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Geomorphic Changes Following Beaver Dam Failure and Abandonment

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GEOMORPHIC CHANGES FOLLOWING BEAVER

DAM FAILURE AND ABANDONMENT

by

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ABSTRACT

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Beaver, their dams and associated networks of dens, side-channels and pools have a profound influence on habitat heterogeneity and the complexity of the environments they occupy. The purpose of this paper is to illustrate the hydrologic and geomorphic interactions between beaver dam establishment and the greater ecosystem as well as quantify the potential geomorphic changes following beaver dam failure and the influence those changes have on the riparian and fluvial ecosystem in a semi-arid environment.

I use a case study of beaver dam breaches in a small unregulated stream, Bridge Creek, in eastern Oregon to illustrate the concepts. Dam breaches are evaluated in two separate reaches of Bridge Creek: the Upper Owens Reach where a dam failed, which was reinforced with post lines as part of an experimental restoration project; and the Boundary Reach where two natural beaver dam failures were recorded.

Given Bridge Creek's position in the Columbia River system below most of the major mainstem dams, it is an important Middle Columbia Steelhead (*Oncorhynchus mykiss*) fishery. The creek is currently degraded and incised through quaternary alluvium with highly simplified in-stream habitat, which is thought to be limiting steelhead production. The riparian corridor is very limited and homogenized due to channel incision and resultant loss of floodplain connectivity.

To aid in the quantification of erosion and deposition and the subsequent influence on fluvial geomorpholoy following beaver dam failure and abandonment high resolution repeat topographic data were collected using a combination of Total Station, ground-based LiDaR, and rtkGPS surveys. The Geomorphic Change Detection software was then used to conduct DEM of difference calculations distinguishing changes due to noise from those due to geomorphic processes. Finally, I applied a mask for geomorphic interpretation of the DoD to segregate the sediment budget spatially to interpret what the changes mean structurally.

At Upper Owens, a pilot treatment site of the restoration, the DoD shows net deposition the first year followed by two years of net erosion. Still, the channel complexity of the reach increased considerably, following reoccupation of the dam site, reinforcement of the dam, expansion of the dam, and the partial breach. The homogenous plane bed morphology transformed into a complex mix of pools, point bars, mid channel bars and vegetated islands. Whereas along Boundary, a control reach, the results of the DoD show net deposition both years and no notable change is observed in the channel configuration following the construction and failure of the beaver dams. Would the changes observed at Upper Owens similar to those observed at Boundary if it were not for the posts?

As beaver populations continue to expand it is increasingly important to understand the influence of not only active beaver dams, but also those that fail and are abandoned. Furthermore it is vital that restoration practitioners, working in streams occupied by dam building beavers or those utilizing beavers in their restoration effort, consider beaver dam failures as a part of their expectation management.

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INTRODUCTION

Before the fur trade nearly extirpated the North American Beaver, beaver ponds covered the landscape and trapped large quantities of sediment in lower order streams shaping many of our watersheds (Naiman et al., 1988). Although beaver populations are continuing to expand (Baker and Hill, 2003) and have re-occupied much of their pre European range; with beaver populations a mere one-tenth their pre European numbers our concept of how the riparian and fluvial environments function is based on systems lacking historic levels of beaver modification (Naiman et al., 1988). Nonetheless, the literature richly describes and documents the importance of beaver dams to the riparian and fluvial environments as well as to both terrestrial and aquatic organisms that depend upon these environments (Payne, 2004). However, it has been noted that the literature contains little information on beaver dam failures and their effect on the fluvial and riparian environment (Butler and Malanson, 2005; Gurnell, 1998; Marston, 1994). Because beaver dams do fail, more information of the how beaver dam failures affect the documented benefits of beaver dams is needed to truly understand fluvial and riparian dynamics in systems modified by dam building beavers.

Furthermore, understanding the influence of beaver dam failures is an important component of expectation management for land managers and restoration practitioners working in or near fluvial environments inhabited by dam building beavers. For instance, those seeking to restore habitat for fishes in a system occupied by dam building beavers are aware of the types of fish habitats created through the construction of a beaver dam such as large woody debris, beaver pond, below dam plunge pool, seasonally flooded floodplain and secondary channels), but lack information needed to predict how a beaver dam failure could alter the available habitat or other ecosystem services provided by the dam modified patch. In this paper I illustrate the potential influence of beaver dam failure on aquatic and riparian habitat and related ecologic consequences in a semi-arid environment through analyses of repeat aerial imagery and topographic surveys to quantify geomorphic change. These geomorphic changes are assessed and used to extrapolate the prospective ecologic relevance of these modifications to the physical environment.

Influence and Importance of Beaver

Beavers (*Castor canadensis*) are frequently referred to as ecosystem engineers. Ecosystem engineers modify and create habitats by altering the physical environment and changing the availability of resources to other organisms in a manner that benefits the engineer (Jones et al., 1994). Beaver, their dams and associated networks of dens, side-channels and pools have a profound influence on habitat heterogeneity and the complexity of the environments they occupy (Baker, 2003; Jones et al., 1994; Naiman, 1988; Wright et al., 2002). Their dams represent prominent discontinuities in the fluvial system (Burchsted et al., 2010).

If actively maintained, a beaver dam complex might persist for many decades and in some cases even centuries (Butler and Malanson, 2005). Generally, once a site is modified by beaver, dams come and go as part of their natural cycle, alternating between occupation and abandonment (Baker and Hill, 2003; Burchsted et al., 2010; Demmer and Beschta, 2008; Naiman et al., 1988; Wright et al., 2004). This cycle creates patches throughout the landscape that are at various successional states, thus increasing the heterogeneity of habitats and in turn increasing the diversity of species present in the landscape (Wright et al., 2002; Wright et al., 2003). The purpose of this paper is to illustrate the interconnectedness between beaver dam establishment, failure and abandonment and consequent geomorphic changes.

Riparian communities along beaver modified stream reaches are distinctly different in plant community composition from those unaffected by beaver modification (Demmer and Beschta, 2008; Wright et al., 2002). For instance, the species richness of wetland facultative and obligate organisms increases in areas surrounding beaver impoundments, contributing up to 25% of the species richness of the riparian zone (Wright et al., 2002). Furthermore, some species may only be found within the beaver modified riparian zone (Bartel et al., 2010; Bonner et al., 2009; Wright et al., 2002).

However, when a dam is breached and the dam is abandoned, what happens to the riparian environment? For the purpose of this paper a beaver dam breach is defined as: ‘A part of the dam is damaged allowing the passage of water enough to begin draining the pond.’ and an abandoned dam as: ‘A dam that is not occupied nor maintained by beavers. No recent (within the year) signs of maintenance or beaver occupation within the pond.’ (see Table 1). Beaver dams may be abandoned in response to a dam failure, a decrease in the functionality of the dam complex (infilling), depletion of food resources, or mortality. When a dam is abandoned the beaver move upstream or downstream to rebuild; that unless the beaver have perished in a catastrophic failure, as a result of disease, or by predation.

To assist with addressing the question of the effect beaver dam failure has on the environment; I have developed a conceptual model, shown in Figure 1. This model illustrates the dynamics of beaver pond evolution, including disturbance (i.e. failure); which can 'reset' the successional trajectory. Inspiration for this model was found in the multi-successional pathways conceptual model of Naiman (1988). The question about the fate of the riparian environment following beaver dam failure and abandonment is of interest because an active beaver dam, a dam that is actively maintained by beaver, provides a host of important ecologic functions (Table 2) in combination with alterations in geomorphology (Table 3) and hydrology (Table 4).

Ecological functions are the culmination of intricate interactions between the biotic and abiotic components of natural systems; these interactions drive processes on which the stability of ecosystems depend (DeGroot et al., 2002). If a beaver dam fails or is abandoned, do associated ecological functions also disappear?

To better address this question, it is important to briefly review the ecological functions associated with beaver dams. Beaver modify the physical state of vegetation when they fell and incorporate it into a dam, which is the central mechanism of ecosystem alteration (Jones et al., 1994). The construction of a dam results in many fundamental changes within the environment that benefit the riparian ecosystem.

By damming a river, a beaver creates its own habitat while altering both the biological and physical attributes upstream and downstream of the pond, in addition to the adjacent area. The dam creates a pond with increased water depth providing protection from predators, such as coyote, as the entrance to lodges and bank dens is submerged and the beaver utilize the waterways for travel and transport of woody material. In high latitudes where streams and rivers freeze during winter months, the deep ponds created by beaver dams buffer against the effects of freezing temperatures; reducing the risk of ice blocking entrances to lodges and dens. In addition, the pond provides an accessible and freeze-free zone for winter food storage in the bottom of the pond (Naiman et al., 1988).

The impoundment increases water retention time which is thought to facilitate ground water recharge (Pollock, 2003). Also, dissipation of stream flows over the pond area provides flood attenuation, produces water velocities in the ponds that are lower than in channels, and increases the likelihood of deposition of suspended sediments. Where sediments do accumulate in the pond, water levels can be raised and in turn expands the inundated area (Naiman et al., 1988; Wire and Hatch, 1943).

The hydrologic changes initiated by the formation of ponds favors the expansion of riparian vegetation that in turn benefits the beavers by replenishing and maintaining a supply of food and building material (Demmer and Beschta, 2008). The new and diverse environmental conditions promote and increase the species richness and diversity of vegetation (Bartel et al., 2010; Bonner et al., 2009; Wright et al., 2002), as well as wildlife that depend upon the riparian zone for their survival, such as waterfowl and song birds (Baker and Hill, 2003; Boyle and Owens, 2007). For instance, it is proposed that populations of a rare butterfly, *Neonympha michellii francisci* (St. Francis' satyr butterfly) are dependent upon two different *Carex* species, each one found in beaver created meadows at different successional states (Bartel et al., 2010).

The establishment, expansion, and diversification of riparian vegetation is driven by the following main factors: a) increased availability of soil moisture as the water table rises, b) increased availability of nutrients, particularly nitrogen, up to 4.3 times (Naiman et al., 1988) and c) increased fine sediment deposits facilitating the germination of willow seeds (Demmer and Beschta, 2008) and other vegetation dependent upon bare mineral soils for germination.

Changes in substrate and water velocity causes a shift in the invertebrate community composition from swift water organisms such as blackflies, scraping mayflies, and net-spinning caddisflies to slow water organisms such as tubificid worms and filtering worms (Naiman et al., 1988). This shift can have an extreme “bottom up” effect on the biota both up and downstream of beaver impoundments (Jones et al., 1994). That is to say that the diversification of the invertebrate community, initiated by the change in the physical habitat available, can exhibit control on the trophic structure up to the top predators of the ecosystem.

Beaver activities stabilize stream flow, aiding in improving and creating fish habitat in degraded stream systems (Wire and Hatch, 1943). Dams increase channel complexity (*i.e.* habitat availability) in turn heterogeneity of flow velocities as well, provide structural protection for various life stages in the form of large woody debris as well as through facilitating the establishment of aquatic and riparian vegetation which also shade the stream and in turn decrease water temperature (NMFS, 2008) it is also speculated that upwelling below the dam is responsible for reduced stream temperatures (Pollock et al., 2007). The pools behind a beaver dam do not readily freeze and are therefore ideal winter habitats for fishes (Baker and Hill, 2003), in addition to providing a rearing area for large juvenile salmon (Collen and Gibson, 2000). Many (Baker and Hill, 2003; Green and Westbrook, 2009) report that until the 1980’s it was a common belief that beaver dams hindered fish passage and for this reason it was a frequent practice to destroy beaver dams to facilitate fish passage.

Land managers and restoration practitioners are increasingly looking to beaver as a riparian restoration tool (Albert and Trimble, 2000; DWR, 2010). It has been suggested that the use of beaver in conjunction with better agricultural grazing practices is an effective way to rehabilitate degraded riparian habitats (Apple, 1985; Baker, 2003; Demmer and Beschta, 2008; NMFS, 2008). For example, beaver have been incorporated into stream restoration efforts to help reconnect incised streams to their floodplains and improve physical habitat for fish and other species of concern (NMFS, 2008).

Beaver dams have been proposed as a buffer against climate change. For instance, in climates with a pronounced dry season, beaver impoundments retain large amounts of water that would have otherwise left the system (Baker and Hill, 2003) thus buffering wetlands from drying (Hood and Bayley, 2008). In regions with a spring runoff, beaver dams retain snowmelt, slowing the flow and facilitating aquifer recharge (O'Brien 2008).

However, not all aspects of beaver dams are viewed as beneficial. In areas inhabited by humans or in close proximity to infrastructure such as roads and railways, beaver impoundments pose the risk of loss or damage to property due to flooding and rising of the water table. If a dam fails upstream of property of infrastructure the potential risk includes both loss of property as well as life (for examples see Table 5). Flooding behind beaver dams may negatively affect upstream terrestrial organisms through destruction of their required habitat, resulting in local species displacement (Jones et al., 1994).

There is much debate about the role of beaver impoundments in altering stream temperature and the subsequent effect on aquatic organisms. The increased surface area and reduced velocities can increase stream temperatures to the detriment of cold water fishes in some regions of the United States (Collen and Gibson, 2000). Reduction in flow velocity increases deposition of fine sediments, potentially clogging the interstitial pore space of spawning gravels. Beaver dams can obstruct fish movements during periods of low stream flow; the degree of detriment caused by obstruction depends on the timing of the low flow period in relation to the movement requirements of the fish present in the system (see review in Collen and Gibson, 2000).

Furthermore, some in both the scientific and land management communities are concerned that selective foraging by beavers could increase the competitive advantage of non-native invasive vegetative species such as *Tamarix* spp. (Salt Cedar) and *Elaeagnus angustifolia* L. (Russian Olive) if introduced in areas where these invasive species are present (Lesica and Miles, 2004; Mortenson et al., 2008). Mortenson *et al.* found a strong correlation between the presence of beaver along the Colorado River and dense populations of the invasive *Tamarix*. Contradictory observations show that beaver activities may decrease the survivorship of invasive species while increasing the abundance of *Salix* spp. (willow) (Albert and Trimble 2000, Baker and Hill 2003, Lesica and Miles 2004). It is not clear from the literature whether beaver activity gives *Tamarix* a competitive advantage over *Salix* only when both are present or simply that when the competition pressures of *Tamarix* are absent the role of beaver activity in encouraging the growth and propagation of *Salix* is more apparent. In riparian zones where *Tamarix* and *E. angustifolia* co-occur with stands of *Populus* spp. (cottonwoods) the selective foraging of beavers on *Populus* spp. in combination with their avoidance of *Tamarix* and *E. angustifolia* results in increased growth rates of the later as the *Populus* spp. are felled and the canopy opens up increasing light availability to the invasive plant species (Lesica and Miles 2004).

Beaver Dam Failures and Abandonment

Beaver dams may be abandoned in response to a dam failure, a decrease in the functionality of the dam complex (infilling), depletion of food resources, or mortality. When a dam is abandoned the beavers move upstream or downstream to rebuild; that is unless the beavers have perished, such as in a catastrophic failure or via predation.

Although there is little information in the literature about the geomorphic consequences of beaver dam failures (Butler and Malanson, 2005; Gurnell, 1998; Marston, 1994), abandonment and the ensuing physical, biological, and ecological implications; a few authors have made contributions worth noting.

Debano and Heede (1987) state that beaver dam failures are detrimental to the environment, causing severe damage to the channel through entrenchment and deterioration of riparian vegetation in response to a drop in the water table.

Green and Westbrook (2009) assessed changes of a 3 kilometer stream reach over a 36-year period after land managers removed approximately 18 beaver dams with the belief that this action would increase fish passage. It is unclear whether the beaver were also removed or if they repeatedly removed dams throughout the 36-year period. Through the analysis of repeat aerial photography, they found that the channel changed from a multi-threaded channel when dammed to a single threaded channel. Dominant riparian vegetation composition changed from open to closed canopy and stream velocity increased. Their results illustrate how rapidly the exclusion of beaver activity can result in degradation of riparian, channel, and flow regime heterogeneity.

Conversely, if beaver are not removed from a system, but allowed to persist as a dynamic entity within the system, how do they influence and shape the riparian environment through a cycle of occupation and abandonment? Butler and Malanson (2005) conducted a 11 year study of beaver dams in several glaciated valleys of Glacier National Park in which they used sediment cores (~7 cores/pond, up to 1 meter) and observations of successional stage to determine the consequences of failed beaver dams. They concluded that failures result in rapid entrenchment downstream of the dam, some evacuation of pond sediments, and rapid colonization of exposed sediments by vegetation. Furthermore, abandoned beaver dams were often found to transform from a pond to a meadow in less than a decade as they filled up with sediment and these sediments were colonized by plants.

Butler and Malanson's (2005) study provides evidence contrary to the assumption that beaver dam failures are exclusively detrimental to the channel and riparian habitat, but it has a few shortcomings limiting the depth of our knowledge and understanding. The authors obtained relatively few sediment cores with a 1 meter probe, but dams can easily exceed 2 meters in height. Additionally, they considered only the soft sediments as pond sediments. My personal observations, while collecting data along Bridge Creek, OR, of beaver pond substrates with alternating layers of coarse and fine sediments, suggests that coarse sediments are also deposited in ponds; particularly during high velocity flows. There are many opportunities for more research to increase the breadth of our understanding of the ecogeomorphic implications of beaver dam failures and abandonment.

Demmer and Beschta (2008) at set out to address land managers concerns that riparia and stream banks would sustain damage from failed beaver dams as well as farmers concerns that beaver are detrimental to crops and irrigation. In a 17 year (1988 - 2004) field study; field notes and photo points, precise known locations in which they took repeat photos, were used to assist in determining the influence of beaver activity on plant communities and channel morphology in Bridge Creek, Oregon. During their study the riparian zones expanded in correlation with the changes in land practices; decreased grazing and ending beaver trapping.

They reported that failed dams resulted in an increase in channel and complexity and roughness relative to both pre-dam and dammed conditions. The observations of 161 dams in this study are presented in Table 6. It is important to note that the pre-dam conditions were that of a degraded semi-arid channel, straight and lacking a healthy riparian zone. Furthermore, the increased landscape habitat complexity provided by the dams (intact and failed) supported a greater variety of plant communities than stream reaches without beaver activity. They concluded that "… the morphological and biological effects of beaver dams, which began with their construction and maintenance, usually continued long after the dams were breached or abandoned." This study by Demmer and Beschta added greatly to the current knowledge of the effects of beaver dam failure on the environment, but it lacks fine scale spatial and temporal quantification of geomorphic change.

Despite interesting work by Butler and Malanson (2005), Demmer and Brechta (2008), and Green (2009), we still do not know what happens to the complexity of the riparian and fluvial environment when beaver dams fail and are abandoned. Are the ecological functions associated with beaver dams (described above) retained following abandonment?

Beaver Pond Evolution

Beaver ponds are in a constant state of physical evolution. As a pond behind a dam fills in with trapped sediments, it develops into a marsh. The resulting marsh then develops into a meadow (Naiman et al., 1988). Fully developed meadows have been observed in place of failed beaver dams in less than a decade (Butler and Malanson, 2005).

Along beaver-occupied reaches, the riparian environment generally follows a cyclic path of succession, from open water to marsh to seasonally-flooded meadow, which is highly modified by the maintenance, failure, or abandonment of beaver dams (Figure 1). A number of authors have suggested that a correlation may exist between beaver selectively foraging on hardwoods, subsequent pond abandonment, and an irreversible succession of riparian vegetation to a conifer dominated forest (Green and Westbrook, 2009; Naiman et al., 1988).

On the other hand, Terwilliger and Pastor (1999) present evidence contrary to the hypothesis that beaver activities can promote a conifer climax community. The authors' hypothesized that the fungal spores required for conifer (in this case Black Spruce) establishment are lacking in beaver meadows despite the close proximity to a spruce forest. They found the fungal spores were present in the feces of small mammals and investigated whether small mammals entering the meadows deposited feces containing the appropriate fungal spores. Nevertheless, Black Spruce planted in beaver meadows do not form ectomychorrizae. This apparent lack of fungal spores in the soil of the beaver meadows can be solely responsible for preventing conifer invasion (Terwilliger and Pastor, 1999). There may also be unknown factors preventing the migration of those fungal spores from the feces into the soil of the meadows or the dense grasses may prevent establishment of the conifers.

Naiman (1988) observed the trajectory of vegetative succession of beaver habitats and remarked that the successional path and intermediate plant communities are highly dependent upon factors such as topography, existing vegetation, history of disease, fire, heribivory, degree and persistence of beaver activity and hydrologic regime. So long as the local beaver population is not removed, an abandoned site is generally re-colonized (Wright et al., 2004). This cyclic path of occupation, abandonment and reoccupation creates landscape patches that are unique and support unique assemblages of vegetation; newly occupied sites support higher plant species richness whereas mid successional patches may support a greater diversity of rare plants, such as the wetland obligate marsh bellflower (*Campanula aparinoides*) (Bonner et al., 2009).

Land Management & Restoration

Beavers and their dam construction are very powerful modifiers of natural ecosystems and therefore have tremendous potential in passive and process based restoration efforts. Currently, the use of beaver in stream restoration is not a common approach, but is gaining momentum. To date beaver have been used in both watershed management (DWR, 2010; Walker et al., 2010) and as restoration agents, particularly in incised streams with homogenized habitat (Albert and Trimble, 2000; Apple, 1985; MacCracken and Lebovitz, 2005; Marston, 1994). Müller-Schwarze and Sun (Payne, 2004) refer to the beaver as, "the greatest original wetland conservationist" and calls for their incorporation into plans for water management especially in wetland conservation, restoration and subsequent effect on improving water quality.

Over the next decade the feasibility and effectiveness of utilizing beaver in land management and restoration goals will become apparent. Many stream restoration projects are subject to much scrutiny as part of programs such as the Intensely Monitored Watershed program (IMW) and Integrated Status and Effectiveness Monitoring Program (ISEMP). However, studies integrating both biologic and physical processes are needed to better understand the influence beaver have as geomorphic agents, on processes such as floodplain formation (Baker and Hill, 2003).

Moreover, the re-introduction or expansion of beaver populations and associated ecosystem modification raises many important questions for land managers: What changes in the channel configuration, in-stream habitat, flow regime, sediment budget, and vegetative communities are likely to occur and what influence will these changes have on associated aquatic and terrestrial organisms? How will these outcomes differ in various physiographic regions? Because of the natural variability and uncertainty in the trajectory of beaver modified environment the results of current and previous studies yield important considerations for expectation management by land managers (Naiman,

1988) and restoration practitioners, contemplating the use of beaver as a restoration agent.

Research Aims & Objectives

The purpose of this study was to explore what happens geomorphically to the fluvial environment following beaver dam failure and abandonment through analyses of repeat aerial imagery and topographic surveys. I use beaver dam breaches in a small unregulated stream, Bridge Creek, in eastern Oregon to illustrate the concepts. Dam breaches are contrasted in two separate reaches of Bridge Creek: the Upper Owens Reach where a dam failed, which was reinforced with post lines (Figure 2) as part of an experimental restoration project; and the Boundary Reach where two natural beaver dam failures were recorded.

Based on the research of Butler and Malanson (2005) as well as Demmer and Beschta (2008), I expected to observe localized channel incision at the base of failed dams propagating into the pond deposits, net retention of pond sediments behind the dam, and an increase in channel sinuosity from the pre-dam and ponded condition after beaver dam failure.

BRIDGE CREEK STUDY AREA

Bridge Creek, in central Oregon Wheeler County, is a 31.7 km, second order tributary to the lower John Day River which drains a 710 km^2, snowmelt driven, watershed northwesterly into the Columbia River (Figure 3). The gradient of Bridge Creek ranges from 0.5% to 3.0%. Given Bridge Creek's position in the Columbia River system below most of the major mainstem dams, it is an important Middle Columbia Steelhead (*Oncorhynchus mykiss*) fishery. The creek is currently degraded and incised through quaternary alluvium with highly simplified instream habitat, which is thought to be limiting steelhead production. The riparian corridor is narrow, in some places non-existent, and homogenized due to channel incision and resultant drop in the water table as well as loss of floodplain connectivity (Pollock et al., 2007).

The upland landcover in the upper portions of the watershed is stratified coniferous forest transitioning, along an elevational gradient, through juniper-steppe to sage steppe communities in the lower portion of the watershed. The riparian zone is dominated by *Salix exigua* Nutt. (narrowleaf/coyote willow), *Salix amygdaloides* Andersson (peachleaf willow) and associated grasses, sedges and forbs. Other woody vegetation includes *Rosa woodsii* Lindl. (wild rose), *Betula occidentalis* (alder), Hook. (water birch), *Cornus sericea* L. (redosier dogwood) and a few *Populus balsamifera* L. ssp. *trichocarpa* Torr. & A. Gray ex Hook., Brayshaw (black cottonwood).

According to Demmer and Beschta (2008), the watershed has a history of intense grazing and removal of beavers. However, between 1988-1992 grazing was reduced and beaver trapping ended when most of the watershed became the jurisdiction of the US Bureau of Land Management (Demmer and Beschta, 2008). A small portion, the Painted Hills Unit, belongs to the National Parks Service as part of the John Day Fossil Beds National Monument; the rest remains private. Although Bridge Creek is unregulated, there are a number of agricultural diversions that alter the stream flow during the crop growing season.

Currently, an innovative restoration project is underway over 25 km of Bridge Creek, employing beaver to help aggrade the incised channel, reconnect it with its - floodplain, increase channel complexity, and specifically to improve salmonid habitat (Pollock et al., 2011). Before commencement of the restoration; three years of intense monitoring established baseline conditions. The project has established control and treatment stream reaches to quantify and monitor the effects of their efforts. Treatment reaches entail installation of beaver dam support structures in locations with suitable habitat and in some existing dams to provide structural support against high flows. Thus far, roughly 100 beaver dam support structures associated with the restoration effort are actively being monitored with an integrated blend of fish, vegetation, and habitat surveys, in addition to beaver activity monitoring, repeat topographic surveys, and repeat aerial imagery (Pollock et al., 2011).

Demmer and Beschta (2008) have documented that beaver dams on Bridge Creek are short lived, with approximately 70% of beaver dams failing within one year (Figure 4). To compensate for the vulnerability, beaver activity and dam stability is promoted by providing structural support (i.e. wood posts) and building materials (i.e. wood) at key locations to encourage beaver to build dams and establish sustainable colonies (Figure 5). Previously, Pollock and others (2007), documented the recovery of an abandoned floodplain just six years after the establishment of a beaver dam, within Bridge Creek, as the dam promoted channel aggradation, raising the water table and enabling the recovery of and re-colonization by riparian vegetation.

A wealth of data provided by prior studies in conjunction with current monitoring efforts in addition to the field manipulations provided by the restoration study in Bridge

Creek made the location ideal for this study. See Pollock *et al.* (2011), NMFS(2008), Demmer and Beschta (2008), and Pollock *et al.* (2007) for additional background.

Upper Owens Study Site

Upper Owens was a pilot treatment reach for the restoration project. The treatment includes providing structural support for the beaver dams in the form of beaver dam support structures (BDSS). BDSS are a series of 3 meter long pine posts that are hydraulically pounded 1.5 meters into the stream bed and adjacent banks creating a line, roughly the shape of a beaver dam, of posts spanning the stream and on occasion onto the active or abandoned floodplain (Figure 6). In this degraded system with low sinuosity, sparse riparian vegetation, and channel entrenchment there is very little flood attenuation. Additionally, there is very little large woody vegetation for the beaver to use in the construction of their dams. The result is that the high flows of this flashy system easily breach or even wash away dams constructed with small willow branches. At Upper Owens, Demmer and Beschta (unpublished data) documented the age of beaver dams at the time of failure from 1998 to 2005; during this time period more than half of the beaver dams failed within one year of construction (Figure 4). The structural supports provided to the dams by the BDSS allow the dams to persist longer than they may have otherwise in this degraded system.

The Upper Owens beaver dam highlighted in this study has a recent history of relatively frequent beaver activity and occupation. Beaver dams were recorded at the this dam site in 1999 - 2000, as well as in 2003 by Demmer and Beschta (unpublished data) no dam is observed in the 2005 NAIP imagery (Figure 7.A), however in 2008 pre-restoration monitoring crews recorded a dam at the site yet again (unpublished data); suggesting that the dam was constructed in summer 2007. The dam size and pond area was fairly consistent during periods of occupation, and was regularly breached during high flows. In early 2009 the dam was reinforced with beaver dam support structures (BDSS). The beaver responded to the structural support by raising the crest elevation, doubling the dam length and greatly expanding the inundated area.

During the spring runoff floods of 2009, the crest of the main portion of the dam exceeded the crest height on a section of dam that the beaver had extended beyond the BDSS near the bank. The flows became concentrated along the unreinforced portion of the dam, with a lower crest height, and the dam was partially breached and subsequently abandoned (Figure 8 & Figure 7.B). This breach created an opportunity to look at geomorphic response following abandonment due to beaver dam failure. Imagery from April 2010 shows the main portion of the beaver dam is still intact, but the breached section has not been repaired indicating that the site has been abandoned (Figure 7.C), October 2010 shows the dam site is still inactive (Figure 7.D). I observed the dam in the field shortly after the initial breaching; the hydrograph of Bridge Creek indicates that the dams breached on the descending arm of a small peak in flows in early May 2009 (Figure 7.E).

Boundary Study Site

The Boundary stream reach is a control reach for the restoration project as it is reflective of the overall condition of Bridge Creek with a single-thread relatively straight and narrow channel entrenched in alluvium (Figure 9) with the 83.3% of the beaver dams documented as failing within one year (Figure 4) after construction (Demmer and Beschta, unpublished data). Imagery from November 2009 shows two small dams natural, unreinforced beaver dams built within the entrenched channel with dam crests below the floodplain (Figure 10.B). Demmer and Beschta (unpublished data) did not record dams at the precise location of either of these dams; they recorded a single dam approximately 15 meters upstream of the lower dam from 2001 to 2003. After Demmer and Beschta's monitoring stopped in 2004 there was no monitoring to show whether or not there were active beaver dams at the sites. However, inferring from their data, the 2005 NAIP and 2009 Blimp imagery and the current restoration project's pre-monitoring data; the two dams present on the Boundary reach during this study were likely constructed in the fall of 2008.

April 2010 UAV drone imagery shows both beaver dams still intact, but with the spring runoff the dam is forcing flows to the lateral edges of the dams (Figure 10.C), October 2010 shows the dams are laterally breached and no longer active ((Figure 10.D). Observations of the aerial imagery and the hydrograph of Bridge Creek indicate that both dams likely breached in early June 2010 ((Figure 10.B-E).

METHODS

Spatial and temporal changes in response to beaver dam failure and abandonment were determined by measuring changes in the sinuosity. This was done primarily through analysis of repeat aerial imagery in addition to ground truthing. Aerial imagery was acquired with a blimp in 2009 and an unmanned aerial vehicle (UAV) drone in April and

October 2010. Additionally, 2005 NAIP imagery was used. (See Figure 7.A-D & (Figure 10.A-D).

The blimp (helikite) was flown at 100 meters with a high resolution digital camera attached under the kite wings acquiring images every 3 seconds. For rectification purposes 1 m^2 targets were constructed out of roofing rubber and white spray paint to add unique numbers to each target. The targets were distributed along the banks and terraces of the reach and laid out in a triangular fashion to reduce distortion during georeferencing. The coordinates of professionally surveyed benchmarks and each target were collected via rtkGPS. These coordinates were imported into ArcGIS 10.0 and georeferenced to their picture in the aerial imagery, thus stitching together the images along each reach. The UAV Drone was flown and imagery was rectified and mosaicked using EnsoMOSAIC by Utah State University's Aggie Air Flying Circus.

To aid in the quantification of erosion and deposition and the subsequent influence on fluvial geomorpholoy, following beaver dam failure and abandonment, high resolution repeat topographic data were collected in May 2009 (Upper Owens site only), November 2009, November 2010, and November 2011 (both Upper Owens site and Boundary reach), using a combination of robotic total station (TS) surveys, ground-based LiDaR (a.k.a.Terrestrial Laser Scanner, TLS), and bathymetry via the use of TS and real-time kinematics global positioning system (rtkGPS). All data were collected with Leica geosystems survey equipment in the geographic coordiante system UTM NAD83 Zone 10N. Aside from the May 2009 survey, annual surveys were conducted in mid to late November, after leaf off, to increase data collection and post processing efficiency. The raw point data from the ground-based LiDaR were filtered to include only ground shots by selecting only the z minimums within a data frame where appropriate or by using Leica Geosystems Cyclone software to isolate and manually remove points representing vegetation from the data point clouds. The data sets were then decimated to a point density of 4 points per m^2. These point data were combined and used to construct slope and point density surfaces along with triangulated irregular networks (TINs) that were in turn used to derive 10 cm resolution digital elevation models (DEMs) for each survey (Figure 11.A-D & Figure 12.A-C) in ArcGIS 10.0.

The surface representation uncertainties were derived from the associated surfaces of slope and data point density using the Geomorphic Change Detection (GCD) Software developed by Wheaton *et al.* (2010) and then used to propagate errors through into 90% confidence interval DEM of difference (DoD) calculations to distinguish net changes due to noise from those inferred to be due to geomorphic processes. Errors may originate from insufficient measurements, inexactness of measurements, poor spatial coverage and/or interpolation errors. Insufficient measurements and poor spatial coverage can occur in areas where data is challenging to collect due to issues such as deep water, thick tangled vegetation, or steep slopes. Inexactness of measurements can result from an unleveled survey rod and prism, a survey rod sinking into soft sediments, vegetation or large woody debris obscuring the ground, or recording of a point while the prism is in motion. All of these data collection errors generate potential for interpolation errors during the creation of the TINs. This is particularly important in fluvial environments, because a large portion of the elevation changes of interest can be of relatively low magnitudes (i.e. < 0.25m). These changes are often similar to the magnitude of uncertainty in the topographic elevation models themselves. The uncertainty in DoD calculated elevation change is propagated from the uncertainties in the original DEM representations and the original survey data (Lane et al., 1994).

Although sediment budgets derived from high resolution (i.e. finer than 1m) DoDs can provide useful insight into gross reach scale geomorphic changes (i.e. degradation vs. aggradation), they can also be used to evaluate more detailed mechanistic inferences of finer-scale processes.

Once the best estimate of uncertainty was acquired, and a thresholded DoD calculated, I applied a mask for geomorphic interpretation of the DoD (expert-based classification of the DoD itself in conjunction with field evidence, photos and other layers) to segregate the sediment budget spatially to interpret what the changes mean structurally (Wheaton, 2008, Chapter 5).

In the context of GIS, a mask is a sub area of an entire dataset that will be included in an analysis (Jones, 1997). The mask was created by converting the DoD raster to a binary raster where 0 = areas of erosion and 1 = areas of deposition. This binary raster was converted to a polygon shapefile and each individual polygon, polygons were split where necessary, was then assigned a geomorphic classification and consequently producing a geomorphic interpretation mask. The geomorphic interpretation mask I used in this analysis contains nine components representative of specific changes in channel morphology; four are the result of deposition: channel infilling, beaver pond deposits, bar development, and overbank deposition, and five are the result of erosion: pool scour, evacuation of pond sediments, head-cut incision, and secondary channel scour. An additional component accounts questionable changes both erosional and depositional. The DoD data that fell within each mask were used to calculate areal and volumetric elevation change distributions and summary statistics.

RESULTS AND INTERPRETATION

The results and interpretation of the aerial imagery time series, ground change detection analysis, and geomorphic interpretation are addressed below. I discuss the results of the each study site, the Upper Owens study site and the Boundary reach, separately with the interpretation of the aerial imagery time series as the first subset, then the second subset the year to year results of the ground change detection and the geomorphic interpretation of the observed changes in chronological order.

3.1. Upper Owens Reach

3.1.1 Aerial Imagery

Aerial imagery shows a dramatic change in channel form from a relatively straight channel lacking diversity in geomorphic units (i.e. pools, riffles, bars, islands) in 2005 to a sinuous channel with a variety of geomorphic units (Figure 7.A – D). Following reoccupation of the dam site, reinforcement of the dam, expansion of the dam, and the partial breach, the channel complexity of the reach increased considerably. The homogenous plane bed morphology transformed into a complex mix of pools, point bars, mid channel bars and vegetated islands. The sinuosity of the reach increased from 1.2 to 1.5 between September 2005 and November 2009. Imagery obtained in April 2010 confirms that these post-breach features unexpectedly persisted throughout the year and a second spring flood (Figure 7.C). Between November 2009 and April 2010 the sinuosity of the reach was maintained at 1.5. From the October 2010 imagery it is evident that the channel created a new path (Figure 7.D) leaving the main channel as seen in November 2009 and April 2010 as a secondary channel and resulting in a slight decrease in the sinuosity to 1.4.

3.1.2. May 2009 to November 2009
Geomorphic Analysis

Geomorphic Change Detection

In the six months following the initial breach of the beaver dam I observed that locally, the processes of erosion and deposition were near equilibrium. According to the 90% confidence interval geomorphic change detection analysis (Figure 13.A-D), deposition (42 +/- 12 m^3), exceeded erosion (32 +/- 7 m^3) even if only slightly so, despite the breach. The bulk of the erosion was concentrated at and near the location of the dam breach along with the upstream foot of the beaver dam. Deposition occurred largely upstream of the beaver dam. Thus, the net morphological sediment budget for the reach is net aggradational (10 +/- 14 m^3) with a minor 7% imbalance (Figure 13.C). The imbalance is an indicator of the percent departure from equilibrium. Here we see a small percent of imbalance, if the reach was indeed depositional during this time period, the signal is not robust. Furthermore, due to the fact that the propagated error is greater than the net change, the net change results are indeterminate.

Geomorphic Interpretation

Although the results of the geomorphic change detection are helpful in giving us a broad picture of the net changes in the sediment budget, for our purposes the results of the geomorphic interpretation are more meaningful in appreciating how these erosional and depositional changes have altered the riparian setting. The geomorphic interpretation of the observed total changes (Figure 14.A-D) indicates 14.15% of the total geomorphic change by volume is from head-cut incision (10 m^3) through the partial breach as well as 19.07% evacuation of pond deposits (14 m^3) has taken place in the lower end of the reach. A mere 1.97% of pool scour (1 m^3) and 1.87% lateral bank erosion (1 m^3) took place on the outside of bends and below the beaver dam in addition to a fraction, 0.59%, on secondary channel scour (0.4 m^3).

The bulk, 39.61% of the geomorphic change was in the development of lateral and central bars (29 m^3). Bar development during this initial adjustment period happened primarily upstream of the main portion of the beaver dam that remained intact as shown in Figure 14.A, but some has taken place downstream of the dam as well. Spring floods impounded by the beaver dam accessed the inset floodplain and inundated vegetated islands depositing 9 m^3 of sediment (11.99%). A small side channel along the periphery of the former pond as well as a pool at the upstream edge of the former beaver pond have filled in and acted as minor sinks for sediment (2 m^3, 2.44%). Additional deposits within the draining beaver pond, not contributing to bar development, were a negligible accounting for 0.48% of the budget (0.4 m^3).

Questionable change accounts for 6 m^3 of geomorphic change in both erosion and deposition of sediment (Figure 15) and is comparable to our overall uncertainty (+/-7 $m^3$for erosion and +/- 12 m^3 for deposition). These questionable areas are the result of interpolation errors, regions of heavy vegetation complicating trustworthy change detection, and the modest amount of data collected during May 2009.

3.1.3. November 2009 to November 2010
Geomorphic Analysis

Geomorphic Change Detection

The net erosion and deposition observed from November 2009 to November 2010, as per the 90% confidence interval geomorphic change detection analysis (Figure 16.A-D), is quite different from the previous year with erosion (184 +/- 41 m^3) accounting for more than twice the volume of deposition (71 +/- 21 m^3). The bulk of the erosion occurred in two localities: i) along the newly cut left anabranch side channel within the former beaver pond, and ii) in the form of lateral channel migration downstream of the former dam; as was also observed in the aerial imagery (Figure 7.C-D). Deposition was fairly evenly distributed both upstream and downstream of the failed beaver dam. Thus, the net morphological sediment budget for the reach is net degradational (-113 +/- 46 m^3) with a -22% imbalance Figure 16.C).

Geomorphic Interpretation

The geomorphic interpretation (Figure 17.A-D) indicates that the incision from head-cutting continued its migration upstream in the year-and-a-half following the dam failure; accounting for 24.12% of the detected geomorphic change (61 m^3) consequently converting the secondary channel into the main channel. Additionally, the formation of the new channel configuration was the result of substantial lateral bank erosion (49 m^3, 19.13% of the total geomorphic change by volume) in the stream bend below the failed beaver dam. A secondary channel, likely created by over flow and partial breaching of the original beaver dam, was scoured further (6 m^3, 2.47%). Several small pools were scoured slightly throughout the reach (4 m^3) accounting for 1.55% of the geomorphic change.

At 17.13% of the observed change, channel infilling dominated the depositional processes (44 m^3) particularly in the upstream portion of the reach as what was the main channel following the initial dam failure filled with sediment. Notable bar development continued both upstream and downstream of the dam (22 m^3, 8.72%). Overbank deposition added 5 m^3 of sediment to the inset floodplains and bars (1.95%).

Questionable change accounts for 24.93% by volume (64 m^3) of the geomorphic change in both erosion and deposition of sediment (Figure 18). These questionable areas are largely in regions outside of the channel and within the densely vegetated riparian zone (Figure 17.A) where terrestrial laser scanning was used to collect data during the November 2009 field season. The laser scanner collects a x,y, and z point data from every surface within its path at the user defined resolution; I used a 10 cm resolution collecting 1 point per 10 cm.

3.1.4. November 2010 to November 2011 Geomorphic Analysis

Geomorphic Change Detection

From November 2010 to November 2011 the 90% confidence interval geomorphic change detection analysis (Figure 19.A-D) shows a continued trend of net erosion (65 +/- 17m^3) exceeding deposition (24 +/- 9 m^3); although the total volume difference is half that of the previous year. So, the net morphological sediment budget for the reach is net degradational (-41 +/- 19 m^3) with a -23% imbalance (Figure 19.C).

Geomorphic Interpretation

The geomorphic interpretation (Figure 20.A-D) designates head-cut incision (22 m^3) as the dominate process, accounting for 24.80% of geomorphic change, as the site of the dam failure. Additionally, lateral bank erosion (21 m^3) at the outside stream bends both upstream and downstream of the failed and abandoned beaver dam continued to erode, as did scouring of the secondary channels immediately below the still intact portions of the dam (9 m^3, 10.45%). Yet again the formation and deepening of pools explained a small portion of erosion (6 m^3, 6.14%).

Channel infilling continued to dominate the depositional processes (13 m3), contributing 14.67% of the total geomorphic change, by filling in portions of the channel that have been largely abandoned as the channel continues to migrate laterally. The development of bars has rapidly declined this year (4 m3, 4.14%). As expected, due to the stream discharges observed in the hydrograph (Figure7.E), a small amount of sediment was deposited in overbank deposition (2 m3, 2.18) even without the dam impounded the flows.

The regions of questionable change declined sharply from last year, accounting for 13 m3 of changes in sediment (Figure 21) and only accounting for 14.55% of the total geomorphic change. This is likely the result of using rtkGPS for data collection, in-stream and on bank, in both the November 2010 and November 2011 field seasons and thus reducing the potential for error in obtaining a valid bare earth surface as was observed in the previous year.

3.2. Boundary Reach

3.2.1. Aerial Imagery

Unlike the transformation witnessed at the Upper Owens reach; the aerial imagery time series of the Boundary reach (Figure 10A-D) shows no notable change in the channel configuration following the construction and failure of the beaver dams. Likewise, the sinuosity of the reach remained at 1.4 between September 2005, November 2009, and April 2010, and increased only slightly from 1.4 to 1.5 between April 2010 and November 2010; after the failure of the two dams.

3.2.2. November 2009 to November 2010 Geomorphic Analysis

Geomorphic Change Detection

In the two years following construction of the beaver dams and after both dams were breached I observed a similar result in the net erosion and deposition as was observed at the Upper Owens site after the initial breach of its beaver dam. That is, according to the 90% confidence interval geomorphic change detection analysis (Figure 22.A-D) deposition (62 +/- 26 m^3), exceeded erosion (12 +/- 3 m^3). Most of the erosion was concentrated at the location of both the dam breaches along with the upstream foot of the downstream beaver dam as well as at the downstream foot of the upstream dam. Deposition occurred largely upstream of each beaver dam. Thus, the net morphological sediment budget for the reach is net aggradational (50 +/- 26 m^3) with a 34% imbalance (Figure 22.C).

Geomorphic Interpretation

The geomorphic explanation for the observed changes (Figure 23.A-D) indicates that beaver pond deposits accounted for the largest portion of the total geomorphic change, 44% by volume (33 m^3), within the reach. These pond deposits demonstrate the rapid aggradation potential behind beaver dams in this locality. Channel infilling contributed the second largest portion of the reach wide deposition (19 m^3, 25.05%). The remaining deposition contributed to building both channel and lateral bars (5 m^3, 6.52%) as well as overbank deposition (6 m^3, 6.25%).

Head-cut incision was the main erosion process (4 m^3) occurring at the site of the both dam breaches, yet only representing 5.88% of the total geomorphic change. On the outside of bends, both lateral bank erosion (3 m^3, 3.99%) and pool scour contributed slightly to erosion (3 m^3, 3.65%). The breach of the beaver dams in the summer of 2010 only resulted in a minimal 1m^3 of pond sediments evacuated (1.87%).

Unlike the November 2009 Upper Owens data, the November 2009 Boundary data was collected exclusively with the rtkGPS in the channel and on the immediate banks only, as a result a minor portion, (2 m3, 2.62%) of the geomorphic change was defined as questionable change (Figure 24).

3.2.3. November 2010 to November 2011 Geomorphic Analysis

Geomorphic Change Detection

The sediment budget for November 2010 to November 2011, as per the 90% confidence interval geomorphic change detection analysis (Figure16.A-D), shows a continued trend of net deposition (71+/- 25 m^3) exceeding erosion (35 +/- 11 m^3) within the reach. The bulk of the erosion occurred just upstream of the location of the breach on each of the beaver dams in addition to a portion of the reach between the two dams. Deposition occurred at various locations throughout the reach; concentrated on the downstream side of the intact portion of each beaver dam, the lower part of the reach and within the small secondary channel. Thus, the net morphological sediment budget for the reach is net aggradational (36 +/- 28 m^3) with a 17% imbalance (Figure 25.C).

Geomorphic Interpretation

The geomorphic interpretation of the observed changes (Figure 26.A-D) shows that channel infilling again accounted for the largest portion of the total geomorphic change, 55.67% by volume (60 m^3), within the reach. Additionally, the failed beaver dams continued to collect a small amount of sediment (3 m^3, 2.86%) as did the bars (3 m^3, 2.41%) and the banks (5 m^3, 4.87%).

Between November 2010 and November 2011 the extent of the beaver dam breaches increased as the dams failed and were not repaired, allowing more sediment to be evacuated from the ponds (29 m^3, 26.82%) and contributing considerably to the net erosion. As in the previous year lateral bank erosion (1 m^3, 1.03%) and pool scour (1 m^3, 1.04%) played minor roles in erosion with the addition of secondary channel scour (2 m^3, 1.69%). Once more only a minor portion (4 m^3, 3.60%) of the geomorphic change was defined as questionable change (Figure 27).

DISCUSSION

At the Upper Owens site no substantial difference was detected between net deposition and net erosion in the first six months post beaver dam failure. The relatively small net deposition is indeterminate in light of the propagated error exceeding the net deposition. This error is not surprising due to the sparse data points collected in May 2009 and the high volume of questionable change arising in the May 2009 to November 2009 analysis. In the two following years the morphological sediment budget was net degradational. The nearly 25% of the questionable morphological change occurring in the November 2009 to November 2010 analysis may well be concealing the true change in sediment. That is to say that the reach may actually be closer to equilibrium with regards to erosion and deposition. I speculate that much of the observed questionable change is a consequence of errors resulting from using the terrestrial laser scanner in the Upper Owens reach during the November 2009 field season. In my experience, along the riparian corridor the willow and grass stands are often fairly dense obscuring the ground surface and preventing the collection of data points on the bare earth. The process of cleaning up the vast data points, removal of points representing vegetation, to obtain a bare earth surface creates many opportunities for misrepresentation of that surface. For example the z minimum point within a defined data frame may be a point along the stem of a willow, many centimeters above the ground, with no ground shots available within the frame for clarification that particular lowest point could be misinterpreted as a ground shot. And so, if there is a true geomorphic signal contained within this questionable change class it is obscured by the noise.

Although the net erosional trend of November 2009 to November 2010 continued in the November 2010 to November 2011 year, and erosion is counter to the restorations project goal of aggrading the channel, the fact that a substantial portion of the erosion was explained by lateral bank erosion in conjunction with the channel evulsion cutting off the more sinuous channel yet facilitating a broader more stable sinuous channel with geomorphic complexity is consistent with the overall project goals (Pollock et al., 2011).

The two beaver dams along the Boundary reach were likely constructed in September 2008, fourteen months before our first topographic survey in November of 2009 and failed approximately June 2010, five months before the second survey in November of 2010. Five months post beaver dam failure the reach was still net depositional. The depositional trend continued, if just slightly so, the following year (November 2010 to November 2011) even though neither of the beaver dams were repaired after the initial breach. It is unfortunate I did not have the opportunity to survey the reach a second time before the dams were breached to obtain data from an active dam with regards to erosion, deposition and geomorphic change within a characteristic Bridge Creek reach, with typical beaver dam establishment within an incision trench. Fortunately, the spatial and temporal extent of the greater study, restoration and monitoring will have ample opportunity to make up for this deficiency.

Contrasting the two study sites we observe that the channel configuration at the Upper Owens site is quite dynamic. The accommodation space available at Upper Owens allowed for the channel to avulse cutting off the more sinuous channel while creating a broader more stable sinuous channel; whereas the Boundary reach displays negligible changes in the channel configuration. I speculate that this difference is due to the longevity of the dams at each site, possibly as a function of whether or not beaver dam support structures are present and the extent of entrenchment. As mentioned previously, the dams at along the Boundary reach are very short lived, with 83.3% failing within the first year, relative to the dams at the Upper Owens site, with 55.8% failing within the first year (Figure 4). Along the Boundary reach the beaver are generally unable to build their dams to a crest height equal or greater than the height of the floodplain and as a result are unable to extend dams onto the floodplain before their dams are breached; likely because the channel is too entrenched. In November 2009, on the Boundary reach, the crest of the up-stream beaver dam sat 0.62m below the floodplain and the downstream dam 0.23m below the floodplain. Conversely, the geomorphic change observed at Upper Owens is indicative of changes that can occur when beaver are able to build and expand their dams onto the floodplain and thus influencing dramatic change. However, would the changes observed at Upper Owens be similar to those observed at Boundary if it were not for the posts?

The spatial and temporal scale at which these observations were made leaves a multitude of questions yet to be answered. What did the year to year geomorphic changes look like before the beaver dam was constructed at the Upper Owens study site? What geomorphic changes occurred downstream of this beaver dam? For instance, did the eroded sediments aid in the creation of bars in the downstream reach or get deposited in a beaver pond downstream to ultimately take part in the formation of a beaver meadow?

Many of these questions will be answered as the data from the remainder of the Upper Owens reach, the other reaches that are a part of the restoration, and the upcoming years of data to be collected are processed and analyzed. Our results presented here are a mere sample of what is to come.

CONCLUSION

Beaver modified riparian environments are highly dynamic systems; providing spatial and temporal heterogeneity within the landscape (Bartel et al., 2010; Demmer and Beschta, 2008; Pollock, 2003). The unique habitats created through beaver modification support a greater diversity of various riparian organisms such as vegetation (Bartel et al., 2010; Bonner et al., 2009; Green and Westbrook, 2009; Hood and Bayley, 2008), and fish (Schlosser and Kallemeyn, 2000). As beaver populations continue to expand (Baker and Hill, 2003; Naiman et al., 1988), it is increasingly important to understand the influence of not only active beaver dams, but also those that fail and are abandoned.

Our results illustrate the dynamism of the fluvial environment following beaver dam failure with the formation of many new geomorphic units, that is if the beaver dams are stable enough that the first high flows do not wash away the dam; the potential success of beaver as a restoration tool; and the need for continued investigation of beaver dam failures in the semi-arid environment of Bridge Creek as well as other locations.

Continuation of this and similar studies in other localities with both analogous and differing watershed demographics will aid in constraining and predicting the probable geomorphic changes after beaver dam failure. Furthermore, these results show the potential trajectory of channel form after dam failure on both newly established dams and stable (or reinforced) dams as well as demonstrate that local net sediment changes need to be addressed in context. For instance, net erosion might be desirable if it is aiding in creating greater channel complexity. These results can aid restoration practitioners, working in streams occupied by dam building beavers or those utilizing beavers in their restoration effort, with expectation management with regards to beaver dam failures.

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Table 1: Definitions Beaver Dam of Terms

Term	Definition
Single dam	A dam structure spanning a channel. This dam may be a discrete structure or a dam composed of many additions to the original structure.
Dam complex	A collection of single dams within a stream reach without interruption of impounded flow.
Active dam	A dam that is actively maintained by beaver. Evidence of an active dam include: fresh mud, newly cut vegetation on the dam or lodge, food cache in the pond behind the dam. These attributes are best measured in the fall or early spring.
Inactive dam	The dam is not maintained, but may be occupied by beavers. Lacks evidence of maintenance yet signs of occupation are present (e.g. fresh tracks, cuttings, scat, and slides).
Abandoned dam	The dam is not occupied nor maintained by beavers. No recent (within the year) signs of maintenance or beaver occupation within the pond; vegetation of pond sediments now above water level. Note: the type and maturity of vegetation indicates age of abandonment.
Dam Failure	A dam that has lost its ability to retain a pond. Dam failures are further divided into collapsed dams and breached dams.
Dam Collapse	The entire dam is destroyed.
Dam Breach	A part of the dam is damaged allowing the passage of water enough to begin draining the pond.

Table 2: Ecological benefits provided by beaver dams

For Beaver
Pond provides protection from predation
In systems prone to freezing, pond provides depth resistant to freezing for food cache and entrance to lodge
Ponds and canals provide an easier way of transporting felled trees
Ponds and canals provide safer means of travel between feeding areas and lodges
Diversity of vegetative species resulting from dam increases access to varied types of forage
Increases availability of building materials (expansion of riparian zone)
For Riparian Vegetation
Raised water table, increased access to water
Increased nutrient retention
Increased rate of soil development (increased organic matter)
Creation of new habitats (e.g. fresh un-colonized bars)
Diversification via increased habitat availability
Browsing by beaver can be beneficial for species, which reproduce sexually or clonally (e.g. willow)
Browsing by beaver can reduce canopy cover, increasing light availability to understory species
For Fish
May increase water temperatures at surface in pond
May decrease water temperatures below dams by building up hydraulic head and increasing upwelling of water (hyporheic flow) downstream of dams
In systems prone to freezing, pond provides depth resistant to freezing
Increased availability of pool habitat (both beaver pond and scour pools at toe)
Increased availability of riffle/bar habitat
Increased hydraulic heterogeneity provides shear zone refugia
Increased structural cover (e.g. wood, emergent vegetation, overhanging cover, deep pond water) to hide from predators
Pour over at dam increases dissolved oxygen, through air entrainment
Reductions in temperature increases dissolved oxygen
Increased upwelling/hyporheic exchange promotes higher survival of embryos
Side channels provide rearing habitat and fish passage

Table 3: Influence of beaver dams on geomorphology

Increased sinuosity
Increased sediment retention (residence time)
Bar formation (increases complexity of channel)
Increased propensity for side channels, backwaters,
Grade control (step system instead of plane bed; helps prevent head-cutting incision)
Increased connectivity to floodplains (act as sink for fine sediments)
Complex mix of geomorphic units increases resilience of system to rapid degradation or aggradation
Vegetation increases drag, promotes deposition in its wake and accelerates flow around it leading to local scour
Pond acts to spread flow out (divergence) and promote deposition
The dam acts to concentrate flow and promote scour

Table 4: Influence of beaver dams on hydrology

Raises water table
Increases inundated area
Slows velocity of water, thereby increasing flood attenuation and residence time of water
Can reduce peak flood magnitudes
Facilitates ground water recharge

Table 5: Summary of accounts and research of beaver dam failures;Modified from (Butler and Malanson 2005).

Source	Aspects and effects of beaver dam failure
Rutherford, 1953	Flood removed 7 beaver dams and 2 lodges, Cache la Poudre River, Colorado, USA.
Anonymous, 1984	Out washed beaver dams released water that damaged drainage culvert and railroad embankment, causing Amtrak passenger train derailment near Williston, Vermont, USA, killing five persons and injuring 149.
Butler, 1989	Several beaver dam failures described in US states of Georgia and South Carolina. One dam failure produced outburst flood in Oglethorpe County, Georgia, that killed four people, floated a truck, and deposited two survivors 3–4 m up in trees.
Stock and Schlosser, 1991	A July 1987 dam collapse on a stream in northern Minnesota, USA, produced a flash flood that dramatically decreased downstream benthic insect density, and also altered downstream fish community structure.
TSB Canada, 1994	A Canadian National freight train derailed near Nokina, Ontario, Canada because of track bed failure caused by a sudden drawdown of water resulting from a failed beaver dam. Two crew members were killed and a third received serious injuries.
Hillman, 1998	Describes a June 1994 outburst flood in central Alberta, Canada, which produced a flood wave 3.5 times the maximum discharge recorded for that creek over 23 years. Five hydrometric stations downstream were destroyed.
VT ANR, 1999	The outburst of a large beaver pond in Fairfield, Vermont, USA, killed two people in an unspecified fashion.
Anonymous, 2003	A freight train in central Michigan, USA, derailed after a beaver dam collapsed and washed out a culvert underneath the railway. Two railway employees suffered minor injuries
Butler and Malanson, 2005	Field work Glacier National Park Montana. Soil probing of failed dams shows entrenchment downstream of the dam, some evacuation of pond sediments, and rapid colonization of exposed sediments by vegetation.
Demmer and Beschta, 2008	Field work on Bridge Creek, OR. Increase in channel roughness and sinuosity in addition to increases in habitat heterogeneity within the landscape due to different vegetative communities supported by dams at various successional stages.
Green and Westbrook, 2009	Field work and analysis of historical aerial photography of Sandown Creek in the East Kootenay region of British Columbia. Channel changed from a multi-threaded to a single threaded channel. Dominate riparian vegetation composition changed from open to closed canopy and stream velocity increased.

Table 6: The outcome of 161 beaver dams monitored along Bridge Creek, OR from 1988-2005. Based on Demmer's data.

Number (%) of dams	Observations
30 (19%)	These dams washed away completely, usually during periods of high flows.
61 (38%)	These dams breached on an end where flows would typically begin to erode the streambank adjacent to the dam and eventually form a new meander around the end of the dam. The remaining portion of a dam would accumulate sediment deposits on its upstream and downstream sides. Coyote willows (*Salix exigua*) growing on the dam would spread roots into the surrounding sand and gravel further stabilizing deposited alluvium.
51 (32%)	These dams breached in the center while both ends of the original dam remained well-anchored along each bank. The remnant dam sections constricted flow and would eventually create an upstream riffle and a downstream pool. These deflectors became stabilized by vegetation and often remained for many years before they were gradually buried by sediment deposits or were undercut. Alluvial deposits usually formed along streambanks upstream and downstream of the former dam.
14 (9%)	These dams remained intact over time while the original pond simply filled with sediment. Water continued to flow over or around these dams, sometimes creating deep plunge pools immediately downstream of a dam. After a few years a channel would reestablish either by cutting through the dam, washing it out completely or by cutting around an end of the dam leaving a large proportion of the deposited sediment in place. A riffle/pool sequence formed where the dam was cut in the center or a new meander formed when the channel cut around the end of the dam.
2 (1%)	The top portion of these dams washed away leaving woody material and rocks embedded along the channel bottom. In these cases the channel became a broad riffle at the former dam site with a shallow pool formed immediately downstream of the original structure.
3 (2%)	A large dam was constructed downstream from an existing dam thus causing the original structure to be inundated by the new pond. The older dam would be partially dismantled and some of the materials would be incorporated into the new dam. The pond associated with the new dam contained relatively large amounts of woody debris and rocks that formed a complex aquatic habitat.

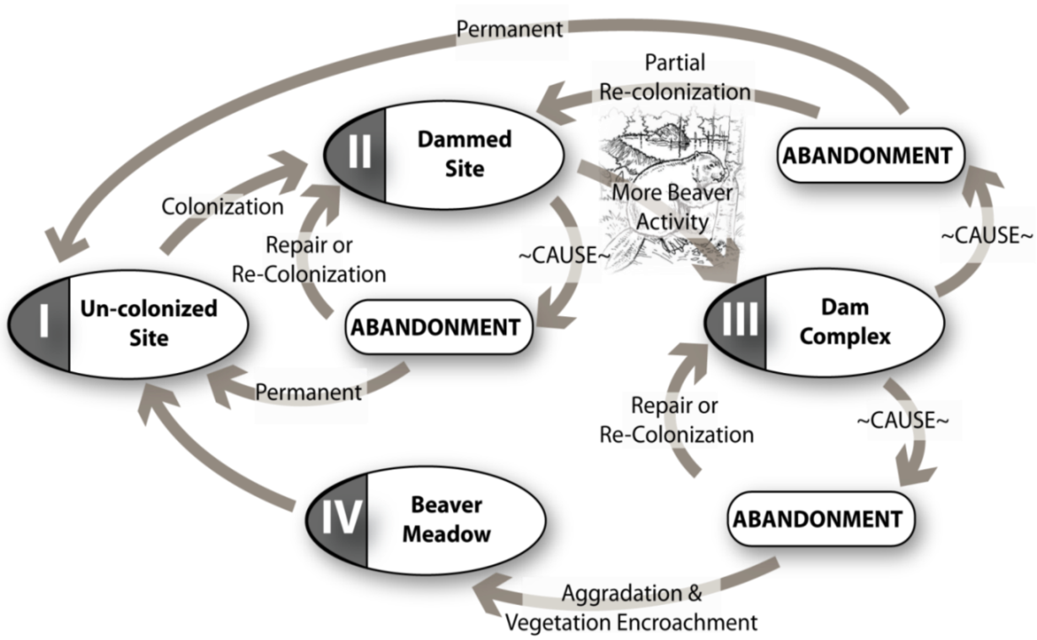


Figure 1: Conceptual model of beaver pond evolution; depicting the potential fate of beaver dams after failure depending on the successional stage at the time of failure and whether the beaver responded by repairing or abandoning the dam or if the dam is re-colonized.

Figure 2: Beaver dam with beaver dam support structures at Upper Owens reach study site in November 2009, six months after the beaver dam was initially breached.

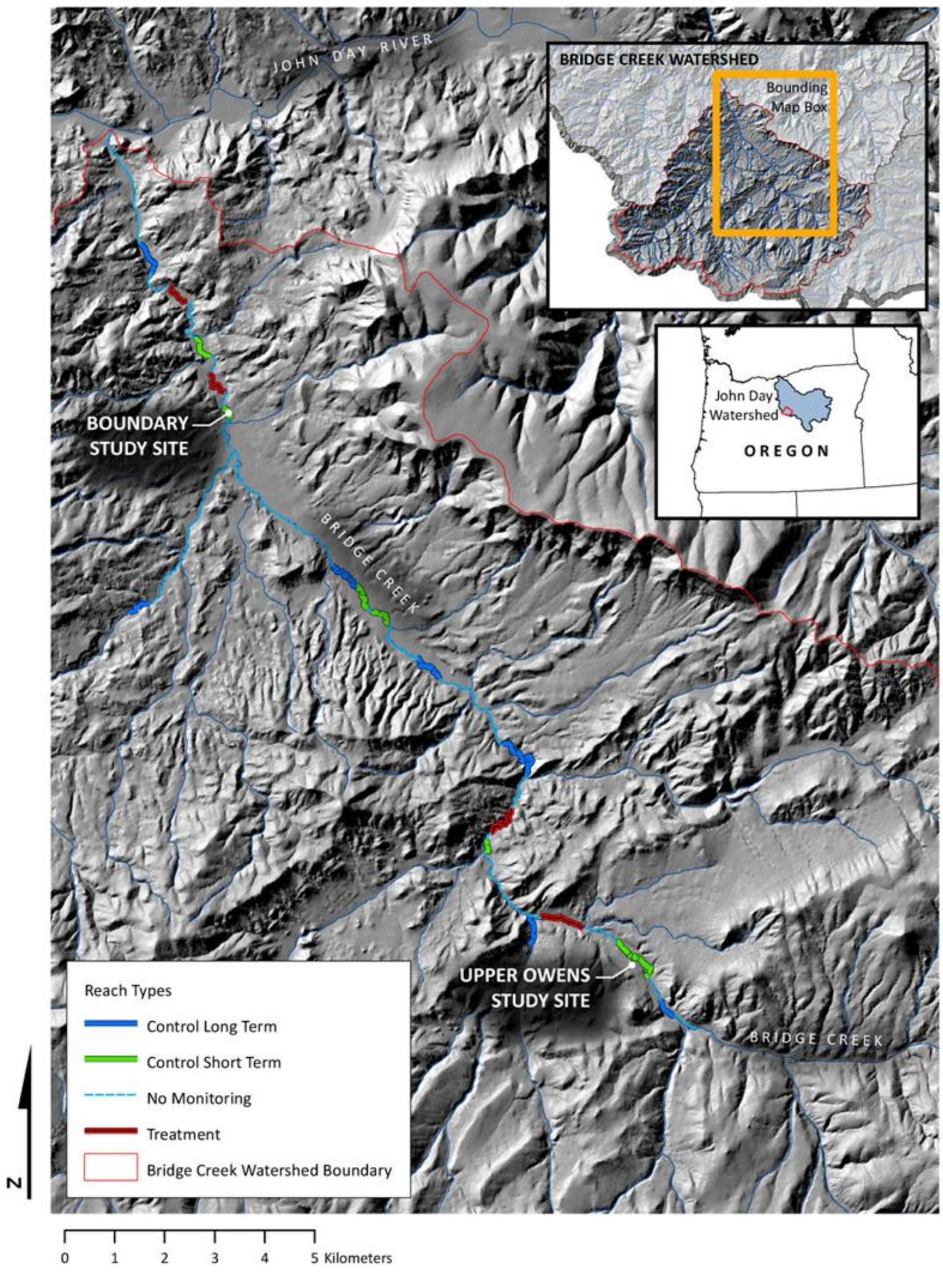


Figure 3: General location map of Bridge Creek showing the locations of the Upper Owens study site and Boundary reach.

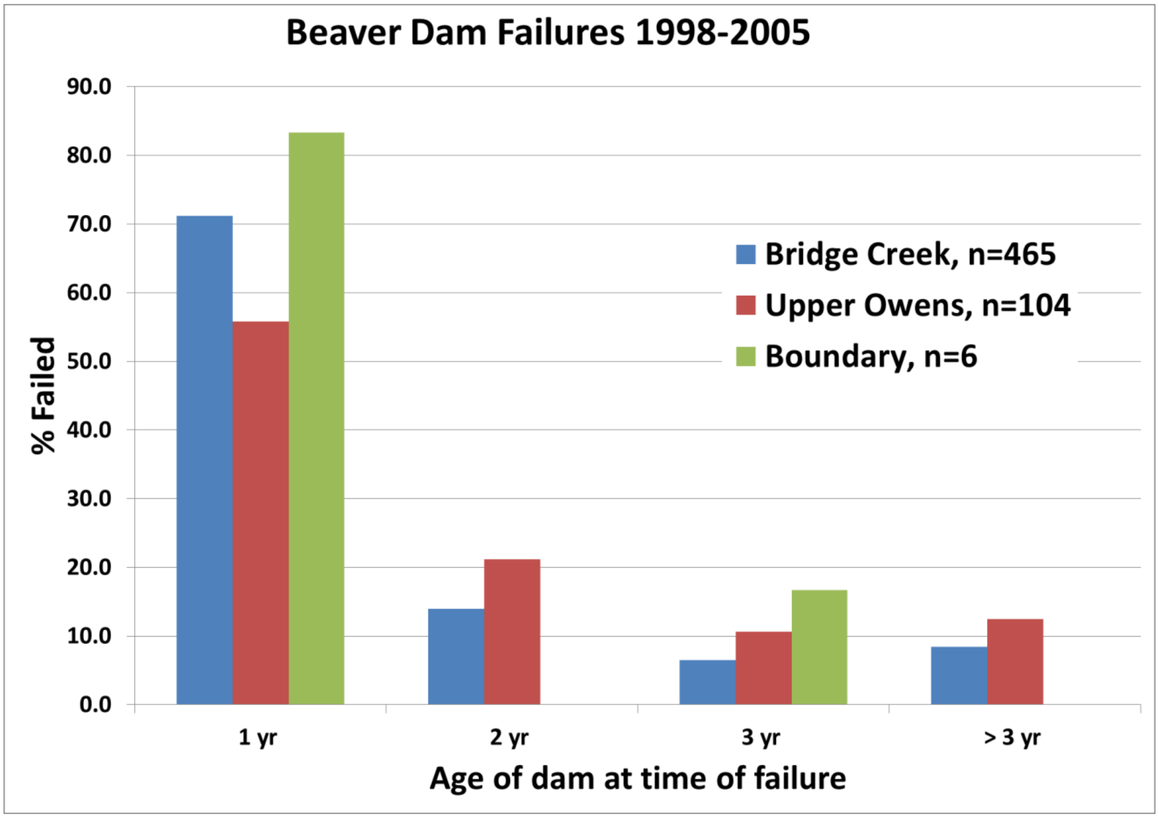


Figure 4: Age of beaver dams along Bridge Creek, OR; the Upper Owens study site; and the Boundary reach at time of failures during the time period 1998-2005. Graph created from Demmer and Beschta unpublished data.

Figure 5: Newly installed Beaver Dam Support Structure on Bridge Creek, OR. Posts are 3 meters in length and pounded approximately 1.5 meters into the ground. Photo credit: Joe Wheaton, November 2010.

Figure 6: Example of a Beaver Dam Support Structure (BDSS) on Bridge Creek, OR, stabilizing a small willow branch weave and impounding the stream flow. Photo credit: Joe Wheaton, November 2010.

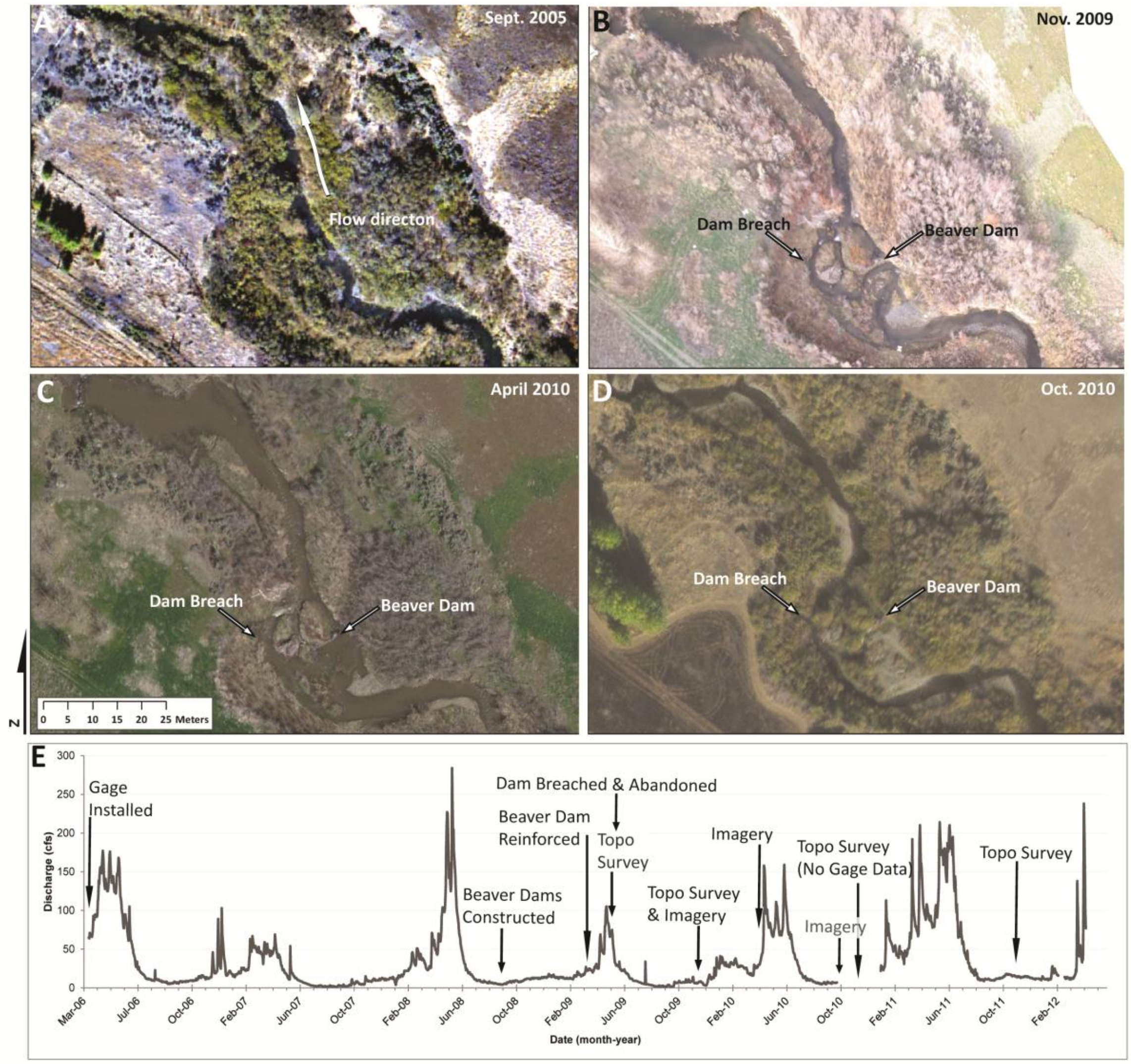


Figure 7: Upper Owens, aerial imagery and hydrograph time series. 7.A: September 2005 NAIP Imagery. 7.B: November 2009 Blimp Imagery. 7.C: April 2010 UAV Drone Imagery. 7.D: October 2010 UAV Drone Imagery. 7.E: Hydrograph showing mean daily stream flow (cfs) and events at the dam site. Hydrograph data from the USGS gage 14046778 BRIDGE CR ABV COYOTE CANYON NR MITCHELL, OR.

Figure 8: Photo of the beaver dam at Upper Owens in May 2009 during the initial breach.

Figure 9: A portion of the Boundary reach showing the straight channel configuration and the alluvium the channel cuts through. Photo credit: Joe Wheaton, November 2010.

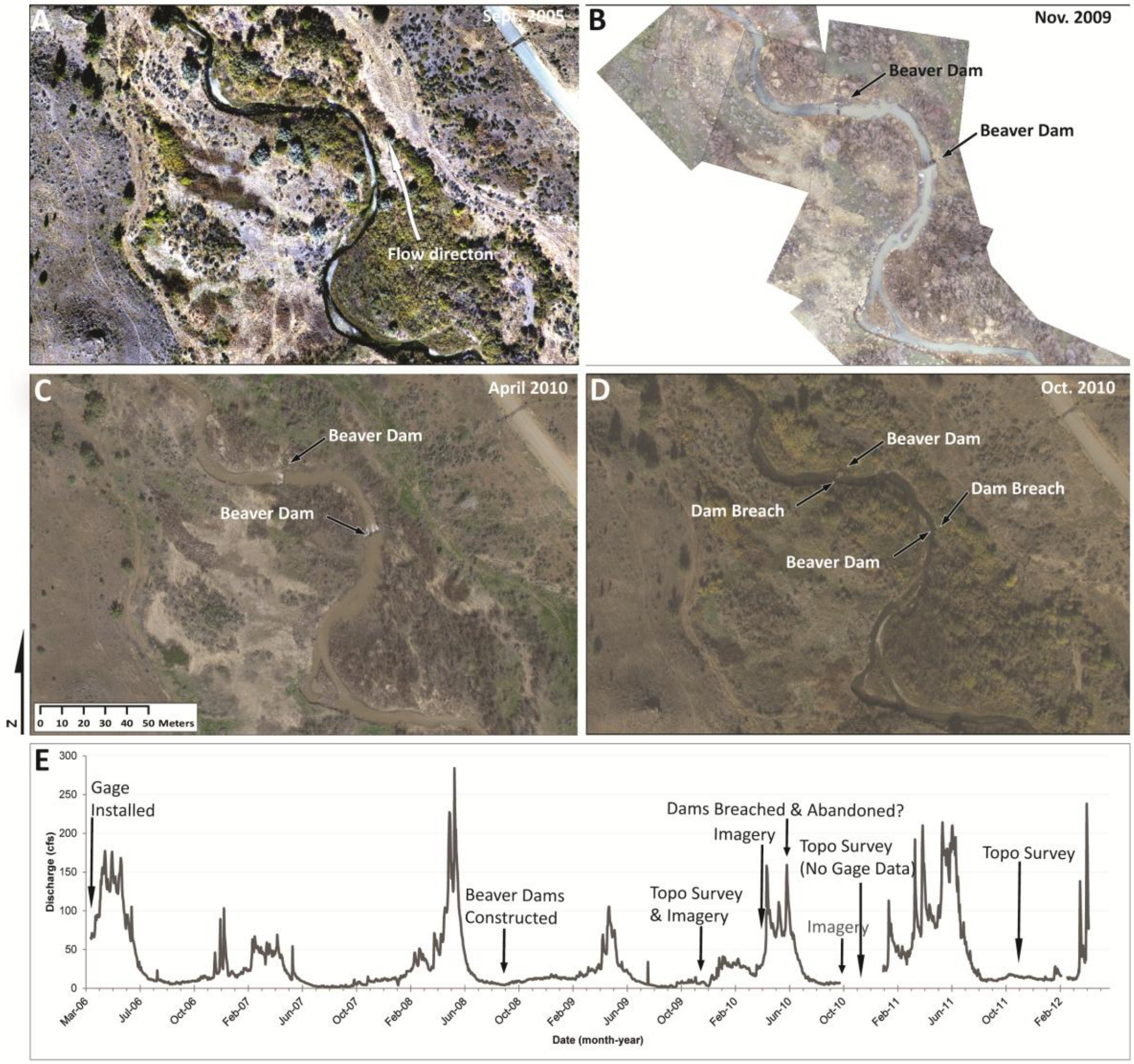


Figure 10 A-D: Boundary, aerial imagery and hydrograph time series. 10.A: September 2005 NAIP Imagery. 10.B: November 2009 Blimp Imagery. 10.C: April 2010 UAV Drone Imagery. 10.D: October 2010 UAV Drone Imagery. 10.E: Hydrograph showing mean daily stream flow (cfs) and events at the Hydrograph data from the USGS gage 14046778 BRIDGE CR ABV COYOTE CANYON NR MITCHELL, OR.

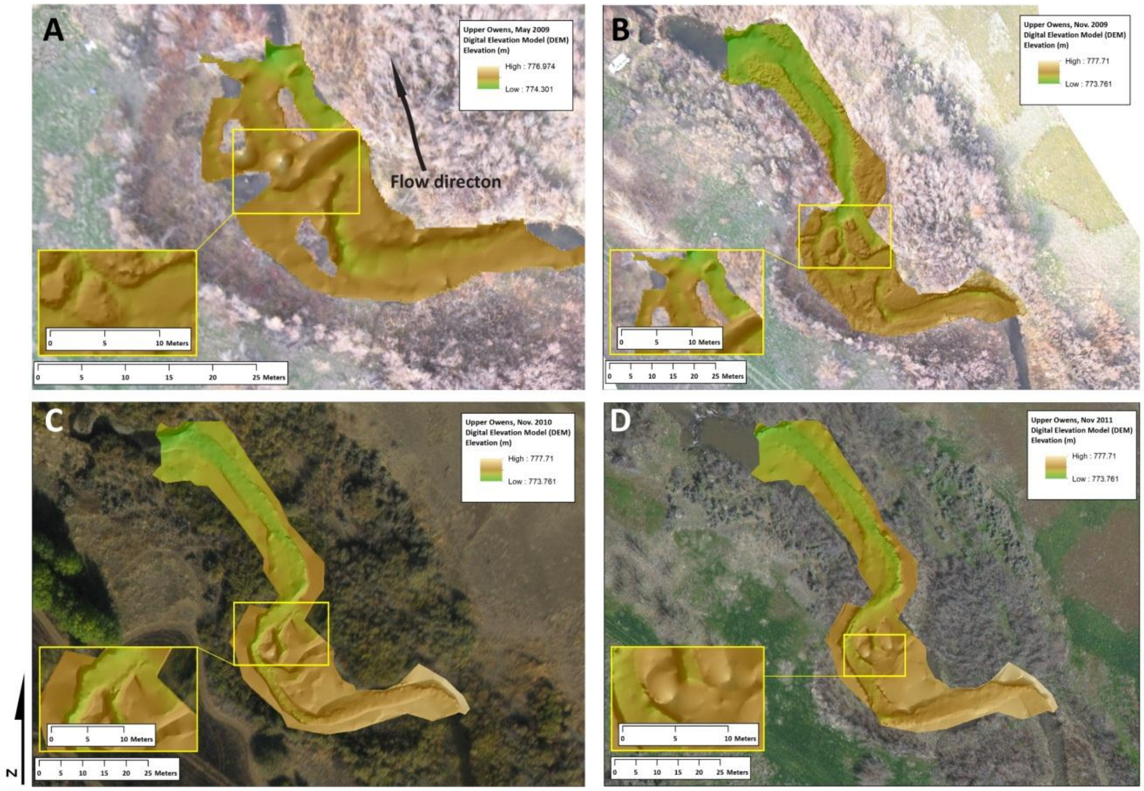


Figure 11: Upper Owens DEMs at 0.10 m resolution displayed at 30% transparency overlaying a hillshade raster created in ArcGIS 10.0. Geographic coordinate system UTM NAD83 Zone 10N.

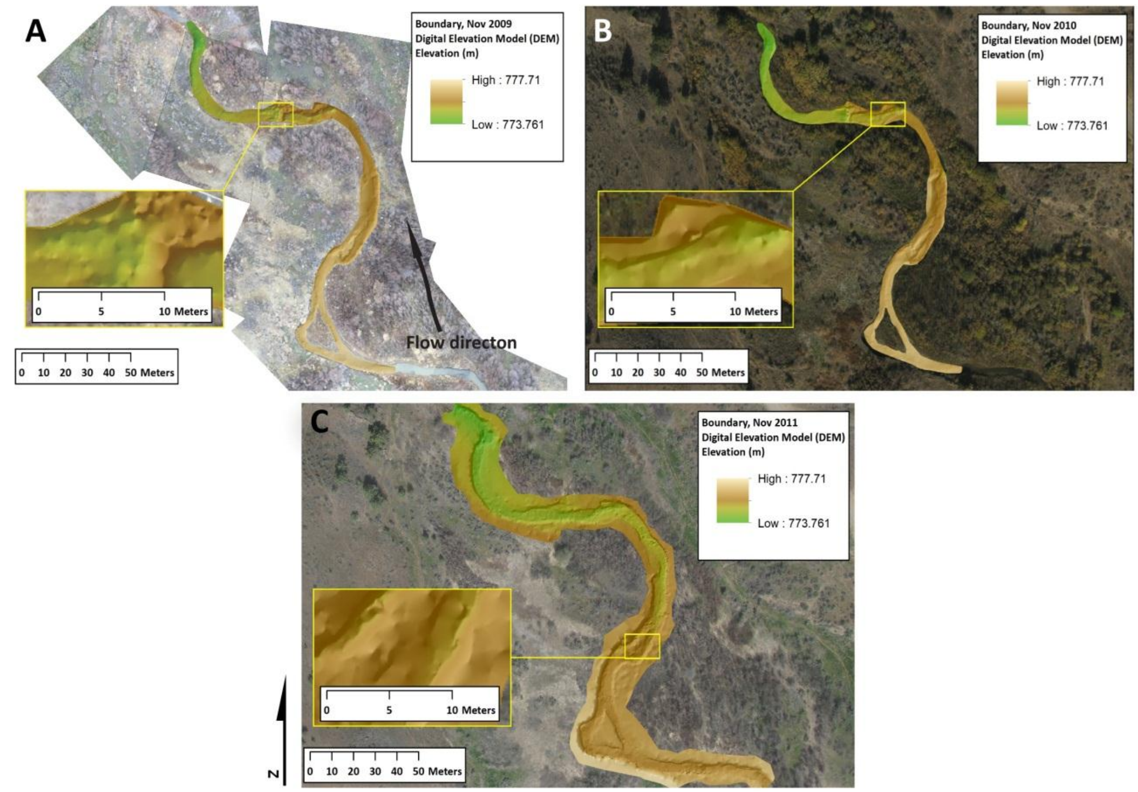
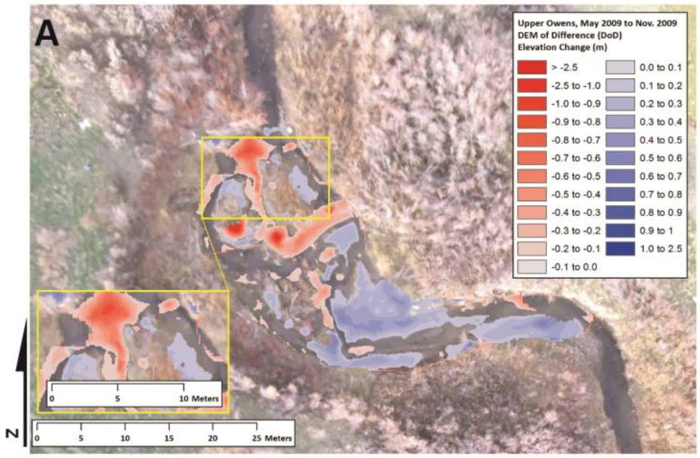
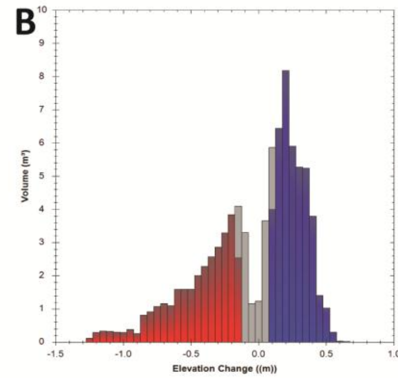


Figure 12: Boundary DEMs 0.10 m resolution displayed at 30%tranparency overlaying a using the geographic coordiante system UTM NAD83 Zone 10N hillshade raster created in ArcGIS 10.0. Geographic coordinate system UTM NAD83 Zone 10N.





C

Attribute	Raw	Thresholded DoD Estimate:			
AREAL:					
Total Area of Erosion (m^2)	210	104			
Total Area of Deposition (m^2)	286	170			
VOLUMETRIC:				± Error Volume	% Error
Total Volume of Erosion (m^3)	38	32	±	7	24%
Total Volume of Deposition (m^3)	48	42	±	12	29%
Total Volume of Difference (m^3)	86	73	±	20	27%
Total Net Volume Difference (m^3)	11	**10**	**±**	**14**	143%
PERCENTAGES (BY VOLUME)					
Percent Erosion	44%	43%			
Percent Deposition	56%	57%			
Percent Imbalance (departure from equilibrium)	6%	7%			

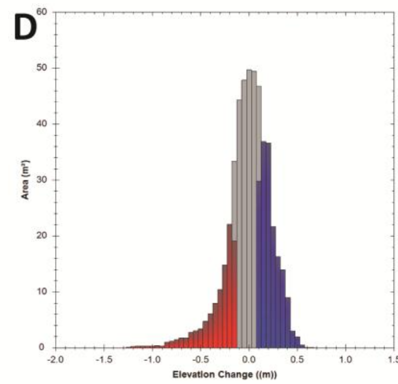
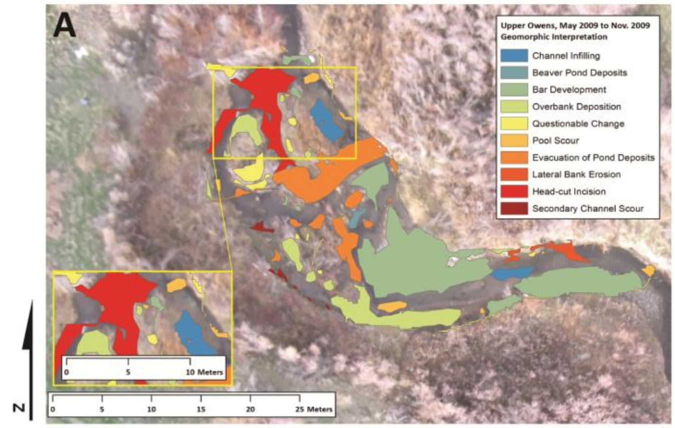
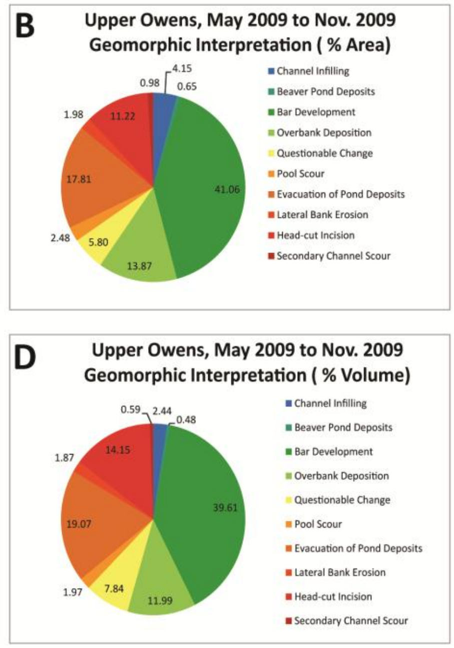


Figure 13: Upper Owens study site May 2009 to November 2009 Ground Change Detection results, 90% confidence interval, conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in 10.A: Raster output showing elevational changes, i.e. erosion and deposition over November 2009 Blimp imagery. 10.B: Histogram showing the distribution of erosion and deposition by volume (m^3). 10.C: Summary statistics. 10.D: Histogram showing the distribution of erosion and deposition by area (m^2).





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Geomorphic Class	Area (m2)	Volume (m3)
Channel Infilling	11.35	1.79
Beaver Pond Deposits	1.77	0.35
Bar Development	112.28	29.00
Overbank Deposition	37.92	8.78
Questionable Change	15.86	5.74
Pool Scour	6.78	1.44
Evacuation of Pond Deposits	48.71	13.96
Lateral Bank Erosion	5.42	1.37
Head-cut Incision	30.68	10.36
Secondary Channel Scour	2.68	0.43
Total	**273.45**	**73.22**

Figure 14: Geomorphic interpretation of channel changes at the Upper Owens site between May 2009 and November 2009, post beaver dam failure, on Bridge Creek, OR. Conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in. 14.A: Geomorphic interpretation output displayed over November 2009 Blimp imagery. 14.B: Pie chart showing percent area of each geomorphic class. 14.C: Summary of geomorphic classes by area (m^2) and volume (m^3). 14.D: Pie chart showing percent volume of each geomorphic class.

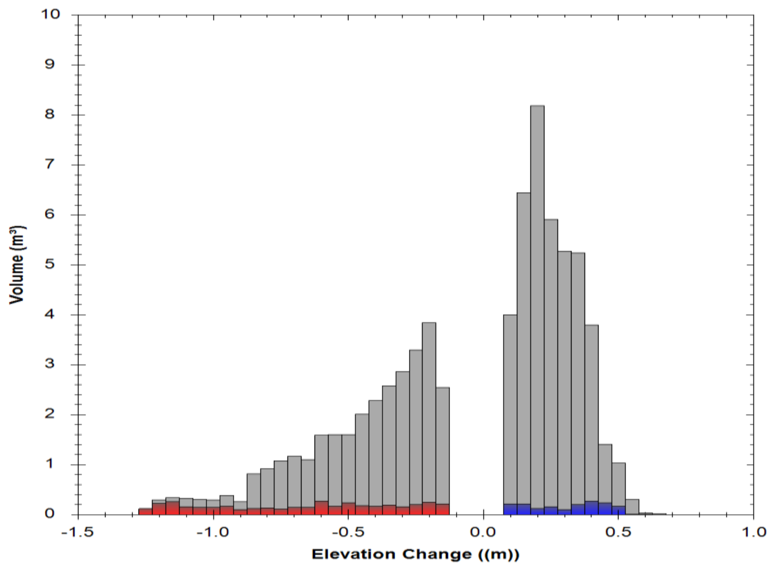
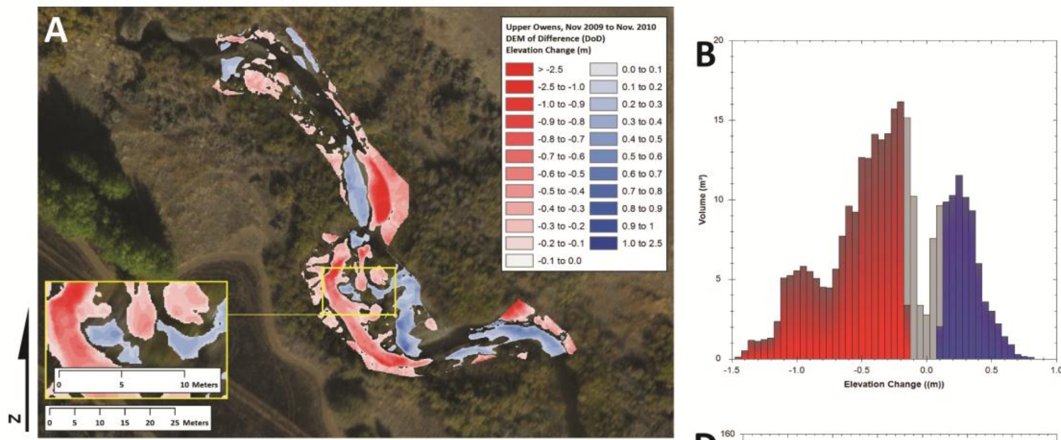


Figure 15: Distribution by volume (m3) of questionable geomorphic change detected at the Upper Owens reach study site between May 2009 and November 2009.



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Attribute	Raw	Thresholded DoD Estimate:			
AREAL:					
Total Area of Erosion (m²)	850	483			
Total Area of Deposition (m²)	531	251			
VOLUMETRIC:				± Error Volume	% Error
Total Volume of Erosion (m³)	209	184	±	41	22%
Total Volume of Deposition (m³)	89	71	±	21	30%
Total Volume of Difference (m³)	298	255	±	62	24%
Total Net Volume Difference (m³)	-120	**-113**	**±**	**46**	-41%
PERCENTAGES (BY VOLUME)					
Percent Erosion	70%	72%			
Percent Deposition	30%	28%			
Percent Imbalance (departure from equilibrium)	-20%	-22%			

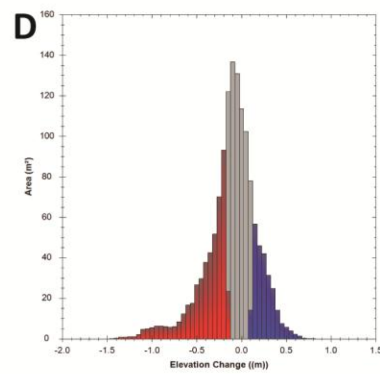
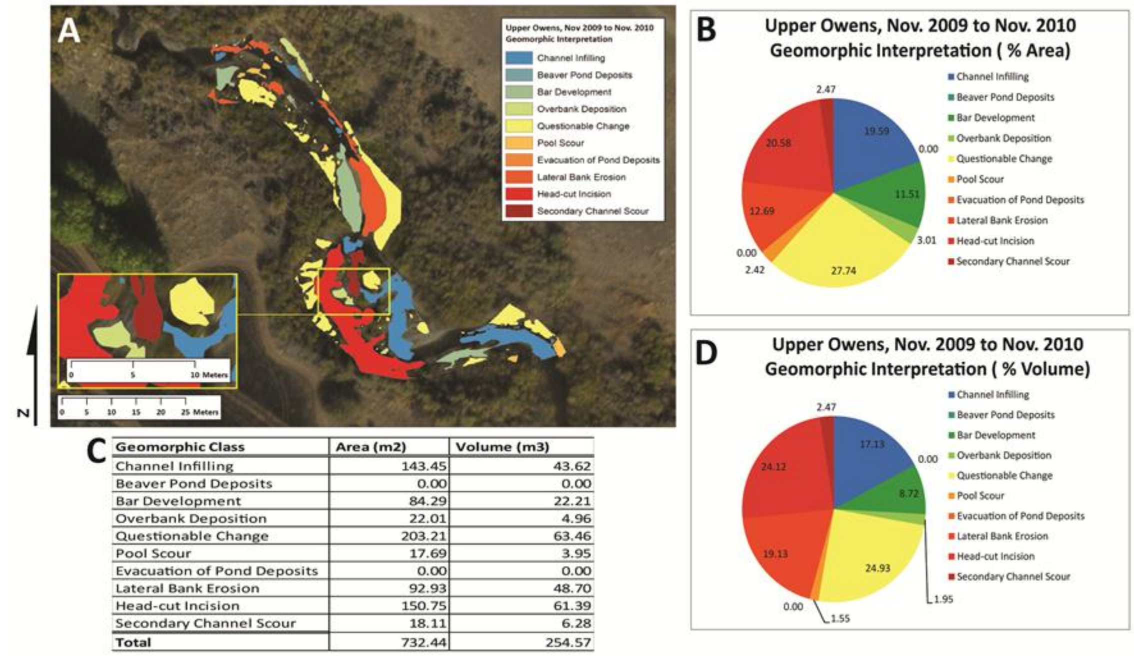


Figure 16: Upper Owens November 2009 to November 2010 Ground Change Detection results, 90% confidence interval. 10.A: Raster output showing elevational changes, i.e. erosion and deposition displayed over October 2010 UAV Drone imagery. 10.B: Histogram showing the distribution of erosion and deposition by volume (m^3). 10.C: Summary statistics. 10.D: Histogram showing the distribution of erosion and deposition by area (m^2).



Geomorphic Class	Area (m2)	Volume (m3)
Channel Infilling	143.45	43.62
Beaver Pond Deposits	0.00	0.00
Bar Development	84.29	22.21
Overbank Deposition	22.01	4.96
Questionable Change	203.21	63.46
Pool Scour	17.69	3.95
Evacuation of Pond Deposits	0.00	0.00
Lateral Bank Erosion	92.93	48.70
Head-cut Incision	150.75	61.39
Secondary Channel Scour	18.11	6.28
Total	732.44	254.57

Figure 17: Geomorphic interpretation of in channel changes between November 2009 and November 2010, post beaver dam failure at the Upper Owens study site, Bridge Creek, OR. Conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in. 14.A: Geomorphic interpretation output displayed over October 2010 UAV Drone imagery. 14.B: Pie chart showing percent area of each geomorphic class. 14.C: Summary of geomorphic classes by area (m^2) and volume (m^3). 14.D: Pie chart showing percent volume of each geomorphic class.

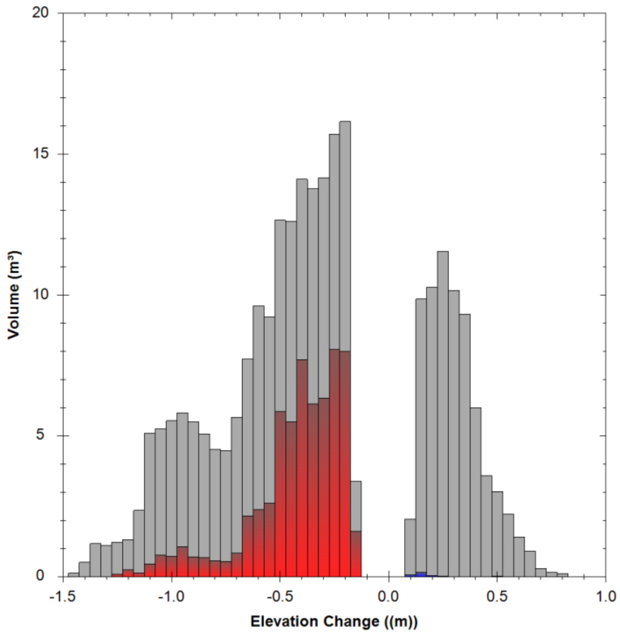
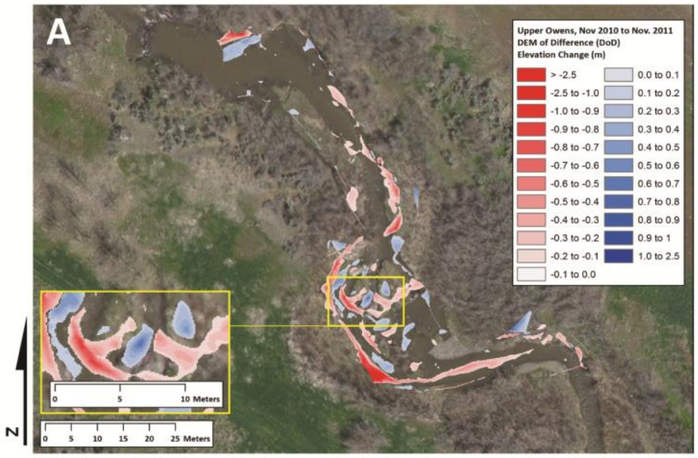
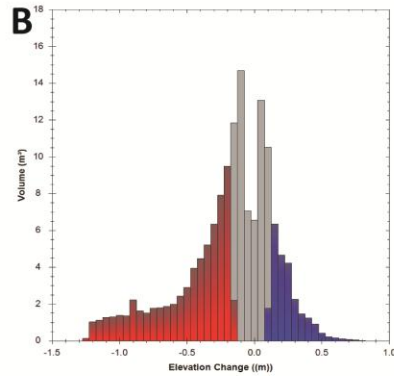


Figure 18: Distribution by volume (m3) of questionable geomorphic change detected at the Upper Owens reach study site between November 2009 and November 2010.





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Attribute	Raw	Thresholded DoD Estimate:			
AREAL:					
Total Area of Erosion (m²)	784	203			
Total Area of Deposition (m²)	638	103			
VOLUMETRIC:				± Error Volume	% Error
Total Volume of Erosion (m³)	97	65	±	17	26%
Total Volume of Deposition (m³)	52	24	±	9	36%
Total Volume of Difference (m³)	149	89	±	26	29%
Total Net Volume Difference (m³)	-44	**-41**	**±**	**19**	-47%
PERCENTAGES (BY VOLUME)					
Percent Erosion	65%	73%			
Percent Deposition	35%	27%			
Percent Imbalance (departure from equilibrium)	-15%	-23%			

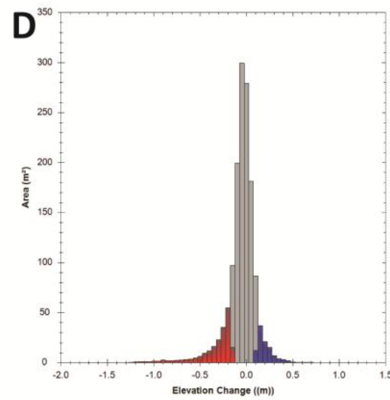
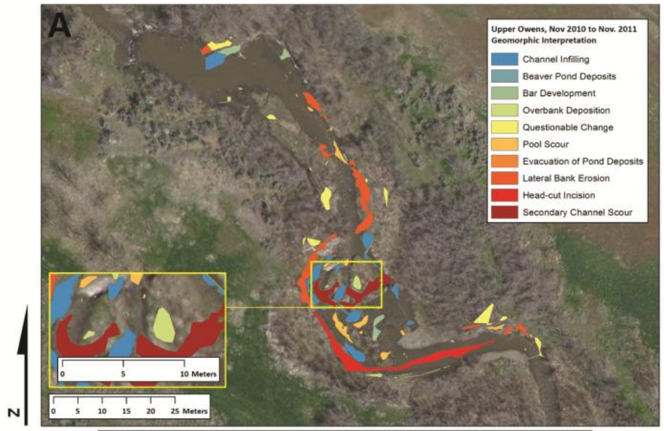
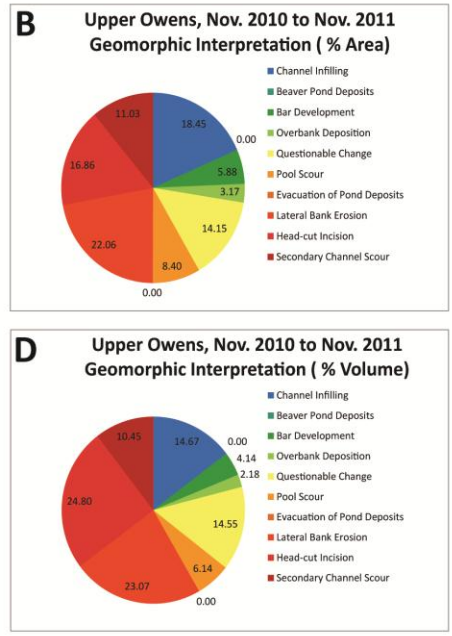


Figure 19: Upper Owens November 2010 to November 2011 Ground Change Detection results, 90% confidence interval. 10.A: Raster output showing elevational changes, i.e. erosion and deposition displayed over April 2010 UAV Drone imagery. 10.B: Histogram showing the distribution of erosion and deposition by volume (m^3). 10.C: Summary statistics. 10.D: Histogram showing the distribution of erosion and deposition by area (m^2).





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Geomorphic Class	Area (m2)	Volume (m3)
Channel Infilling	56.36	13.12
Beaver Pond Deposits	0.00	0.00
Bar Development	17.96	3.70
Overbank Deposition	9.69	1.95
Questionable Change	43.21	13.01
Pool Scour	25.66	5.49
Evacuation of Pond Deposits	0.00	0.00
Lateral Bank Erosion	67.40	20.63
Head-cut Incision	51.51	22.17
Secondary Channel Scour	33.68	9.34
Total	305.47	89.41

Figure 20: Geomorphic interpretation of in channel changes between November 2010 and November 2011, post beaver dam failure at the Upper Owens study site, Bridge Creek, OR. Conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in. 14.A: Geomorphic interpretation output displayed over April 2010 UAV Drone imagery. 14.B: Pie chart showing percent area of each geomorphic class. 14.C: Summary of geomorphic classes by area (m^2) and volume (m^3). 14.D: Pie chart showing percent volume of each geomorphic class.

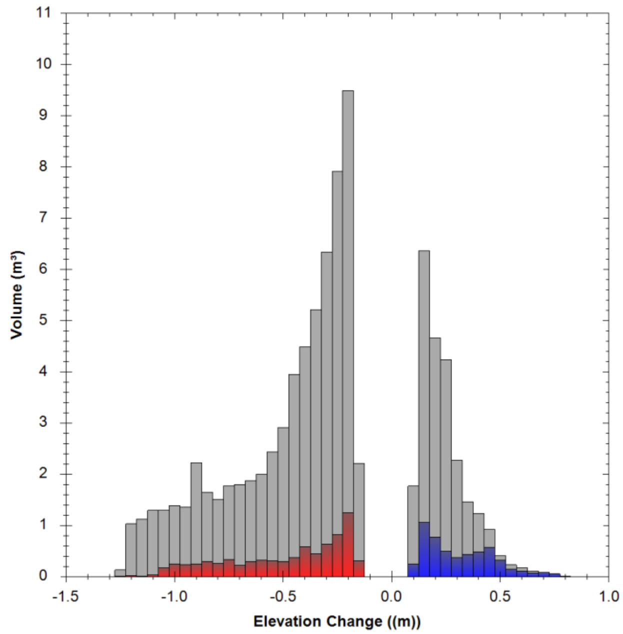
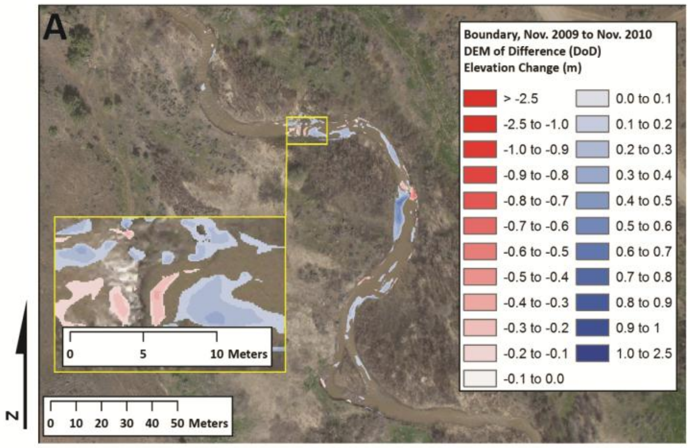
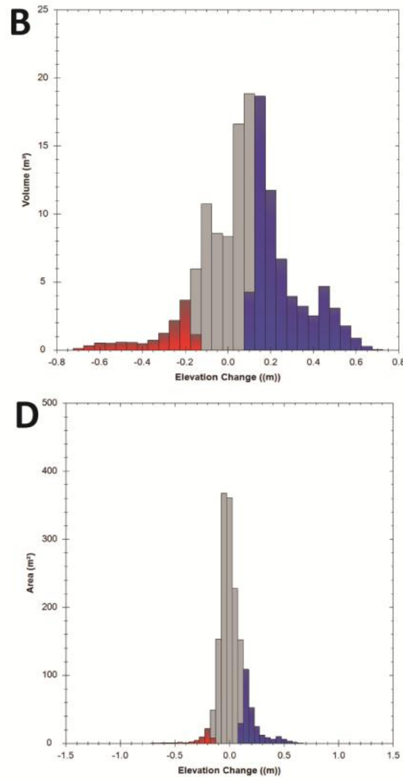


Figure 21: Distribution by volume (m3) of questionable geomorphic change detected at the Upper Owens reach study site between November 2010 and November 2011.

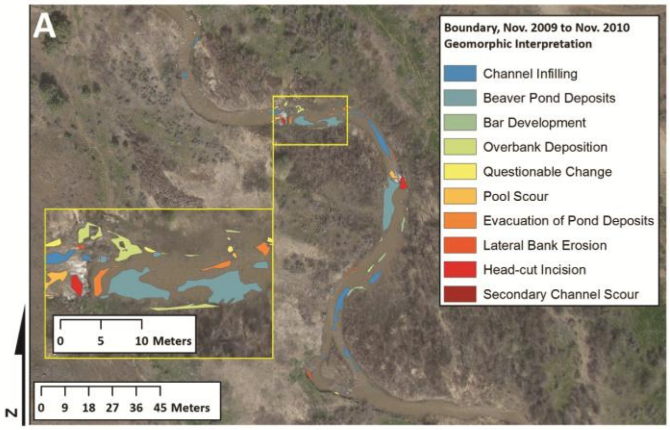


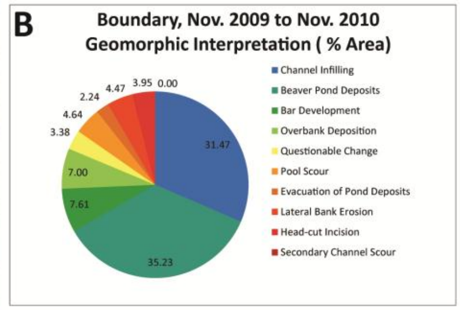


C

Attribute	Raw	Thresholded DoD Estimate:		± Error Volume	% Error
AREAL:					
Total Area of Erosion (m²)	615	53			
Total Area of Deposition (m²)	975	263			
VOLUMETRIC:				± Error Volume	% Error
Total Volume of Erosion (m³)	36	12	±	3	25%
Total Volume of Deposition (m³)	101	62	±	26	42%
Total Volume of Difference (m³)	138	74	±	29	39%
Total Net Volume Difference (m³)	65	**50**	**±**	**26**	53%
PERCENTAGES (BY VOLUME)					
Percent Erosion	26%	16%			
Percent Deposition	74%	84%			
Percent Imbalance (departure from equilibrium)	24%	34%			

Figure 22: Boundary November 2009 to November 2010 Ground Change Detection results, 90% confidence interval. 10.A: Raster output showing elevational changes, i.e. erosion and deposition displayed over April 2010 UAV Drone imagery. 10.B: Histogram showing the distribution of erosion and deposition by volume (m^3). 10.C: Summary statistics. 10.D: Histogram showing the distribution of erosion and deposition by area (m^2).





C

Geomorphic Class	Area (m2)	Volume (m3)
Channel Infilling	99.40	18.53
Beaver Pond Deposits	111.27	32.68
Bar Development	24.03	4.82
Overbank Deposition	22.10	4.62
Questionable Change	10.67	1.94
Pool Scour	14.66	2.70
Evacuation of Pond Deposits	7.08	1.38
Lateral Bank Erosion	14.13	2.95
Head-cut Incision	12.47	4.35
Secondary Channel Scour	0.00	0.00
Total	315.81	73.97

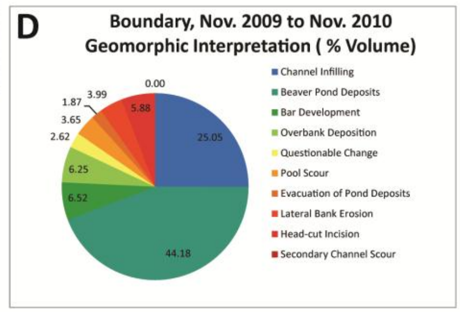


Figure 23: Geomorphic interpretation of in channel changes between November 2009 and November 2010, post beaver dam failure at preliminary study site on Boundary reach, Bridge Creek, OR. Conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in. 14.A: Geomorphic interpretation output displayed over April 2010 UAV Drone imagery. 14.B: Pie chart showing percent area of each geomorphic class. 14.C: Summary of geomorphic classes by area (m^2) and volume (m^3). 14.D: Pie chart showing percent volume of each geomorphic class.

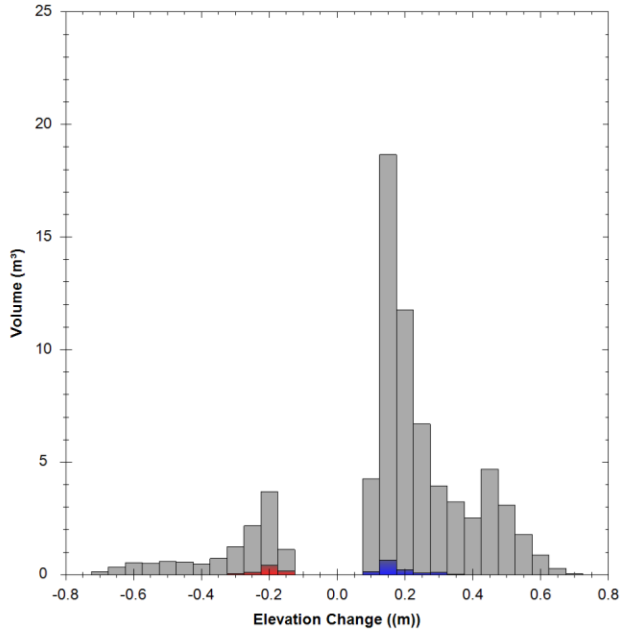
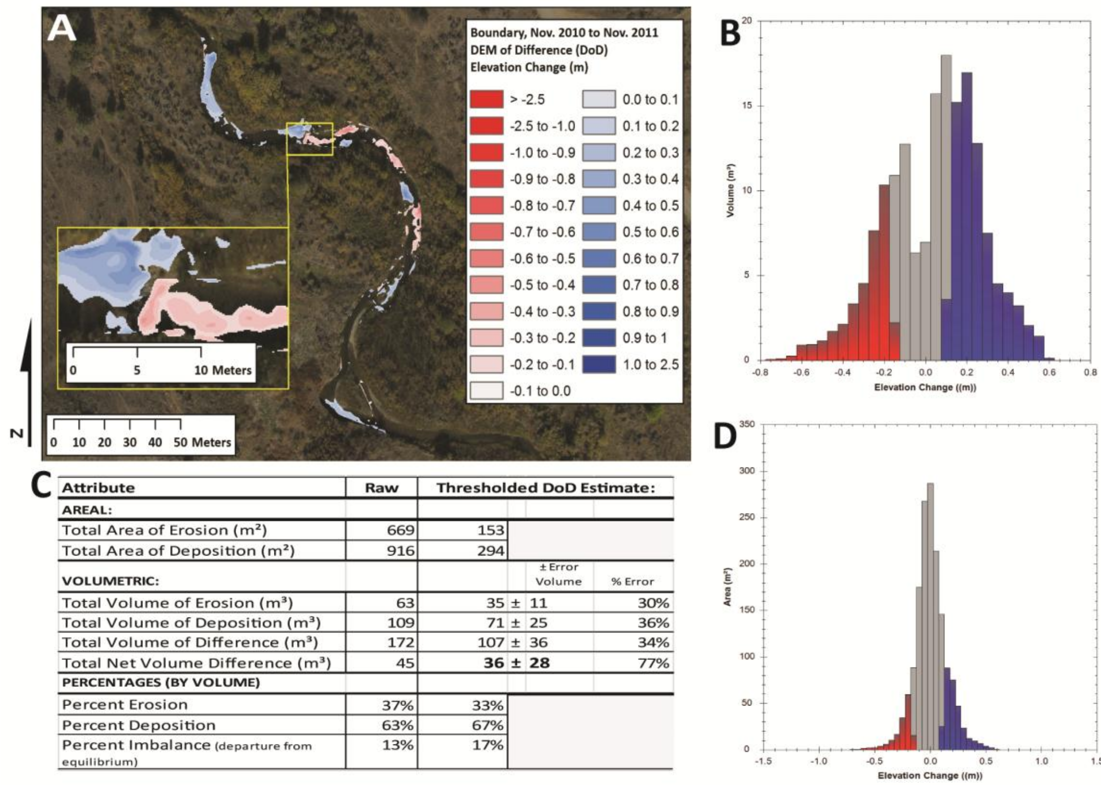
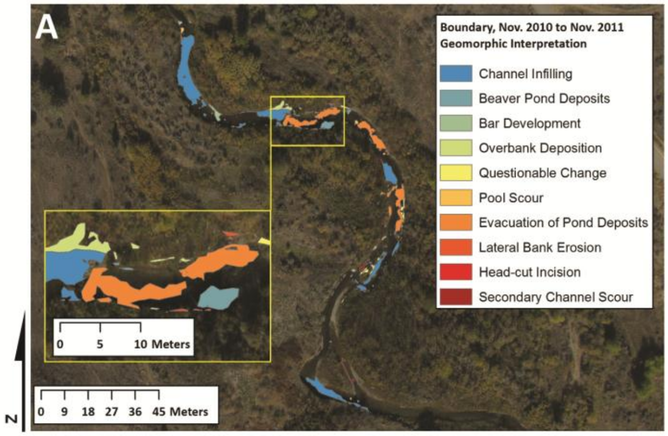


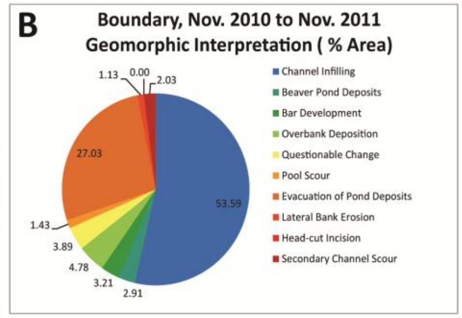
Figure 24: Distribution by volume (m3) of questionable geomorphic change detected at the Boundary reach between November 2009 and November 2010.



Attribute	Raw	Thresholded DoD Estimate:			
AREAL:					
Total Area of Erosion (m^2)	669	153			
Total Area of Deposition (m^2)	916	294			
VOLUMETRIC:				± Error Volume	% Error
Total Volume of Erosion (m^3)	63	35	±	11	30%
Total Volume of Deposition (m^3)	109	71	±	25	36%
Total Volume of Difference (m^3)	172	107	±	36	34%
Total Net Volume Difference (m^3)	45	**36**	±	**28**	77%
PERCENTAGES (BY VOLUME)					
Percent Erosion	37%	33%			
Percent Deposition	63%	67%			
Percent Imbalance (departure from equilibrium)	13%	17%			

Figure 25: Boundary November 2010 to November 2011 Ground Change Detection results, 90% confidence interval. 10.A: Raster output showing elevational changes, i.e. erosion and deposition displayed over October 2010 UAV Drone imagery. 10.B: Histogram showing the distribution of erosion and deposition by volume (m^3). 10.C: Summary statistics. 10.D: Histogram showing the distribution of erosion and deposition by area (m^2).





C

Geomorphic Class	Area (m2)	Volume (m3)
Channel Infilling	239.33	59.52
Beaver Pond Deposits	12.98	3.06
Bar Development	14.32	2.58
Overbank Deposition	21.34	5.21
Questionable Change	17.39	3.85
Pool Scour	6.40	1.11
Evacuation of Pond Deposits	120.72	28.68
Lateral Bank Erosion	5.03	1.10
Head-cut Incision	0.00	0.00
Secondary Channel Scour	9.06	1.81
Total	446.57	106.92

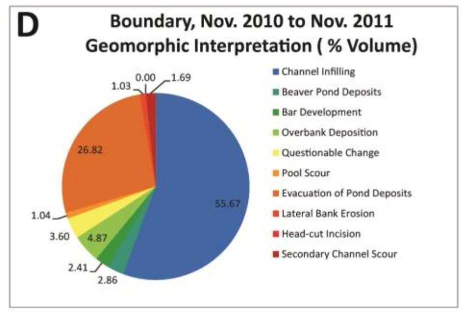


Figure 26: Geomorphic interpretation of in channel changes between November 2010 and November 2011, post beaver dam failure at preliminary study site on Boundary reach, Bridge Creek, OR. Conducted in Arc GIS 10.0 using GCD 5.2 Ground Change Detection Uncertainty Analysis plug-in. 14.A: Geomorphic interpretation output displayed over October 2010 UAV Drone imagery. 14.B: Pie chart showing percent area of each geomorphic class. 14.C: Summary of geomorphic classes by area (m^2) and volume (m^3). 14.D: Pie chart showing percent volume of each geomorphic class.

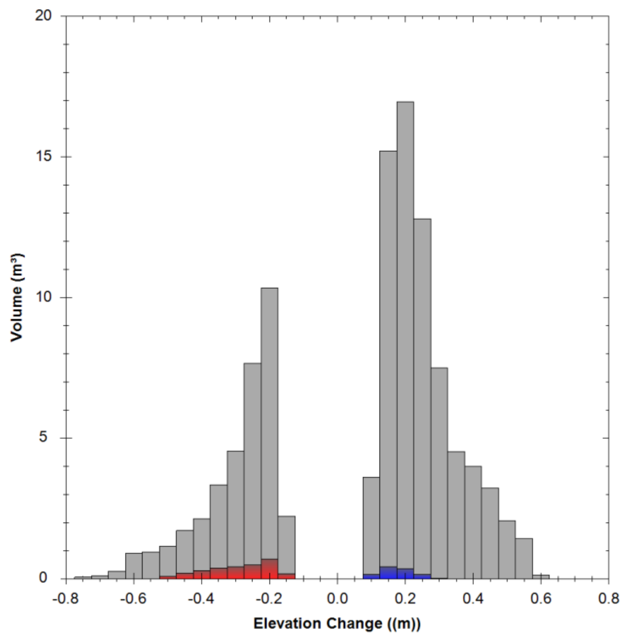


Figure 27: Distribution by volume (m3) of questionable geomorphic change detected at the Boundary reach between November 2009 and November 2010.