. A 20% turnover rate suggests that 80% of the dammable reaches are dammed at any particular time, and that on average any given site has a dam on it for 80% of the time (see also Naiman *et al.*, 1988).

Data from Snodgrass (Snodgrass, 1997 – Figure 4) suggests that 40 years after reintroduction of beavers to a 77 000 ha protected area near the Savannah River in South Carolina less than 15% of the sites colonized had been abandoned. This indicates an 85% occupancy rate. Remillard *et al.* (1987) studied patch dynamics of beaver ponds in Adirondacks State Park in New York over a 42 year period and found that the beaver had colonized most of the suitable habitat, and that the cycle of beaver pond colonization, abandonment and recolonization ranged between 10 and 30 years, but did not specify the average duration for which the ponds were occupied. This is consistent with the work of Neff (1959), who summarized 70 years of observations of a beaver pond in the Rocky Mountains of Colorado and found that it had been abandoned twice over that time (for 16 and 8 years) but had been continuously occupied for the previous 30 years (occupied 66% of the time). The 16 year abandonment is a little anomalous in that it was the result of a forest fire that destroyed the beaver colony. In general, site abandonment by beavers is often attributed to a depletion of the food supply and reoccupation of abandoned sites attributed to regeneration of food supplies (Hall, 1971; Hodgdon, 1978).

Bridge Creek is a sediment-rich stream in a semi-arid environment, so the cited occupancy rates are not directly applicable, but they do suggest that under a variety of natural conditions, with trapping pressures removed, beaver populations will expand to colonize most of the suitable habitat and then maintain a relatively high occupancy rate of that habitat. Our own observations of Bridge Creek suggest that many dams are abandoned because they rapidly backfill with sediment during one or two storm events, and the system of canals and pools that beavers need to provide protection while accessing their foraging areas, lodges and dams cannot be maintained.

Not all incised reaches contain beaver dams, even though the BLM database indicates that they have been there for brief periods (mostly ≤2 yrs) in the past. Observations along these reaches suggest that they are geomorphologically similar in terms of stream gradient and the width of the incision trench. However, most sites without beaver dams also have limited amounts of riparian vegetation, usually just a narrow corridor of small-diameter (<1 cm) willows alongside the stream. In contrast, sites with beaver dams have much more abundant riparian vegetation (see, e.g., Figure 7). We speculate that beaver have not dammed additional reaches because of a lack of vegetation needed both for food and for the construction of dams and lodges. This is a reasonable hypothesis because the hydrologic and geomorphic conditions are clearly suitable, as evidenced by the existing colonies along Bridge Creek. Predation (and trapping) is another potential factor limiting the establishment of beaver colonies along Bridge Creek, and may be the ultimate fate of the young beavers that disperse each year from the colonies. However, vulnerability to natural predation is a function of the extent to which beavers can build dams to create ponds and lodges where they are safe.

Thus it is possible that for an incised stream to recover it needs riparian vegetation in order for beaver dams to be built, but for riparian vegetation to widely establish, beaver dams need to be constructed. This would explain why an incised stream such as the mainstem of Bridge Creek, most of which is has recently been put in the public domain and is not subject to much grazing or agricultural pressures within the riparian corridor, does not contain more riparian vegetation and has only a few reaches that are actively aggrading. In this system, it appears that aggradation is dependent on the presence of both riparian vegetation and beavers, suggesting that aggradation rates have biological controls as well as physical controls. From a restoration perspective then it does make sense, at least initially, to create inset floodplains in some reaches so that enough riparian vegetation can become established to support beaver colonies. A less expensive restoration approach would be to provide beaver with the woody material needed for food and dam construction. This approach has been tried elsewhere briefly to restore incised streams, with positive results (Apple *et al.*, 1983; Apple, 1985). Dams were constructed and they quickly backfilled with sediment. However, the

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long-term fate of the beavers and the dams were not documented and it did not appear that the experiment was carried out for long enough for a colony to become permanently established.

If the number of beaver dams were increased throughout Bridge Creek, through either natural or artificial means, it is reasonable to ask whether at some point the system would become sediment supply limited, such that aggradation rates in dammed reaches would decrease. To answer this question, we estimated the existing annual sediment yield in Bridge Creek and compared it with the sediment retained by the beaver dams we examined in this study. We estimated sediment yield by two methods: (1) by using the Revised Universal Soil Loss Equation (Renard *et al.*, 1997) and (2) by using instream sediment loads measured over a three year period at a United States Geological Survey gauging station at Bear Creek, a nearby incised stream with a similar geology and a slightly smaller watershed size. The RUSLE approach estimated a soil loss of 0·05 mm yr^{-1} or a total annual sediment volume of 34 850 m^3. The USGS data, after adjusting for the differences in drainage basin size, yielded an estimated annual sediment volume of 52 900 m^3, which is equivalent to a soil loss rate of 0·08 mm yr^{-1}. The total sediment retained by all of the beaver dams in our study was 7200 m^3 and the mean dam age was 3 years. This suggests that, adjusted to an annual basis, the 13 beaver dams removed between 5 and 7% of the total sediment load. Thus we conclude that the number of beaver dams in Bridge Creek could increase substantially, by at least an order of magnitude, before there was any measurable change in average aggradation rates upstream of the dams.

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References

Apple LL. 1985. *Riparian Habitat Restoration and Beavers*, USDA Forest Service General Technical Report RM-120; 489–490.

Apple LL, Smith BH, Dunder JD, Baker BW. 1983. The use of beavers for riparian/aquatic habitat restoration of cold desert, gully-cut stream systems in southwestern Wyoming. In American Fisheries Society/Wildlife Society joint chapter meeting, Logan, UT, 1983; 123–130.

Braskerud BC. 2001. The influence of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands. *Journal of Environmental Quality* **30**: 1447–1457.

Brown GW, Krygiier JT. 1970. Effects of clearcutting on stream temperatures. *Water Resources Research* **6**: 1133–1139.

Buckley GL. 1992. *Desertification of the Camp Creek Drainage in Central Oregon, 1826–1905*, master's thesis. University of Oregon: Eugene, OR.

Butler DR, Malanson GP. 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment; geomorphology, terrestrial and freshwater systems. In 26th Binghamton Symposium in Geomorphology, Binghamton, NY, Hupp CR, Osterkamp WR, Howard AD (eds); 255–269.

Carollo FG, Ferro V, Termini D. 2002. Flow velocity measurements in vegetated channels. *Journal of Hydraulic Engineering* **128**: 664–673.

Columbia – Blue Mountain Resource Conservation and Development Area (CBMRC). 2005. *John Day Subbasin Plan*. Northwest Power and Conservation Council: Portland, OR.

Cooke RU, Reeves RW. 1976. *Arroyos and Environmental Change in the American Southwest*. Oxford University Press: London.

Darby SE, Simon A. (eds). 1999. *Incised River Channels*. Wiley: Chichester.

DeBano LF, Heede BH. 1987. Enhancement of riparian ecosystems with channel structures. *Water Resources Bulletin* **23**: 463–470.

Elliot AH. 2000. Settling of fine sediment in a channel with emergent vegetation. *Journal of Hydraulic Engineering* **126**: 570–577.

Elmore W, Beschta RL. 1987. Riparian areas: perceptions in management. *Rangelands* **9**: 260–265.

Elmore W, Kauffman B, Vavra M, Laycock WA, Pieper RD. 1994. Ecological implications of herbivory in the west. In *Riparian and Watershed Systems: Degradation and Restoration*, Proceedings of the 42nd annual meeting of the American Institute of Biological Sciences, Washington, DC, AIBS (ed.); 212–231.

Gurnell AM. 1998. The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography* **22**: 167–189.

Hall AM. 1971. *Ecology of Beaver and Selection of Prey by Wolves in Central Ontario*, master's thesis. University of Toronto: Ontario.

Harvey M, Watson C. 1986. Fluvial processes and morphological thresholds in incised channel restoration. *Water Resources Bulletin* **22**: 359–368.

Hodgdon HE. 1978. *Social Dynamics and Behavior Within an Unexploited Beaver Population*, doctoral dissertation. University of Massachusetts: Boston, MA.

Johnson DR, Chance DH. 1974. Presettlement overharvest of upper Columbia River beaver populations. *Canadian Journal of Zoology* **52**: 1519–1521.

Copyright © 2007 John Wiley & Sons, Ltd.

Johnston CA, Naiman RJ. 1990a. Aquatic patch creation in relation to beaver population trends. *Ecology* **71**: 1617–1621.
Johnston CA, Naiman RJ. 1990b. The use of a geographic information system to analyze long-term landscape alteration by beaver. *Landscape Ecology* **4**: 5–19.
Kiffney PM, Richardson JS, Feller MC. 2000. Fluvial and epilithic organic matter dynamics in headwater streams of southwestern British Columbia, Canada. *Archiv fuer Hydrobiologie* **683**: 1–21.
Leopold LB, Wolman MG, Miller JP. 1964. *Fluvial Processes in Geomorphology*. Freeman: San Francisco, CA.
McCullough MC, Harper JL, Eisenhauer DE, Dosskey MG. 2005. Channel aggradation by beaver dams on a small agricultural stream in Eastern Nebraska. *Journal of the American Society of Agricultural and Biological Engineers* **57**: 107–118.
Meentemeyer RK, Butler DR. 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. *Physical Geography* **20**: 436–446.
Morgan LH. 1986. *The American Beaver – a Classic of Natural History and Ecology*. Dover: Toronto, Ontario.
Nagle GN. 1993. *The Rehabilitation of Degraded Riparian Areas in the Northern Great Basin*, master's thesis. Cornell.
Naiman RJ, Johnston CA, Kelley JC. 1988. Alteration of North American streams by beaver. *BioScience* **38**: 753–761.
Naiman RJ, Melillo JM, Hobbie JE. 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology* **67**: 1254–1269.
Neff DJ. 1959. A seventy-year history of a Colorado beaver colony. *Journal of Mammalogy* **40**: 381–387.
Nehlsen W, Williams JE, Lichatowich JA. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* **16**: 4–21.
Pastor J, Bonde J, Johnson C, Naiman RJ. 1993. Markovian analysis of the spatially dependent dynamics of beaver ponds. *Lectures on Mathematics in the Life Sciences* **23**: 5–27.
Peacock KA. 1994. *Valley Fill and Channel Incision in Meyer's Canyon, Northcentral Oregon*, master's thesis. Oregon State: Corvallis, OR.
Pollock MM, Heim M, Werner D. 2003. Hydrologic and geomorphic effects of beaver dams and their influence on fishes. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer K, Gurnell A. (eds). American Fisheries Society: Bethesda, MD; 213–233.
Ponce VM, Lindquist DS. 1990. Management of baseflow augmentation: a review. *Water Resources Bulletin* **26**: 259–268.
Poole GC, Berman CH. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* **27**: 787–802.
Prosser IP, Chappell J, Gillespie R. 1994. Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia. *Earth Surface Processes and Landforms* **19**: 465–480.
Remillard MM, Gruendling GK, Bogucki DJ. 1987. Disturbance by beaver (*Castor canadensis*) and increased landscape heterogeneity. In *Landscape Heterogeneity and Disturbance*, Turner MG (ed.). Springer: New York; 103–121.
Renard KG, Foster GA, Weesies DK, McCool DK, Yoder DC. 1997. *Predicting Soil Erosion by Water: a Guide to Conservation Planning with the Revised Universal Soil Loss Equation*, Agriculture Handbook 703. United States Department of Agriculture: Washington, DC.
Rosgen DL. 1994. A classification of natural rivers. *Catena* **22**: 169–199.
Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology: Pagosa Springs, CO.
Russell IC. 1905. *Preliminary Report on the Geology and Water Resources of Central Oregon*. Department of the Interior, U.S. Geological Survey: Washington, DC.
Scheffer PM. 1938. The beaver as an upstream engineer. *Soil Conservation* **3**: 178–181.
Schumm S, Harvey M, Watson C. 1984. *Incised Channels: Morphology, Dynamics and Control*. Water Resources: Littleton, CO.
Shields FD. Jr., Brookes A, Haltiner J. 1999. Geomorphological approaches to incised stream channel restoration in the United States and Europe. In *Incised River Channels; Processes, Forms, Engineering and Management*, Darby SE, Simon A. (eds). Wiley: Chichester; 371–394.
Shields FD. Jr., Knight SS, Cooper CM. 1995. Rehabilitation of watersheds with incising channels. *Water Resources Bulletin* **31**: 971–982.
Simon A, Rinaldi M, Hupp CR, Darby SE. 1995. Channel evolution, instability, and the role of the 1993 floods in the loess area of the Midwestern United States. In Association of American Geographers 91st annual meeting; abstracts. Association of American Geographers, Southeastern Division: Washington, DC.
Smith DG. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. *Geological Society of America Bulletin* **87**: 857–860.
Snodgrass JW. 1997. Temporal and spatial dynamics of beaver-created patches as influenced by management practices in a south-eastern North American landscape. *Journal of Applied Ecology* **34**: 1043–1056.
Stabler DF. 1985. *Increasing Summer Flow in Small Streams Through Management of Riparian Areas and Adjacent Vegetation – a Synthesis*, USDA Forest Service General Technical Report GTR-RM-120; 206–210.
Vandekerckhove L, Poesen J, Oostwoud Wijdenes D, Nachtergaele J, Kosmas C, Roxo MJ, De Figueiredo T. 2000. Thresholds for gully initiation and sedimentation in Mediterranean Europe. *Earth Surface Processes and Landforms* **25**: 1201–1220.
Welcher KE. 1993. *Holocene Channel Changes of Camp Creek; an Arroyo in Eastern Oregon*, MA thesis. University of Oregon.
White DS. 1990. Biological relationships to convective flow patterns within stream beds. *Hydrobiologia* **196**: 149–158.
Wissmar RC. 1994. *Ecological Health of River Basins in Forested Regions of Eastern Washington and Oregon*, PNW-326. U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR.
Wissmar RC, Smith JE, McIntosh BA, Li HW, Reeves GH, Sedell JR. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s–1990s). *Northwest Science* **68**: 1–35.
Zierholz C, Prosser IP, Fogarty PJ, Rustomji P. 2001. In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales. *Geomorphology* **38**: 221–235.

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