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Article *in* Earth Surface Processes and Landforms · July 2014

DOI: 10.1002/esp.3576

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(wileyonlinelibrary.com) DOI: 10.1002/esp.3576

The impact of beaver dams on the morphology of a river in the eastern United States with implications for river restoration

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Received 12 March 2013; Revised 15 March 2014; Accepted 20 March 2014

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ABSTRACT: Restoration projects in the United States typically have among the stated goals those of increasing channel stability and sediment storage within the reach. Increased interest in ecologically based restoration techniques has led to the consideration of introducing beavers to degraded channels with the hope that the construction of beaver dams will aggrade the channel. Most research on beaver dam modification to channels has focused on the long-term effects of beavers on the landscape with data primarily from rivers in the western United States. This study illustrated that a role exists for beavers in the restoration of fine-grained, low gradient channels.

A channel on the Atlantic Coastal Plain was analyzed before, during, and after beaver dams were constructed to evaluate the lasting impact of the beaver on channel morphology. The channel was actively evolving in a former reservoir area upstream of a dam break. Colonization by the beaver focused the flow into the channel, allowed for deposition along the channel banks, and reduced the channel width such that when the beaver dams were destroyed in a flood, there was no channel migration and net sediment storage in the reach had increased. However, the majority of the deposition occurred at the channel banks, narrowing the channel width, while the channel incised between sequential beaver dams. The study indicated that where channels are unstable laterally and bank erosion is a concern, the introduction of beavers can be a useful restoration tool. However, because of the likelihood of increased channel bed erosion in a reach with multiple beaver dams, they may not be the best solution where aggradation of an incised channel bed is the desired result. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: beaver dam; restoration; bank stability

Introduction

A purpose of many stream restoration projects is to raise the longitudinal profile of a degraded channel bed and to reconnect the active channel to its floodplain (e.g. Palmer *et al.*, 2005). These are channels that have eroded vertically, incising into their beds as a consequence of hydromodification in the contributing area. One popular restoration method has been to install a series of low head check dams which reduce hydrograph peaks and induce deposition upstream of each dam (e.g. Wilcox *et al.*, 2001). Channel spanning beaver dams can affect channel morphology in much the same manner as engineered check dams. Ponding upstream of beaver dams increases the local water depth, reduces flow velocities, and dissipates stream energy which in turn induces deposition of suspended sediment and channel aggradation upstream of the dams (Naiman *et al.*, 1986; Butler and Malanson, 1995; Pollock *et al.*, 2007; Green and Westbrook, 2009). The ability of beaver dams to affect aggradation of an incised stream channel has made them an attractive option for restoration that is ecologically based and requiring minimal human intervention (Palmer *et al.*, 2009; Burchsted *et al.*, 2010). Potential application of beavers has focused on incised rivers in the western United States, as evidenced by a recent short course in Utah (www.beaver.joewheaton.org). However, the beaver population in the eastern United States has been growing (Harrelson, 1998; Burchsted and Daniels, 2014), making the wide-spread application of beaver to a broader range of river restoration projects possible.

Dam removal has become a part of many river restoration projects, particularly where the dams are low-head mill dams that no longer serve a purpose, are structurally unsound, and represent a local flooding hazard. Removing a low-head dam remains controversial due to uncertainties regarding the anticipated export of accumulated fine sediment from the reservoir area as the impoundment reverts to a channel. Because fine sediments are building components of beaver dams along with wood and stones (Gurnell, 1998), beavers have promise in the restoration of these river systems. Beavers have the potential to construct temporary dams that may help stabilize the channel forming in the former reservoir area and limit the export of fine sediment. Thus, the addition of beaver dams may provide a natural way to enhance emergent channel stability so that structurally unsound dams may be removed.

Despite increases in beaver population and the potential for application of beaver in the restoration of Atlantic Coastal Plain channels, data from this region remains limited. For the beaver to become a widely viable restoration option, the impact of beaver dams on sedimentation rates, channel morphology, and channel stability needs to be quantified across a diversity of study areas. This paper presents a case study of the impacts of beaver dams on a low gradient, fine-grained alluvial channel on the Atlantic Coastal Plain. A human-built dam on a river in eastern Virginia was breached. As a channel developed in the former reservoir area, beaver inhabited the area and built a series of dams. Channel morphology was measured before, during, and after the beaver dams were present, enabling an analysis of the impacts of beaver dams on channel morphology and sediment retention in the former reservoir and an evaluation of the applicability of existing models of sediment aggradation at beaver dams. This study contributes to the assessment of beavers as a restoration option by presenting data from a low gradient system following dam removal. We evaluate the contribution of beaver dams to channel stability and sediment retention, two common goals in river restoration.

Background

Beaver dams built within the main channel punctuate the longitudinal river profile and cause the channel to flow through a series of impoundments joined by free flowing reaches (Burchsted *et al.*, 2010). Multiple dams of different heights are often built on a single river channel, creating a range of impounded water levels to accommodate multiple beaver lodge entrances (Gurnell, 1998). Backwater upstream from beaver dams can increase groundwater levels and create suitable environments for emergent vegetation (Collen and Gibson, 2001; Westbrook *et al.*, 2006). As vegetation establishes in beaver impoundments, accumulating sediment is stabilized in place. Reduced reservoir space in beaver impoundments increases the rate of overbank flooding, re-routing the flow into multiple canals and channels (Woo and Waddington, 1990; Burchsted *et al.*, 2010; Westbrook *et al.*, 2011). Overbank flows may lead to main channel avulsions, the formation of diversion channels on floodplains, and stable multi-thread channel systems with vegetation occupying the areas between the channel threads (Woo and Waddington, 1990). Floodplains develop diversity in vegetation and channel morphology, creating heterogeneity in the physical and biological components of the riparian corridor (Townsend and Butler, 1996; Burchsted and Daniels, 2014). Through this process, landscapes with active beaver populations can be transformed into beaver meadows comprised of multi-thread channels in low gradient valleys (Ruedemann and Schoonmaker, 1938; Ives, 1942; Naiman *et al.*, 1988; Hay, 2010; Westbrook *et al.*, 2011; Polvi and Wohl, 2012). The multi-thread channel structure characteristic of these meadows is maintained by the presence of multiple beaver dams and the planform stability of these channels has been attributed to the presence of the beaver dams (Townsend and Butler, 1996). After beaver dams were removed from an area in British Columbia, the meadow landscape adjusted to a narrow, single thread channel (Green and Westbrook, 2009). An alteration in landscape upon loss of active beavers has also been related to decreases in groundwater levels and the subsequent loss of robust willow populations (Marshall *et al.*, 2013).

The ability to modify the physical characteristics and species richness of a habitat around its needs has led to the characterization of the beaver as an 'ecosystem engineer' (Lawton and Jones, 1995; Jones *et al.*, 1997). There have been a limited number of attempts to reintroduce beavers in specific locations with the intention that the beavers would modify the existing landscape by aggrading a degraded river and improving the riparian ecosystem. Both the North American Beaver (*Castor canadensis*) and the European Beaver (*Castor fiber*) have been introduced to landscapes for restoration purposes (Gorshkov *et al.*, 1999; Nyssen *et al.*, 2011). The use of beavers as part of channel stabilization and riparian restoration efforts in North America dates to the 1930s when 500–600 beavers were released into areas where Civilian Conservation Corps workers had built initial dam structures in Idaho, Utah, Oregon, Washington, and Wyoming (Ruedemann and Schoonmaker, 1938). More recently, beavers were introduced to 14 different streams in Wyoming to improve habitats for waterfowl, and within one year of their introduction, they had created 31 ponds (McKinstry and Anderson, 2002). Three to five years after the introduction of 23 beavers in seven riparian rehabilitation areas in New Mexico, increases in water table levels and riparian vegetation were measured and attributed to the presence of beaver dams (Albert and Trimble, 2000). Recent studies have linked beaver dam characteristics with changes in channel flows. In western Colorado, the ponds formed upstream of high-head (greater than 1.2 m) beaver dams had a morphology that led to cool bottom waters. The ponds were deep but with a small surface area, and water leaving the ponds reduced temperatures in the downstream channel and also in shallow groundwater flowpaths (Fuller and Peckarsky, 2011). This finding contributed to defining the appropriate use of beavers to enhance stream cooling for trout habitat (Collen and Gibson, 2001; Fuller and Peckarsky, 2011). The rise in groundwater tables around beaver dams has led to suggestions that for broad recovery of riparian willow stands in Yellowstone National Park, the beaver must re-colonize the area (Marshall *et al.*, 2013).

The desired time frame for beaver dam use in channel restoration is in part a function of the aggradation rate in the ponds. Widespread prescribed use of beavers to aggrade an incised river channel requires predictive models of beaver induced aggradation rates and volumes. Beaver dams can aid in channel bed aggradation and riparian area regeneration during a restoration project but be undesirable over the long term because of the possibility of channel avulsions and multi-thread channel formation. Most studies that have estimated sedimentation volumes and rates associated with beaver ponds have focused on the historical alteration to the landscape as a consequence of beaver removal. The result has been widely divergent estimates of the sediment volumes retained by beaver dams in the past. For example, sediment accumulation prior to the removal of 18 beaver dams in the Purcell Mountains in south-eastern British Columbia in the 1980s was estimated to be between 290 m^3 and 406 m^3 over a 3 km reach (Green and Westbrook, 2009). By extrapolating from measured sediment depths at six beaver dams in Nebraska, 1450 m^3 of sediment was estimated as having been stored over 736 km of river channel (McCullough *et al.*, 2004). Sedimentation rates from eastern North America are available only for the boreal forest areas of sub-arctic Quebec (Naiman *et al.*, 1986; Naiman *et al.*, 1988), where the surface areas of the beaver ponds were used as an indication of sediment volume in the pond. The average estimate was an accumulation of 1000 m^3 of sediment per beaver pond from which the authors extrapolated that under the historic beaver population sediment retention in the watershed was equal to a depth of 42 cm over the watershed area.

Existing empirical models that predict aggradation rate were developed using data from channels in the mid-western (Naiman *et al.*, 1986) and western United States (Butler and Malanson, 1995; Pollock *et al.*, 2007). Butler and Malanson (1995) compared measurements of aggradation at beaver dams to sedimentation volumes at eight ponds in Montana. They found that channel bed slope had a strong influence on pond sedimentation rates, reflecting the importance of beaver dam height and shape for sediment accretion. Combining their measured sedimentation data with estimates of beaver dam age, the authors developed Equation (1) to predict the average sedimentation rate using the age of the pond, where AR is the aggradation rate in centimeters per year and age is measured in years.

$$\ln(AR) = 2.99 - 0.71\ln(age) \tag{1}$$

Using aggradation rates and volumes measured upstream of 13 beaver dams in the Columbia River Valley in Oregon that ranged in age from one to six years, Pollock *et al.* (2007) developed a similar empirical model to relate the age of the dam to the rate of sedimentation in the upstream pond:

$$\ln(AR) = -0.96 - 0.9093\ln(age) \tag{2}$$

where AR is the aggradation rate in meters per year and age is measured in years. We present the Pollock model in a similar format as Equation (1) to illustrate the similarity in the models. Both models predict maximum sedimentation rates immediately after dam formation with rates decreasing with time.

Study Site

Kimages Creek is a second-order tributary to the James River in eastern Virginia (Figure 1). The Creek drains an area of 10.55 km^2 where land cover is a mix of forest (70%), shrub vegetation (11%), wetlands (12%) and cultivation/development (7%) (NOAA Coastal Services Center, 2009). Undisturbed forests and agricultural fields are immediately adjacent to the study reach, which has not experienced significant land-use change in the past 100 years. Kimages Creek is typical of the Eastern Coastal Plain, where rivers are dominated by fine-grained alluvial and have low gradients (Meade, 1982; Hupp, 2000). Sediments in the study reach were predominantly fine-grained with median particle sizes between 0.2 and 0.5 mm. The median channel slope was 0.002 m/m.

Kimages creek was dammed in 1927 when a 3 m high, 50 m wide earthen dam was built to create a 72.4 ha impoundment to increase fishing and recreation opportunities in the area (Dougherty, 2008). The dam remained in place for 79 years until the left side was breached following a large storm in October 2006. As the reservoir drained, new reaches of Kimages Creek evolved in the former impoundment. In late July or early August 2008, beaver dams were constructed in the channel at locations B105, B170, and B185 downstream from the uppermost extent of the former reservoir (Figure 1). The beaver dams varied in height between 0.5 and 2.1 m and all extended across the channel width, as illustrated by the dam at B105 m (Figure 2). The beavers were not introduced to the area, and the dams were constructed without any outside intervention. The beaver dams remained in place until being destroyed by a two-year return interval storm event on November 15, 2009 that was accompanied by a number of smaller events such that the area was inundated for approximately a month. Flow rates on Kimages Creek were correlated to flows measured at the Chickahominy gage, which is the closest US Geographical Survey (USGS) gage to the study site and provided a continuous flow record from 1942 to present (Figure 3).

Methods

Channel morphology was evaluated from July 2007 and January 2010 through cross-section surveys at 104 m, 142 m, 172 m, and 198 m (Figure 1). Cross-sections were measured using a Topcon Total Station GTS-230W or a level and stadia rod. A polyvinylchloride (PVC) marker was placed at each cross-section to aid in identifying repeat survey locations between field

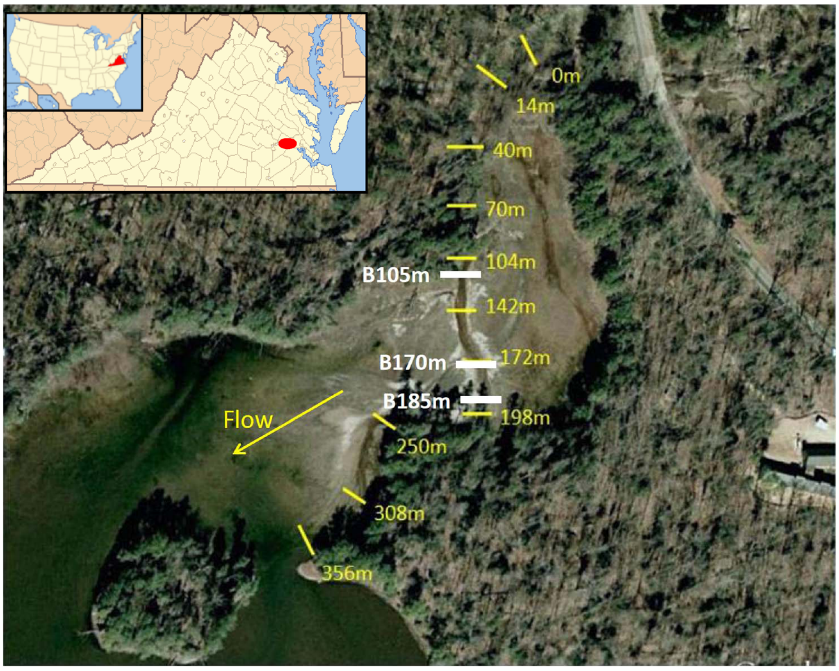

Figure 1. Study area with locations of permanent cross-sections marked by thin yellow lines and cross-section labels to the right of the marker. Beaver dam locations are marked by thick white lines and labels to the left of the lines. The beaver dam sites are labeled with the letter B at the beginning of each identifier. The man built dam is approximately 1300 m downstream of the area shown. The inset in the upper left shows the location of the study area in Virginia. The base image is from the Virginia Geographic Information Network, courtesy of the Commonwealth of Virginia, and the inset of the state of Virginia was created from the ESRI database. Kimages Creek is located at 37°20′11.91"N; 77°12′24.47"W. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 2. Photograph of the beaver dam at B105. Cross-section 104 was measured just upstream in the beaver pond. The beaver dam was 7.6 m wide and 1.3 m high (photograph taken on January 9, 2009]. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

campaigns. Data collected prior to August 2008 illustrated the channel morphology before beaver dam formation and have been described in Cannatelli and Curran (2012). Later surveys measured the impact of the beaver dams on the channel form. The locations of the cross-sections with respect to the beaver dams enabled an evaluation of channel changes immediately upstream of the dam at B105 m, immediately downstream of the dam at B170, at a location approximately equidistant between dams at B105 and B170, and 13 m downstream of the dam sequence (Table I). Cross-section surveys from January 2010 were measured two months after dam destruction and documented the lasting impacts of beaver colonization on the channel. Bulk streambed and bank grain size samples were collected in 2008 and 2010 (Table I). A minimum sample size of 100 g was collected at each site (Rice and Church, 1996). All samples were returned to the laboratory, dried, and sieved into 0.5 Φ size fractions. In 2008 additional sediment samples were collected and analyzed from a part of the Kimages Creek upstream of the backwater created by the dam.

The measured cross-sections were used to quantify changes in channel morphology between survey dates. Channel bed and bank aggradation and erosion were evaluated by comparing total widths and depths as well as bankfull areas between successive surveys (Table I). Bankfull was determined for the evolving channel cross-sections as the elevation of the lower channel bank at sites where a defined floodplain had not yet developed. Because the sediment was not evenly distributed longitudinally over the channel reach, we did not attempt to extrapolate the measured sediment areas into volumes.

Results

The impact of a beaver dam on the upstream channel area was measured at the 104 m cross-section. The beaver dam built in July 2008 at B105 was 2.1 m high and 7.62 m wide, spanning the channel and increasing the height of the left bank by over half a meter. This was the largest of the beaver dams in the study reach. Within the first months of dam formation, there was spatially even aggradation of the channel bed as fine sediments traveling downstream were deposited in the newly formed beaver pond (Figure 4a; Table I). The bankfull area was only slightly reduced by channel aggradation because deposition on the channel bed was offset by an increase in bank height. Channel bed aggradation continued upstream of the dam at B105, but was spatially uneven between the October 2008 and January 2009 surveys (Figure 4a). The left side of the channel bed aggraded more than the right, indicating the beginning of channel narrowing and deepening. Sediments continued to deposit on the left side of the channel, reducing overall channel width by almost 2 m and increasing the median grain sizes of the channel bed and banks (Table I), until the beaver dam was broken in November 2009. The final cross-section morphology measured in January 2010 was of a deep, narrow channel with an adjacent, shallower overflow channel. The bankfull area of the main channel was greatly reduced by a net accumulation of 0.14 m^2 of sediment (Table I). The cross-section did not migrate laterally and the bank locations remained stable throughout the study period.

Cross-section 142 was located on a fairly straight reach of the channel, mid-way between the beaver dams at B105 and B170 (Figure 1). Thus, it was between the expected effects of a reduced sediment supply downstream of the upstream dam and the backwater ponding effects from the downstream dam. Changes in cross-section morphology between initial beaver dam construction in July 2008 and the survey in October 2008 were limited to right bank erosion with minimal changes in overall bankfull area (Figure 4b; Table I). By January 2009, approximately six months after beaver dam construction, there had been a measurable increase in channel depth and lateral shift in the location of the channel thalweg, which identifies the deepest point in the channel. The thalweg returned to its original location after the beaver dams were destroyed, during which time there was also general bed degradation and fining. Channel bank sediments became courser while the amount of silt and clay fraction decreased (Table I). The January 2010 survey showed cross-section 142 had developed a narrow, deep channel with stable banks and experienced a net loss of 1.63 m^2 of sediment, increasing in bankfull area (Table I).

The downstream effects of beaver dam formation were measured at cross-section 172, located 2 m downstream of the

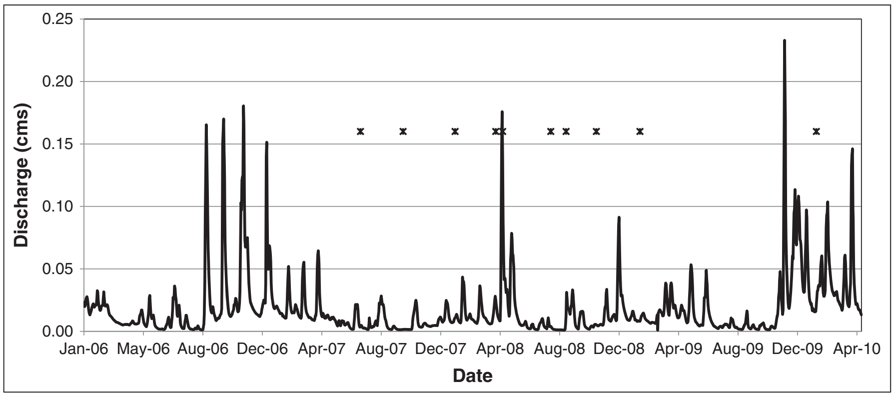

Figure 3. Hydrograph of flows through Kimages Creek from 2006 through April 2010. Field campaign dates are marked with x's on the hydrograph.

Table I. Details at measured cross-sections. All beaver dams were built in July 2008 and destroyed in November 2009

Cross-section location	Location relative to beaver dams	Survey dates	Thalweg depth (m)	Thalweg aggradation rate (m/yr)	Bankfull area (m^2)	Rate of change in bankfull area (m^2/yr)	Channel bed D_{50} (mm)	Channel banks D_{50} (mm)	Per cent sediment less than 0.062 mm	Aggradation rate predicted by Equation (1) (m/yr)	Aggradation rate predicted by Equation (2) (m/yr)
104 m	Upstream of beaver dam at 105 m	7.2008	1.30		8.28		0.21	0.12	9.3		
		8.2008	1.07	5.32	7.47	9.74				1.16	3.67
		10.2008	1.51	−1.74	8.74	−7.65				0.53	1.35
		1.2009	1.22	−0.96	6.39	9.41				0.33	0.72
		1.2010	0.98	−0.63	2.66	3.74	0.28	0.20	10.0	0.15	0.27
142 m	Between beaver dams at 105 m and 170 m	7.2008	0.35		1.20						
		8.2008	0.65	0.48	0.88	3.84	0.48	0.09	20.4	1.16	3.67
		10.2008	0.69	0.84	1.07	−1.15				0.53	1.35
		1.2009	0.83	1.72	2.06	−3.97				0.33	0.72
		1.2010	1.26	−0.85	4.16	−2.09	0.22	0.22	4.7	0.15	0.27
172 m	Downstream of beaver dam at 170 m	7.2008	0.41		1.32						
		8.2008	0.39	1.08	1.32	0.07	0.40	0.09	11.7	1.16	3.67
		10.2008	0.48	−0.30	1.65	−1.97				0.53	1.35
		1.2009	0.43	1.96	1.89	−0.98				0.33	0.72
		1.2010	0.92	0.08	2.81	−0.91	0.22	0.22	4.2	0.15	0.27
198 m	13 m downstream of beaver dam sequence	7.2008	1.00		3.50						
		8.2008	0.63	0.12	2.21	15.54	0.08	0.10	27.5	1.16	3.67
		10.2008	0.64	2.76	1.06	6.86				0.53	1.35
		1.2009	1.10	−2.08	1.87	−3.23				0.33	0.72
		1.2010	0.58	−0.58	1.07	0.80	0.26	0.32	1.8	0.15	0.27

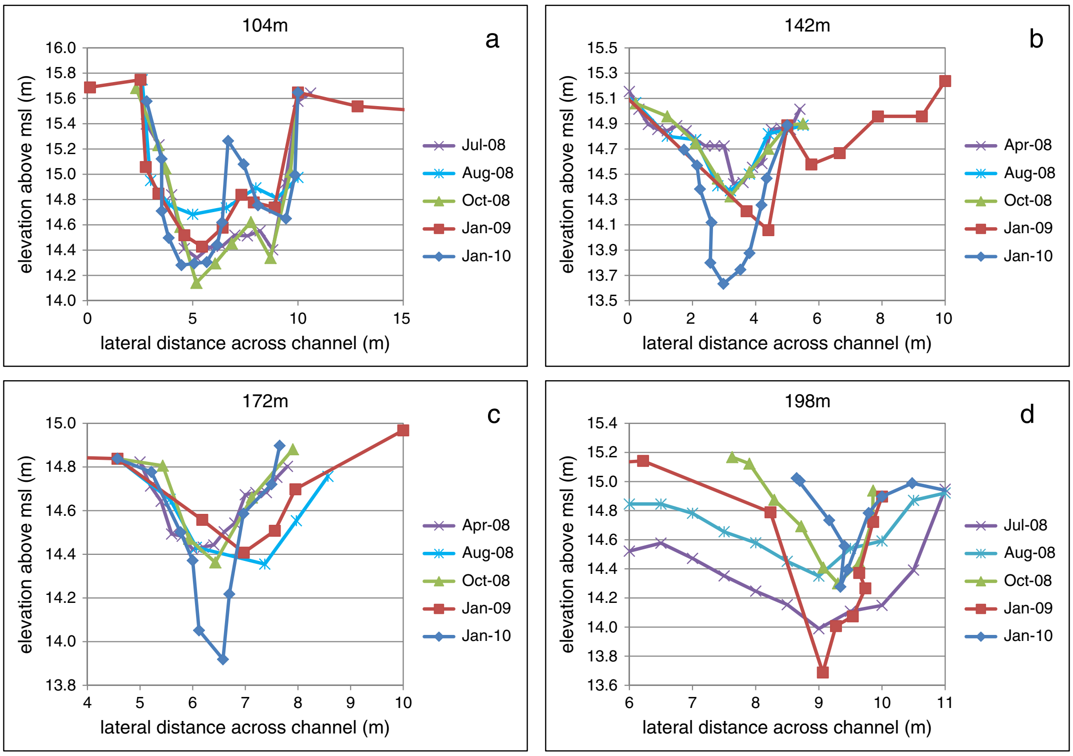

Figure 4. Surveyed channel cross-sections. (a) 104 m, immediately upstream of dam B105; (b) 142 m, mid-distant between dams at B105 and B170; (c) 172 m, immediately downstream of dam B170; (d) 198 m, 13 m downstream of the dam sequence. All dams were removed during a flood in November 2009. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

second beaver dam. Within the first months of dam construction in July 2008 the channel area eroded by 0.424 m^2 which shifted the location of the thalweg by approximately 1 m (Figure 4c; Table I). This initial erosion was attributed to beaver activity during dam building as beavers often utilize fine-grained sediments in dam construction, and the erosion was focused on the bank and not the channel bed as would have been the case if the erosion had resulted from bed scour. Deposition of 0.424 m^2 returned the cross-section to its original size and shape by the October 2008 survey (Figure 4c). However, between October 2008 and January 2009, the channel thalweg migrated laterally such that the channel location was similar to that measured in August 2008 immediately following dam construction. This was a temporary change in channel location and accompanied an increase in bankfull area. The survey in January 2010, after the removal of the beaver dams, showed the channel had returned to its original position and the bed had degraded by 0.5 m. Changes in the grain sizes of the bed and banks were similar to those measured at cross-section 142. The bed experienced overall fining while the banks coarsened. The final cross-section morphology had a bankfull area 0.38 m^2 larger than prior to beaver dam presence and a smaller median grain size (Table I).

The downstream effects of the beaver dam sequence on channel morphology were measured at cross-section 198, which was 13 m downstream of the final beaver dam in the study reach. The channel at this location was broad and flat prior to beaver dams construction, making identification of a bankfull area in August 2008 difficult (Figure 4d; Table I). By the October survey, after the upstream beaver dams had been in place for approximately three months, the channel at 198 m had experienced aggradation and developed a measureable channel area (Figure 4d). The channel subsequently eroded by 0.72 m^2 and increased in bankfull area while the beaver dams were in place. However, after the beaver dams were destroyed in November 2009, the channel area was measurably smaller as sediment deposited within the channel aggraded the bed by 0.6 m, making the channel depth equal to what it was in October 2008 (Table I). The reduction in bankfull area and aggradation of the channel bed are attributed in part to the deposition of sediment previously stored behind the upstream beaver dam sequence. Channel bed and bank D_{50} values were measurably coarser in 2010 when compared to the 2008 samples, indicating the influx of material from upstream (Table I).

We used the thalweg data measured on Kimages Creek to evaluate the applicability of available models of aggradation around beaver dams. Aggradation rates using Equation (1) (Butler and Malanson, 1995) and Equation (2) (Pollock *et al.*, 2007) were compared to measured rates of aggradation or erosion at each cross-section (Table I). Both models calculated aggradation rate using the age of the beaver dam, and because all dams in Kimages Creek existed for the same time frame, the predicted aggradation was constant across the cross-sections in both models. Equation (2) predicted a total thalweg aggradation of 6.01 m at each cross-section which was approximately four times the prediction of 2.17 m of thalweg aggradation using Equation (1). In contrast, field measurements documented fluctuations in thalweg depths with both aggradation and erosion at each cross-section. The net change in channel thalweg elevation over the time period of beaver dam presence ranged from maximum thalweg erosion of 0.42 m at cross-section 198 to maximum thalweg aggradation of 0.91 m at cross-section 142. Changes in thalweg elevation were more varied than either model could predict as each cross-section experienced different rates of aggradation and erosion between surveys.

Discussion

The dams built on Kimages Creek remained in place for less than two years, which recent studies have shown to be a common length of time for the existence of a beaver dam on a modern day channel (Bunte *et al.*, 2011; Burchsted and Daniels, 2014; Levine and Meyer, 2014). Although the channel was in place when the beaver dams were built, it had not formed a stable morphology as it had recently emerged from the reservoir backwater (Cannatelli and Curran, 2012). Unconstrained channel formation in former reservoirs has been characterized by bank failures and frequent lateral channel migrations which have resulted in erosion of former reservoir sediments (Doyle *et al.*, 2003). At Kimages Creek beaver dams aided in stabilizing the channel form by minimizing channel migration and allowing for aggradation at the banks, as evidenced by measured channel narrowing at all the cross-sections as sediment deposited onto the banks. The stabilizing effect on channel morphology is also illustrated by the decrease in cross-sectional bankfull area at 198 m (Table I) and the temporary nature of the lateral shift in channel thalweg position at cross-sections 142 and 172.

The changes to Kimages Creek morphology were more varied than the scenario of beaver pond sedimentation leading to channel avulsions, formation of multi-thread channels, and eventual landscape aggradation that has been suggested by a number of studies of historic beaver populations (e.g. Woo and Waddington, 1990; Wright *et al.*, 2002; Polvi and Wohl, 2012). Morphology changes in Kimages Creek also showed much more variability than model predictions of overall channel aggradation by deposition of between 2.17 and 6.01 m at the beaver ponds. When the measured changes in the reach were summed, there was 1.18 m^2 of net sediment storage in Kimages Creek while the beaver dams were in place and 2.43 m^2 of net storage after they broke. Part of the poor model fit may be a consequence of model dependence on thalweg elevation. The models predicted thalweg aggradation without considering the dynamic state of the channel morphology which included changes to channel width and bankfull area that varied spatially over the reach. Net channel aggradation in Kimages Creek occurred at the upper and lower most cross-sections (104 and 198 m) while the sites between beaver dams (142 and 172 m) increased in bankfull area through channel bed degradation. These morphology changes suggest that channel bank stability increased while the beaver dams were in place such that after flooding removed the beaver dams, erosion was almost entirely through bed incision and not channel migration. The impact of beaver colonization on Kimages Creek was channel narrowing and enhanced morphologic definition as the banks stabilized through aggradation.

Our measurements from Kimages Creek add quantitative support for a recent hypothesis emphasizing a limited impact of beaver dams on landscapes (Persico and Meyer, 2013; Burchsted and Daniels, 2014; Levine and Meyer, 2014). Previous studies of beaver dams have indicated the long-term impact on channel morphology (Butler, 2012; Polvi and Wohl, 2012) included bed aggradation and a decrease in bankfull area, particularly in ponds upstream of beaver dams (Naiman *et al.*, 1988; Butler and Malanson, 1995). However, where beaver dam breaching has been included in a study time frame, channel bed erosion has been documented. Re-examination of Holocene era pond sedimentation has led to a finding that net aggradation of channel beds was not a cause of major landscape aggradation in Yellowstone National Park in Wyoming (Persico and Meyer, 2013). A study in Oregon of channels subject to beaver dam building and destruction over a recent 17-year period showed a similar lack of channel bed aggradation (Levine and Meyer, 2014), as did a comparison study of reaches with and without beaver dams in north-eastern Connecticut (Burchsted and Daniels, 2014). These studies found that although sediment did accumulate in the ponds while the dams were in place, the accumulated sediment was eroded downstream once the dams breached.

Channel grain size data indicate the accumulation of reservoir sediment on the channel bed within Kimages Creek was temporary while the dams were in place. Grain size measurements from a free flowing reach of Kimages Creek upstream of the reservoir backwater had an average D_{50} of 0.37 mm on the channel bed and an average D_{50} of 0.35 mm on the channel banks. Cross-sections 104, 142, and 172 had average bed and bank grain sizes near these values in July 2008, prior to or immediately following beaver dam formation. While the dams were in place, fine-grained reservoir sediment accumulated in the beaver ponds and over the reaches between dams. The same cross-sections experienced bed fining and increased similarity between bed and bank grain sizes as sediments from the former reservoir deposited within the reach. When the dams broke, the accumulated sediments were transported downstream of the beaver dam sequence. The average grain size at cross-section 198 was much finer than the upstream cross-section initially but increased after the dams broke to be closer to the values measured upstream. Where channel sediments have included cohesives, bed incision has been more common than channel widening following beaver dam removal (Burchsted and Daniels, 2014). Sediments in Kimages Creek included silt and clay size fractions, although the proportions decreased with the removal of the beaver dams. Channel incision was documented and quantified by the changes in cross-sectional shape during and after beaver dam presence in Kimages Creek.

The contribution of temporary beaver dams to stabilize bank locations and maintain channel morphology provides an indication and evaluation of the potential for the use of beavers in river restoration projects, particularly those in former reservoir impoundments where the soils are fine-grained. Previous speculation on the use of beaver dams in river restoration projects has focused on channels with a stable width that have incised following hydromodification in the contributing area (McCullough *et al.*, 2004; Pollock *et al.*, 2007) and illustrated the potential use of beaver dams through case studies. After beaver dams had been present on streams in the Columbia River valley, Pollock *et al.* (2007) reported that deposition on the channel bed had reduced the channel slope by an average of 1.3%. With this result the authors suggested that incised channels do not need to widen prior to bed aggradation if beaver dams were introduced into the channel evolution pathway. In Nebraska, McCullough *et al.* (2004) compared aggradation in a channel with beaver dams to that achieved by a nearby river restoration. After 12 years the channel with beaver dams had aggraded an average of 0.65 m. The lasting impact of the beaver dams on Kimages Creek was not broad channel aggradation or a change in bed slope. Instead the beaver dams advanced formation of a stable morphology in the emerging channel. Prior to beaver dam formation, the downstream portion of the study reach had been unstable in its channel morphology in response to storm flows smaller than the two-year flow, leading to lateral migrations and large amounts of sediment transport (Cannatelli and Curran, 2012). While the beaver dams were in place, fluctuations in channel thalweg location decreased, and during the two-year storm that removed the beaver dams the channel maintained the narrowed channel width and thalweg path established while the dams were in place. The channel morphology stabilized such that when the flow rate and flow velocities increased, erosion was almost entirely through incision of the channel bed. The channel maintained its planform morphology despite beaver dam removal occurring in the winter when vegetation was dormant and would not have contributed to bank stability. Our findings indicate a role for beavers in the restoration of fine-grained, low gradient channels. Where channels are unstable and bank erosion is a concern, a beaver dam can help provide lateral stability and allow for bank aggradation. However, the potential for vertical channel incision within a beaver dam sequence may limit general application of beaver dams in restoration projects.

Conclusions

This study of Kimages Creek demonstrates the potential for beaver to be a part of channel restoration projects in low gradient, fine-grained streams. Kimages Creek was actively eroding, aggrading, and migrating laterally as a consequence of the breaching of a downstream dam when beavers colonized the area. The addition of beaver dams focused the flow into a defined channel, allowed for deposition along the channel banks, and reduced the channel width such that when the beaver dams were destroyed in a flood, there was no channel migration. Net sediment storage increased in the reach with the majority of the deposition at the channel banks, narrowing the channel width between sequential beaver dams. Thus, the overall channel response to the beaver dams in Kimages Creek was to stabilize the channel cross-section laterally, indicating the utility of beaver dams to river restorations where lateral channel stability is a primary goal. The occurrence of channel bed incision between sequential beaver dams cautions against broad application of beaver dams to applications where broad channel aggradation or a change in bed slope are not desired.

Our findings indicate a useful role for beavers in the restoration of fine-grained, low gradient stream systems and also where dam removals are a part of the restoration efforts. The majority of previous studies of the impact of beaver dams on channel reaches have been focused on incised channels in western states and little has been quantified about how beavers may impact coastal plain rivers. This case study has demonstrated the potential use of beavers over short timescales to aid in the stabilization of a forming channel following a dam removal. Where channels are unstable laterally and bank erosion is a concern, as is often the case of a forming channel in a former reservoir area following dam removal, the beaver dam can be a useful tool. However, because of the likelihood of increased channel bed erosion in a reach with multiple beaver dams, they would not be the best solution where aggradation of an incised channel bed is the desired result.

Acknowledgements—The authors are grateful for the support provided by the VCU Rice Center, where the study site was located. The authors thank Celine Heckel-Jones and Alison Stevens for their help with the field data and manuscript suggestions. They also thank the reviewers for the time they spent with the manuscript. Support for this research was provided by NSF CBET Proposal 0967918.

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