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Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed

Design Rationale and Hypotheses

October 2012

U.S. DEPARTMENT OF COMMERCE
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Design Rationale and Hypotheses

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Table of Contents

List of Figures

List of Tables

Executive Summary

The incised and degraded habitat of Bridge Creek is thought to be limiting a population of steelhead (*Oncorhynchus mykiss*) listed as threatened under the U.S. Endangered Species Act. A logical restoration approach is to improve their habitat through reconnecting the channel with portions of its former floodplain (now terraces) to increase both stream and riparian habitat complexity. Using conventional restoration techniques to achieve such objectives can be quite costly, because it involves moving and grading large volumes of fill with heavy equipment that exposes bare ground and is usually followed by extensive revegetation efforts. Here we seek a cost-effective, process-based approach to restore geomorphic, hydrologic, and ecological functions of this degraded system, helping a small, extant beaver (*Castor canadensis*) population build longer-lived dams.

Currently, the beaver population is limited because their dams are short-lived. Most beaver dams are constructed within the incision trench and during high discharge events the full force of flood waters is concentrated on these dams rather than dissipating across floodplains. Consequently most dams breach and fail within their first season. The primary hypothesis we are testing is that by assisting beaver to create stable colonies and aggrade incised reaches of Bridge Creek, there will be measurable improvements in riparian and stream habitat conditions and abundance of native steelhead. The main restoration design challenge is to help beaver build dams that will last long enough to lead to the establishment of stable colonies. If this can be accomplished, the beaver dams should promote enough aggradation to reverse channel incision and reap a number of well documented positive ecosystem benefits associated with dynamic beaver dam complexes that will benefit steelhead and other species.

We are assisting the beaver using an extremely simple and cost-effective restoration treatment. The treatment involves installing round wooden fence posts approximately 0.5 to 1 m apart across potential floodplain surfaces (now terraces) and the channel at a height intended to act as the crest elevation of an active beaver dam. This report provides details of the design rationale and design hypotheses employed and summarizes placement of the 85 beaver dam support (BDS) structures installed in four reaches in 2009. Additionally, the ongoing monitoring campaign devised to test these design hypotheses is discussed and some preliminary observations from the first year of the campaign are presented.

Five variants of the restoration treatment were used; post lines only, post lines with wicker weaves, construction of starter dams, reinforcement of existing active beaver dams, and reinforcement of abandoned beaver dams. The biodegradable posts are intended to buy enough time for 1) beaver to occupy the structures and build on or maintain the structures as their own dams and 2) aggradation to take place in the slack waters of the pond from the dam and promote reconnection with a floodplain (terrace). Just as with natural beaver dams, individual dams are expected to be transient features on the landscape, expanding and contracting, coming and going as they lose functionality for beaver (e.g., when a pond fills with sediment). The treatment design is geared to saturate four distinct reaches of Bridge Creek with BDS structures so that enough potential dams are available to the current beaver population that they can pick and choose the best sites to establish stable, multidam complexes to support healthy and persistent colonies.

Acknowledgments

Many people have contributed and continue to contribute to the success of the Bridge Creek Restoration and Monitoring Project and our thanks go out to all of them. The project and this report are possible because of a collective desire among numerous individuals in various federal and state agencies and nongovernmental organizations to help restore stream habitat and rebuild the population of steelhead that once thrived in the John Day River basin.

In particular, the project would not have been successful without the efforts of Ian Tattam, our field manager and steelhead expert. He spent countless hours surveying streams, counting and tagging fish, tracking beaver, and generously opening his home to students and scientists passing through the Bridge Creek watershed. Nicholas Weber also worked tirelessly to make this project successful and as of 2011 played an even more central role in the project as the new field manager. Others who have contributed substantially to the collection of field data include Matt Allen and Bryn Fleming, Eco Logical Research, Inc. Rick Demmer, U.S. Bureau of Land Management, deserves thanks for the many years he spent surveying Bridge Creek for beaver activity and for helping develop many of the concepts that were incorporated into this project.

We also appreciate the contributors to this project who are listed by organization below.

- Field Crew: Matt Allen, Sean Anderson, Emma Anspach, John Decker, Bryn Fleming, Taira Flute, Andrae Genus, Bryan Mathias, Andrew McClary, Dan Myers, Rob Ottoway, Levi Raber, Brian Rhode, Sam Rizza, Bill Tattam, and Ian Tattam.
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- Oregon Natural Desert Association: Alexa Bontager, Brent Fenty, and Kate Martin.
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- Private landowners and ranchers in Bridge Creek: David and Linda Gorton, Jake Polvi, and Jim Woodward.
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Introduction

The Bridge Creek Intensively Monitored Watershed Project is a long-term study to restore stream and riparian habitat along the incised and degraded lower 32 km of Bridge Creek, a tributary to the John Day River in eastern Oregon (Figure 1), and to measure the physical and biological changes that occur as a result of the restoration. The overarching restoration goal is to measurably increase the number of wild steelhead (*Oncorhynchus mykiss*) that use this system, which are part of a larger population listed as threatened under the U.S. Endangered Species Act (NMFS and NWFSC 2008). This project is part of NWFSC's Integrated Status and Effectiveness Monitoring Program, which is developing methods to accurately assess changes in salmonid habitat and salmonid populations within the Columbia River basin. Thus the results of this project are integral to designing future restoration and monitoring projects throughout the Pacific Northwest.

The main stem of Bridge Creek is typical of many incised streams throughout the western United States in that it is confined within a narrow incision trench and high flows rarely access its former floodplain (Figure 2b) (Shields et al. 1995, Beechie et al. 2007). Typically, incision also results in a loss of channel planform and bedform complexity (Schumm et al. 1984, Rosgen 1996, Shields et al. 1999). Channel incision also affects groundwater-surface water interactions and often results in lowered water tables and reduced hyporheic exchange (Darby and Simon 1999). Manifestations of these changes include decreased stream flows, less riparian vegetation, and increased stream temperatures. The overall effect is a simplification of habitat and subsequent reduction in its quality for both instream and riparian biota. This describes much of Bridge Creek, where there are many simplified, linear, plane-bed reaches with a narrow band of willows growing on either side of the stream within a confined incision trench.

By contrast, in other reaches within Bridge Creek the incision trench has widened to create inset floodplains or terraces (Figure 2d), and in some of these reaches, beaver (*Castor canadensis*) have built numerous dams and established colonies. Where such dam complexes are present, water tables are elevated and the channel bed is rapidly aggrading such that the stream can now flood some of the inset terraces (Pollock et al. 2007). In such cases, system complexity has greatly increased, the stream and riparian condition appears to be improving markedly, and the system is restoring itself. These sites, though few in number, provide an example of how incised streams can naturally restore themselves.

These phenomena are not unique to Bridge Creek. It is well-known that beaver dam complexes provide numerous ecosystem benefits, primarily through reconnecting streams to their former floodplains by raising water level elevations and causing widespread aggradation of the incised streambed (reviewed in Pollock et al. 2003, Westbrook et al. 2006, Westbrook et al. 2010). We have also observed beaver dam building within narrow incision trenches, but these dams rarely last more than a year and are typically destroyed during spring floods (Demmer and Beschta 2008). This is because within an incision trench there is limited floodplain access or

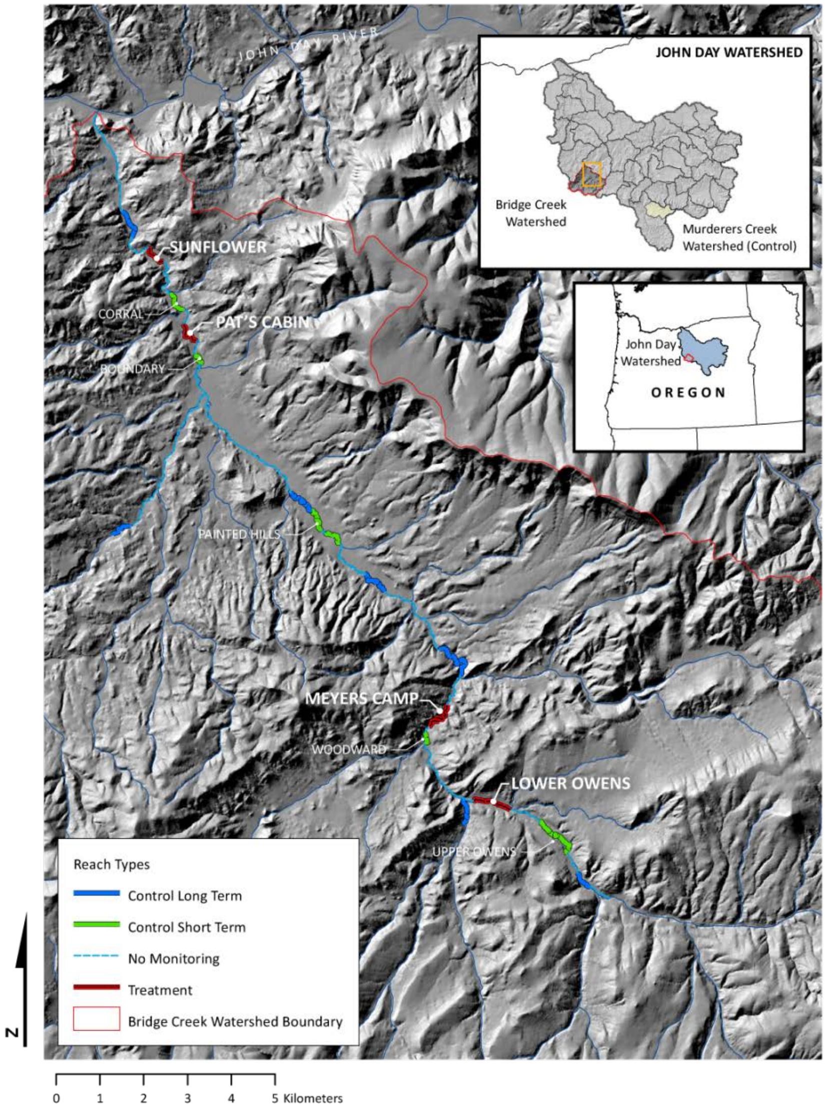


Figure 1. Location and vicinity maps of Bridge Creek. The inset maps show the location of Bridge Creek and Murderers Creek in the John Day River basin of eastern Oregon. The main map shows the mainstem Bridge Creek drainage network and the primary treatment reaches described in this report.

planform complexity to help disperse flow energy. Beaver dams are often the only large structural element within incision trenches and they are unable to retain their structural integrity when the full force of spring floods acts upon them.

Such observations of beaver dams lead to a basic question: Can beaver be encouraged to build dams in narrow reaches of incised streams where a wide inset floodplain has not yet developed, and would such dam building lead to the formation of stable colonies with subsequent improvements in riparian and stream habitat conditions? That is, can we actively work with beaver and provide them with structure to help them build relatively stable dams in

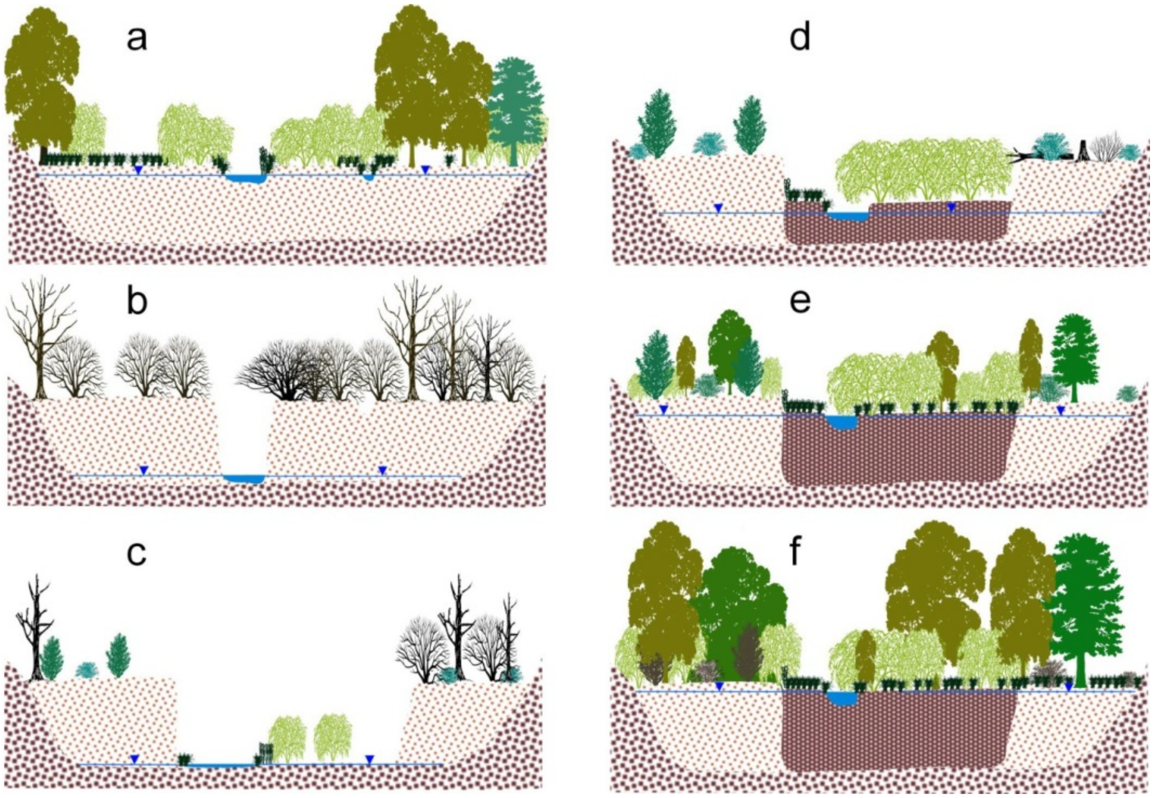


Figure 2. Sequence of channel incision and aggradation typical of streams in semiarid landscapes with cohesive fine-grained banks. Light brown fill is old alluvium, medium brown fill is bedrock, and dark brown fill is new alluvium. Water table is demarcated with a blue line. The stages are: a) the channel prior to incision; b) rapid downcutting (to a hard surface such as bedrock) occurs within a period of a few years, usually as a result of a land use change such as channel straightening or increased discharge; c) over decades, the incised channel slowly erodes its banks and forms an inset floodplain, with little aggradation occurring and the water table remaining near the bedrock; d) as the channel increases in planform complexity and structural roughness, elements such as large wood and beaver dams enter the system, aggradation begins and the water table slowly rises, increasing groundwater recharge and hyporheic exchange, and riparian vegetation covers the inset floodplain; e) aggradation continues until riparian species can reoccupy the former floodplain; and f) aggradation may continue to preincision conditions, but often remains at stage d or e such that there are one or more inset terraces. (Reprinted with permission from Pollock et al. 2007, copyright Wiley & Sons, Ltd.)

incision trenches that would last long enough to trap sediment and cause aggradation of the bed such that the stream could reconnect to former floodplains?

The dramatic changes in physical habitat and channel reconfiguration that beaver can produce are precisely the sorts of changes many attempt to mimic in much more costly restoration interventions with the use of heavy equipment, engineered restoration designs, imported building materials, and an extensive permitting process. Since beaver are a free source of labor and the structures they build are exempt from costly permit requirements, if they can achieve the same as or better than outcomes of human-based stream restoration efforts, the economic implications are significant (McKinstry et al. 2001). The primary means by which we are “working” with beaver is to help them build stable dams with the use of inexpensive, biodegradable structural support (i.e., wood fence posts) that can be installed cheaply with logistically simple procedures (i.e., using portable hydraulic post drivers). This study seeks to address the general hypothesis that, by working with beaver to create stable colonies and aggrade incised reaches of Bridge Creek, there will be measurable improvements in riparian and stream habitat conditions and the abundance of native steelhead.

This report presents the restoration design rationale and hypotheses of a long-term restoration and monitoring program designed to test those hypotheses. We start by providing some background related to observations of natural beaver dams in Bridge Creek. We then cover the methods employed in developing the restoration design and implementing the restoration treatment.

Background

Observations of Natural Beaver Dams in Bridge Creek

From 1988 to 2004, the U.S. Bureau of Land Management surveyed the lower 32 km of Bridge Creek 1–2 times per year for the presence of beaver dams (Demmer and Beschta 2008). These data provide information on the longevity of beaver dams and the locations where beaver colonies persist. Our analysis of the Bureau of Land Management survey data used by Demmer and Beschta (2008) indicated that most of the dams were extremely short-lived, with many lasting less than a year. Field observations suggest the majority were breached during annual spring floods or by flash floods that sometimes occur in the summer.

Using Demmer and Beschta (2008) data and a digital elevation model from the 2005 aerial Light Detection and Ranging (LIDAR) survey by Washington State University's Watershed Sciences Department (http://www.opentopography.org), we qualitatively examined the spatial patterns of beaver dams to determine whether there was a relationship between beaver dam persistence and near stream geomorphology. We found that beaver dams failed and were subsequently abandoned under a wide range of geomorphic conditions, but most of the dams that failed and were not repaired were built in reaches with relatively narrow incision trenches. These reaches were characterized by a lack of active floodplain or inset floodplain and hydraulic geometry in which channel width hardly expanded with increasing discharge and stage. In contrast, the small number of dams that persisted for more than a year were usually located in reaches where there was an adjacent stream terrace 50 m or wider and low enough in elevation (usually within a meter of the streambed) that it could be flooded by a typical beaver dam as well as by spring floods.

The highest rates of dam persistence were found within a 1.5 km reach of Bridge Creek bordering the Painted Hills National Monument and about 12 km upstream from the mouth (Demmer and Beschta 2008). Within this area is a small population of 1–4 beaver colonies that has persisted more or less continuously since about 1990 (Demmer and Beschta 2008). Much of this reach contains a 50–80 m wide floodplain inset within a broader incision trench. Many of these dams are backfilled with sediment and have been colonized by riparian and wetland vegetation, such that they look more like large, stream-adjacent wetlands rather than an open pool. Within these wetlands, beaver maintain multiple channels such that they can access the vegetation, which they then utilize as food and building material for their dams and lodges. These multiple channels also disperse flow, which likely helps to reduce the frequency or severity of dam breaching. In many reaches, the entire width of the inset terraces are flooded or have saturated soils. Where these dam complexes exist, the riparian and wetland vegetation has greatly expanded relative to the rest of Bridge Creek. Although in any given year individual beaver dams within a complex may be abandoned and new dams constructed, it appears that throughout this area, beaver have built a series of stable, self-sustaining ecosystems that provide them with the necessary food and shelter for stable colonies to persist.

Outside of the Painted Hills National Monument, few colonies persist for more than 2 years and most dams are maintained for less than 1 year (Demmer and Beschta 2008). The contrast in longevity between the stable colonies within the Painted Hills National Monument and the short-lived colonies elsewhere along Bridge Creek is striking, particularly since many of the ephemeral colonies were built on the main stem above two major tributaries, where flows are much lower. Since young beaver (kits) are born in the spring and typically disperse 2 years later, a breeding pair that establishes a colony in the fall must persist for at least 2.5 years to successfully produce offspring that may expand the zone of influence of beaver. This suggests that for the existing beaver population to expand, dam and colony longevity must be increased.

Mechanisms of Beaver Dam Breaching in Incision Trenches

Demmer and Beschta (2008) categorized the mechanisms of beaver dam breaching in Bridge Creek for a period of 17 years, which is particularly helpful in understanding why beaver colonies fail to persist. They reported that of 161 beaver dams observed from 1988–1993 along 25.4 km of lower Bridge Creek, 30% washed away completely, 32% breached in the center, and on 38%, flows eroded the bank on one end of the dam. Another 9% remained for a few years, with the dam backfilling with sediment, then a new channel forming by cutting through the dam, washing it out, or cutting around the edge of the dam. The remaining 3% either partially breached (1%) or the dam was inundated by another dam further downstream (2%).

The Demmer and Beschta (2008) analysis of dam breaching mechanisms and our own observations of beaver dams in Bridge Creek during high flows suggest that breached dams were often built in an incision trench where high flows had limited access to a potential floodplain or terrace. Further, in some instances, it appears that the concentrated flows over dams in the incision trench also caused scouring below dams and undermined them, causing collapse. Some breached dams had a section missing, almost always near the deepest point of the dam, suggesting that dam breaching is often related to excessive hydrostatic pressure on the upstream dam face. In reaches where the incision trench has substantially widened, observations indicate that high flows spread out onto an adjacent floodplain or terrace surface and pressure against the dam face is alleviated. Unfortunately in much of Bridge Creek, high flows are confined within a narrow incision trench. Thus the flow depth increases above the height of the dam and pressure increases against the dam face. During such overtopping events, breaching can also result from erosion of the dam top simply because the shear stress is sufficient to entrain some of the woody and nonorganic material that compose the dams. We have observed some dams where a top portion of a section of dam was missing, but there wasn't complete dam breaching, a situation that is explained by erosive processes rather than excessive pressure against the face of the dam. We also observed that when dams breached by endcutting a new channel around a dam and through a bank, the thalweg was often partially or completely filled with sediment just upstream of the dam.

Collectively, these observations and data suggest two sequential events occurred that often resulted in (relatively) stable dams and the persistence of colonies:

1. Beaver constructed dams with a tall, narrow section built within the bankfull channel or incision trench, and a shorter, long section built across a terrace such that high flows dispersed across the entire length of the dam and over a low terrace and were not

concentrated in the incision trench. The total length of such dams were generally much wider (50–80 m) than dams built only within the incision trench (4–7 m).

2. There was subsequent rapid aggradation behind dams. Because Bridge Creek has a high sediment load (35,000–53,000 $m^3 \cdot yr^{-1}$), aggradation can be fairly rapid behind beaver dams, depending on local sediment supplies, with beds rising 40 cm within the bankfull channel during the first year (Figure 3) (Pollock et al. 2007). Frequently, dams completely backfill with sediment such that a new aggraded bed formed, the stream slope lowered, bed substrate composition shifted from cobble to silt (when the pond was aggrading) and then to gravel, and a plunge pool formed below the dam.

Synthesis of Observations

Based on observations of intact and failed dams along Bridge Creek and consideration of the likely mechanisms for dam failures, we can explain the overall lack of persistent beaver colonies throughout much of Bridge Creek. However, the persistent beaver dam colonies and subsequently richer function of the Painted Hills Monument reach gives us an insight into what is possible within Bridge Creek. Collectively, these observations helped to guide us toward a restoration strategy of working with beaver in Bridge Creek to achieve floodplain connectivity and reverse the detrimental effects of stream incision.

We hypothesized that the addition of strategically placed beaver dam support (BDS) structures within incised reaches would facilitate longer lasting dams, which in turn would promote bed aggradation and reconnection of floodplain surfaces and an overall increase in both instream and riparian habitat heterogeneity and habitat quality. “Longer-lasting dams” is taken here to mean long enough to retain structural integrity and functionality for more than a year. Such longer-lived, less transient dams are hypothesized to become building blocks for resilient

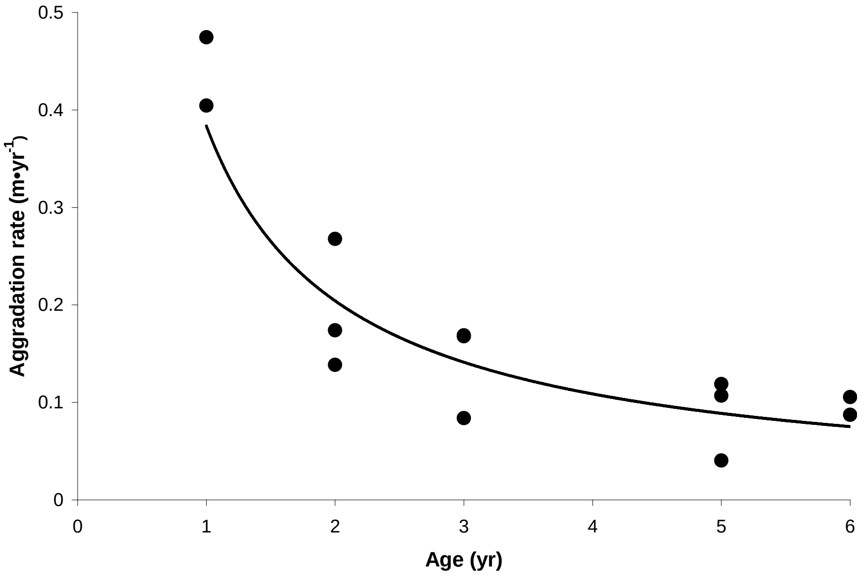


Figure 3. Sediment aggradation rates behind beaver dams in Bridge Creek. (Reprinted with permission from Pollock et al. 2007, copyright Wiley & Sons, Ltd.)

and dynamic beaver dam complexes that support thriving colonies of beaver (e.g., the stream reaches in Painted Hills National Monument).

Although resilience and dynamics may seem at odds with each other, it is worth noting that activity in natural beaver dam complexes ebbs and flows and these are far from static features in the landscape (Naiman et al. 1988, Pastor et al. 1993, Burchsted et al. 2010). Individual dams within a dam complex may be washed out or abandoned, but the importance of individual dams is not as critical as the combination of different dams within a broader dam complex. Individual dams may serve different functional purposes or be at different stages in their trajectories. While overall an active dam complex should have dams that boast longer dam life than those typically found in Bridge Creek, the significance of the failure of an individual dam in a dam complex is much less than that of an isolated beaver dam. The resilience of a dam complex is its ability to maintain a healthy and stable system state (i.e., population) despite disturbances or external forcings. If other suitable locations are available, a colony may also be able to retain resiliency by shifting to a new location and abandoning a dam complex when its functionality decreases (Naiman et al. 1988, Burchsted et al. 2010). This leads to a dynamic, shifting habitat mosaic in time and space (Tockner and Stanford 2002), which we hypothesize in turn promotes habitat complexity and resilience for beaver and species such as steelhead that benefit from the beaver dam complexes.

Although reintroduction or relocation of beaver has been proposed to achieve ecosystem restoration goals (e.g., see Albert and Trimble 2000, McKinstry et al. 2001, McKinstry and Anderson 2002), we are not aware of any other studies that have actively assisted beaver in the construction of dams. Similarly, we know of no proven techniques for employing this restoration strategy. Thus in 2008 we conducted a pilot study to assess the viability of strengthening existing beaver dams or creating structures that would later be utilized by beaver to build stable dams. The pilot study also allowed us to experiment with some techniques to better understand what kind of structural support would lead to the construction of stable beaver dams and to help refine our techniques. The results of that study were used as the basis for development of the methodology for the placement and installation of BDS structures as described in the Methods section below. Although there is potential to promote a more rapid response by augmenting the beaver population with beaver relocated to Bridge Creek from other watersheds, this is not currently part of the restoration design or experiment.

By providing some short term (<10 yr) structural complexity in a stream system generally lacking structure, we hypothesize that we will set in motion natural processes by which the stream restores its natural dynamics. This is the expected outcome of the project. Beaver dams will facilitate fluvial geomorphic changes that include sediment retention, streambed aggradation, increased stream sinuosity, pool formation, increased stream length, reduced stream slope, reduced bed shear stress, and a shift in the bed composition from cobble toward gravel (Pollock et al. 2007, Demmer and Beschta 2008). Beaver dams should also raise water tables in the alluvial aquifer and thus help to greatly expand the amount of riparian forest and reduce stream temperatures (Lowry 1993, Westbrook et al. 2006, Pollock et al. 2007). Previous research has shown that these are reasonable outcomes to expect from the presence of stable beaver dams, particularly in streams with high sediment loads (Scheffer 1938, Pollock et al. 2003, McCullough et al. 2005, Westbrook et al. 2010).

Site Description

This restoration and monitoring project is being conducted in Bridge Creek, Oregon, (lat 44.6492°N, long 120.2455°W). Bridge Creek is a 710 km^2 watershed draining northwesterly into the lower John Day River. Elevation ranges from 500 m at the mouth to 780 m at the upper end of our study site to 2,078 m at Mt. Pisgah, the highest point in the watershed. The basin is dominated by sagebrush (*Artemisia* spp.) steppe and juniper (*Juniperus occidentalis*) steppe in the lower elevations, with the vegetation changing progressively with increasing elevation to forests dominated by ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea englemannii*). The main stem of Bridge Creek is in a semiarid landscape with 7.4 cm average cumulative summer rainfall (June-September) and average daily maximum and minimum summer temperatures of 26.9°C and 8.7°C, respectively. Average annual cumulative precipitation in Bridge Creek at 800 m elevation is 28.7 cm with an additional 46.2 cm of snow occurring in the fall, winter, and spring months. Average daily maximum and minimum winter (November-April) temperatures are 9.6°C and –1.9°C, respectively. Temperature and precipitation data were obtained from National Climate Data Center station 355638 (online at http://www.ncdc.noaa.gov/oa/ncdc.html).

Most of the main stem and lower tributary reaches of Bridge Creek are incised, thus the riparian vegetation is generally limited to a very narrow band along the stream. Riparian vegetation in this portion of the river is dominated by willows (*Salix* spp.), primarily coyote willow (*S. exigua*) and to a lesser extent onecolor willow (*S. monochroma*), Pacific willow (*S. lasiandra*), MacKenzie's willow (*S. prolixa*), and peach-leaf willow (*S. amygdaloides*). Black cottonwood (*Populus trichocarpa*) is present in small quantities in some areas, as are a variety of shrubs and emergent vegetation. The geology of Bridge Creek is dominated by thick layers of basalt and andesite that originated from numerous lava flows during the Eocene and Oligocene epochs. There are also substantial areas of highly erosive volcanic ash known as the John Day Formation that originated from a series of volcanic eruptions in the Miocene epoch. The surface geology along our study site is generally cohesive, fine-grained quaternary alluvium, much of which is derived from the ashes of the John Day Formation. Lenses of alluvial gravels and cobble are also present in some exposed banks. Active lateral erosion into these coarser deposits is an important source of coarse sediment for the construction of active bars, which provide critical spawning habitat for steelhead. Some reaches contain occasional bedrock outcrops that help limit the depth of incision.

Soils on the site are diverse and range in field texture from silty clay loam near the present stream to coarse loamy sand on the lower terraces. Soil bulk density values range 1.4–1.5 $g \cdot cm^{-3}$ while porosities range 52–57% (Lowry 1993). Edaphic variability appears to be related to several factors, including relative height and distance of the soils profile from the stream, hillslope erosion rates, and sediment transport processes (Lowry 1993). Sediment loads within Bridge Creek are high, due to the erosive nature of the John Day Formation, the sparse vegetation, and the high intensity, short duration rainfall events that are common to the region in the summer months.

Methods

This report summarizes the implementation of the first phase of the restoration treatment, and as such, the restoration design and implementation are the focus of our methodological description here. We also review the site selection elements of that design and review what pretreatment monitoring took place to document baseline conditions. The focus of the broader intensively monitored watershed effort and restoration experiment in Bridge Creek is to help beaver build stable dams for the purposes of creating habitat that will benefit the steelhead population. Specific design hypotheses help articulate the details of those designs. These hypotheses were formulated across a range of nested spatiotemporal scales and their testing provides the basis for the ongoing monitoring campaign.

Site Selection

We used an aerial LIDAR (light detection and ranging) and color photography survey from Utah State University's Watershed Sciences Department (2005, online at http://www.OpenTopography.org) combined with field surveys to identify 4 pairs of geomorphically similar reaches within the lower 32 km of the main stem of Bridge Creek. For each pair we assigned one reach as a control, where the stream would be left unrestored (and may recover naturally or remain in a degraded state), and the other as a treatment, where active restoration would occur (Figure 1). We also identified two reaches within the Painted Hills National Monument where beaver are abundant and have been active there at least since 1988 (Demmer and Beschta 2008), and used them as positive control sites. We also selected two sites on two tributaries to Bridge Creek (Bear and Gable creeks) to use as additional control sites within the watershed that were outside the main stem, primarily for the purpose of monitoring steelhead populations. Site selection within the Bridge Creek drainage was generally limited to public lands and where other constraints, such as current land use activities or archaeological sites, did not preclude a restoration treatment. Because the overall goal is to cause a detectable population level increase in the steelhead that utilize this system, we also selected another tributary to the John Day (Murderers Creek) as a control watershed outside the Bridge Creek main stem where we could monitor steelhead populations to compare population trends of steelhead to changes in the population of Bridge Creek as a whole (Figure 1) (NMFS and NWFSC 2008).

Pretreatment Monitoring

For several years before and now continuing during the restoration treatment, numerous biological and physical parameters have been measured within the treatment and control sites for the purpose of detecting physical and biological changes resulting from our restoration treatment. These are listed in Table 1 and described in more detail in NMFS and NWFSC (2008).

Table 1. The restoration project seeks to create change at three spatial scales: watershed, reach, and individual structures, with expected differences in the response time needed to detect change.

Treatment site	Control site	Temporal scale of detection	Hypothesis for treatment areas	Data collection
Watershed level				
Bridge Creek, lower 32 km	Murderers Creek	5–10 yr	Cumulative restoration actions will result in a measurable population level change in the steelhead that use this system.	Juvenile outmigration, spawner counts, redd counts on Bridge and Murderers creeks
			Base flow discharge will increase.	Gage stations at Bridge and Murderers creeks
			Beaver population will increase.	Dam, pond, and lodge census
Site level				
Sunflower, Pat's Cabin, Meyer's, Lower Owens	Corral, Boundary, Woodward, Upper Owens	1–10 yr	Floodplain connectivity will increase through the process of aggradation.	Topographic and aerial surveys of channel and stream adjacent terrace morphology
			Riparian vegetation will increase.	Aerial surveys (remote drone and fixed wing)
			Sinuosity will increase.	Aerial surveys
			Stream gradient will decrease.	Topographic and aerial surveys of channel and stream adjacent terrace morphology
			Pool frequency will increase.	Habitat surveys
			Pool depth will increase.	Habitat surveys
			Substrate will shift from cobble towards gravel.	Habitat surveys
			Stream temperatures will decrease.	Stream temperature loggers
			Number of multichannel reaches will increase.	Topographic and aerial surveys of channel and stream adjacent terrace morphology
			Conversion from plane-bed to pool-riffle morphology.	Habitat surveys
			Juvenile fish density will increase.	Juvenile mark-recapture surveys 3 times/yr
			Juvenile fish growth rate will increase.	Juvenile mark-recapture surveys 3 times/yr
			Juvenile fish size/fitness will increase.	Juvenile mark-recapture surveys 3 times/yr
			Groundwater levels will increase (only being monitored and tested in Lower and Upper Owens).	Water level logger well fields
			Beaver colony density will increase.	BDS structure survey/beaver dam census

Table 1 continued. The restoration project seeks to create change at three spatial scales: watershed, reach, and individual structures, with expected differences in the response time needed to detect change.

Treatment site	**Control site**	**Temporal scale of detection**	**Hypothesis for treatment areas**	**Data collection**
Structure level				
Sunflower, Pat's Cabin, Meyer's, Lower Owens	Corral, Boundary, Woodward, Upper Owens	1–3 yr	Beaver will build dams on bare post lines.	BDS structure survey/beaver dam census
			Reinforced existing dams will last longer than those that are unreinforced.	BDS structure survey
			Reinforced abandoned dams will last longer than those that are unreinforced.	BDS structure survey
			Post lines with willow weaves and starter dams will behave similarly to beaver dams as described below.	BDS structure survey
			Reinforced beaver dams will have certain hydrogeomorphic effects:	BDS structure survey
			1. A backwater pool will form upstream.	BDS structure survey
			2. A scour pool will form downstream.	BDS structure survey
			3. A transverse bar will form downstream of the scour pool.	BDS structure survey
			4. Stream-adjacent terraces will flood more frequently.	BDS structure survey
			5. A multichannel planform will develop.	BDS structure survey
			6. Aggradation will occur upstream of the structure, eventually filling in the upstream pool.	BDS structure survey
			7. Beaver will utilize starter dams to establish new colonies.	BDS structure survey/beaver dam census
			8. Fish densities in backwater pools will be higher than reaches without such pools.	Juvenile mark-recapture surveys in winter
			9. Transverse bars will become sites of steelhead spawning.	Redd surveys

Defining Hypotheses at Multiple Scales

This study seeks to test hypotheses regarding the effects of restoration at three nested spatial scales:

1. The scale of the individual structure within a reach that receives a restoration treatment,
2. The scale of the entire reach that is treated, and
3. The scale of the Bridge Creek watershed, that is, the cumulative effects of treating multiple reaches.

The hypothesis for each of these scales and the data being collected to test these hypotheses is provided in detail in Table 1 and described below.

We are making comparisons between treatment and controls before and after the implementation of the restoration actions as a means to increase the power to detect changes in the physical habitat and steelhead responses. These before-after-control-impact (BACI) designs have been employed in areas where spatial replication is low or not possible to best detect environmental impacts (Steward-Oaten and Bence 2001). How long after the treatment monitoring will occur depends on the process being tested. For example, biological responses like utilization and occupation can be tested within the first year, whereas a population-level response will take multiple generations to test. We implemented BACI-like designs in a nested hierarchy to compare restored and unrestored areas at the watershed, subwatershed, and reach scales. At the watershed scale, Bridge Creek is being compared to nearby Murderers Creek, where ongoing intensive monitoring of steelhead populations and physical habitat conditions is already occurring. Within the main stem of Bridge Creek, comparisons are being made between control and manipulated reaches, separated by enough distance to minimize movement between reaches by steelhead parr. The hierarchical design helps identify the scale of influence of the restoration actions (which may differ between physical habitat and steelhead responses) and the appropriate scale at which restoration efforts of this type should be monitored (Underwood 1994). Preproject data have been collected in Bridge Creek since 2005. Postproject monitoring is expected to last approximately 10–20 years; however, large changes in responses should occur earlier than this and may highlight reasons to adapt the intensive monitoring.

Hypotheses at the Watershed Scale

At the scale of the entire Bridge Creek watershed, we are primarily interested in testing the overarching hypothesis that we can concentrate enough restoration activity within a single watershed such that there is a measurable population-level change in the steelhead that utilize the system (Table 1). To test this hypothesis, we have been monitoring returning steelhead populations at Bridge Creek and Murderers Creek, a similarly sized stream in the John Day River basin where no restoration is occurring (Figure 1). Over the long-term (10+ years), if the restoration treatments in Bridge Creek have a cumulative effect on the steelhead population, we hypothesize that a change in population characteristics should be observable, relative to the population characteristics of the Murderers Creek population (Table 1). Since the main restoration treatment we are employing is assisting beaver to improve instream and riparian habitat for steelhead, a corollary prediction at the scale of the Bridge Creek watershed is that we should see a general increase in the beaver population in Bridge Creek. Finally, at the watershed scale we hypothesize that beaver dams will elevate water tables and increase groundwater-surface water exchange. Thus if there is sufficient long-term storage of water in alluvial aquifers, summer baseflows may also increase (Table 1).

Hypotheses at the Reach Scale

At the reach scale, the general restoration objective is to aggrade entire incised sections (0.5–1 km long) of Bridge Creek such that the channel is reconnected to former floodplains and all the attendant benefits of increased channel complexity and floodplain reconnection are realized (Table 1). The BDS structures in a reach are designed to work in concert with each other (much like multiple dams in a natural beaver dam complex) to cause net aggradation of bed elevations and increase habitat complexity by promoting the establishment of more stable beaver colonies and associated dam complexes. Although the net predicted response is aggradation, both local erosion and deposition are necessary processes to build dynamic functioning fluvial habitats with the sort of habitat complexity we seek for steelhead. For example, erosion of banks may be critical for providing a coarse-grained sediment supply locally to build bars that provide good spawning habitat. Similarly, building bars in areas of divergent flow can be helpful in forcing zones of convergent flow nearby that promote scour and the subsequent construction or maintenance of pool habitat (MacWilliams et al. 2006).

At the reach scale, we predict numerous changes in physical and biological parameters in the restored reaches relative to the control reaches, as enumerated in Table 1. Generally speaking, we expect to see improvements in steelhead population parameters in the restored reaches, such as growth, abundance, and fitness. Physical parameters where we expect to see detectable change are listed in Table 1. Examples of physical changes we expect to see include increased aggradation resulting in increased planform and bedform complexity (i.e., higher sinuosity, more pools, increased sediment sorting, multiple channels), more floodplain access, raised water tables, decreases in stream temperatures, an expansion of the riparian forest, and an increase in the number of beaver dams.

We hypothesize that ultimately these physical changes will result in several positive feedback loops that will yield improved habitat conditions for beaver that in turn will lead to the construction of more beaver dams, which will continue to improve habitat conditions and make it more suitable for the establishment of stable beaver colonies, as illustrated in Figure 4. This figure also illustrates the habitat improvements resulting from beaver dam construction that will benefit steelhead and other salmonids (e.g., Chinook salmon [*Oncorhynchus tshawytscha*]). Such benefits include lower water temperatures, increased baseflows, greater diversity of substrate sizes, and more pool habitat.

The four treatment reaches range in length from 0.5 to 1.0 km. Baseline monitoring of Bridge Creek suggests potential colony densities of 2 to 4 km^{-1}, with colonies generally occupying dam complexes comprised of three to eight individual dams. As such, the individual structures placed in these reaches were typically placed in sequences of five to eight structures, designed to mimic the functionality of a dam complex that might be occupied and maintained by one colony and to provide additional sites in the event of dam breaching. Given the currently low densities of beaver populations in Bridge Creek and the fact that beaver kits remain with their parents for 2 years, any population response may take multiple generations to be detected as

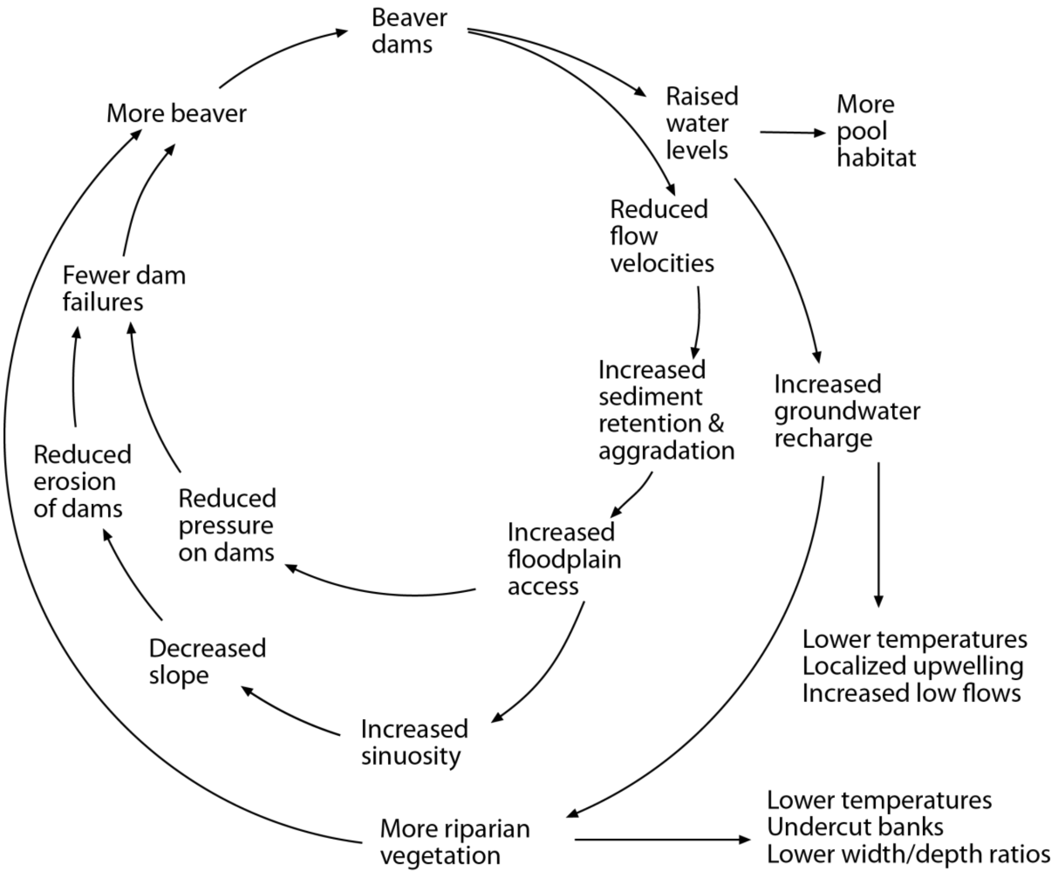
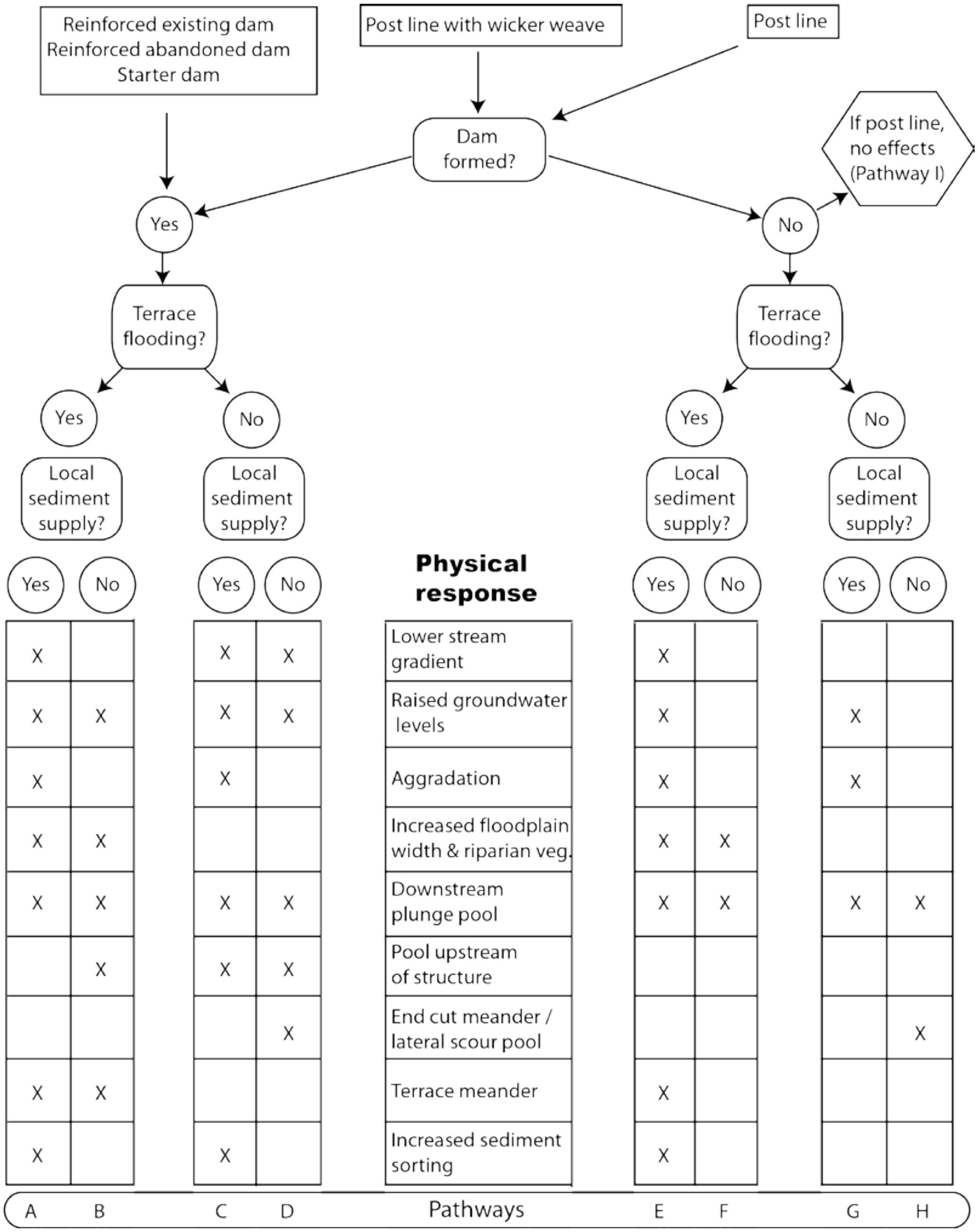


Figure 4. Conceptual diagram of the hypothesized positive physical feedback loops for beaver and steelhead from the presence of beaver dams. The key barrier to this feedback loop in Bridge Creek is that individual dams do not persist long enough to realize or maintain the hypothesized benefits.

a response (i.e., at least 4 years). Initially, we might expect a redistribution of the existing beaver population from more marginal dam sites into the zones where sequences of BDS structures were installed and they may be able to establish dam complexes that can eventually (i.e., 2–3 generations of kits later) support a stable colony.

Hypotheses at the Scale of Individual Structures

At the scale of individual structures, predicted response depends on the type of structure installed. Five types of BDS structures were installed to test the response of beaver and the response of the stream to structures at the scale of the individual structure and the treatment area: starter dams (SD), post lines (PL), post lines with wicker weaves (PLWW), reinforced abandoned dams (RAD) and reinforced existing dams (RED). Each treatment reach has similar, broad-level objectives as described above, while each of the structures has specific hydrogeomorphic objectives, or more correctly, competing hypotheses as to how the structure is likely to respond depending on which type of structure was installed and what stochastic processes occur after installation (Figure 5). For example, a RAD or SD may backfill with sediment. The composition of that fill (i.e., fine or coarse sediment) depends on the availability



Physical response	A	B	C	D	E	F	G	H
Lower stream gradient	X		X	X	X			
Raised groundwater levels	X	X	X	X	X		X	
Aggradation	X		X		X		X	
Increased floodplain width & riparian veg.	X	X			X	X		
Downstream plunge pool	X	X	X	X	X	X	X	X
Pool upstream of structure		X	X	X				
End cut meander / lateral scour pool				X				X
Terrace meander	X	X			X			
Increased sediment sorting	X		X		X			

Figure 5. A BDS structure can follow multiple pathways (A through I), depending on the type of structure and the natural processes acting on it. Thus the predicted hydrogeomorphic changes created by a structure largely depend on the timing, sequence, and magnitude of natural processes such as beaver dam construction, debris transport, bank failures, and floods.

of sediment sources (e.g., coarse gravels in Bridge Creek often sourced locally from bank failure of coarse-grained alluvial deposits). Likewise, for a PLWW, the hydrogeomorphic response of the stream to the structure will largely depend on whether or not it is colonized by beaver. The structures are designed to follow multiple pathways, with multiple possible outcomes, depending on the stochastic events acting upon them. Thus the structure-specific objectives can best be thought of as a series of if-then pathways in a flow chart (Figure 5). Defining objectives for the individual structures helps to identify what type of structure is most suitable or effective for a given location and whether we can accurately predict the local hydrogeomorphic response of the stream to a structure. However, the structure-specific objectives are of secondary importance to the objectives of the reach-scale treatment and the entire project (Table 1).

It is important to emphasize that although every structure had a specific design for how it was supposed to function in the event of beaver colonization, all of the structures were placed with consideration for what might happen in the event that beaver did not utilize the structure. Given the limited beaver population currently in Bridge Creek, part of the restoration design was to provide an oversupply of potential stable dam complex sites for beaver to expand into. We fully expected that many of the individual structures would not be utilized and the overall distribution of beaver habitat to be underseeded. SDs, PLWWs and REDs were all designed to promote aggradation whether or not beaver actively colonized or maintained them. We hypothesize that the longevity of those deposits will be positively correlated with active beaver maintenance.

By contrast, PLs that are not colonized by beaver may promote collection of mobile woody debris and other material, which could lead to localized deposition and scour and even the potential washing out of part or all of the PL structure. Although such a response was not our primary design objective, it is a perfectly acceptable backup plan, as this may increase the channel complexity locally, which should be an improvement in terms of steelhead habitat. The worst case scenario is that such structures will simply wash away, providing no real benefit, but no harm either.

Structure Design and Installation Details

Structure Siting

At the reach scale, structures were placed at a frequency to capitalize on all opportunities to promote aggradation and floodplain reconnection throughout the treatment area. In many instances, secondary structures placed a short distance downstream from a primary structure were used to avoid steep gradient drops within the treatment area that could potentially result in excessive scour and limit the likelihood of headcutting and undermining of structures upstream. Additionally, the presence of multiple structures in series provides capacity for a colony to build a multiple dam complex. This is a typical strategy that beaver employ, which seems to provide additional resiliency in that the significance of any single dam failure is less important when an intact dam is in close proximity. This is important because beaver need a stable colony to consistently produce offspring. However, the dynamics of individual dam failure and evolution should not be confused with necessarily promoting an “unstable colony” or “unstable dam complex.” It takes 2 years to produce offspring, and if colonies fail in less than 2 years, it limits the likelihood of colony persistence and population expansion. In Bridge Creek, individual dam failure is so common (Demmer and Beschta 2008) that establishment of larger dam complexes and stable colonies is currently rare.

Further, beaver colonies cycle through individual dams within a complex and the boundaries of the colony are not static. Beaver may move their primary dam and lodge in response to environmental conditions, such as dam breaching or pool filling, exhaustion of building or food supplies, etc. (Morgan 1986, Naiman et al. 1988). Beaver colonies frequently move the focus of their activity within an area or a complex, thus the frequency of maintenance of any particular dam changes over time and dam sites may be temporarily abandoned, only to be repaired later when conditions such as the regrowth of willow make the site desirable again.

Where the stream is incised, structural support that lengthens the life of dams can expand food supplies for beaver insofar as it may continue to flood terraces and floodplain surfaces or raise groundwater levels such that willow can become established and grow. In older beaver dams, trees often grow out of the dams themselves. In incised settings without the structural support (artificial or natural), such dams are breached and eroded away quickly during regular high flow. The breaching of the dam brings a corresponding drop in water levels, an isolation of the terrace from the stream, and a drop in the abundance of riparian vegetation such as willows (i.e., a negative feedback loop).

Within a reach, the location of a given type of BDS structure was determined by site-specific conditions. The consideration for the siting of individual structures is elaborated below. The type and intended functions of each structure are provided in Table 2 (Lower Owens, Meyer’s Camp, Pat’s Cabin, and Sunflower). The locations of each structure are shown for Lower Owens in Figure 6, Meyer’s Camp in Figure 7, Pat’s Cabin in Figure 8, and Sunflower in Figure 9. For additional maps, see Appendix A. Below we elaborate on the different BDS structure types and their design rationale.

Starter dams

SDs (Figure 10) had the most criteria for siting. Generally, they were placed in locations where:

1. The water elevation upstream of the dam could be raised to the level of a terrace, so that flow would be dispersed across the terrace and it would be less likely that the structural integrity of the dam would be compromised.
2. The incision in the surrounding area was generally less than 1–1.5 m so that additional dams built were more likely to be stable.
3. The backwater from the pond would provide access to soft banks upstream of the dam, which would act as suitable locations for bank lodges.
4. There was adequate access to existing food and building supplies (e.g., existing wood and riparian vegetation).
5. There was no existing beaver colony nearby (i.e., within 300 m).

Table 2. Description of BDS structure types installed in four reaches of Bridge Creek in September 2009: Lower Owens, Meyer's Camp, Pat's Cabin, and Sunflower. Locations of each structure are provided in Figure 6 through Figure 9. PL = post line, PLWW = post line with wicker weave, SD = starter dam, RED = reinforced existing dam, and RAD = reinforced abandoned dam.

BDS no. by reach	BDS no. total	Year installed	Structure type	Totals	
Lower Owens					
LO-01	1	2009	PL	PL	6
LO-02	2	2009	RAD	RAD	3
LO-03	3	2009	RAD	PLWW	17
LO-04	4	2009	PLWW	SD	5
LO-05	5	2009	PLWW	RED	3
LO-06	6	2009	PLWW	Subtotal	34
LO-07	7	2009	SD		
LO-08	8	2009	PL		
LO-09	9	2009	PL		
LO-10	10	2009	PLWW		
LO-11	11	2009	PLWW		
LO-12	12	2009	PLWW		
LO-13	13	2009	SD		
LO-14	14	2009	PLWW		
LO-15	15	2009	SD		
LO-16	16	2009	PLWW		
LO-17	17	2009	PLWW		
LO-18	18	2009	PL		
LO-19	19	2009	PL		
LO-20	20	2009	RED		
LO-21	21	2009	PL		
LO-22	22	2009	RED		
LO-23	23	2009	RED		
LO-24	24	2009	PLWW		
LO-25	25	2009	SD		
LO-26	26	2009	RAD		
LO-27	27	2009	PLWW		
LO-28	28	2009	PLWW		
LO-29	29	2009	PLWW		
LO-30	30	2009	PLWW		
LO-31	31	2009	PLWW		
LO-32A	32	2009	SD		
LO-32B	33	2009	PLWW		
LO-32C	34	2009	PLWW		
Meyer's Camp					
MC-01	35	2009	PL	PL	5
MC-02	36	2009	RED	RAD	0
MC-03	37	2009	RED	PLWW	9
MC-04	38	2009	PL	SD	0
MC-05	39	2009	PLWW	RED	2
MC-06	40	2009	PLWW	Subtotal	16

Table 2 continued. Description of BDS structure types installed in four reaches of Bridge Creek in September 2009: Lower Owens, Meyer's Camp, Pat's Cabin, and Sunflower. Locations of each structure are provided in Figure 6 through Figure 9. PL = post line, PLWW = post line with wicker weave, SD = starter dam, RED = reinforced existing dam, and RAD = reinforced abandoned dam.

BDS no. by reach	BDS no. total	Year installed	Structure type	Totals	
Meyer's Camp (continued)					
MC-07	41	2009	PL		
MC-08	42	2009	PLWW		
MC-09	43	2009	PLWW		
MC-10	44	2009	PLWW		
MC-11	45	2009	PLWW		
MC-12	46	2009	PL		
MC-13	47	2009	PL		
MC-14	48	2009	PLWW		
MC-15	49	2009	PLWW		
MC-16	50	2009	PLWW		
Pat's Cabin					
PC-01	51	2009	SD	PL	5
PC-02	52	2009	PLWW	RAD	1
PC-03	53	2009	PLWW	PLWW	7
PC-04	54	2009	SD	SD	2
PC-05	55	2009	PLWW	RED	0
PC-06	56	2009	PLWW	Subtotal	15
PC-07	57	2009	PLWW		
PC-08	58	2009	PL		
PC-09	59	2008	PL		
PC-10	60	2009	PLWW		
PC-11	61	2009	PL		
PC-12	62	2009	PL		
PC-13	63	2009	PLWW		
PC-14	64	2009	PL		
PC-15	65	2009	RAD		
Sunflower					
SF-01	66	2009	SD	PL	5
SF-02	67	2009	PLWW	RAD	0
SF-03	68	2009	PLWW	PLWW	11
SF-04	69	2009	PLWW	SD	4
SF-05	70	2009	PLWW	RED	0
SF-06	71	2009	PL	Subtotal	20
SF-07	72	2009	SD		
SF-08	73	2009	PLWW		
SF-09	74	2009	PLWW		
SF-10	75	2009	PLWW		
SF-11	76	2009	PL		
SF-12	77	2009	SD		
SF-13	78	2009	PLWW		
SF-14	79	2009	PL		

Table 2 continued. Description of BDS structure types installed in four reaches of Bridge Creek in September 2009: Lower Owens, Meyer's Camp, Pat's Cabin, and Sunflower. Locations of each structure are provided in Figure 6 through Figure 9. PL = post line, PLWW = post line with wicker weave, SD = starter dam, RED = reinforced existing dam, and RAD = reinforced abandoned dam.

BDS no. by reach	**BDS no. total**	**Year installed**	**Structure type**	**Totals**	
Sunflower (continued)					
SF-15	80	2009	PL	PL	21
SF-16	81	2009	PL	RAD	4
SF-17	82	2009	SD	PLWW	44
SF-18	83	2009	PLWW	SD	11
SF-19	84	2009	PLWW	RED	5
SF-20	85	2009	PLWW	Grand total	85

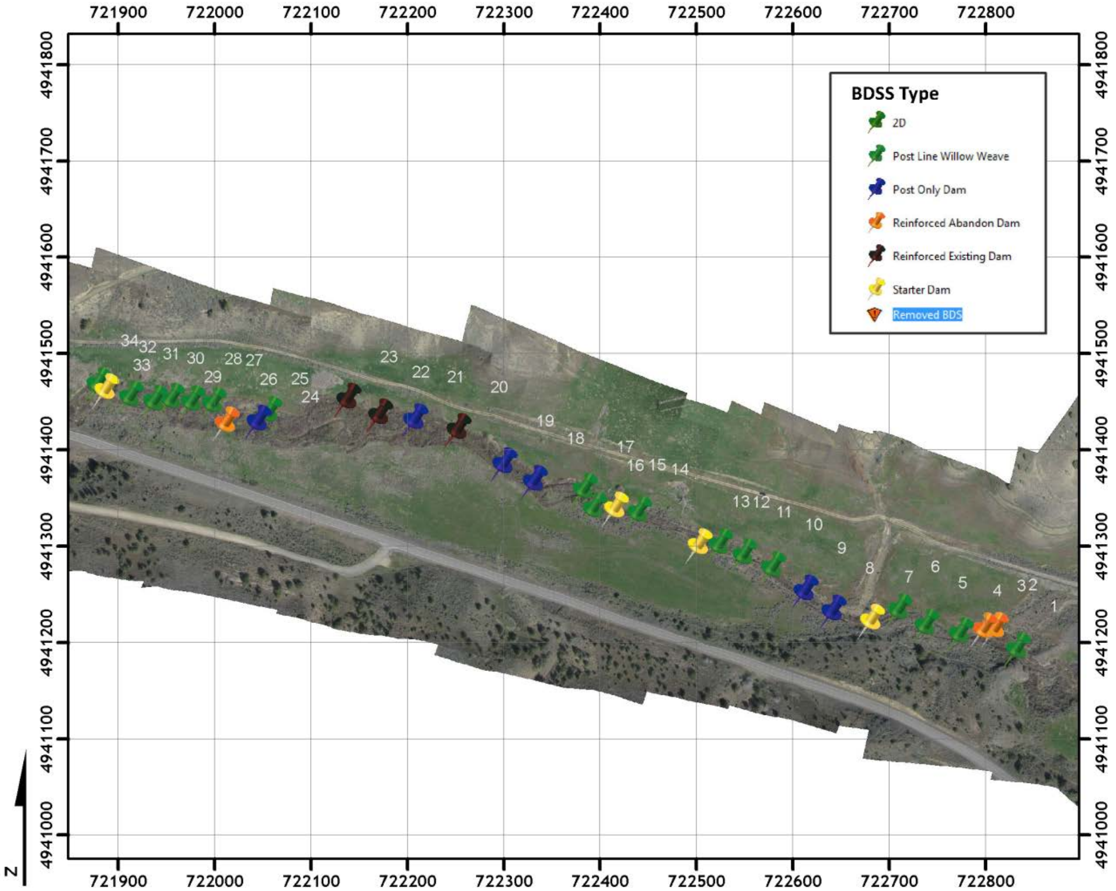


Figure 6. Location of BDS structures installed in 2009 in the Lower Owens reach. Coordinates are UTM system (i.e., each grid cell is 100 m × 100 m).

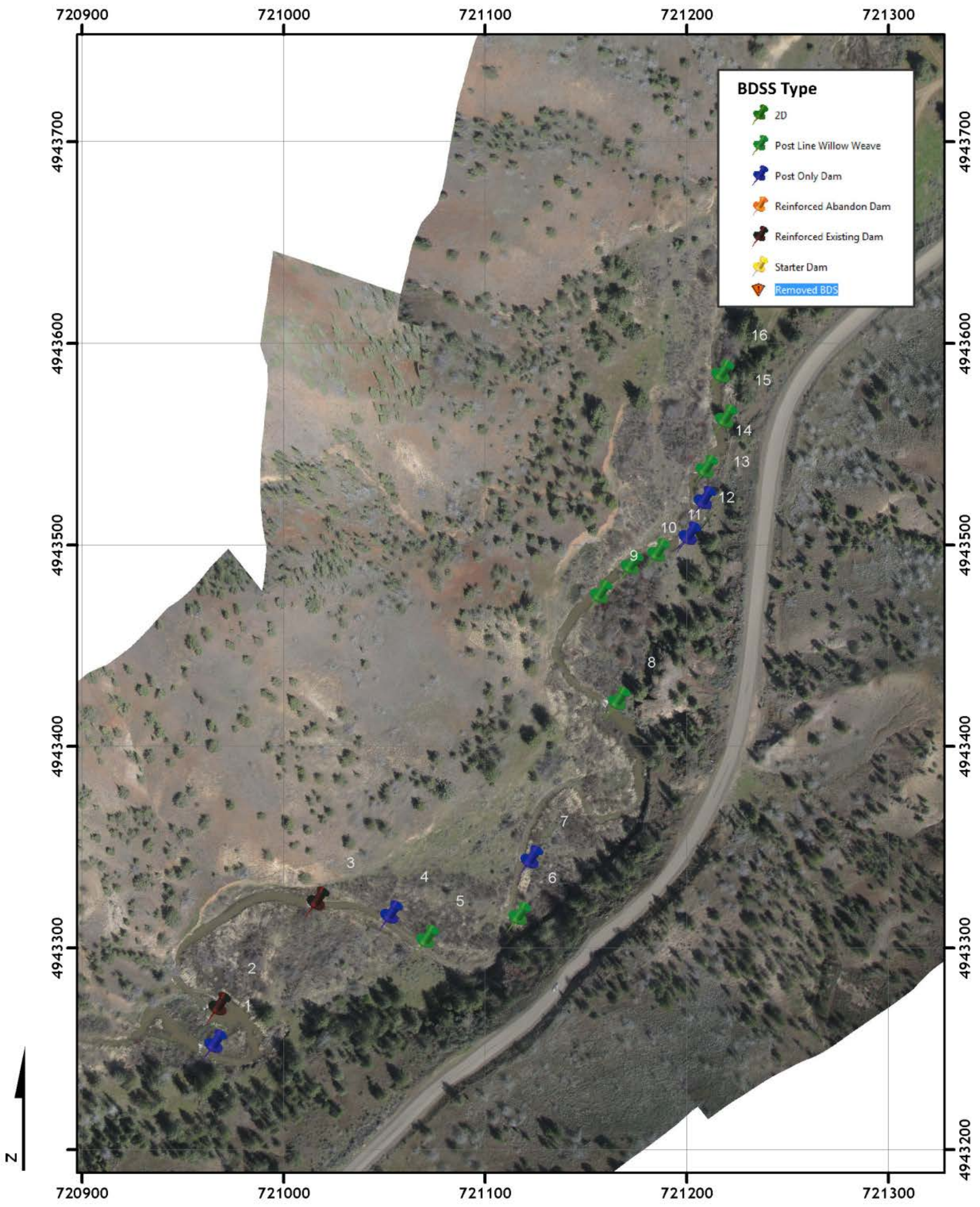


Figure 7. Location of BDS structures installed in 2009 in the Meyer's Camp reach. Coordinates are UTM system (i.e., each grid cell is 100 m × 100 m).

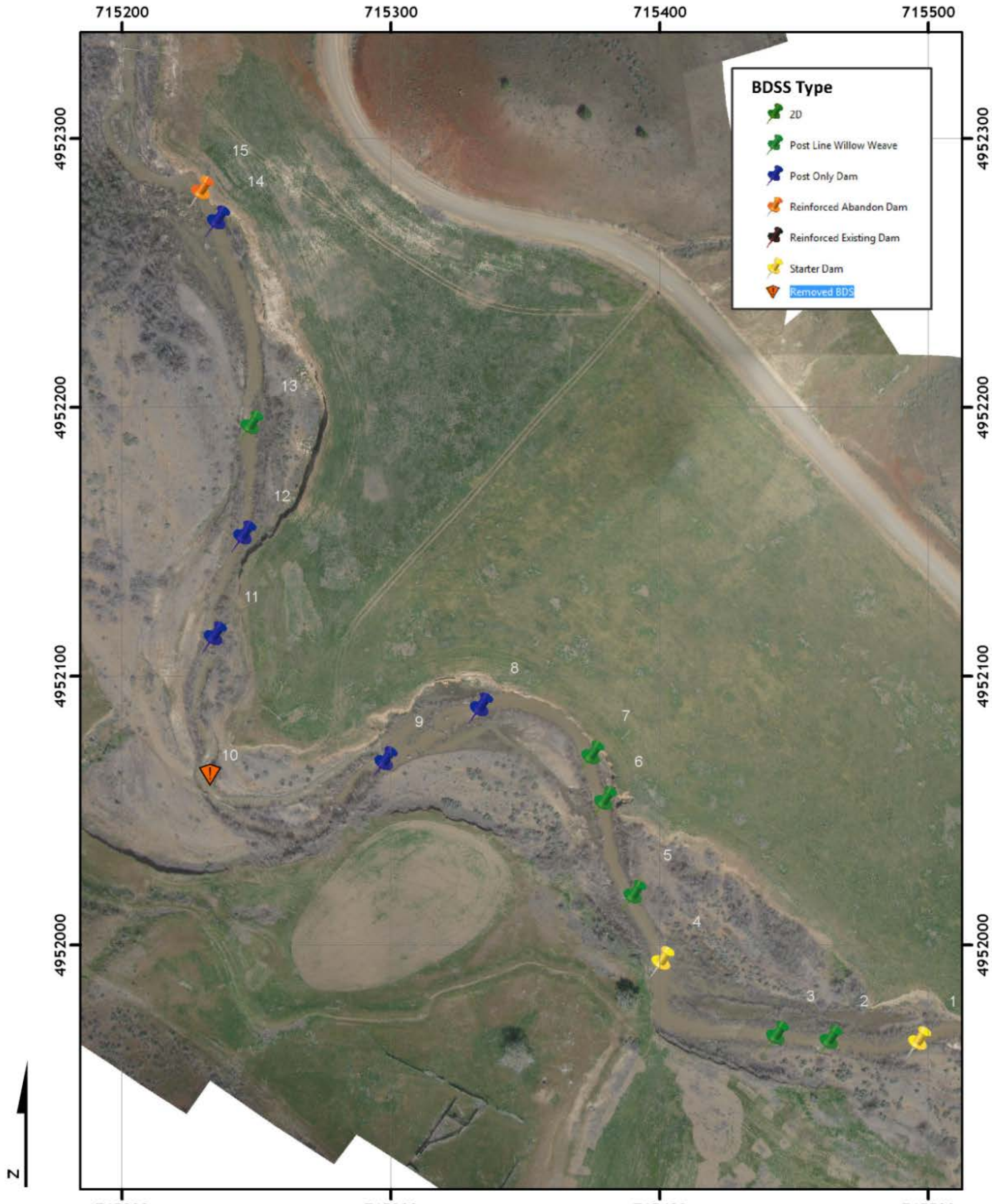


Figure 8. Location of BDS structures installed in 2009 in the Pat's Cabin reach. Coordinates are UTM system (i.e., each grid cell is 100 m × 100 m).

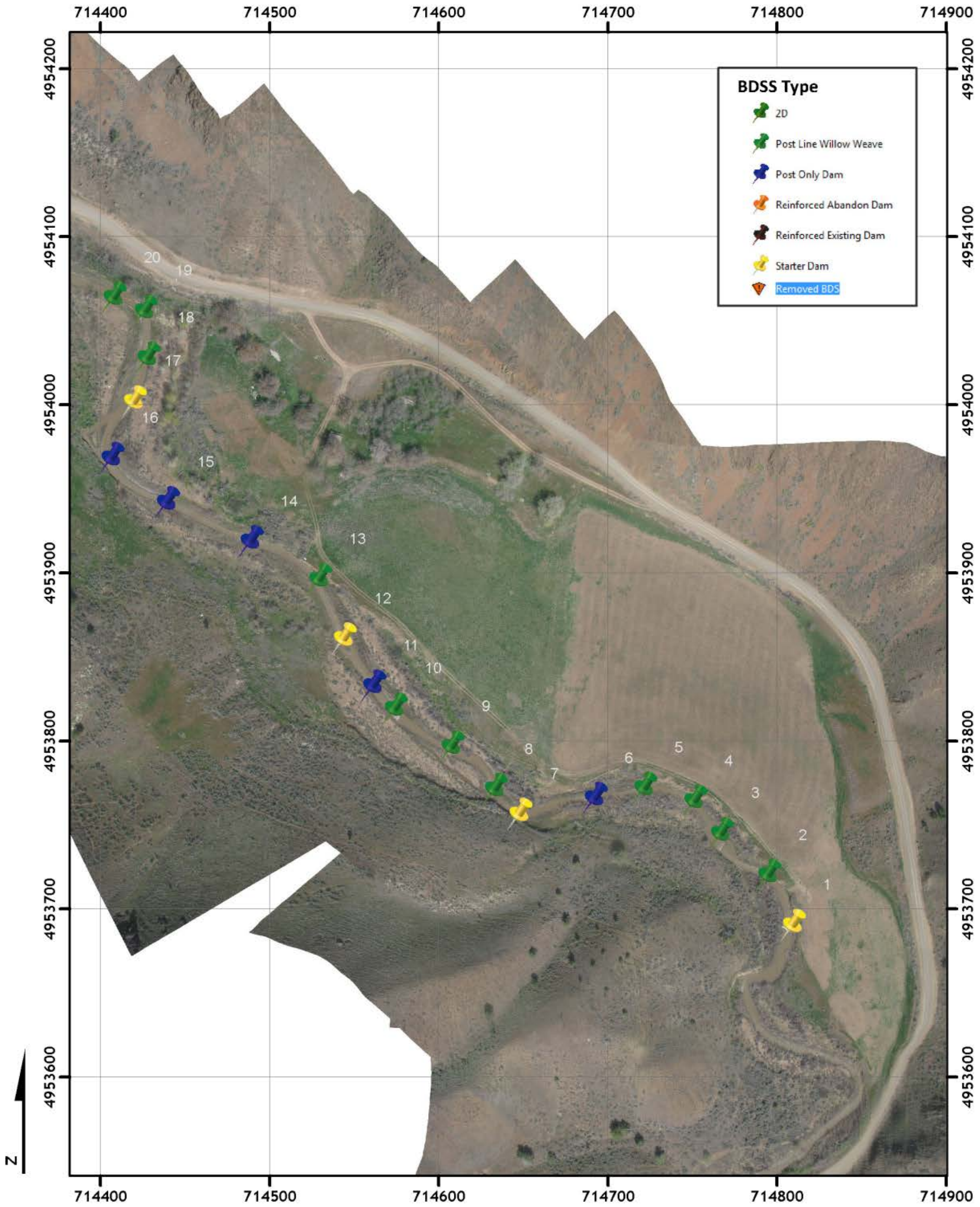


Figure 9. Location of BDS structures installed in 2009 in the Sunflower reach. Coordinates are UTM system (i.e., each grid cell is 100 m × 100 m).

Figure 10. A typical SD (SF-17 at Sunflower) with willow branches woven between vertical posts and the back side sealed with rock and clay. Note that the dam height is sufficient to divert flow onto the river left terrace, mimicking a stable beaver dam.

Post lines with wicker weaves

PLWWs (Figure 11) were the most common type of structure installed and served a variety of purposes. They were always placed where aggradation was not only desirable but also deemed geomorphically plausible to increase channel access to stream adjacent terraces. PLWWs mimic the functional impact of beaver dams in the short term, and were used to invoke a geomorphic response whether or not they were actively colonized and utilized by beaver in the short term. They were also used to promote one or more of the following:

- Increase stream sinuosity,
- Increase the number of pools (from mix of beaver pond upstream of structure, scour pool downstream of structure, and bar forced pools),
- Direct flow away[1] from an eroding cut bank, and
- Provide potential sites for future beaver dam construction (i.e., conversion from single dam to dam complex).

The specific intended purposes of a given PLWW were determined by site-specific geomorphic conditions.

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[1] Note that flows could be usefully directed at banks with good local sediment supplies of coarse alluvium to build bars and fish habitat. However, due to concerns from the Bureau of Land Management, this opportunity was avoided and in some cases actively discouraged as part of the design.

Figure 11. A PLWW is similar to an SD, but acts more like a weir in that water is allowed to flow through the willow branches such that low flows are not overtopping the structure and the woven branches may not extend to the top of the posts. These may naturally seal up by trapping sediment and organic material moving downstream or they may be utilized by beaver. Note that beaver have started to colonize this PLWW, as evidenced by the chewed stems aligned parallel to the flow in the middle of the photograph.

To achieve the broader goal of reversing the impacts of homogenized habitat from channel incision, extensive use of PLWWs was employed to kick-start the recovery. We recognized that the existing population of beaver in Bridge Creek is low and the likelihood of colonization of any one structure is correspondingly low without additional beaver population supplementation. As mentioned earlier, population supplementation is not part of the current restoration treatment. Population supplementation of beaver was originally intended to be part of the restoration plan, but concerns about disease, lack of an adequate food supply, regulations pertaining to the live trapping and release of beaver, and logistical considerations precluded the timely introduction of additional beaver to the treatment areas. Thus the PLWWs roughly simulate some of the functions of beaver dams, and in particular help to cause aggradation of the streambed such that floodplain reconnection should begin to occur throughout the treatment areas. This is particularly useful in areas that are highly entrenched with limited riparian vegetation and where beaver would be unlikely to build a dam even if PLs were installed. Eventually, as the PLWWs allow for floodplain reconnection within much of the treatment area and the existing beaver population expands (either naturally or through supplementation), the need for PLWWs should diminish as they begin to be replaced by actual beaver dams.

Post lines

PLs (Figure 12) were placed in sites where a future beaver dam was desired and where geomorphic conditions were suitable for a dam. In contrast to PLWWs, PLs by themselves were limited to sites where there was minimal risk if no aggradation occurred because beaver did not use them to build a dam. These structures were not intended to be functional unless beaver utilized them to build a dam.

Reinforcement of existing and abandoned dams

All active or intact abandoned beaver dams within the treatment areas were stabilized with posts (Figure 13) to lengthen their functional life, since most dams along the incised Bridge Creek have been shown to last less than a year (Demmer and Beschta 2008). Any abandoned dams with significant structure remaining were reinforced (Figure 14). These were sites where beaver had previously built dams and with additional structure available might do so again.

Structure Installation Overview

The details of how an individual BDS structure was installed depended on the structure type and site-specific conditions. The details of the precise installation of specific structures

Figure 12. The purpose of a PL is to provide a site where beaver can build a stable dam. They generally create little or no geomorphic changes unless utilized by beaver.

Figure 13. Any active dams within the treatment areas were strengthened with posts to lengthen their functional life, since most dams along the incised Bridge Creek have been shown to last less than a year (Demmer and Beschta 2008). This structure was one of four dams built in sequence in Lower Owens to form a new colony. Within 1 year, all four dams had backfilled with sediment, which improved floodplain connectivity and habitat complexity, but made the site unsuitable for beaver. However, because we had installed additional PLs just downstream, the beaver were able to use them to build new dams, which allowed the colony to persist.

were decided in the field based on a combination of the functional design criteria described above, logistical constraints, and common sense. Although the design and installation techniques described are certainly amenable to providing detailed design drawings and plans for every single structure ahead of construction, such activities would greatly increase the design costs and lengthen the construction process.

One of the secondary hypotheses associated with this restoration technique is that when working to harness the natural geomorphic processes of the stream and the labor of beaver to do the work of restoration for us, detailed designs and expensive construction methods are not necessary. If this hypothesis is supported, the transferability of this low-cost restoration technique to other streams may be one of the most valuable contributions of this experiment. Thus a robust and defendable but ultimately simple design and construction process was employed to keep implementation costs at a minimum. Much more investment has been made in carefully formulating hypotheses associated with these treatments and designing and implementing monitoring campaigns to test those hypotheses.

Figure 14. Any abandoned dams with significant structure remaining were reinforced with posts, since these were sites where beaver had previously built dams and with additional structure available might do so again. Beaver abandoned this dam (PC-15 in foreground) and one immediately downstream (not in photograph) after they were breached by high flows. Within a year following reinforcement by posts, beaver rebuilt this dam and built two more dams on PLs (one visible immediately upstream of PC-15, the other farther upstream), resulting in a flooded terrace and complex, multichannel habitat forming on river left and diverting flow away from a high exposed bank on river right.

The physical construction methods are described here. All structures were built with 2 m long, 7–10 cm diameter, untreated lodge pole pine (*Pinus contorta*) fence posts that were stripped of their bark. Using a chainsaw, a point was made at one end of the post. The posts were spaced approximately 0.5–1 m apart and driven into the active channel and inset floodplain with a handheld hydraulic post pounder. Inert mineral oil was used as hydraulic fluid, which allowed it to be safely used around water. Where the depth of the incision trench was a meter or less, the posts in the trench were installed so that the tops were at the same level or slightly elevated above a stream adjacent terrace. This height is well within the height range of natural beaver dams currently found on Bridge Creek.

Beaver dam heights on Bridge Creek typically range between 0.5 and 1.5 m, but may be as high as 2 m (Pollock unpubl. data). Where the depth of the incision trench was greater than 1 m, the elevation of the post lines was either left at 1 m above the channel bed or cut down to about 0.5 m. The risk of having structures more than 1 m high within a confined incision trench is that flow cannot disperse onto a stream-adjacent terrace and the forces acting on the structure will be sufficient to reduce structural integrity, either through undermining, endcutting, or in-channel scour. By reducing the height, the forces acting on the structure are reduced, but so is the corresponding potential for aggradation. If aggradation is successful but beaver colonization is not, these structures can be built upon in subsequent years with subsequent BDS structure installation, until such time that colonization may take place or floodplain reconnection occurs.

PLWWs and SDs also utilized willow whips that were woven between the posts as tightly as possible. These two structure types also had a line of cobble placed at the base of the willows on the upstream side to help prevent headcutting beneath the structure. The placement of cobble at the base of a dam is a common practice by beaver and we simply mimicked that design. Coyote willow, the most abundant willow along Bridge Creek, was the preferred material for wicker weaves, as it reproduces vegetatively by producing basal shoots that form dense clonal colonies of long-stemmed shoots that are relatively unbranched. Long, flexible stems that extend across most of the incision trench were preferred, as these impart the most strength to the structure. The advantage of using coyote willow was that all materials could be locally sourced (generally within 100 m of structures). Since coyote willow primarily reproduce vegetatively, harvesting building materials for the wicker weaves actually promoted regrowth, similar to the response observed when they are thinned by beaver. Further, the food value for beaver of 1-year-old coyote willow stems is much greater than older branches. Thus removal of older stems and the subsequent sprouting of numerous young shoots increases the food supply for beaver. Branches or shoots of other tree species, such as cottonwood, juniper, or Douglas fir were tried, but their less flexible nature and more branching structure suggests they may not be as effective.

A notable distinction between the PLWWs and beaver dam construction techniques is the orientation of the woody material. Beaver place many of the branches on the dams parallel to the flow (e.g., see Figure 11). This creates a wider downstream dam face or mattress of material and may help to minimize downstream scour relative to the PLWWs. The PLWWs are placed perpendicular to the flow because that is a more efficient use of building materials. Moreover, in monitoring beaver activity and colonization of wicker weaves, it is much easier to spot beaver activity and colonization of BDS structures by the placement of cuttings parallel to the flow (Figure 11). By contrast, woody debris and branches that wash down and rack on the dam tend to orient themselves perpendicular to the flow.

While PLWWs were designed to be initially permeable to water, SDs were intended to form a pool upstream and behave like a beaver dam, so additional rock, mud, and organic material were applied to the dam face to create a relatively impermeable structure sufficient to raise the water levels and disperse flow over a stream-adjacent terrace. This again was mimicking the construction methods beavers tend to use (Morgan 1986, Muller-Schwarze and Lixing 2003).

For all structures, the following rules (where applicable) were applied.

1. Within the incision trench, the planform shape of the PL was either straight or convex downstream (i.e., the center of the PL within the bankfull channel is the most downstream post) with the ends of the PL extending upstream along the bank(s), typically 5–10 m, when bank erosion was not desired. A straight PL perpendicular to the main flow promotes parallel streamlines. A straight PL angled toward one bank can promote

the shunting of flow to one side of the channel or the other. A convex downstream shape promotes divergent flow and keeps flow from concentrating in the thalweg downstream of the BDS structure and creating excessive scour, which can undermine the posts.

2. Where possible, PLs extended roughly perpendicular to stream flow along any low terraces within 1 m elevation of the low flow channel, extending no more than 15 cm above the terrace elevation, sufficient to disperse flow across the terrace and help create a more tortuous path for the flow to follow prior to returning to the main channel (Figure 10 and Figure 14). Where appropriate, a gap was left on the terrace PL for a new channel to flow through once the channel aggraded to the elevation of the terrace. Gaps were strategically placed to take advantage of any depressions or old channels on the terrace and existing riparian vegetation, and to increase stream sinuosity. In some cases, however, beaver dammed up gaps, but this typically resulted in dispersed flow in multiple channels across the terrace downstream from the beaver dam, as typically happens with natural beaver dams extending across a low terrace.
3. The distance between structures roughly approximated the natural distance between beaver dams, and was a function of channel slope. Generally, structures were placed close enough to each other that the pool formed by one structure backed up water to the base of the next structure upstream. This helped to ensure that beaver have safe upstream-downstream access while the pool exists and that most of the length of the bed will aggrade once the pools fill in. Having a pool form on the downstream end of a structure also lessened the vertical distance between the water level at the top and bottom of the structure, helping to reduce scour depth and the potential for the BDS structure to be undermined by excessive scour.
4. Where there was a structural gap within an abandoned beaver dam (e.g., a portion of the dam had breached), posts were installed in the gap.
5. Within the bankfull channel, posts were pounded 1 m deep into the bed where possible, but this target depth could not always be achieved, primarily due to the presence of large cobble.

Structure Location Details

In 2009, 21 PLs, 44 PLWWs, 11 SDs, 5 REDs, and 4 RADs were installed in the four reaches: Lower Owens, Meyer’s Camp, Pat’s Cabin, and Sunflower (Table 2). A total of 34 structures were placed in Lower Owens, 16 in Meyer’s Camp, 15 in Pat’s Cabin, and 20 in Sunflower. The total stream length treated was 3.5 km. Distances between structures ranged from 5 m to 89 m and averaged 30 m. For each of the four reaches, the type and location of each structure is illustrated in Figure 6 through Figure 9.

Conclusions

The incised and degraded habitat of Bridge Creek is thought to be limiting the population of ESA-listed steelhead. We are assisting a small, extant beaver population to restore geomorphic, hydrologic, and ecological functions in this system. The primary hypothesis we are testing is that by working with beaver to create stable colonies and aggrade incised reaches of Bridge Creek, there will be measurable improvements in riparian and stream habitat conditions, which will translate to increased abundance of steelhead.

Continued monitoring is assessing the geomorphic and biological changes that are occurring at individual structures (21 PLs, 44 PLWWs, 11 SDs, 5 REDs, and 4 RADs) and to the reaches as a whole (Lower Owens, Meyer's Camp, Pat's Cabin, and Sunflower). Such monitoring will be used to test the hypotheses outlined in Table 1 and to assess whether the structures follow one of the stochastic developmental pathways outlined in Figure 5, or whether there are additional pathways followed that were unanticipated. Ongoing monitoring will also allow us to modify structural designs as needed for the purposes of achieving the overarching goal of improving stream and riparian habitat.

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Appendix A: BDS Structure Maps

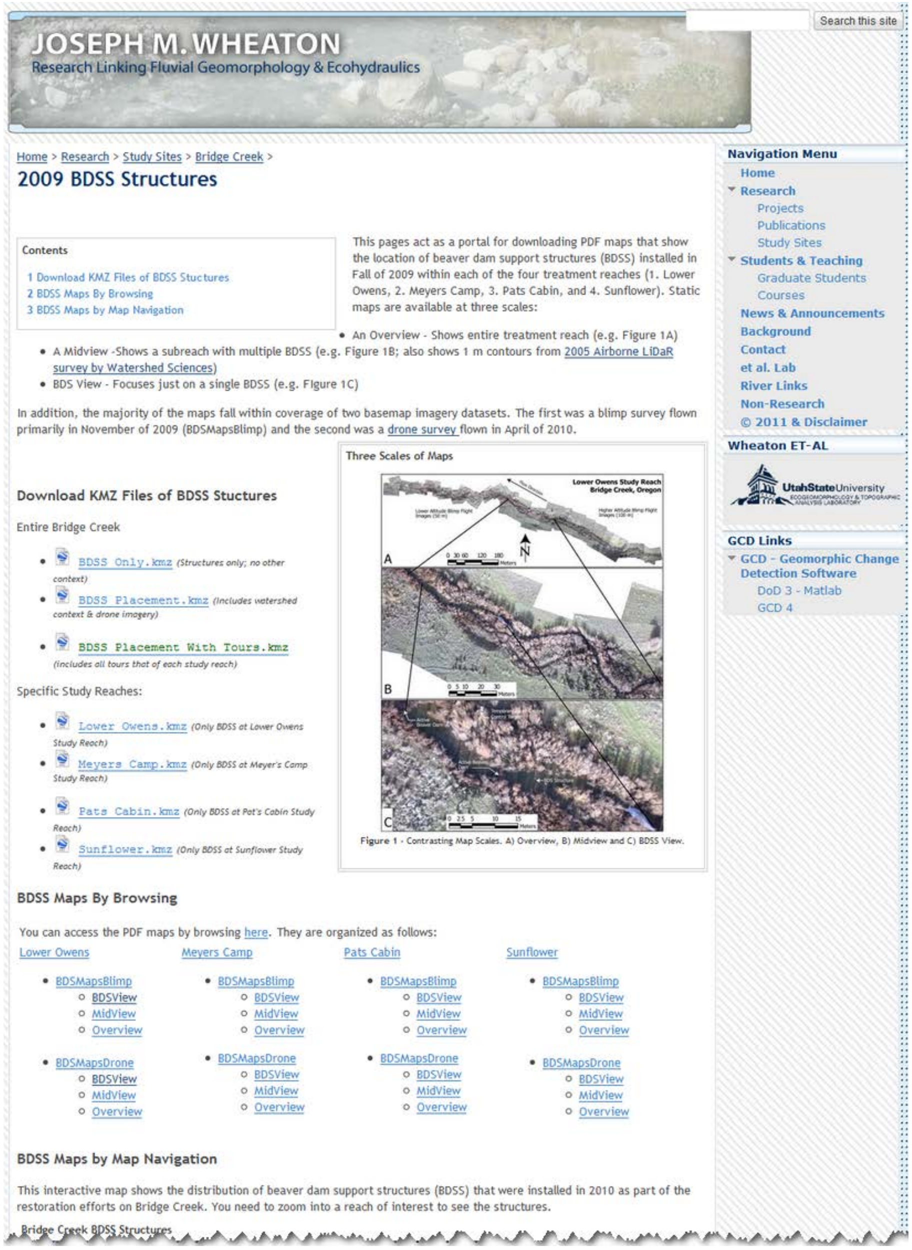
Appendix A contains selected maps showing the locations of the beaver dam support (BDS) structures in four reaches. The maps are overlaid on two base maps: 1) a blimp aerial photography survey performed in November 2009 by Utah State University's ET-AL, and 2) a drone aerial photography survey performed in April 2010. The drone imagery provides complete coverage of all BDS structure sites, whereas the blimp has some gaps in coverage in the upper part of the Lower Owens reach and the upper half of the Pat's Cabin reach.

The complete set of maps is provided at two scales, midview and overview, and a BDSview of each structure is available from the authors. For each of the 85 BDS structures, two maps (one on each base) are available (the BDSview). They are included separately because of the large file sizes (approximately 400 MB total). The overview maps show all structures within the reach and is similar to those figures shown in Figure 6 through Figure 9. The midview maps divide the reaches into two or three segments and show between several and a dozen structures each. To maintain the fidelity of the high resolution base imagery, the individual file sizes of the PDFs vary between 2 MB and 10 MB. Table A-1 lists hyperlinks to all the individual maps.

A Web portal for navigating to each map by browsing, through interactive maps or Google Earth *.kmz files, has been created. At the portal (Figure A-1) are the hyperlinks listed in Table A-1. Access to that Web site can be obtained by contacting Joseph Wheaton at Utah State University's Watershed Sciences Department (telephone 435-797-2465 or e-mail Joe.Wheaton@usu.edu). Ten of the midview drone aerial images are shown in this appendix for reference (Figure A-2 through Figure A-11). The *.kmz files can be browsed and show the locations of all structures and have pop-up balloons with images of every structure, links to Picassa albums, and links to the BDSview maps for each structure (e.g., Figure A-12).

Table A-1. List of hyperlinks to all the static PDF maps by reach. BDSview maps show just individual BDS structures. Midview maps show several BDS structures within the reach. Overview maps show all structures in the reach.

Lower Owens	**Meyer's Camp**	**Pat's Cabin**	**Sunflower**
BDS maps blimp • BDSview (33 maps) • Midview (2 maps) • Overview (1 map)	BDS maps blimp • BDSview (17 maps) • Midview (3 maps) • Overview (1 map)	BDS maps blimp • BDSview (15 maps) • Midview (3 maps) • Overview (1 map)	BDS maps blimp • BDSview (20 maps) • Midview (2 maps) • Overview (1 map)
BDS maps drone • BDSview (33 maps) • Midview (2 maps) • Overview (1 map)	BDS maps drone • BDSview (17 maps) • Midview (3 maps) • Overview (1 map)	BDS maps drone • BDSview (15 maps) • Midview (3 maps) • Overview (1 map)	BDS maps drone • BDSview (20 maps) • Midview (2 maps) • Overview (1 map)



Home > Research > Study Sites > Bridge Creek >

2009 BDSS Structures

Contents

1 Download KMZ Files of BDSS Stuctures
2 BDSS Maps By Browsing
3 BDSS Maps by Map Navigation

This pages act as a portal for downloading PDF maps that show the location of beaver dam support structures (BDSS) installed in Fall of 2009 within each of the four treatment reaches (1. Lower Owens, 2. Meyers Camp, 3. Pats Cabin, and 4. Sunflower). Static maps are available at three scales:

- An Overview - Shows entire treatment reach (e.g. Figure 1A)
- A Midview -Shows a subreach with multiple BDSS (e.g. Figure 1B; also shows 1 m contours from 2005 Airborne LiDaR survey by Watershed Sciences)
- BDS View - Focuses just on a single BDSS (e.g. FIgure 1C)

In addition, the majority of the maps fall within coverage of two basemap imagery datasets. The first was a blimp survey flown primarily in November of 2009 (BDSMapsBlimp) and the second was a drone survey flown in April of 2010.

Three Scales of Maps

Figure 1 - Contrasting Map Scales. A) Overview, B) Midview and C) BDSS View.

Download KMZ Files of BDSS Stuctures

Entire Bridge Creek

- `BDSS Only.kmz` *(Structures only; no other context)*
- `BDSS Placement.kmz` *(Includes watershed context & drone imagery)*
- `BDSS Placement With Tours.kmz` *(includes all tours that of each study reach)*

Specific Study Reaches:

- `Lower Owens.kmz` *(Only BDSS at Lower Owens Study Reach)*
- `Meyers Camp.kmz` *(Only BDSS at Meyer's Camp Study Reach)*
- `Pats Cabin.kmz` *(Only BDSS at Pat's Cabin Study Reach)*
- `Sunflower.kmz` *(Only BDSS at Sunflower Study Reach)*

BDSS Maps By Browsing

You can access the PDF maps by browsing here. They are organized as follows:

Lower Owens

- BDSMapsBlimp
  - BDSView
  - MidView
  - Overview
- BDSMapsDrone
  - BDSView
  - MidView
  - Overview

Meyers Camp

- BDSMapsBlimp
  - BDSView
  - MidView
  - Overview
- BDSMapsDrone
  - BDSView
  - MidView
  - Overview

Pats Cabin

- BDSMapsBlimp
  - BDSView
  - MidView
  - Overview
- BDSMapsDrone
  - BDSView
  - MidView
  - Overview

Sunflower

- BDSMapsBlimp
  - BDSView
  - MidView
  - Overview
- BDSMapsDrone
  - BDSView
  - MidView
  - Overview

BDSS Maps by Map Navigation

This interactive map shows the distribution of beaver dam support structures (BDSS) that were installed in 2010 as part of the restoration efforts on Bridge Creek. You need to zoom into a reach of interest to see the structures.

Bridge Creek BDSS Structures

Figure A-1. Screen shot of Web portal for downloading individual pdf maps and browsing interactively in Google Maps, including the ones in this appendix.

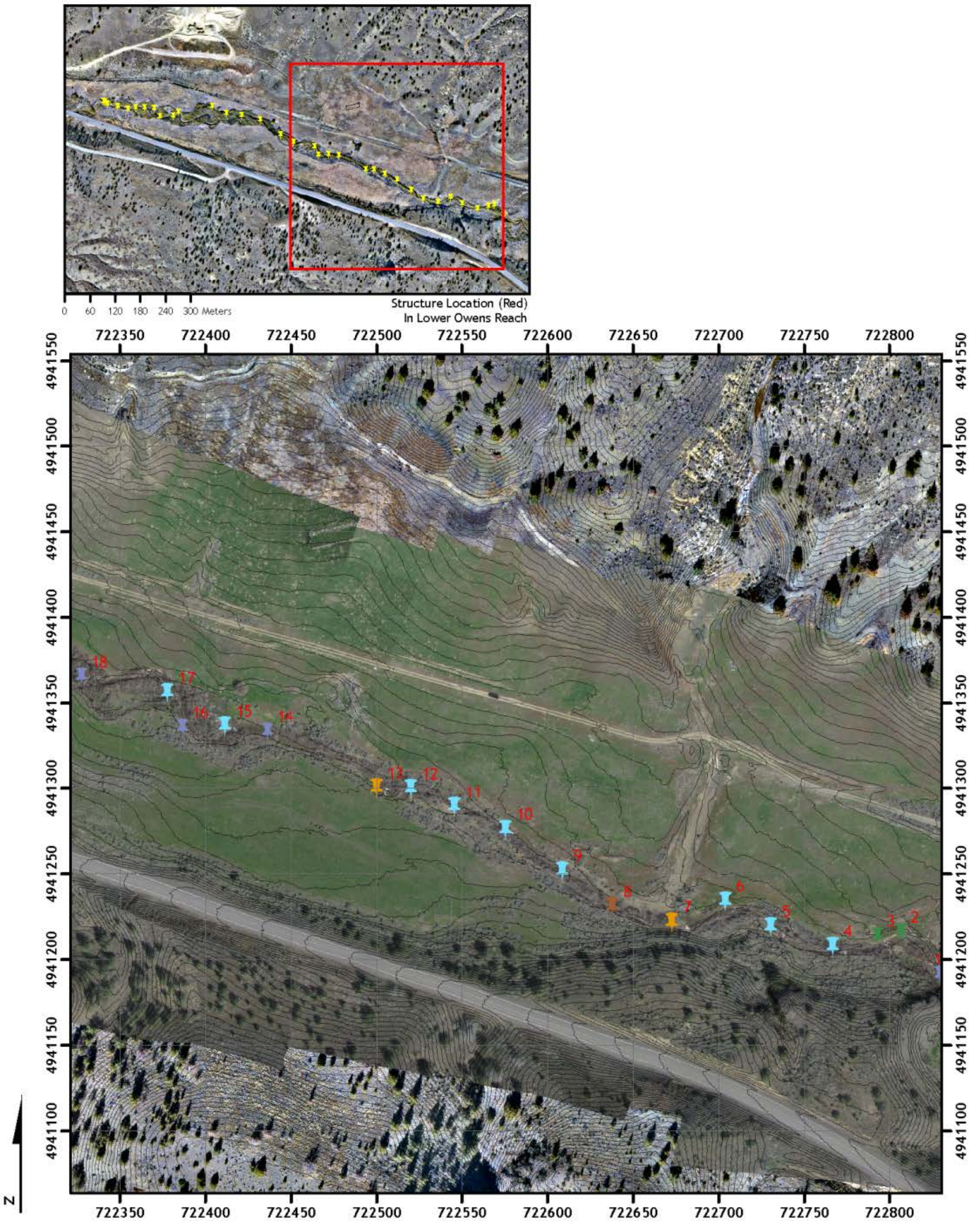


Figure A-2. Midview map of upper reach at Lower Owens with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

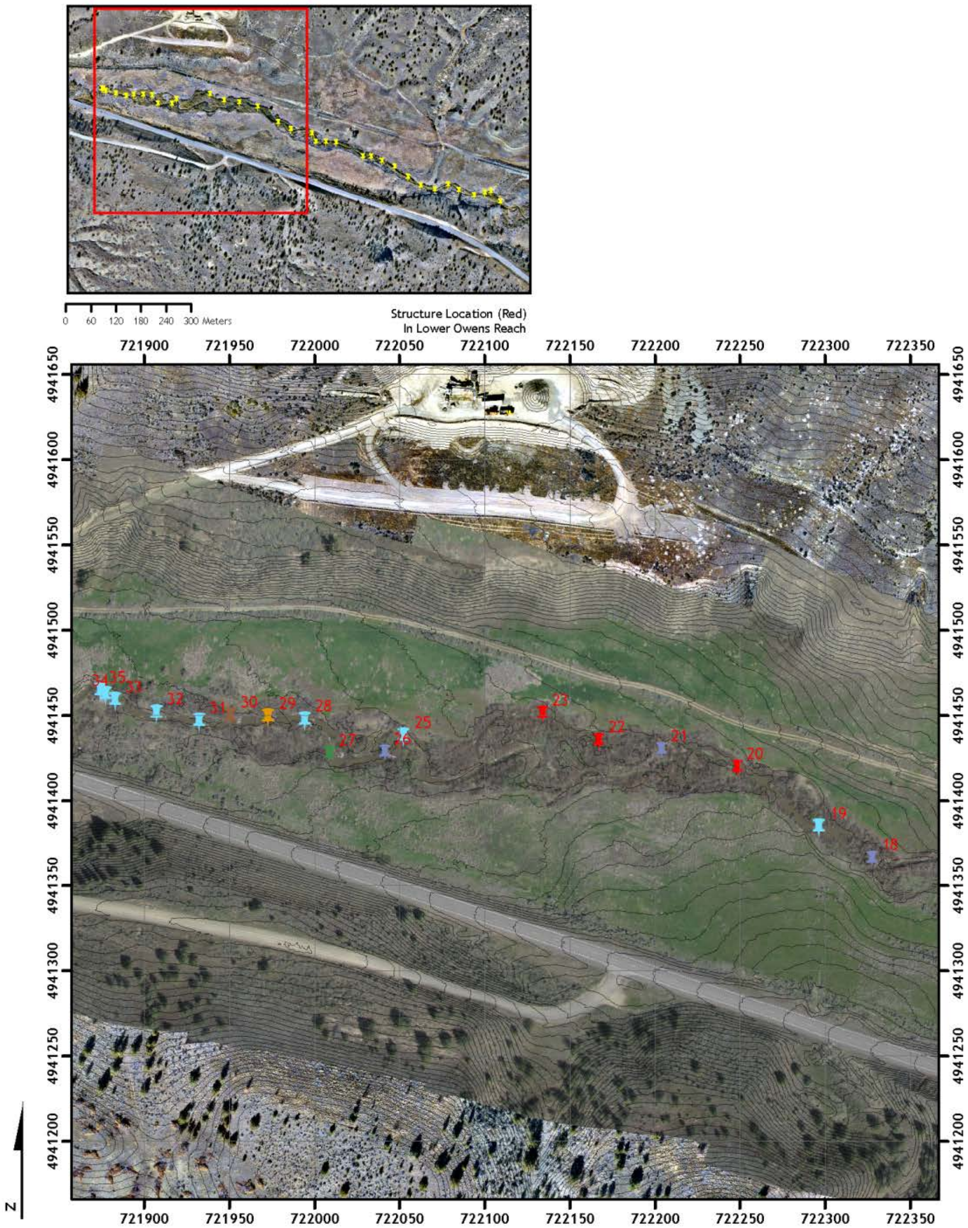


Figure A-3. Midview map of lower reach at Lower Owens with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

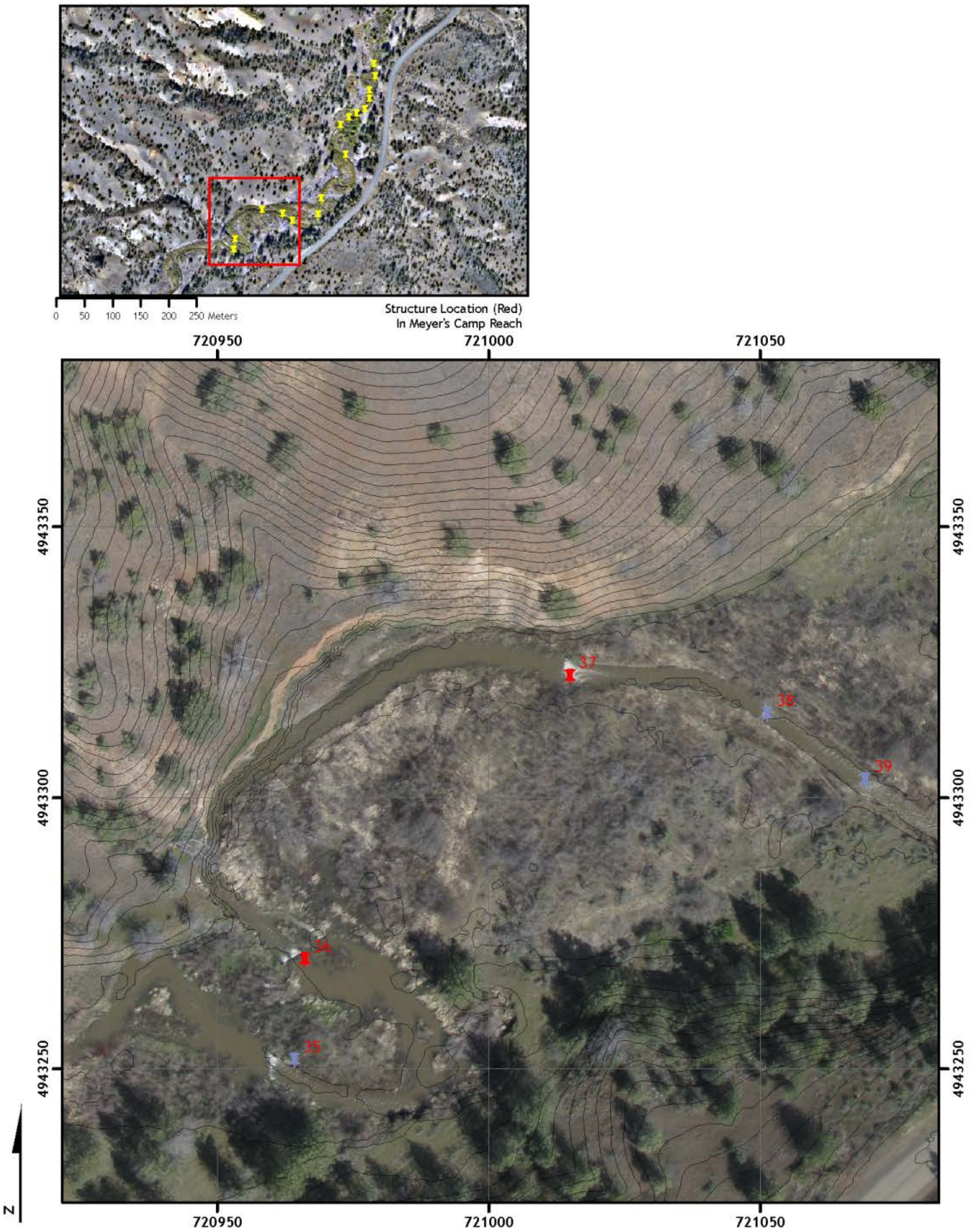


Figure A-4. Midview map of upper reach at Meyer's Camp with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

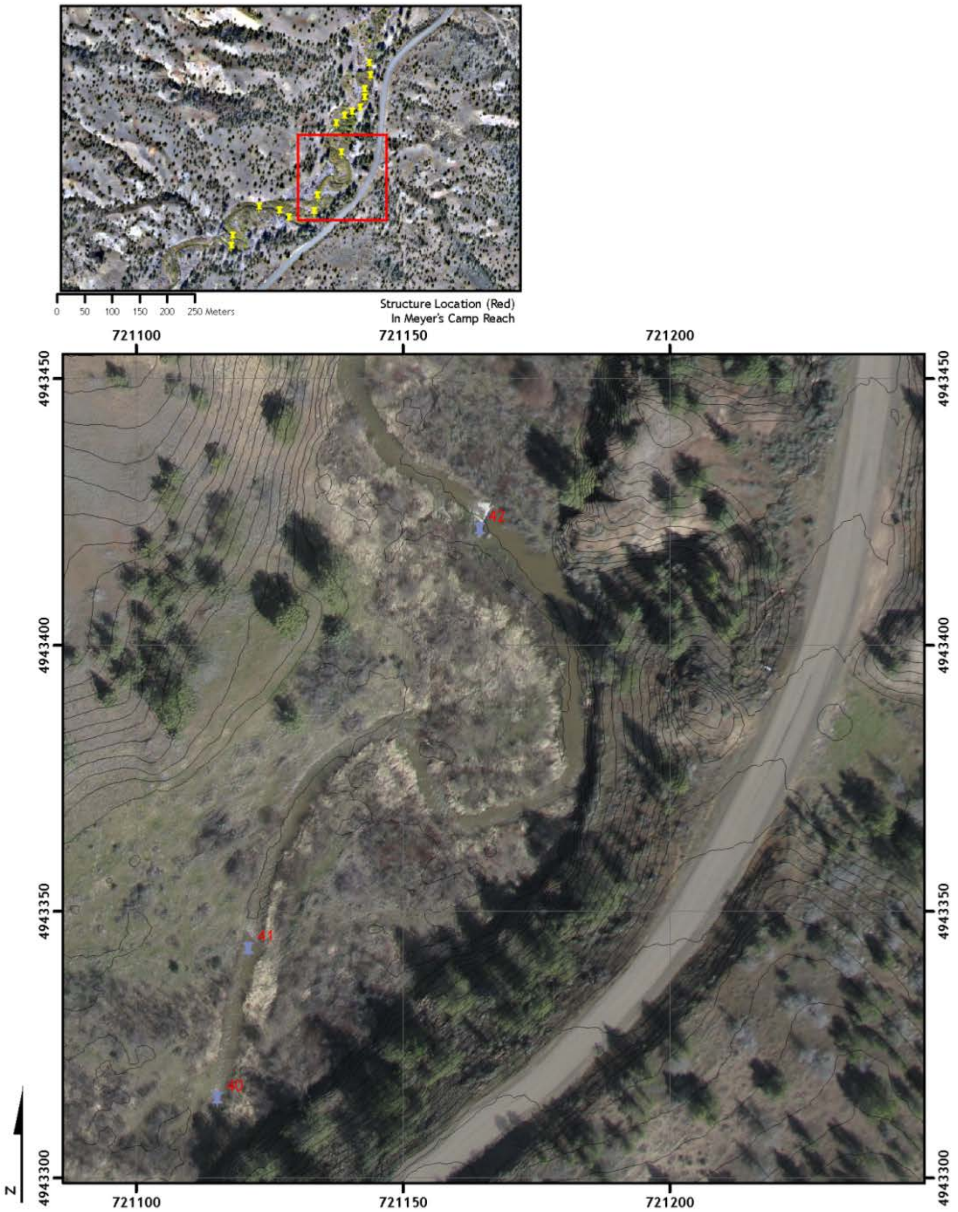


Figure A-5. Midview map of middle reach at Meyer’s Camp with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

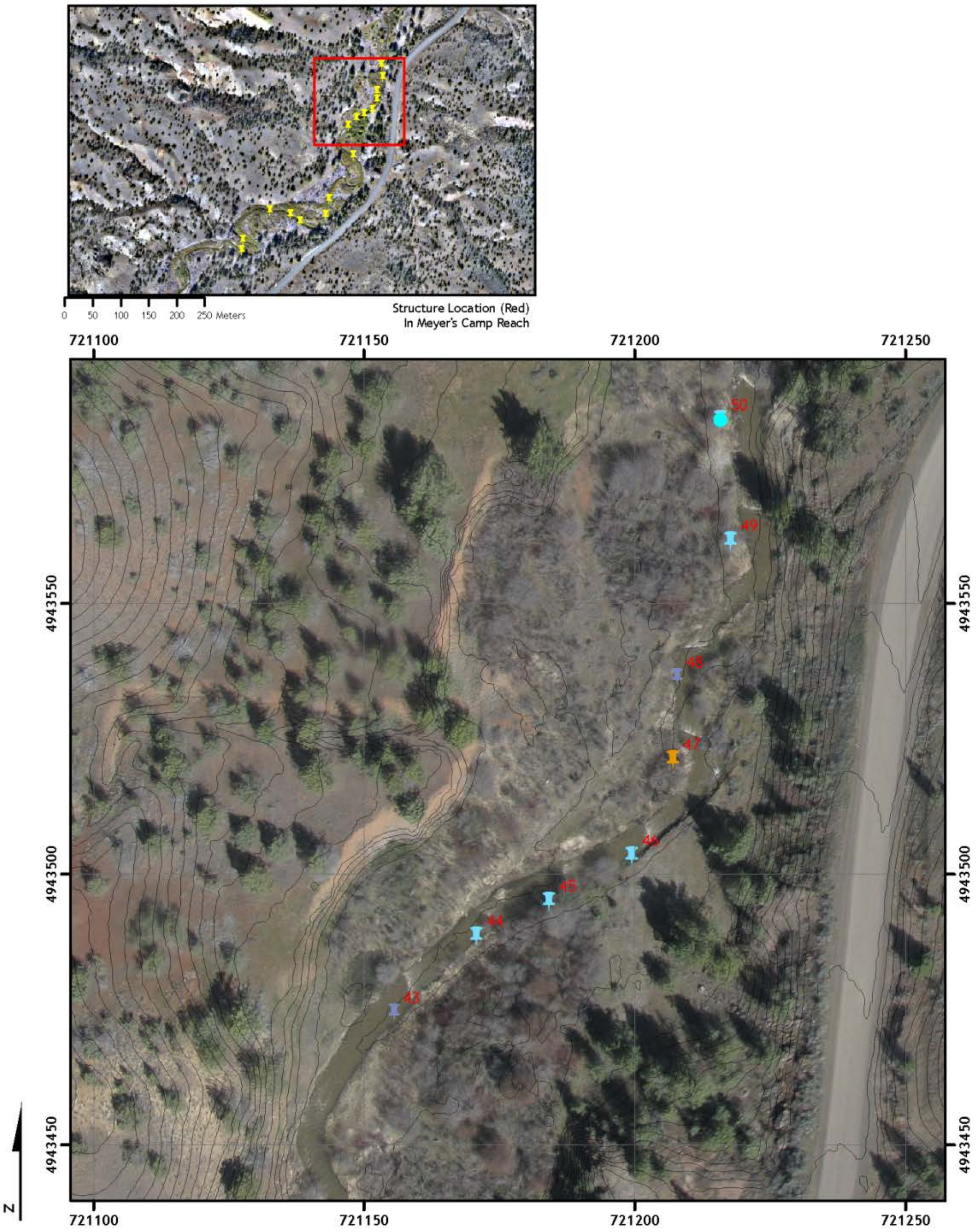


Figure A-6. Midview map of bottom reach at Meyer's Camp with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

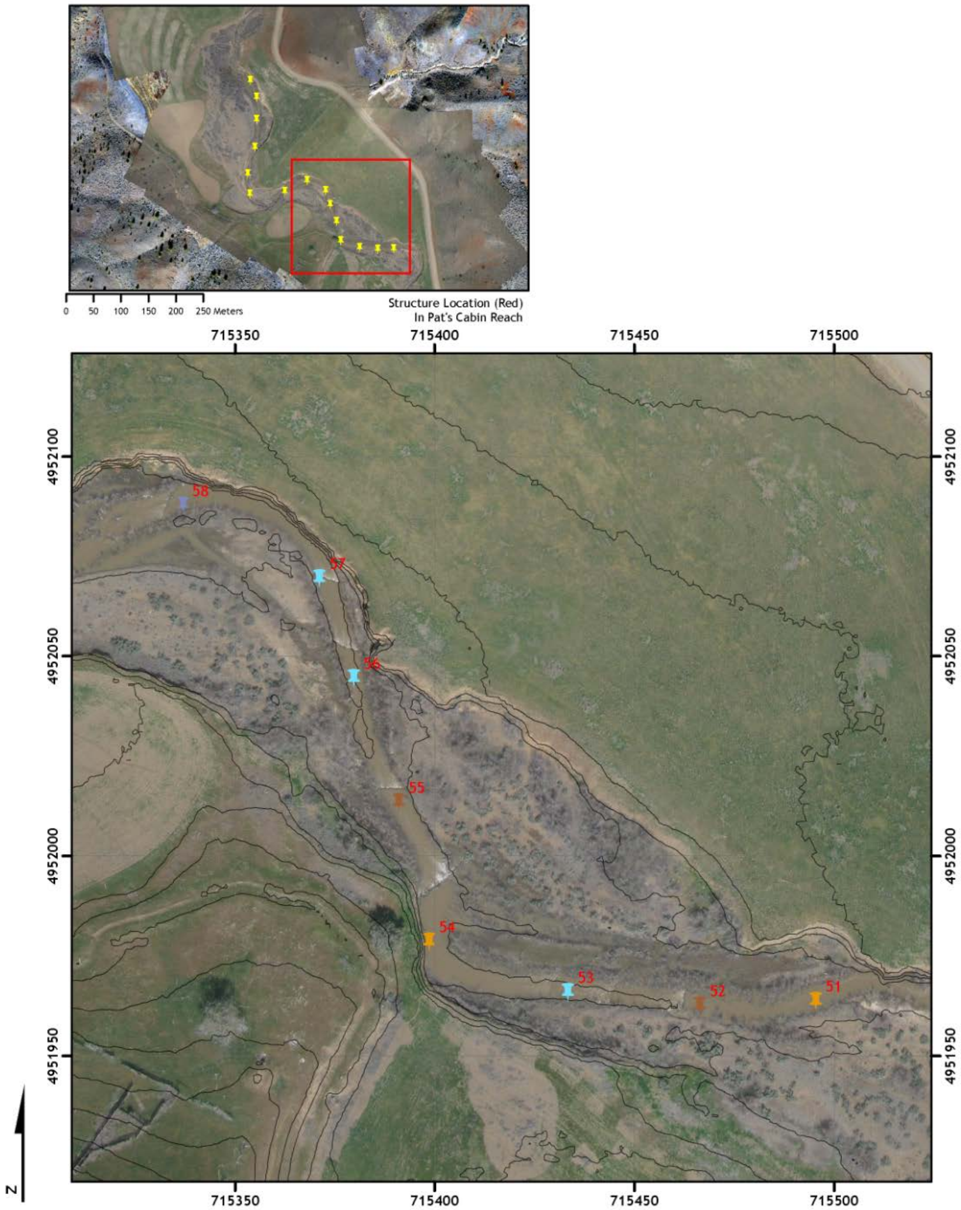


Figure A-7. Midview map of top reach at Pat’s Cabin with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

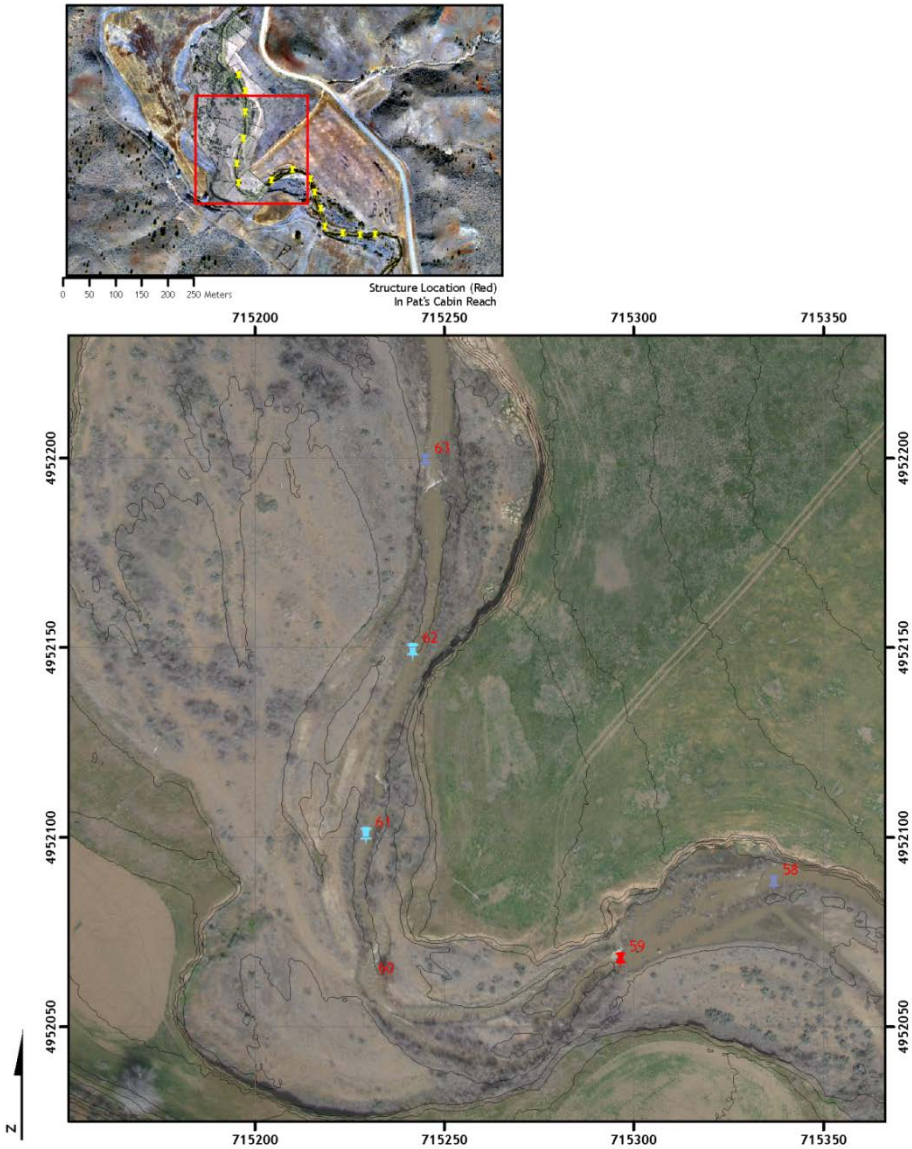


Figure A-8. Midview map of middle reach at Pat's Cabin with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

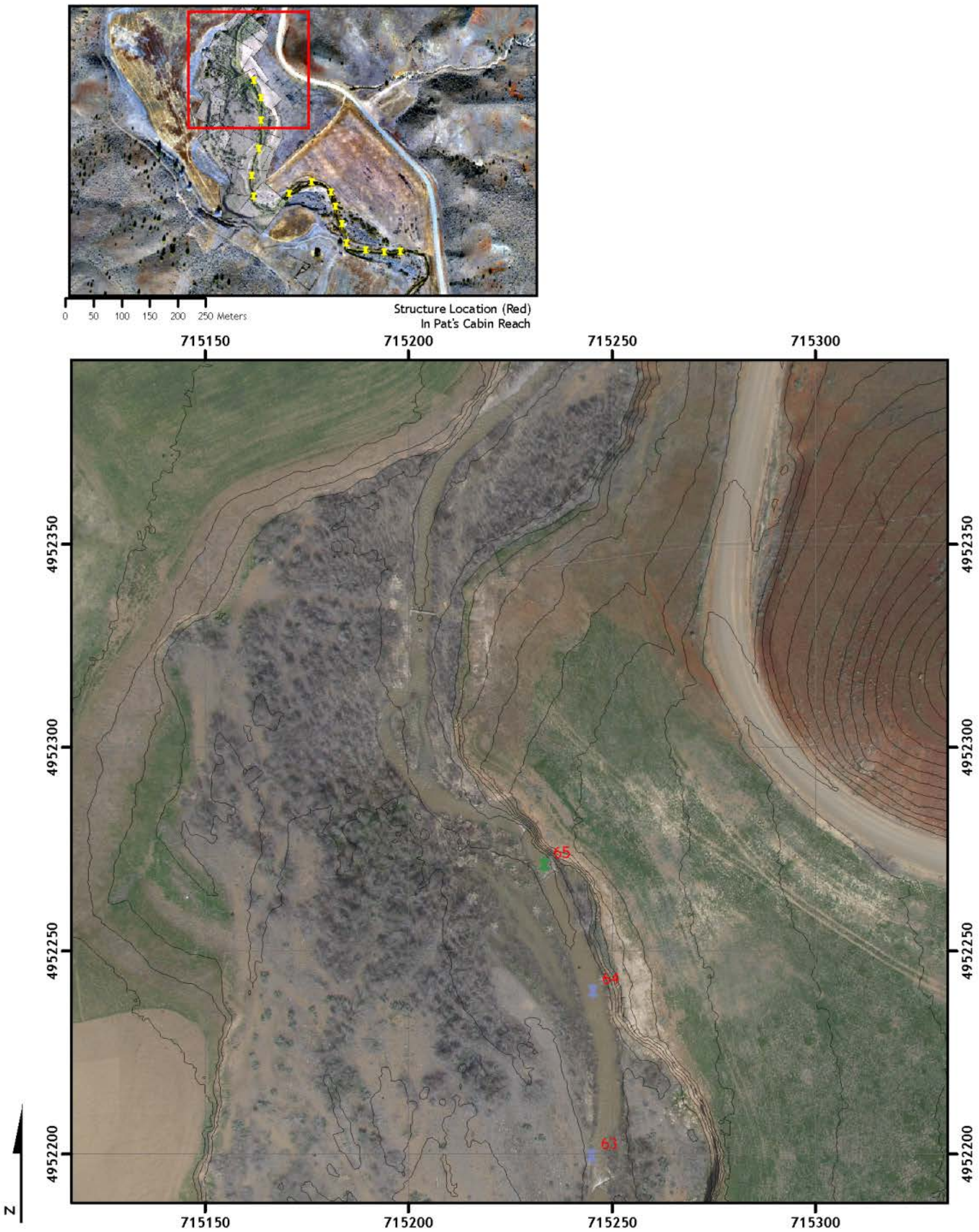


Figure A-9. Midview map of bottom reach at Pat's Cabin with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

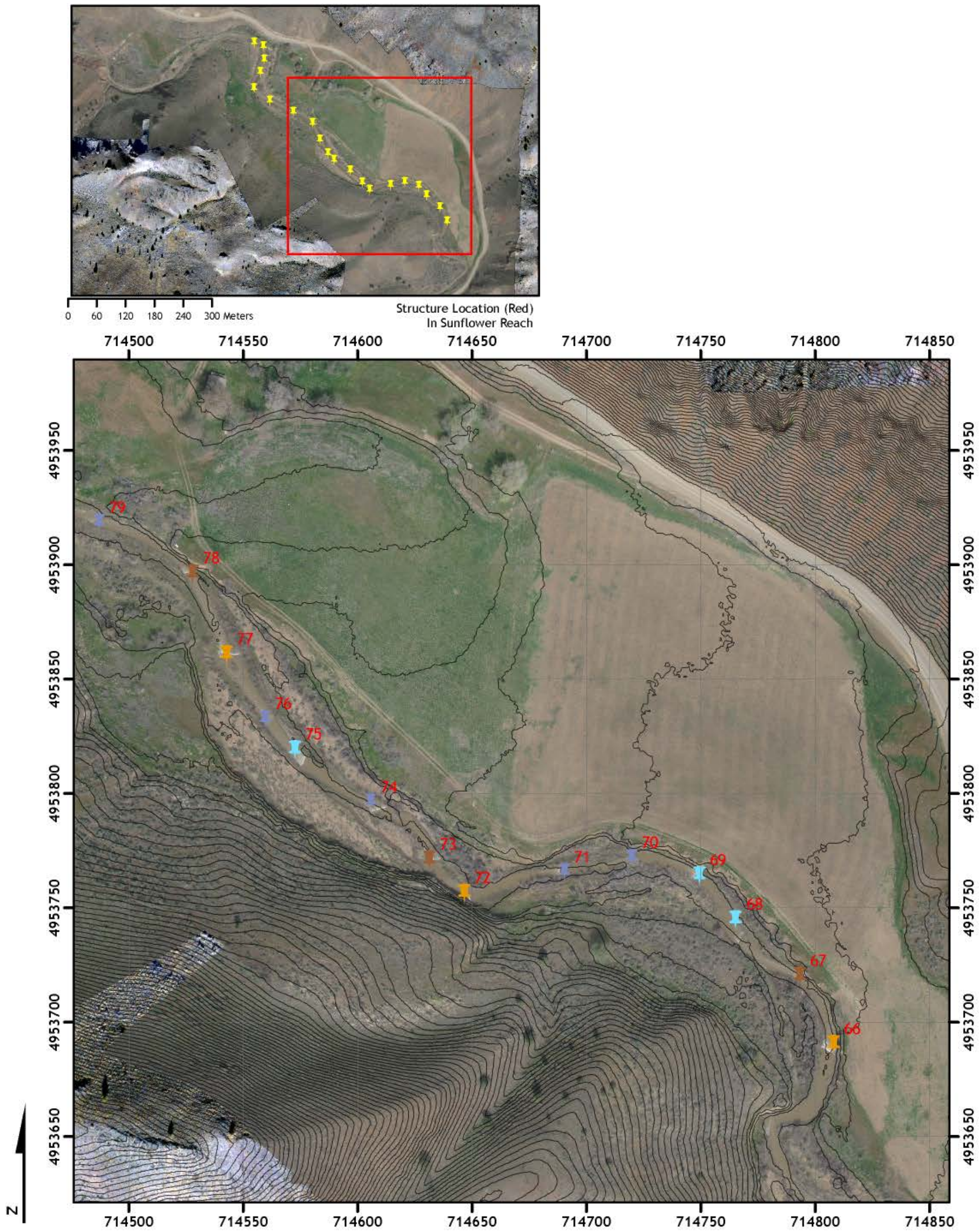


Figure A-10. Midview map of top reach at Sunflower with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.

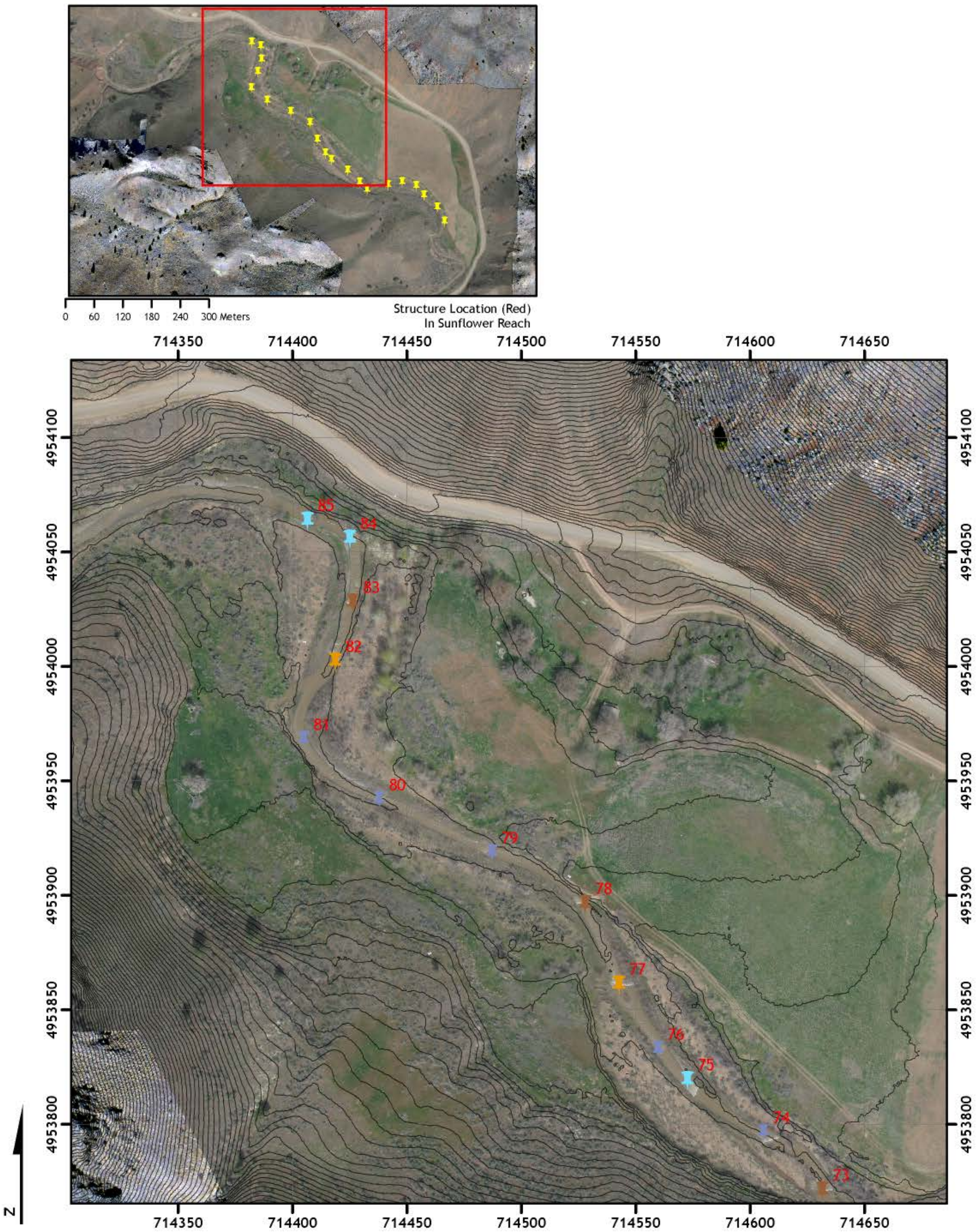
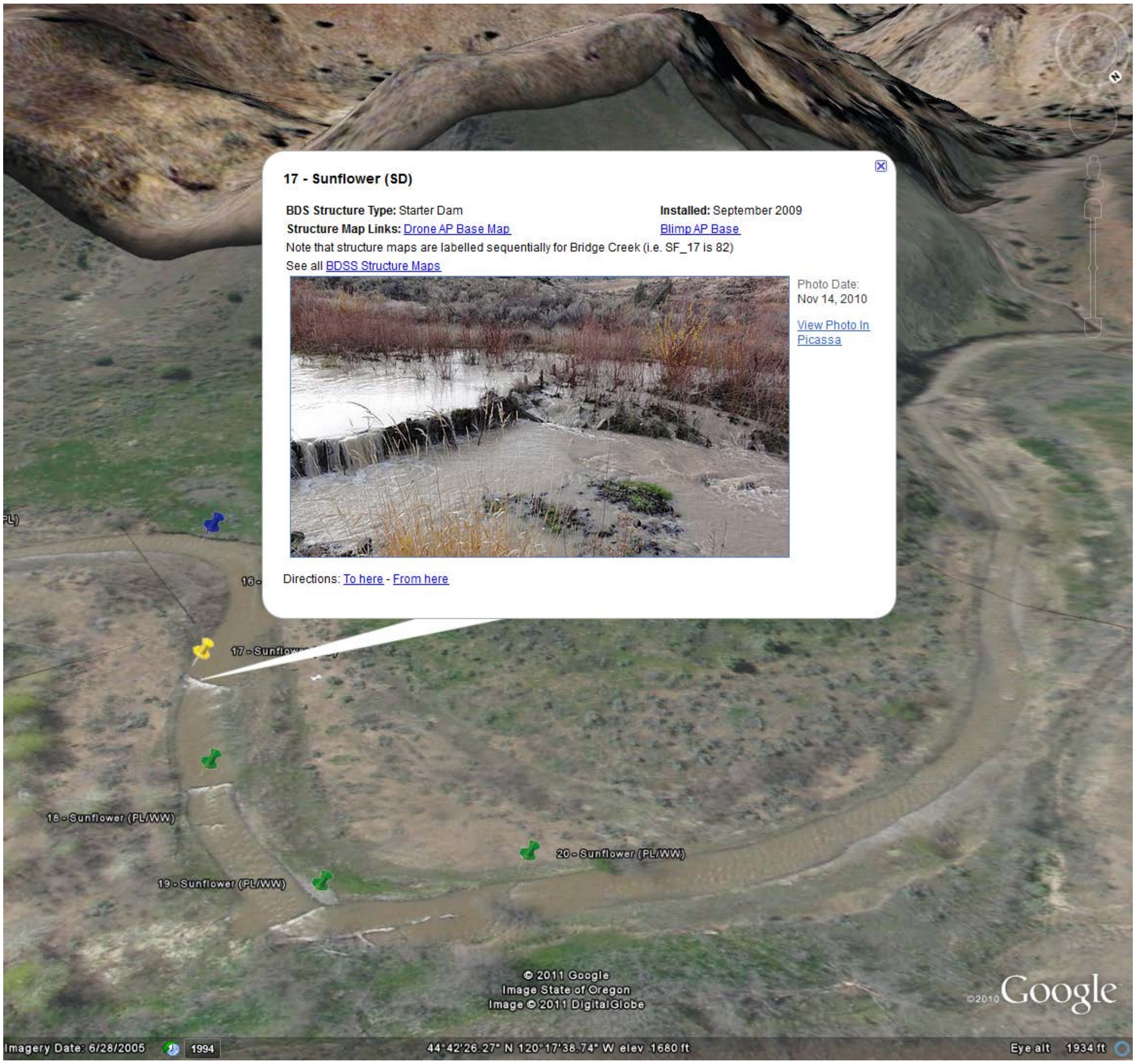


Figure A-11. Midview map of bottom reach at Sunflower with April 2010 drone aerial imagery as base map and 1 m contour intervals derived from the Watershed Sciences Department 2005 LIDAR survey. Coordinates are UTM system in 50 m increments.



17 - Sunflower (SD)

BDS Structure Type: Starter Dam

Installed: September 2009

Structure Map Links: Drone AP Base Map

Blimp AP Base

Note that structure maps are labelled sequentially for Bridge Creek (i.e. SF_17 is 82)

See all BDSS Structure Maps

Photo Date:
Nov 14, 2010

View Photo In Picassa

Directions: To here - From here

Figure A-12. Screen shot from Google Earth illustrating an example at Sunflower of the pushpins denoting each structure type and the balloons at each structure, which provide links to the BDSView pdfs and links to geotagged Picassa albums of every structure.

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