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WORKING WITH BEAVER TO RESTORE SALMON HABITAT IN THE BRIDGE CREEK INTENSIVELY MONITORED WATERSHED

DESIGN RATIONALE & HYPOTHESES

INTERIM REPORT

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CONTENTS

SUMMARY

The incised and degraded habitat of Bridge Creek is thought to be limiting the population of ESA-listed steelhead (*Oncorhynchus mykiss*). A logical restoration intervention is to improve their habitat through reconnecting the channel with portions of its former floodplain (now terraces) to increase stream habitat complexity and the extent of riparian vegetation. Using conventional restoration techniques, such interventions often involve massive grading operations, major revegetation efforts, and are extremely expensive. Here, we seek to partner with a small, extant beaver population to restore geomorphic, hydrologic and ecological functions of this degraded system by helping beaver build longer-lived dams. Currently, the beaver population appears 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 are 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 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 abundance of native steelhead. The main restoration design challenge was is to help beaver build dams that would 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 feedbacks associated with dynamic beaver dam complexes that will benefit steelhead and other species.

An extremely simple and cost-effective restoration treatment is being employed as part of the Bridge Creek Intensively Monitored Watershed (IMW) project. The treatment involves installing round wooden fence posts across potential floodplain surfaces (now terraces) and the channel approximately 0.5 to 1 m apart and at a height intended to act as the crest elevation of an active beaver dam. After initial experimentation with the approach in 2008 with 16 structures, a full restoration experiment was implemented in 2009 with 84 structures installed. 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 abandon 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) for aggradation in the slackwaters of the pond from the dam to take place 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 beaver dam support (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 multi-dam complexes to support healthy and persistent colonies.

This report provides details of the design rationale and design hypotheses employed and summarizes the placement of the 84 BDS structures installed 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. Within months of installation, roughly 25% of the structures were occupied and modified by beaver. As compared to unreinforced dams, the structures generally faired better through their first major floods with most structures either remaining intact or experiencing only minor breaching that were easily repaired by beaver. Owing partly to the high sediment loads in Bridge Creek, the geomorphic response has been rapid, with net aggradation documented in all reaches and some degree of floodplain reconnection taking place in all four treatment reaches. Design hypotheses were formulated at scales ranging from the watershed to the individual structure and it is too early to

definitively test all these and report what elements of the restoration intervention have been successful or have not worked. However, the preliminary monitoring results do reveal a dramatic and rapid shift in the heterogeneity of in-channel and riparian habitat, as well as some degree of floodplain reconnection. Thus, initially, it appears that the treatment is working, and only time and future monitoring will tell whether this simple restoration effort is enough to push Bridge Creek into a more dynamic and healthy system that can be maintained by beaver. Until the beaver population expands into more persistent colonies, some degree of maintenance (e.g. replacing fence posts or raising crest elevations) may be able to achieve similar results as the beaver would have in terms of floodplain reconnection and gains in habitat complexity.

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 Endangered Species Act (NMFS and NWFSC 2008). This project is part of NOAA's Integrated Status and Effectiveness Monitoring Program (ISEMP), which is developing methods to accurately assess both 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 mainstem 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) (Beechie *et al.*, 2007; Shields *et al.*, 1995). Typically, incision also results in a loss of both channel planform and bedform complexity (Rosgen, 1996; Schumm *et al.*, 1984; 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 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, do provide an example of how 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 stream bed (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 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 is acting upon them.

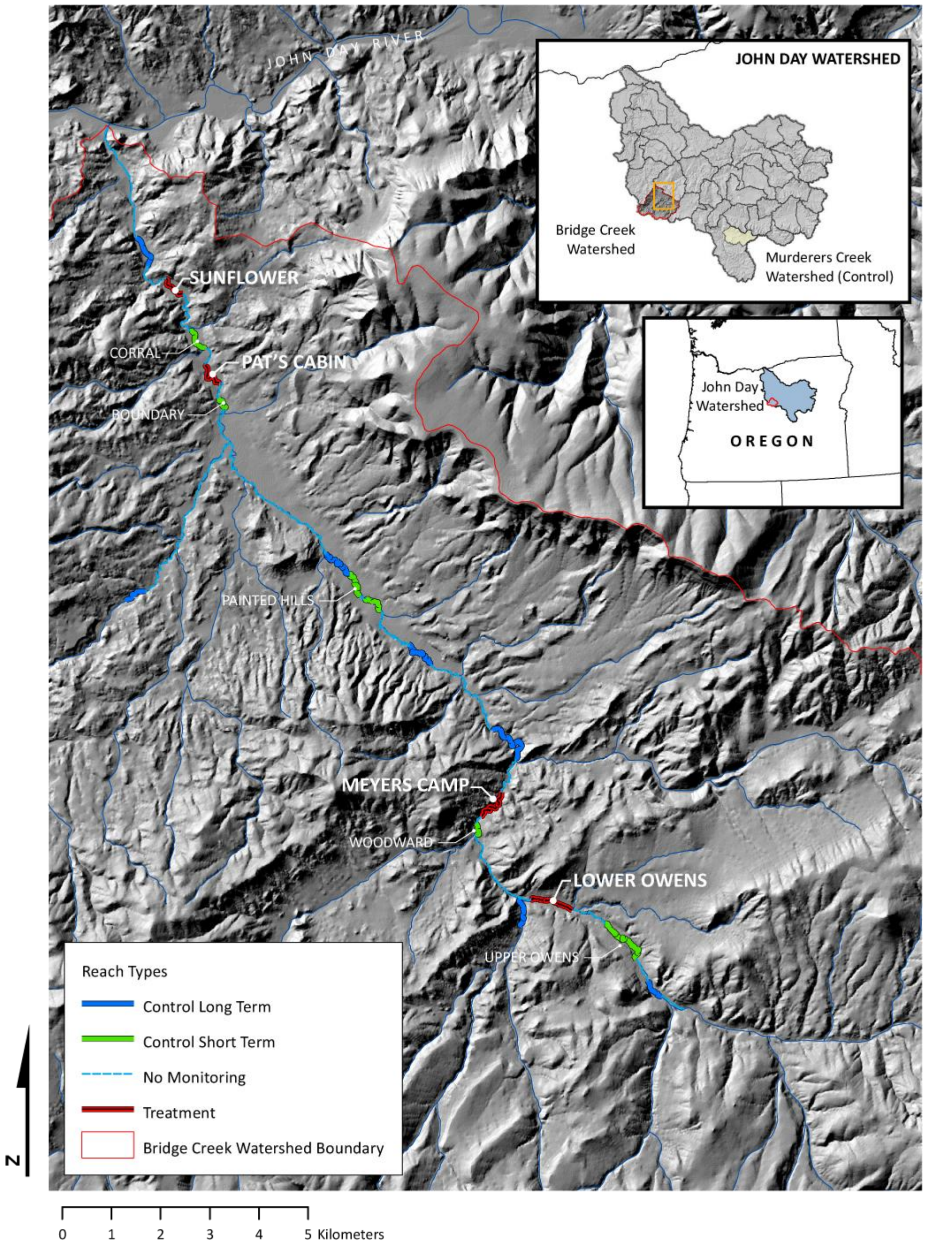

Figure 1 - Location & Vicinity Maps of Bridge Creek. The inset maps show the location of Bridge Creek and Murderers Creek in the John Day River basin of eastern Oregon. The main map shows the mainstem Bridge Creek drainage network and the primary treatment reaches described in this report.

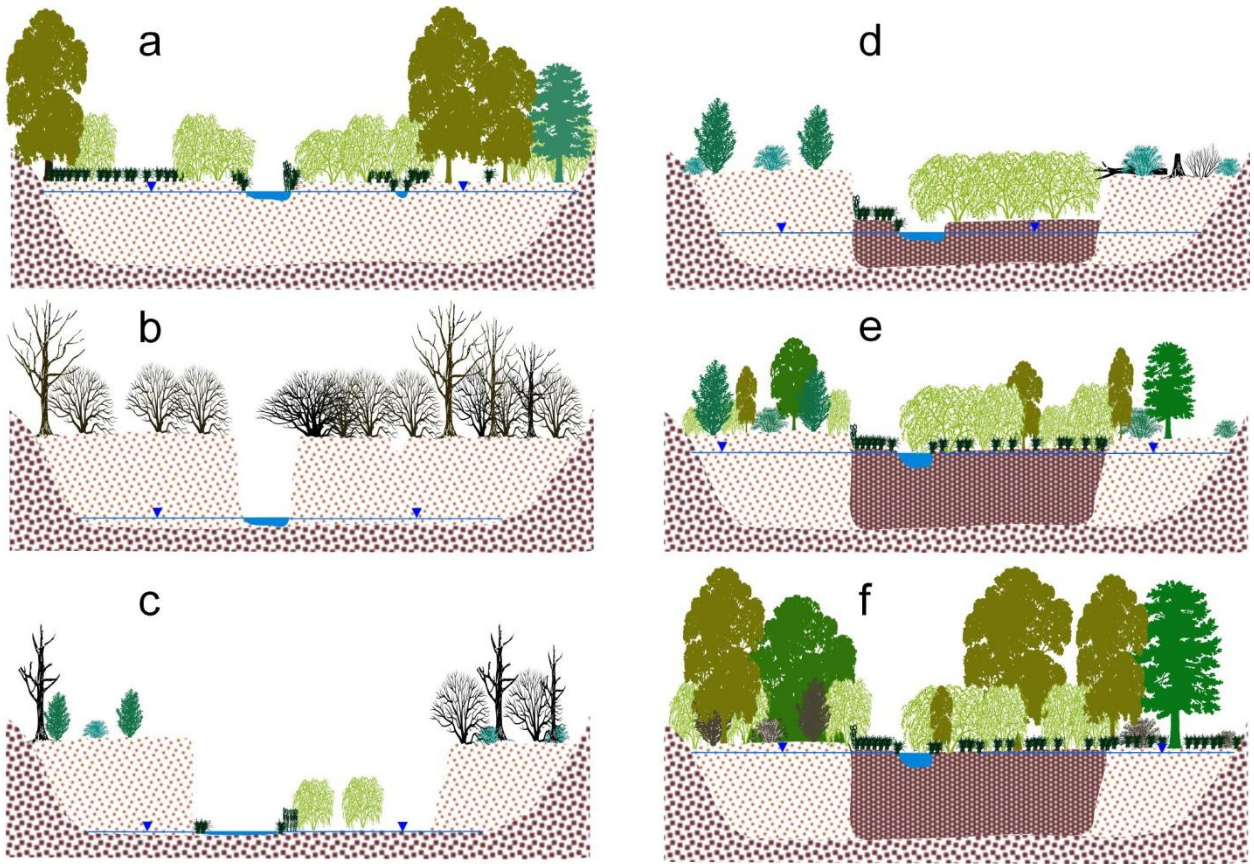

Figure 2. Sequence of channel incision and aggradation typical of streams in semi-arid landscapes, with cohesive fine-grained banks. Light colored fill is alluvium, darker fill is bedrock. Water table is demarcated with a blue line. a) channel prior to incision, b) rapid downcutting (to a hard surface 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 re-occupy the former floodplain, f) aggradation may continue to pre-incision conditions, but often remains at stage d) or e) such that there are one or more inset terraces.

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 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, the import of 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 or better outcomes as human-based stream restoration efforts, the economic implications are significant (McKinstry *et al.*, 2001a). The primary means by which we are exploring 'working with beaver' is to help them build stable dams is with the use of inexpensive, bio-degradable structural support (i.e. wood fence posts) that can be installed cheaply and with logistically simple installation procedures (i.e. 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 abundance of native steelhead.**

This report presents the restoration design rationale and hypotheses, and highlights some of the preliminary data from the first year and half of a long term monitoring campaign 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. The results are used to describe

BACKGROUND

OBSERVATIONS OF NATURAL BEAVER DAMS IN BRIDGE CREEK

From 1988 to 2004, the Bureau of Land Management surveyed the lower 32 km of Bridge Creek for the presence of beaver dams 1-2 times per year (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 BLM survey data also indicate that most of dams were extremely short lived, and that many of them lasted less than a year. Presumably, the majority of them were breached during the annual spring floods or the flash floods that sometimes occur in the summer.

Using Demmer and Beschta's (2008) data and a digital elevation model from an aerial Light Detection and Ranging (LIDAR) survey from Watershed Sciences (2005; Available at OpenTopography.org) we examined the spatial patterns of beaver dams to determine if there was a relationship between beaver dam persistence and nearstream geomorphology. What we found was that beaver dams failed and were subsequently abandoned under a wide range of geomorphic conditions, but that most of the dams that failed and were not repaired were built in reaches with relatively narrow incision trenches. These reaches were characterized by the 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.

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 there has been a small population of 1-4 beaver colonies that has persisted more or less continuously since around 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 50-80 m 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. Though 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 provides 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 one 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 mainstem above 2 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 a 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 observed 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 and then a new channel forming by cutting through the dam or 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%).

Demmer and Beschta's (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 thalweg at the deepest point of the dam, suggesting that dam breaching is often related to excessive hydrostatic pressure on the upstream dam face. In a functional reach, as high flows increased this flow would spread out onto an adjacent floodplain or terrace surface, and some of this pressure would be alleviated. However, in Bridge Creek high flows are often confined within a narrow incision trench. Thus the flow depth increases above the height of the dam pressure is concentrated on the dam. During such overtopping events, breaching can also result of erosion of the dam material during high flows simply because the shear stress at the top of the dam is sufficient to entrain some of the woody and non-organic material that makes up the dams. We have observed some dams where a top portion of a reach of dam was missing, but there wasn't complete dam breaching, a situation that is explained by erosive processes. We also observed that when dams breached by end-cutting 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.

Such observations suggest two major types of sequences occurred that resulted in stable dams:

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 were not concentrated in the thalweg. The total length of such dams were generally much wider (50-80 m) than dams built only within the incision trench (4-7 m). The dispersed flows of the wide dams should lower the depth of water flowing over them during floods, and thus the

hydrostatic pressure against the bankfull or thalweg section of the dam should be reduced. A wide dam that lowers flow depths (while also reducing flow velocities) should also reduce dam breaching from erosion.

2) There was rapid aggradation behind dams. Because Bridge Creek has a high sediment load, 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). Dams completely backfilled 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.

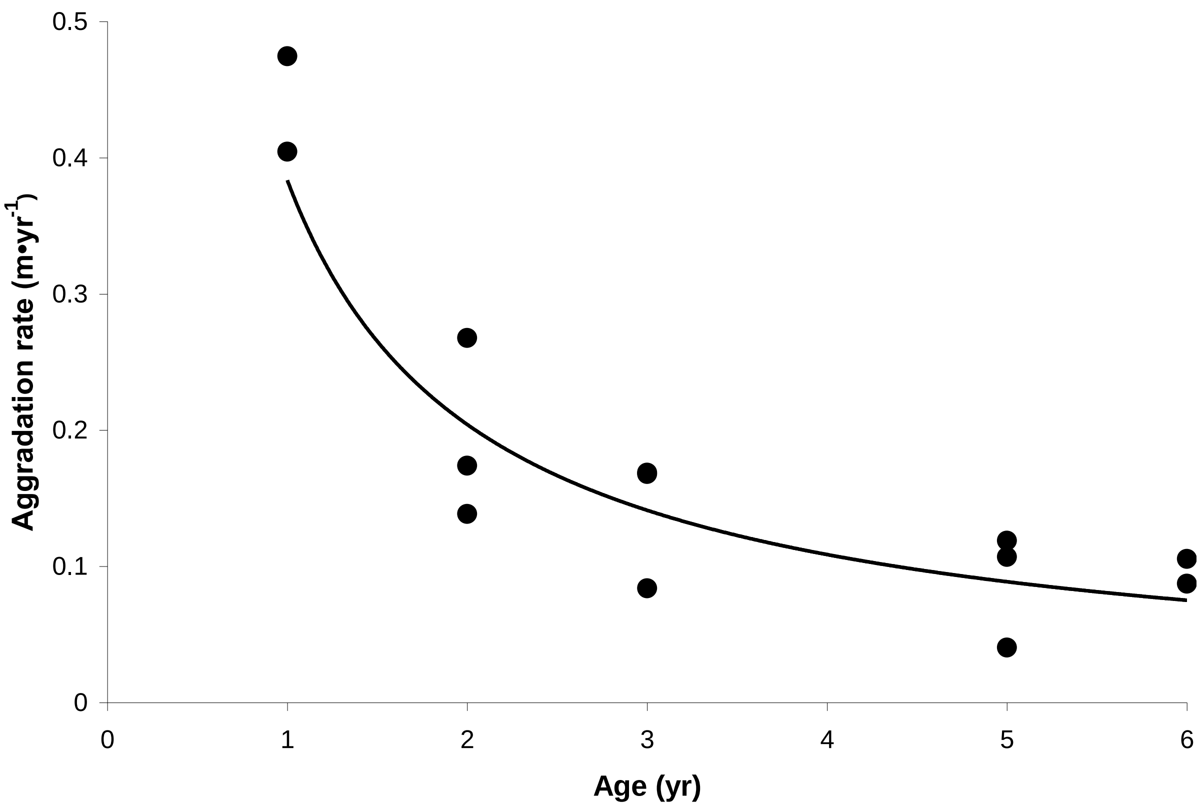

Figure 3. Sediment aggradation rates behind beaver dams in Bridge Creek (From Pollock et al. 2007).

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 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 towards a restoration strategy or 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 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 retain structural integrity and functionality for more than a year. Such longer-lived, less transient dams are hypothesized to become building blocks for resilient and dynamic beaver dam complexes which support thriving colonies of beaver (e.g. 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 (Burchsted *et al.*, 2010; Naiman *et al.*, 1988; Pastor *et al.*, 1993). 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 trajectory. While overall, an active dam complex should have dams that boast longer dam life then 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 (Burchsted *et al.*, 2010; Naiman *et al.*, 1988). This leads to a dynamic shifting habitat mosaic (Tockner and Stanford, 2002) in time and space, 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, relocation or conservation of beaver has been proposed to achieve ecosystem restoration goals (e.g. see Albert and Trimble, 2000; McKinstry and Anderson, 2002; McKinstry *et al.*, 2001b), 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 be later utilized by beaver to build stable dams from. 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 both 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 should 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, stream bed 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 towards gravel (Demmer and Beschta, 2008; Pollock *et al.*, 2007). 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; Pollock *et al.*, 2007; Westbrook *et al.*, 2006). 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 (McCullough *et al.*, 2005; Pollock *et al.*, 2003; Scheffer, 1938; Westbrook *et al.*, 2010).

SITE DESCRIPTION

This restoration and monitoring project is being conducted along the lower 30 km of Bridge Creek in eastern Oregon, USA (44.6492°N, 120.2455°W). Bridge Creek is a 710 km^2 watershed draining northwesterly into the lower John Day River with 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-steppe (*Artemisia* spp.) and juniper-steppe (*Juniperous occidentalis*) 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 mainstem of Bridge Creek is in a semiarid landscape with 7.4 cm average cumulative summer rainfall (June – September) and average daily maximum and daily minimum summer temperatures of 26.9 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 daily minimum winter (November – April) temperatures of 9.6 and -1.9°C, respectively. Temperature and precipitation data were obtained from National Climate Data Center station 355638 (available at: http://www.ncdc.noaa.gov/oa/ncdc.html).

Most of the mainstem and lower tributary reaches of Bridge Creek are incised and 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 *S. monochroma, S. lasiandra, S. prolixa* and *S. amygdaloides*. Black cottonwood (*Populus trichocarpa*) is present in small quantities 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 of the Eocene and Oligocene period. 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. 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. Where active lateral erosion is taking place into these coarser deposits, they are 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 from 1.4-1.5 g cm^{-3} while porosities range from 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 pre-treatment monitoring took place to document baseline conditions. The focus of the broader IMW effort and restoration experiment in Bridge Creek is to partner with beaver to help restore the steelhead population in Bridge Creek. 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 and color photography survey from Watershed Sciences (2005; Available at OpenTopography.org) combined with field surveys to identify 4 pairs of geomorphically similar reaches within the lower 32 km of the mainstem 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 Creek and Gable Creek) to use as additional control sites within the watershed that were outside of the mainstem, 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 of the Bridge Creek mainstem 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).

PRE-TREATMENT MONITORING

For several years before and now continuing during the restoration treatment, numerous biological and physical parameters have been measured within both 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 detail in NMFS and NWFSC (2008).

Table 1. **The restoration project seeks to create change at 3 different spatial scales: watershed, reach and individual structures, with expected differences in the response time needed to detect change.**

Spatial Scale	Treatment Site(s)	Control Site(s)	Temporal Scale of Detection	Hypothesis for Treatment Areas	Data Collection
Watershed Level					
	Bridge Creek- Lower 32 Km	Murderers Creek	5-10 yrs	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
				Baseflow discharge will increase	Gage Stations at mouth of Bridge and Murderers Ck
				Beaver population will increase	Dam, Pond and Lodge Census
Site Level					
	Sunflower, Pat's Cabin, Meyers, L. Owens	Corral, Boundary, Woodward, U. Owens	1-10 yrs	Floodplain connectivity will increase through the process of aggradation	Total station surveys of channel and stream adjacent terrace morphology. Aerial surveys
				Riparian vegetation will increase	Aerial surveys (remote drone and fixed wing)
				Sinuosity will increase	Aerial surveys (remote drone and fixed wing)
				Stream gradient will decrease	Topographic & 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 dominated to gravel dominated	Habitat surveys
				Stream temperatures will decrease	Stream temperature loggers
				Number of multichannel reaches will increase	Total station surveys of channel and stream adjacent terrace morphology. Aerial surveys
				Conversion from plane-bed to pool-riffle morphology	Habitat surveys
				Juvenile fish density will increase	Juvenile mark-recapture surveys 3x/yr
				Juvenile fish growth rate will increase	Juvenile mark-recapture surveys 3x/yr
				Juvenile fish size/fitness will increase	Juvenile mark-recapture surveys 3x/yr
				Groundwater levels will increase (only being monitored & tested in Lower & Upper Owens	Water level logger well fields
				Beaver colony density will increase	BDSS survey/Beaver dam census
Structure Level					
	Sunflower, Pat's Cabin, Meyers, L. Owens	Corral, Boundary, Woodward, U. Owens	1-3 years	Beaver will build dams on bare post lines	BDSS survey/Beaver dam census
				Reinforced Existing Dams will last longer than those that are unreinforced	BDSS survey
				Reinforced Abandoned Dams will last longer than those that are unreinforced	BDSS survey
				Post lines with willow weaves and starter dams will behave similarly to beaver dams as described below.	BDSS survey
				Reinforced beaver dams will have certain hydrogeomorphic effects:	
				1. A backwater pool will form upstream	BDSS survey
				2. A scour pool will form downstream	BDSS survey
				3. A transverse bar will form downstream of the scour pool	BDSS survey
				4. Stream-adjacent terraces will flood more frequently	BDSS survey
				5. A multi-channel planform will develop	BDSS survey
				6. Aggradation will occur upstream of the structure, eventually filling in the upstream pool	BDSS survey
				7. Beaver will utilize starter dams to establish new colonies	BDSS 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 site of Steelhead spawning	Redd surveys

DEFINING HYPOTHESES AT MULTIPLE SCALES

This study seeks to test hypothesis 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,
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 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 replication is low or not possible to best detect environmental impacts (Steward-Oaten and Bence, 2001). How long ‘after’ the treatment 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 Murderer’s Creek, where ongoing intensive monitoring of steelhead populations and physical habitat conditions is already occurring. Within the mainstem 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). Pre-project data has been collected in Bridge Creek since 2005. Post-project 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. To test this hypothesis we have been monitoring steelhead populations at the treatment and control sites within Bridge Creek and at the control sites on Murderers Creek (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 ‘partnering with 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, we hypothesize that beaver dams will elevate water tables, increase groundwater-surface water exchange, and thus potentially decrease stream temperatures. If there is sufficient long-term storage of water in alluvial aquifers, we hypothesize that summer baseflows may also increase.

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 of bars in areas of divergent flow can be helpful in forcing zones of convergent flow nearby that promote scour and the subsequent construction and/or maintenance of pool habitat (MacWilliams *et al.*, 2006).

At the reach scale we predict numerous changes in both 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, 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 result in 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, which will benefit steelhead and other salmonids (e.g. Chinook). 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 3-4 km^{-1}, with colonies generally occupying dam complexes comprised of 3 to 8 individual dams. As such, the individual structures placed in these reaches were typically placed in sequences of 5 to 8 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 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.

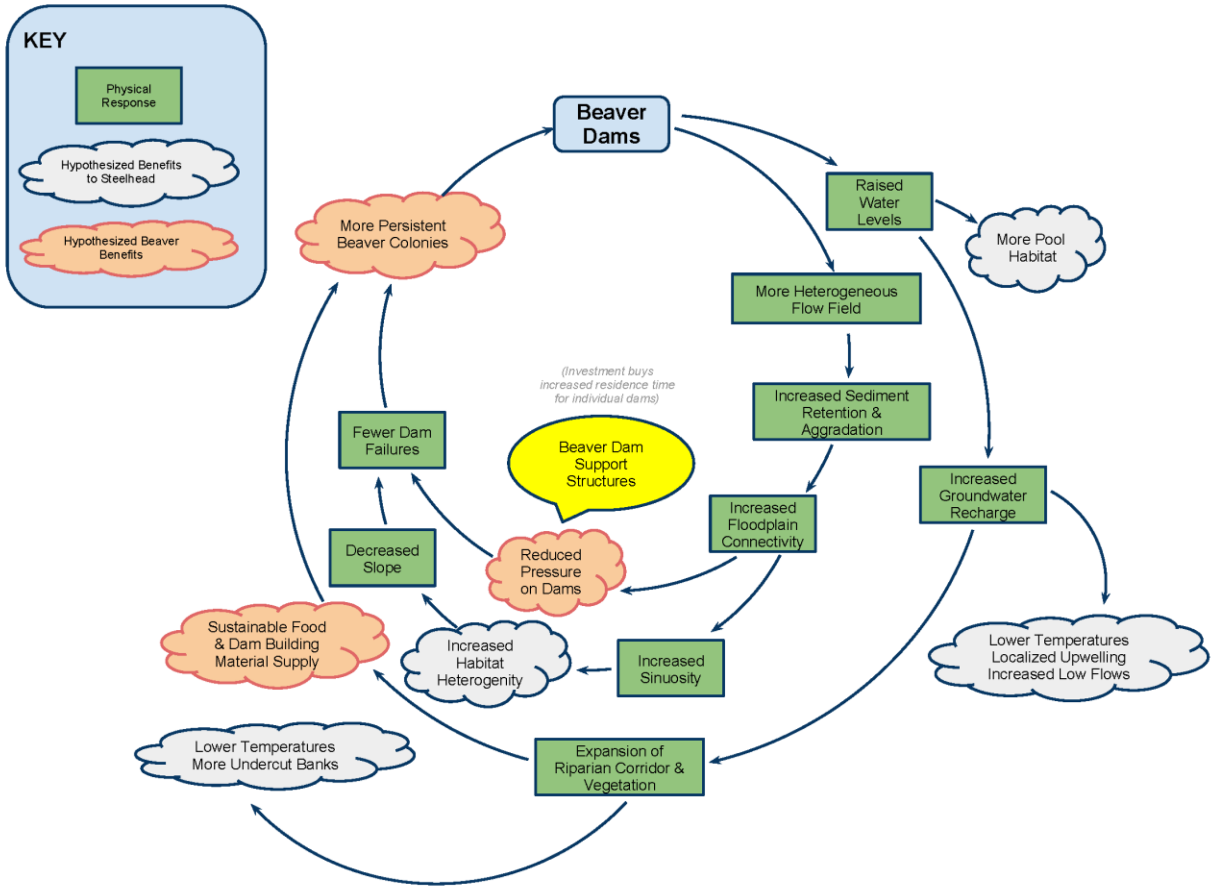

Figure 4 – Beaver Dam Feedback Loops. This conceptual diagram shows the hypothesized positive physical feedback loops for both beaver and steelhead from the presence of beaver dams. The key barrier to this feedback loop in Bridge Creek is that individual dams do not persist for long enough to realize or maintain the hypothesized (cloud) benefits. The yellow callout shows where beaver dam support structures (the primary restoration intervention) fits into this process.

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 both the response of beaver and the response of the stream to structures at both the scale of the individual structure and of 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 reinforced active dam or starter may back fill with sediment. The composition of that fill (i.e. fine or coarse sediment) depends on the availability of sediment sources (e.g. coarse gravels in Bridge Creek often sourced locally from bank failure of coarse-grained alluvial deposits). Likewise, for a post line or wicker weave, 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 relative to the objectives of the reach-scale treatment and the entire project** (Table 1).

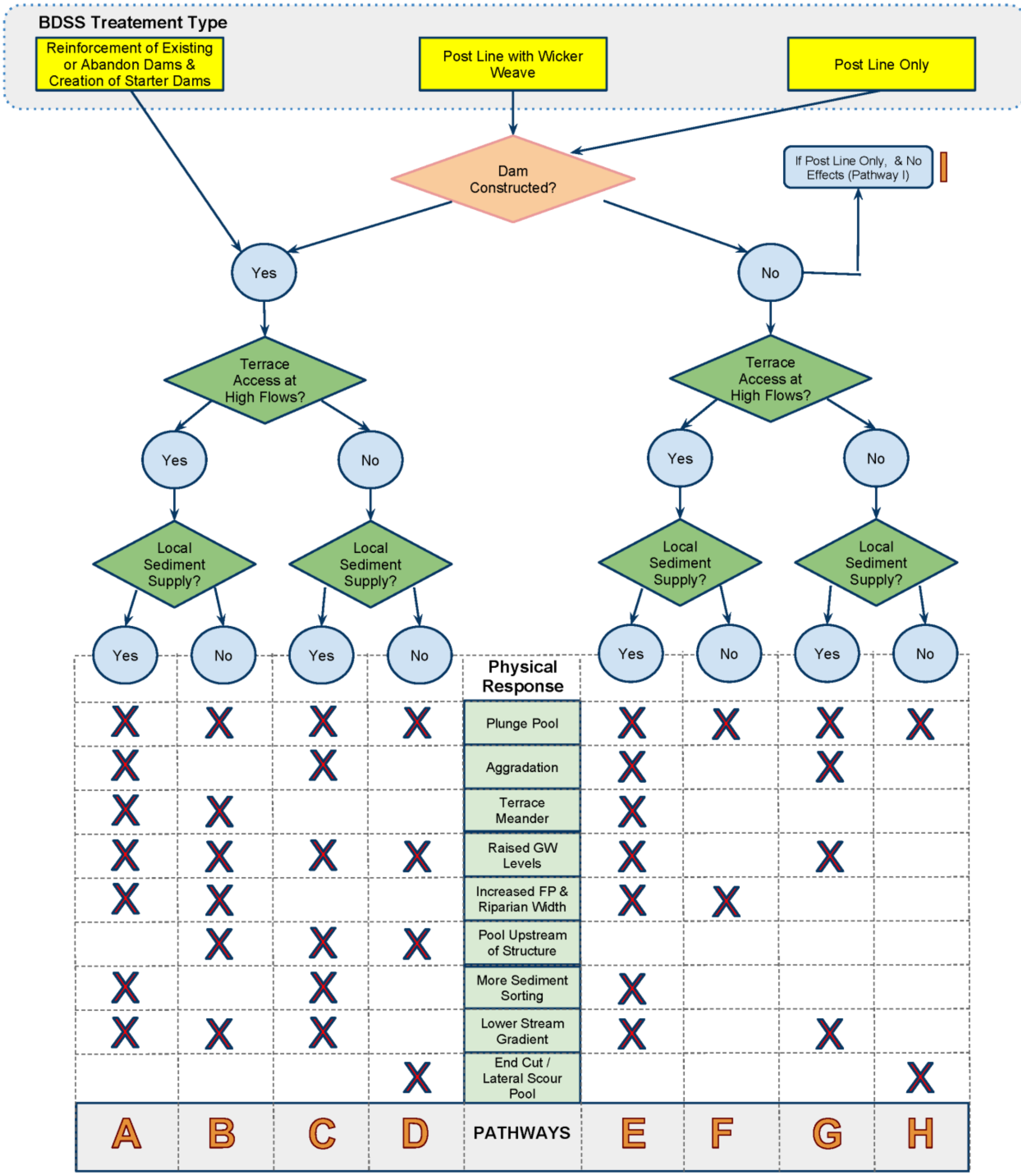

Figure 5. **A BDSS can follow multiple pathways (A through I) depending on the type of BDSS and the natural processes acting upon it. Thus the predicted hydrogeomorphic changes created by a structure largely depends on the timing, sequence and magnitude of natural processes such as beaver dam construction,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

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 under-seeded. Starter dams, wicker weaves and reinforced existing dams all were 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, post lines that are not colonized by beaver will likely promote trash racking which could lead to localized deposition and scour and even the potential washing out of part or all of the post line 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 head-cutting and undermining of structures upstream. Additionally, the presence of multiple structures in series provides capacity for a colony to build a dam complex of multiple dams. This is a typical strategy 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 as necessary promoting ‘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 of 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, threat of predation, exhaustion of building or food supplies, etc. Beaver colonies frequently move the focus of their activity within an area or a complex and 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 Tables 2 (Lower Owens) 3 (Meyer's Camp), 4 (Pat's Cabin) and 5 (Sunflower). The locations of each structure are shown for Lower Owens in Figure 6, for Meyer's Camp in Figure 7, for Pat's Cabin in Figure 8 and Sunflower in Figure 9. For additional maps of every individual structure, see Appendix A.

Table 2. Description and Observations of BDS Structures installed in Lower Owens Treatment Reach of Bridge Creek in September 2009. Pathways refer to those illustrated in Figure 5. See also Figure 5 for predicted hydrogeomorphic outcomes at specific structures.

BDS # (By Reach)	BDS # (Total)	Year Installed	Structure Type	Pathway Followed-see Figure 5)	Beaver Sign (Sept. 2010)	Sept. 2010 Notes	2010 (Sept.) Modifications/ Adaptive Management
LOWER OWENS							
LO-01	1	2009	PL	I	None	Trash racked on RR. Several posts lost in RL thalweg	reinstall missing posts, WW to divert flow to RL terrace and away from high eroding bank below
LO-02	2	2009	RAD	A	None	Mostly aggraded, appears stable, high unstable bank on RR providing sediment	None
LO-03	3	2009	RAD	A	None	Mostly aggraded, appears stable, high unstable bank on RR providing sediment	None
LO-04	4	2009	PL/WW	G	Some beaver cuttings	Aggraded to ht of WW, one post missing, long pool US of aggradation	Install new PL/WW above LO4 to bring high flows onto RR terrace
LO-05	5	2009	PL/WW	G	None	Posts not installed to optimal depths because of cement debris / cobble on RR. Several posts lost on RL and flow cutting into high bank on RR	Install new PL/WWs above LO5 to bring high flows onto RR terrace and divert flow away from high bank on RL
LO-06	6	2009	PL/WW	B	Beaver built small dam, but now appears abandoned	plunge pool didn't form because dam diverted flow to RL O/F channel-terrace meander	None
LO-07	7	2009	SD	A	Beaver cutting and some additions to SD, but now appears abandoned	Lots of aggradation and debris accumulation. Very solid structure. Terrace meander on RR where large cobble prevent installation of posts	Build up SD with new post line/WW just above existing line to bring more high flows onto RR terrace, and in to high flow channel near cottonwood
LO-08	8	2009	PL	H	a few beaver cuttings	Accumulated debris, limited functional benefits	WW and install a few posts on RR to push onto RR terrace during high flows
LO-09	9	2009	PL	H	None	Accumulated debris, pushing flow into RL bank	WW to control flow direction
LO-10	10	2009	PL/WW	G	None	Minimal WW, limited functional benefits	Improve WW
LO-11	11	2009	PL/WW	H	None	Deep plunge pool below. Aggradation, but not compete	None
LO-12	12	2009	PL/WW	G	None	Lots of aggradation US, deep pool DS created in part by LO13	None
LO-13	13	2009	SD	A	None	Flow mostly on RR, but some flow still on RL, pushing into high bank.	build new PL/WW upstream on aggraded bed to push flow onto RR terrace and away from high RL bank
LO-14	14	2009	PL/WW	G	None	Aggradation. Double row of posts.	None
LO-15	15	2009	SD	B	Some beaver cuttings	big meander formed on RR in OF channel, minimal deposition US. New channel is gravel bedded and complex	None
LO-16	16	2009	PL/WW	H	None	Flow is minimal in channel due to LO15 Meander	None

Abreviation Key: RAD = Reinforced Active Dam, RED = Reinforced Abandoned Dam, PL = post line, WW = wicker weave, SD = starter dam, RR = river right, RL = river left, US = upstream, DS = downstream.

Table 2 (Cont).

BDS # (By Reach)	BDS # (Total)	Year Installed	Structure Type	Pathway Followed-see Figure 5)	Beaver Sign (Sept. 2010)	Sept. 2010 Notes	2010 (Sept.) Modifications/ Adaptive Management
LOWER OWENS (cont.)							
LO-17	17	2009	PL/WW	B	old beaver activity on BDSS. Fresh beaver cuttings	BA/TRA sealed structure to make dam. Flow diverted on RL to create meandering and multi-thread channel. Pool and aggradation above. Complex	None
LO-18	18	2009	PL	I	None	long post line, waiting for beaver	None
LO-19	19	2009	PL	I	some dam-building on BDSS, beaver cuttings	minimally built BD and debris accumulation, but enough to push flow into RR side channel.	None
LO-20	20	2009	RED	A	recent beaver cuttings	Dam completely backfilled with sediment and flow now dispersed across RL terrace.	None
LO-21	21	2009	PL	I	None	multiple channels in this area, lots of debris accumulations near PL, but not because of PL	None
LO-22	22	2009	RED	A	Some beaver cuttings	Dam completely backfilled with sediment and flow now dispersed across RL terrace, in multiple channels	None
LO-23	23	2009	RED	A	Some beaver cuttings	Dam completely backfilled with sediment and flow now dispersed across RL terrace, in multiple channels	None
LO-24	24	2009	PL/WW	A	New B Dam	Active BD, flow dispersing across RL terrace	None
LO-25	25	2009	SD	A	debris and beaver activity improved dam	Lots of aggradation, multiple channels, complex	Raise BDSS with PL/WW just above channel to continue to push flow to RR terrace
LO-26	26	2009	RAD	X	None	Deep existing scour pool below dam led to headcutting of structure and loss of dam	rebuild PL, no WW
LO-27	27	2009	PL/WW	C	beaver improved PL/WW	Very aggraded probably in part due to LO26 failure, nice plunge pool below, undercut bank and pool above on RR	install new PL/WW on aggraded surface to bring high flows onto RL terrace
LO-28	28	2009	PL/WW	H	Some beaver cuttings	Posts lost in thalweg caused some loss of capacity to aggrade, but improved meandering	
LO-29	29	2009	PL/WW	A	Active BD	Active BD mostly filled with sediment.	install new PL/WW on aggraded surface to bring high flows onto RL terrace
LO-30	30	2009	PL/WW	B	Some beaver cuttings	Beaver activity plugged structure but doesn't appear actively maintained.	
LO-31	31	2009	PL/WW		Some beaver cuttings	Beaver activity plugged structure but doesn't appear actively maintained.	
LO-32A	32	2009	SD	A	Some beaver cuttings	RR Terrace Meander cut around 32B & C	Extend PL/WW across T meander
LO-32B	33	2009	PL/WW	H	Some beaver cuttings		Extend PL/WW across T meander
LO-32C	34	2009	PL/WW	H	Some beaver cuttings		Extend PL/WW across T meander

Abreviation Key: RAD = Reinforced Active Dam, RED = Reinforced Abandoned Dam, PL = post line, WW = wicker weave, SD = starter dam, RR = river right, RL = river left, US = upstream, DS = downstream.

Table 3. Description and Observations of BDS Structures installed in Meyer's Camp Treatment Reach of Bridge Creek in September 2009. Pathways refer to those illustrated in Figure 5. See also Figure 5 for predicted hydrogeomorphic outcomes at specific structures.

BDS # (By Reach)	BDS # (Total)	Year Installed	Structure Type	Pathway Followed-see Figure 5)	Beaver Sign (Sept. 2010)	Sept. 2010 Notes	2010 (Sept.) Modifications/ Adaptive Management
MEYER'S CAMP							
MC-01	35	2009	PL	A	Extensive beaver cuttings, near active dam	Aggradation diverted main flow to RL side channel, causing meander cut-off	Install PL above MC1 to divert flow to RR channel and prevent meander cut-off from occurring. Chinook spawning below.
MC-02	36	2009	RED	A	Active BD	Aggradation but also pool upstream- multiple channels, very complex habitat	None
MC-03	37	2009	RED	A		Aggradation but also pool upstream, hasn't filled in completely yet	extend post lines 2-3 posts on RR and RL to spread flow to RR terrace, as should have been done last year.
MC-04	38	2009	PL	I	some debris accumulation created minimal scour pool		WW
MC-05	39	2009	PL/WW	H	minimal scour	Minimal WW	Improve WW
MC-06	40	2009	PL/WW	H	minimal scour	Minimal WW	Improve WW
MC-07	41	2009	PL	I			WW
MC-08	42	2009	PL/WW	A	Beaver dam built above posts = excessive ds scour and posts tipping	Big deep scour pool downstream, posts tipped but not missing, top of BD above posts is gone	posts are loose in substrate and tipped. Straighten up and pound posts in a bit deeper
MC-09	43	2009	PL/WW	H	None	Minimal WW, minimal scour	improve WW
MC-10	44	2009	PL/WW	H	None	Minimal WW, minimal scour	improve WW
MC-11	45	2009	PL/WW	H	None	Minimal WW, minimal scour	improve WW
MC-12	46	2009	PL	I	None	minimal scour	WW
MC-13	47	2009	PL	I	None	lots of trash accumulation, big pool us that was pre-existing, some posts missing on RL	replace missing posts, improve WW
MC-14	48	2009	PL/WW	F	None	Minimal WW, minimal scour	improve WW
MC-15	49	2009	PL/WW	F	None	Minimal WW, minimal scour	improve WW
MC-16	50	2009	PL/WW	F		Deep pool above, some deposition below due to rock weir just below BDSS. *Not much evidence of local sediment supplies from MC 4-15	replace tipped posts, improve WW

Abreviation Key: RAD = Reinforced Active Dam, RED = Reinforced Abandoned Dam, PL = post line, WW = wicker weave, SD = starter dam, RR = river right, RL = river left, US = upstream, DS = downstream.

Table 4. Description and Observations of BDS Structures installed in Pat's Cabin Treatment Reach of Bridge Creek in September 2009. Pathways refer to those illustrated in Figure 5. See also Figure 5 for predicted hydrogeomorphic outcomes at specific structures.

BDS # (By Reach)	BDS # (Total)	Year Installed	Structure Type	Pathway Followed-see Figure 5)	Beaver Sign (Sept. 2010)	Sept. 2010 Notes	2010 (Sept.) Modifications/ Adaptive Management
PAT'S CABIN							
PC-01	51	2009	SD	A	Active BD	Posts were installed too low so no access to RR terrace during high flows which led to bank cut meander on RL	Rebuild PL to correct height, extend across RL meander and WW or let beaver work to push high flows to wide RR terrace
PC-02	52	2009	PL/WW	C	beaver cutttings	more or less complete aggradation with small plunge pool below and gravel bedding on aggradation	replace 1-2 posts that are slightly tipped
PC-03	53	2009	PL/WW	C	beaver cutttings	more or less complete aggradation with small plunge pool below and gravel bedding on aggradation	replace 1-2 posts that are slightly tipped
PC-04	54	2009	SD	A	some dam maintenance. Lodge us on RL	Both Aggradation and pool upstream. Some damage where fish passage was built on rl. Bedrock on RL so hard to get posts in deep enough	Repair with 1-2 posts and WW to push flow and scour to rr
PC-05	55	2009	PL/WW	D	some dam maintenance	Beaver activity throughout PC 1-9, lots of cuttings, varying levels of BDSS maintenance / improvements	Repair with 1-2 posts and some WW or let beaver work to push flow onto RL terrace.
PC-06	56	2009	PL/WW	D	some dam maintenance	Beaver activity throughout PC 1-9, lots of cuttings, varying levels of BDSS maintenance / improvements	Repair with 1-2 posts and some WW or let beaver work to push flow onto RL terrace.
PC-07	57	2009	PL/WW	D	some dam maintenance	Beaver activity throughout PC 1-9, lots of cuttings, varying levels of BDSS maintenance / improvements	Repair with 1-2 posts and some WW or let beaver work to push flow onto RL terrace.
PC-08	58	2009	PL	I	some dam maintenance. Lodge us on RR	This aggraded us and ds because of PC9. Not really used, but beaver lodge just us on RR	rebuild PL on us aggradation for beaver colonization to disperse flow across RL terrace and to help relieve pressure on PC9, which is quite high
PC-09	59	2008	PL	A	Active BD	bifurcated flow around BDSS. Plunge pool on RL at base of meander and away from BDSS.	Install several low posts on RL meander to keep water at height of BDSS. Note: 10/2010. beaver rebuilt low dam to plug meander just us of new posts
PC-10	60	2009	PL/WW	I	None	OHA requested removal over concern that stream x road crossing would be inundated	Remove all posts
PC-11	61	2009	PL	I	none	High risk location in deep trench, posts not deep in substrate because of cobble probability of blowout was high. Numerous posts missing	Abandon this structure
PC-12	62	2009	PL	I	beaver cuttings	High risk location in deep trench, probability of blowout was high, but not as high as previous structure. Numerous posts missing, thalweg scour pool	Rebuild PL/WW and hope beaver build a dam there or else it is likely to blow out again
PC-13	63	2009	PL/WW	C	Active BD	beaver actively working area to create pool extending from PC 12-15	reinforce dam with a few posts
PC-14	64	2009	PL	B	Active BD	Some flow dispersing to RL terrace	None
PC-15	65	2009	RAD	B	Active BD, Lodge us on RR	Extensive flow dispersal across RL terrace. Lots of new willow growth. New lodge	None

Abreviation Key: RAD = Reinforced Active Dam, RED = Reinforced Abandoned Dam, PL = post line, WW = wicker weave, SD = starter dam, RR = river right, RL = river left, US = upstream, DS = downstream.

Table 5. Description and Observations of BDS Structures installed in Sunflower Treatment Reach of Bridge Creek in September 2009. Pathways refer to those illustrated in Figure 5. See also Figure 5 for predicted hydrogeomorphic outcomes at specific structures.

BDS # (By Reach)	BDS # (Total)	Year Installed	Structure Type	Pathway Followed-see Figure 5)	Beaver Sign (Sept. 2010)	Sept. 2010 Notes	2010 (Sept.) Modifications/ Adaptive Management
SUNFLOWER							
SF-01	66	2009	SD	A	some cuttings and BDSS maintenance	SD was not built high enough to access RL Terrace, resulting in partial blowout	Rebuild PL and make sure it is high enough to access RL terrace during high flows and relieve pressure on SF2-6
SF-02	67	2009	PL/WW	H	none	SF 2-6 were all in a confined trench and did not have much terrace access during high flows. Sediment appears limited. Most had lateral scour pools, some bank erosion and loss of multiple posts	Rebuild PL and improve WW. If it blows out again, consider abandonment
SF-03	68	2009	PL/WW	H	none	see above	Rebuild PL and improve WW. If it blows out again, consider abandonment
SF-04	69	2009	PL/WW	H	none	see above	Rebuild PL and improve WW. If it blows out again, consider abandonment
SF-05	70	2009	PL/WW	H	none	see above	Rebuild PL and improve WW. If it blows out again, consider abandonment
SF-06	71	2009	PL	H	some cuttings	see above	Abandon and move PL/WW downstream slightly where high flow access to RR terrace is more likely.
SF-07	72	2009	SD	D	some cuttings	Deep lateral scour pool formed on RR where fish passage was built, resulting in SD failure, but aggradation from SF8 has lowered gradient and created a pool that partially encompasses SF7	reinstall missing posts and WW so high flow can access RR terrace
SF-08	73	2009	PL/WW	E	some cuttings	Nice terrace meander and plunge pool below	Increase height with new PL/WW to ensure that high flow moves to RL terrace and doesn't undermine structure and to help prevent scour at SF7
SF-09	74	2009	PL/WW	H	None	Not much sediment accumulation	none
SF-10	75	2009	PL/WW	H	None	Some aggradation and scour around BDSS, but not much sediment	Improve WW
SF-11	76	2009	PL	I	None	Slight accumulation of debris	None
SF-12	77	2009	SD	A	None	Dam scoured out where fish passage constructed, resulting in SD failure and scouring of sediment that accumulated upstream	Rebuild PL/WW so that high flows can access RL and RR terraces
SF-13	78	2009	PL/WW	H	None	Cottonwood branch WW. Not very effective	none
SF-14	79	2009	PL	I	None	Cottonwood branch WW. Not very effective	none
SF-15	80	2009	PL	I	None	Cottonwood branch WW. Not very effective	none
SF-16	81	2009	PL	D		Beaver built small dam in summer 2010, pushing flow into channel on RL up against high bank, but so far predicted effects are minimal. On path D at the moment	Extend PL to RL bank across high flow channel so beaver have more structure to work with.
SF-17	82	2009	SD	A	Active dam	Both Aggradation and pool upstream, dispersed flow across RL terrace. Has the most beaver activity in SF	none
SF-18	83	2009	PL/WW	H	some cuttings	Not much of a plunge pool downstream, probably because RR posts failed early, steep gradient, not a good location for a structure.	none
SF-19	84	2009	PL/WW	C	some cuttings	Performed well, but not much aggradation because of steep gradient	none
SF-20	85	2009	PL/WW	C	some cuttings	Perfromed well, but not much aggradation because of steep gradient	None

Abreviation Key: RAD = Reinforced Active Dam, RED = Reinforced Abandoned Dam, PL = post line, WW = wicker weave, SD = starter dam, RR = river right, RL = river left, US = upstream, DS = downstream.

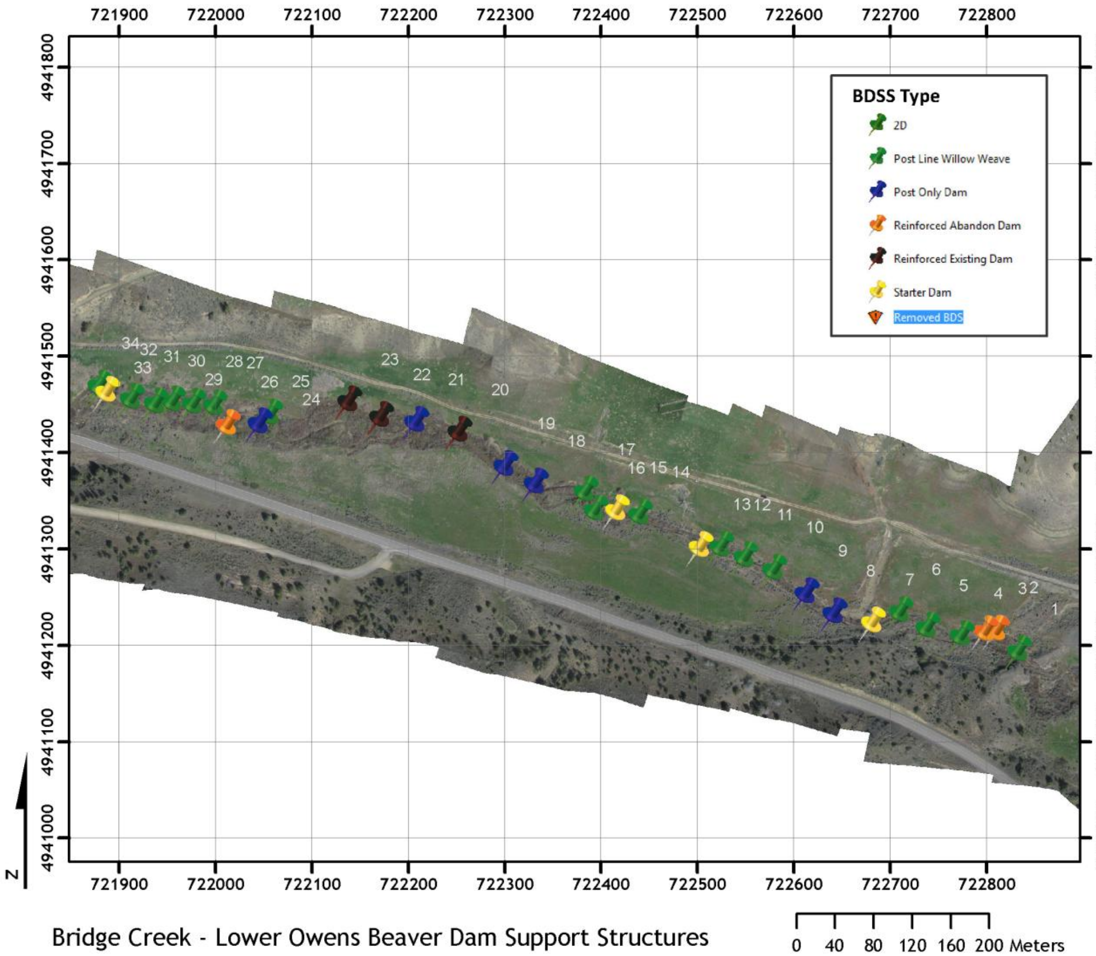

Figure 6. Location of BDS structures installed in 2009 in the Lower Owens Reach.

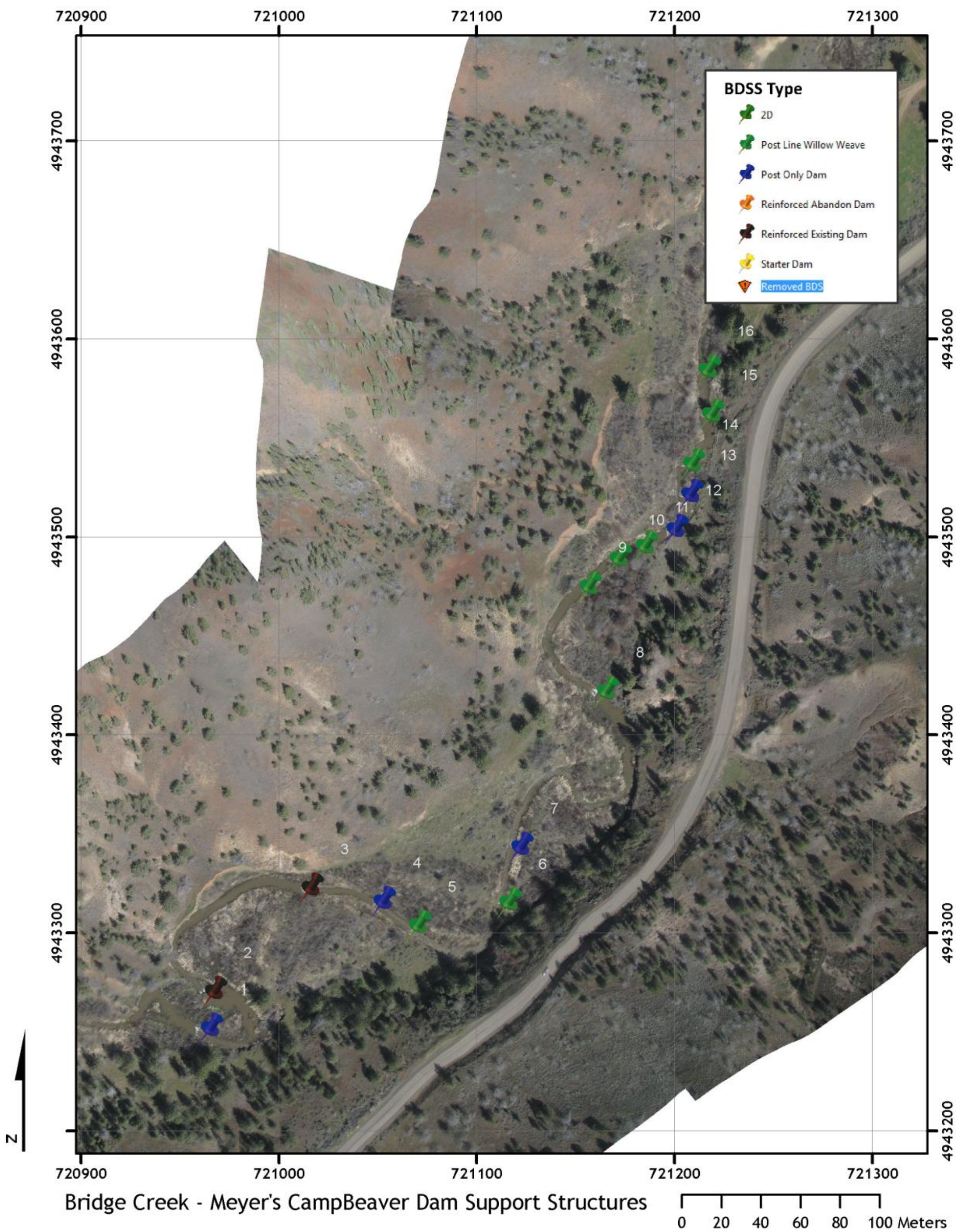

Figure 7. Location of BDS structures installed in 2009 in the Meyers Camp Reach.

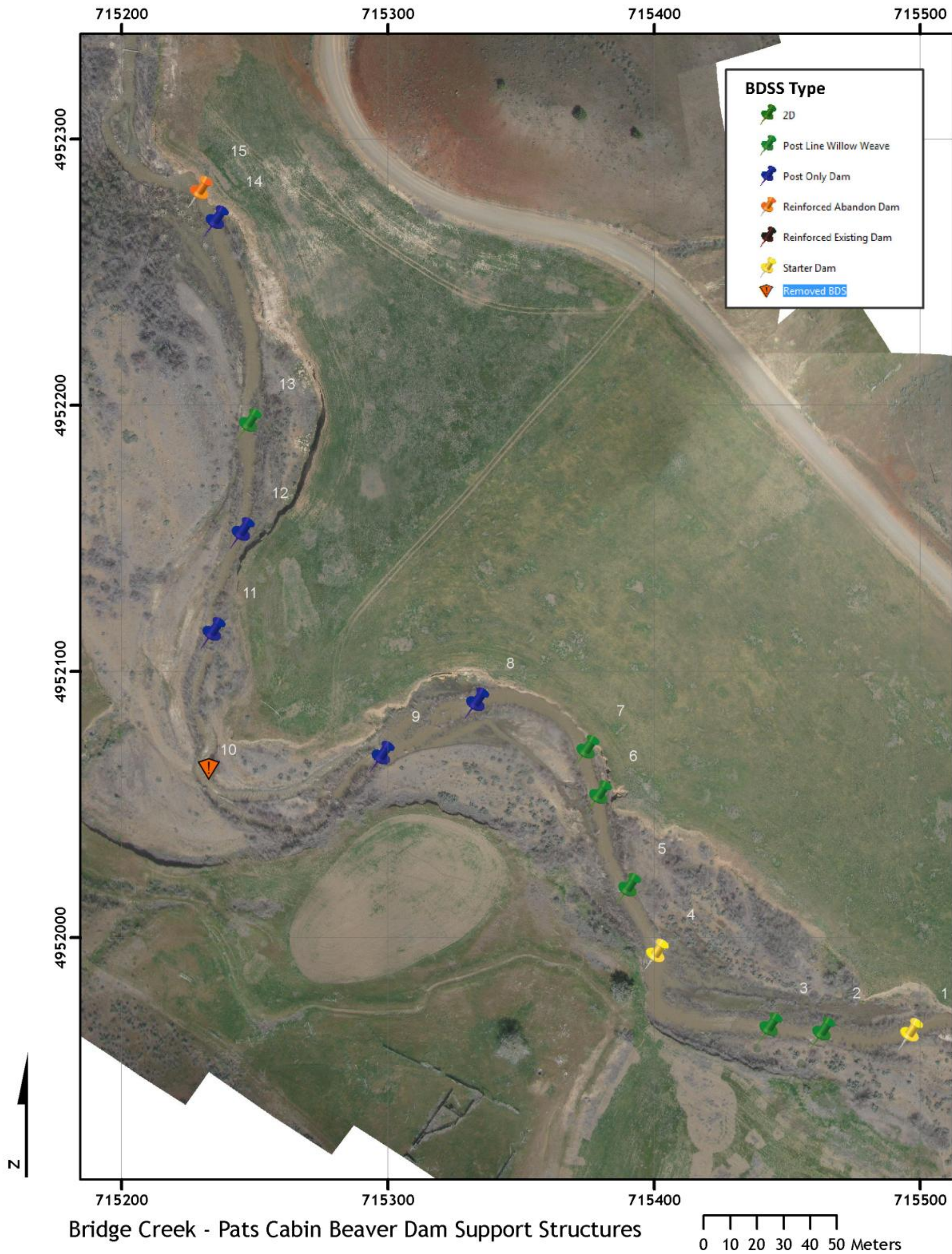

Figure 8. Location of BDS structures installed in 2009 in the Pats Cabin Reach.

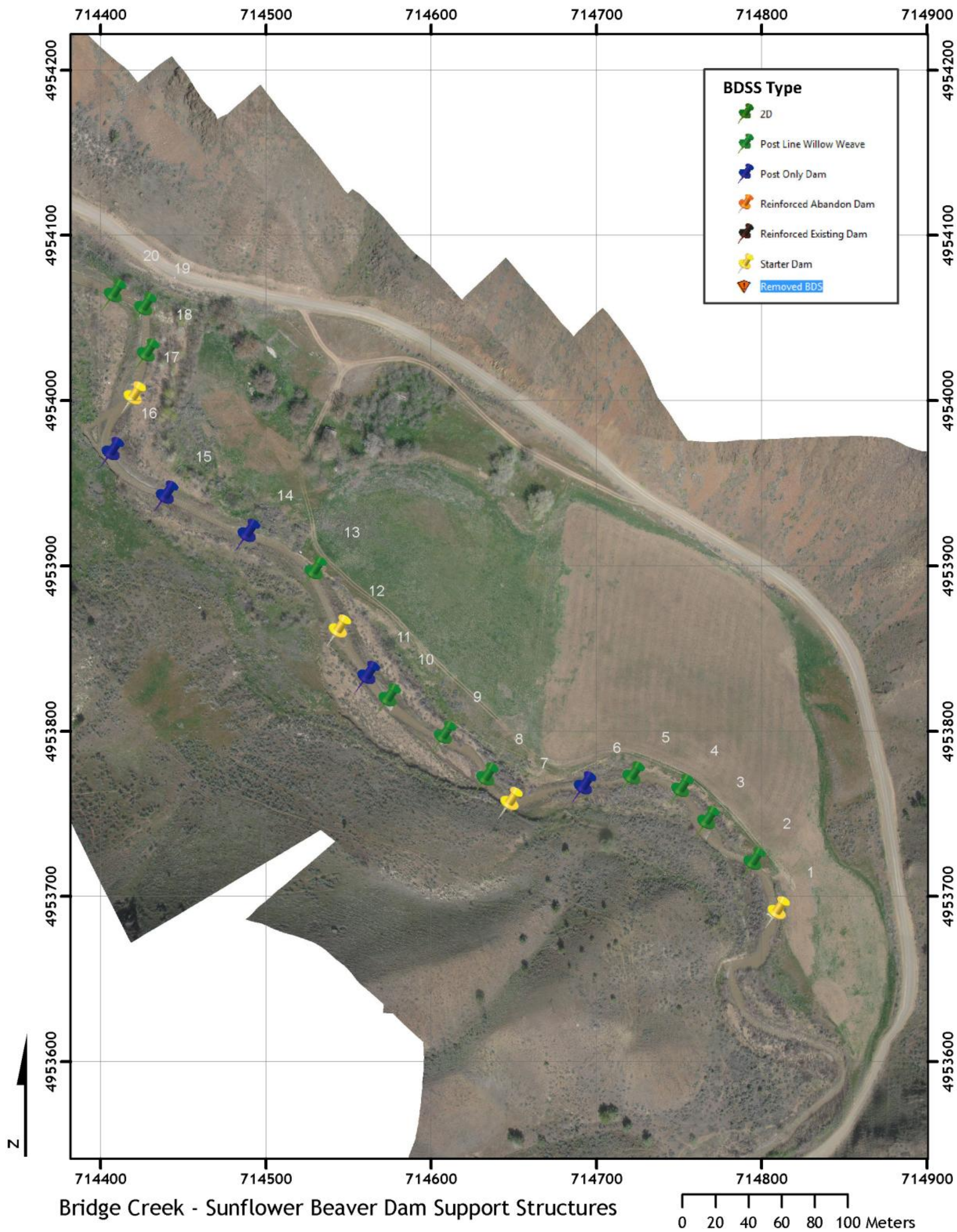

Figure 9. Location of BDS structures installed in 2009 in the Sunflower Reach.

Below we elaborate on the different BDS structure types and their design rationale.

STARTER DAMS

Starter dams (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 that were 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 ad building supplies (e.g. existing wood and riparian vegetation)
5. There was no existing beaver colony nearby (i.e. within 300 m)

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

POST LINES WITH WICKER WEAVES

Post Lines with Wicker Weaves (Figure 11) were the most common type of structure installed and served a variety of purposes. They were always placed where aggradation was both desirable and 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 in stream sinuosity
- Increases in the number of pools (from mix of beaver pond upstream of structure, scour pool downstream of structure, and bar forced pools)
- To direct flow away[1] from an eroding cut bank
- To 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 was determined by site-specific geomorphic conditions.

Figure 11. A post line with wicker weave is similar to a starter dam, but acts more like a weir in that water is allowed to flow through the willow branches such that low flows are not over topping 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 on the right of the photograph, aligned parallel to the flow.

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 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

[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 BLM, this opportunity was avoided and in some cases actively discouraged as part of the design.

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 post lines with wicker weave roughly simulate some of the functions of beaver dams, and in particular help to cause aggradation of the stream bed 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 post lines were installed. Eventually, as the wicker weaves allow for floodplain reconnection within much of the treatment area and the existing beaver population expands (either naturally or through supplementation), the need for wicker weaves should diminish as they begin to be replaced by actual beaver dams.

POST LINES

Post Lines (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 PLWW, post lines by themselves were limited to sites where there was minimal risk if no aggradation occurred because beaver did not did not use them to build a dam. These structures were not intended to be functional unless beaver utilized them to build a dam.

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

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.

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 one 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 post lines just downstream the beaver were able to use them to build new dams which allowed the colony to persist.

STRUCTURE INSTALLATION

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 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 systems throughout the west 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.

The physical construction methods are described here. All structures were built with 2 m long, 7-10 cm diameter, untreated lodgepole pine fence posts that were stripped of their bark. Using a chainsaw, a point was made at one end of the post. The posts were space approximately 0.5-1 m apart and driven into the active channel and inset floodplain with a handheld hydraulic post-pounder (e.g. see Crowder Hydraulic Tools: http://www.crowderhydraulictools.com/hydraulic-post-drivers.htm) that uses inert mineral oil. 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- 1.5 m, but may be as high as 2 m (Pollock et al. unpublished data). Where the depth of the incision trench was greater than 1 m, the elevation of the post lines were either left at 1 m above the channel bed or cut down to about 0.5 m. The risk of having structures > 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, end-cutting 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.

Post lines with wicker weaves and starter dams 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 head cutting 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 was the preferred material for wicker weaves, as it sends out runners that produce shoots that form dense groves of long stemmed shoots that are relatively unbranched. Long branches or 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 meters of structures). Since coyote willow primarily reproduce vegetatively, harvesting of building materials for the wicker weaves actually promoted regrowth, similar to the response observed when they are thinned by beaver. Further, the food value 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 wicker weaves 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 wicker weaves. The wicker weaves 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 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 wicker weaves were designed to be initially permeable to water, starter dams were intended to form a pool upstream and to 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 post line should either be straight or convex downstream (i.e. the center of the post line within the bankfull channel is the most downstream post) with the ends of the post line extending upstream along the bank(s), typically 5-10 m, when bank erosion is not desired. A straight post line perpendicular to the main flow promotes parallel streamlines. A straight post line 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 BDSS and creating excessive scour, which can undermine the posts.
2. Where possible, post lines extended roughly perpendicular to stream flow along any low terraces within one meter 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 (Figures 10 and 14). Where appropriate, a gap was left on the terrace post line 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. However, in some cases, 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 also 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.

In September and November, 2010, approximately one year after installation, all the structures were surveyed to assess the evolution pathway each followed, to assess the extent of beaver activity, to examine structural integrity and to determine if there were any surprising or unexpected outcomes.

Figure 14. Any abandoned dams with significant structure remaining were also 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) and one immediately below it after it was breached by high flows. Within a year following reinforcement by posts, beaver rebuilt the dam and built two more dams on postlines immediately upstream (PC 13 and 14-just visible upstream in the photograph), resulting in a flooded terrace and complex, multichannel habitat forming on river left and diverting flow away from a high exposed bank or river right.

RESULTS

RESTORATION TREATMENT

A total of 84 structures were installed in four different treatment reaches (Tables 2-5). The four treatment reaches included Lower Owens, Meyers Camp, Pats Cabin and Sunflower (Figures 6-9). Of the 84 BDS structures installed, five were reinforced existing dams (REDs), four were reinforced abandoned dams (RADs), ten were new starter dams (SDs), forty-four were wicker weaves (WWs) and twenty one were post lines (PLs) (Tables 2-5).

Appendix A shows three different Scales of Maps: A) an overview scale (i.e. the reach), B) a Mid-view scale (i.e. the future dam complexes) and C) BDSS View (i.e. the individual structure). The mid-view scale also shows 1 m contours from 2005 Airborne LIDAR survey by Watershed Sciences. The majority of the maps fall within coverage of two base map imagery datasets. The first was a blimp survey flown primarily in November of 2009 and the second was a drone survey flown in April of 2010.

PRELIMINARY MONITORNG OBSERVATIONS

HYPOTHESIS TESTING AT THE WATERSHED SCALE

Recall, the primary hypothesis we are testing at the watershed scale is whether 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). With only the first year of post treatment fish monitoring data, it is far too early for us to test this hypothesis. Similarly, we will require multiple years of data to assess whether there has been an increase in baseflow and an increase in the beaver population.

HYPOTHESIS TESTING AT THE REACH SCALE

At the reach scale we hypothesized that the physical changes brought about by the structures and beaver activity would result in several positive feedback loops that will culminate in improved habitat conditions for beaver that in turn will lead to the construction of more beaver dams, which will continue to improve habitat conditions for steelhead and make it more suitable for the establishment of stable beaver colonies. Within the first year of treatment, we did see both physical responses and beaver activity that begin to help test this hypothesis (Table 2). However, this preliminary evidence only provides part of the support for this self-sustaining feedback hypothesis and more time is needed to thoroughly test this idea.

BEAVER ACTIVITY

Beaver utilized a number of structures, and the level of activity varied by treatment reach (8/34, 4/16, 10/14, 3/20, for L. Owens, Meyers, Pats Cabin and Sunflower, respectively). There was clear evidence of beaver dam maintenance on 25 of the structures (i.e. 30%). Given the size of the current beaver population, and the over-seeding philosophy of the design, this is a relatively high utilization rate.

LOWER OWENS

When structures were installed in Lower Owens Reach, beaver were in the process of building dams centered around what would eventually become structure LO22. Three dams that were in the process of being built were reinforced with posts (LO20, LO22 and LO23) and beaver continued to increase the height or the length of these dams after post installation. Beaver also built another dam upstream of LO20 that did not use a BDS structure. A year after installation all four of these dams had mostly filled with sediment but there still evidence of some dam maintenance by beaver. There was also evidence of beaver dam building activity on LO17, LO19, LO24 and LO25, LO27 and LO29. There is extensive evidence of beaver cuttings from LO17 to LO34 and it appears that there is a healthy colony or colonies of beaver in the area.

Above LO17 the reach becomes more confined and locations suitable for beaver dams are limited, even with structures present. However on the upper end of Lower Owens Reach, two abandoned dams were reinforced (LO2 and LO3) and a starter dam was installed on LO7. A year later, there was evidence that beaver had done some maintenance on LO7 and had begun to build a dam on LO6, but appears to have subsequently been abandoned. There was evidence of recent feeding in the area, but so far nothing to suggest that an active dam-building colony is being established. The LO8-LO13 cluster is in a highly confined reach and beaver activity is mostly absent. There was very minimal cutting activity near the LO13 starter dam, the only location suitable for a wide dam. The LO14-17 cluster also had minimal activity, but the LO15 PLWW and L17 starter dam raised water levels sufficient to back flow up onto high flow channels, helping to create multiple channels and increase sinuosity, helping to create an environment more suitable for beaver. There appear to be four areas of activity in Lower Owens that are thought to correspond to four colonies, but lodges have not been identified in all areas and the exact number of colonies is unknown.

MEYERS CAMP

Prior to the installation of BDS structures, Meyers Camp had an one large existing dam and another very low dam (< 20 cm). When we began installing structures, we reinforced the large dam, installed a post line on the low dam and placed an additional 14 structures in the reach. Almost immediately, the beaver raised the level of the small dam to the height of the posts (about 1 m) and built a third dam on the next structure upstream. Another large dam was built a ways downstream of these three dams (MC8, which was a post line). This dam was built approximately 30 cm above the post line height. During high spring flows, the dam height lead to excessive scour downstream, creating a 1.5 m deep pool, but also undermining the posts and causing the dam to breach in the center. A year after installing the structures, there is still abundant activity at the 3 dams at the upper end of the reach and evidence of beaver cuttings in isolated places further downstream but no additional dam building. The MC 9-16 cluster was not utilized by beaver. Meyers Camp has at least one active colony at the upstream end, with either a second colony or solo beaver in middle portion of the reach.

PATS CABIN

There were high levels of beaver activity at the Pats Cabin reach, with 10 of 14 structures being utilized by beaver. There were also 3 new lodges, and cuttings were apparent throughout the reach even near structures that were not used by beaver to create dams. Activity appears to be centered on PC1 and PC8, both starter dams, and PC15, a reinforced abandoned dam. Essentially the entire reach was being utilized by beaver except for the area just upstream and downstream of a low-flow road crossing. No structures were installed near the road so as to avoid flooding it, and one structure (PC10) was removed because it was determined to be too close to the road. This left 14 structures that could be utilized by beaver. Prior to the placement of structures, bank beaver were present, but there were no beaver dams with 5 km of the reach. We do not yet have precise estimates of the beaver populations and number of colonies in Bridge Creek, and for now must infer number of colonies from number of lodges, dams, and dam complexes. Pats Cabin reach is currently being maintained by at least two distinct beaver colonies, but could be as many as four.

SUNFLOWER

Prior to installation of the BDS structures, Sunflower Reach had minimal beaver activity, perhaps one or two bank beaver at the downstream end. Following structure installation, beaver began utilizing the areas around the 3 of the 4 starter dams built in the reach (SF1, SF7 and SF17), as evidenced by dam maintenance, fresh cuttings and feeding stations. Most of the activity was centered around SF17 and a year later, a new dam was being started on SF16, but activity is minimal. SF7 was undermined by excessive scour during spring floods and there was minimal activity observed a year after installation. There was evidence of fresh dam maintenance on SF1, but beaver usage of most of the structures throughout the reach was minimal, and a year after installation, beaver activity was low. Currently, it appears that Sunflower is being maintained by 1-2 active colonies, one at the upstream end and one at the downstream end, though some of this activity could be from a solo beaver. No wood lodges have been observed, and the beaver are presumed to be living in the banks.

HYPOTHESIS TESTING AT THE SCALE OF INDIVIDUAL STRUCTURES

PATHWAYS FOLLOWED

Table 2 describes each of the type of structures installed in fall of 2009 and the pathway (Figure 5) that was being followed one year later in the fall of 2010. A total of 84 structures were installed in four different treatment reaches: 5 reinforced existing dams, 4 reinforced abandoned dams, 10 starter dams, 44 wicker weaves and 21 post lines (Tables 2-5). REDs, RADs and SDs, generally followed path A (dams that flooded terraces and stored sediment), the path that was most beneficial in terms of creating geomorphic changes that help restore stream function. Overall, 23 of 84 structures had followed path A only a year after installation, the most of any path.

Wicker Weaves followed the highest diversity of paths, in part because of their total number (44), but also because they were the least predictable in terms of assessing likely geomorphic outcomes. Eighteen of 44 WWs followed path H, which along with 4 PLs that followed Path H, make it the second most commonly followed Path after Path A. Path H (no dam, no terrace access and no sediment accumulation) provided minimal geomorphic changes that helped restore stream function and was not a particularly desirable outcome. Another 15 WWs were utilized by beaver or trapped enough debris that they functioned as dams (Paths A-D) and helped to increase stream function, Another 8 WWs slowed the flow of water such that terrace flooding occurred during high flows (Path F), but did not trap sediment, nor were they used by beaver.

Of the 21 Post lines installed, 12 of them followed path I, that is nothing happened to them. They were not utilized by beaver and did not accumulate appreciable amounts of debris. They simply remained as a line of posts, continuing to provide a site for beaver dam construction. Dams were formed on 5 of the Post lines, four following Path A and one following Path D, and debris accumulated on another 4, sufficient to cause some minimal geomorphic changes (Path H).

GEOMORPHIC CHANGES

Over 168 maps showing the placement of all 84 individual structures with high-resolution, low altitude aerial imagery are shown in Appendix A. As the topographic surveys following construction in 2009 and a year later in 2010 were spatially continuous for each treatment reach, detailed topography and change detection maps over one year of change can also be derived for all 84 structures (e.g. Figure 15). These detailed analyses are ongoing. Figure 15 shows one example at Pats Cabin reach of the topographic changes recorded from repeat rtk-GPS surveys of the reach and a basic uncertainty analysis using techniques described in Wheaton et al. (2010). Figures 15A & C show that the net response was one of channel aggradation by over 245 m^3 in a system that has tended to be extremely prone to strong pattern of net incision (degradation). Interestingly, as Figures 15B & D suggest, there was a complex but spatially coherent and predictable pattern of both erosion and deposition that led to this net aggradation. Roughly 40% of all the volumetric change was aggradation in ponds above BDS structures (e.g. Figure 15 E & F), which was often coupled with creation of small scour pool below the BDS structure and subsequent creation of transverse and lateral bar deposits immediately downstream of the scour pools. Thus, in the first year of post restoration monitoring, the BDS structures are promoting precisely the hypothesized response of pond aggradation leading to floodplain reconnection (see aerial photos). Interestingly, the structures are also promoting systematic alternating patterns of erosion and deposition which are acting to break up the armored and homogenized plane-bed habitat of the channel into a dynamic mix of deep pools (which are desperately needed by steelhead for rearing, temperature refugia and foraging) as well as fresh active gravel bars (excellent spawning habitat).

This same type of data has been collected at all four treatment reaches as well as six other control reaches in Bridge Creek. Topographic surveys are repeated annually in November after leaf-off and prior to winter and spring high-flows. The geomorphic change detection analysis allows direct spatio-temporal quantification of the restoration response and geomorphic response to beaver activity.

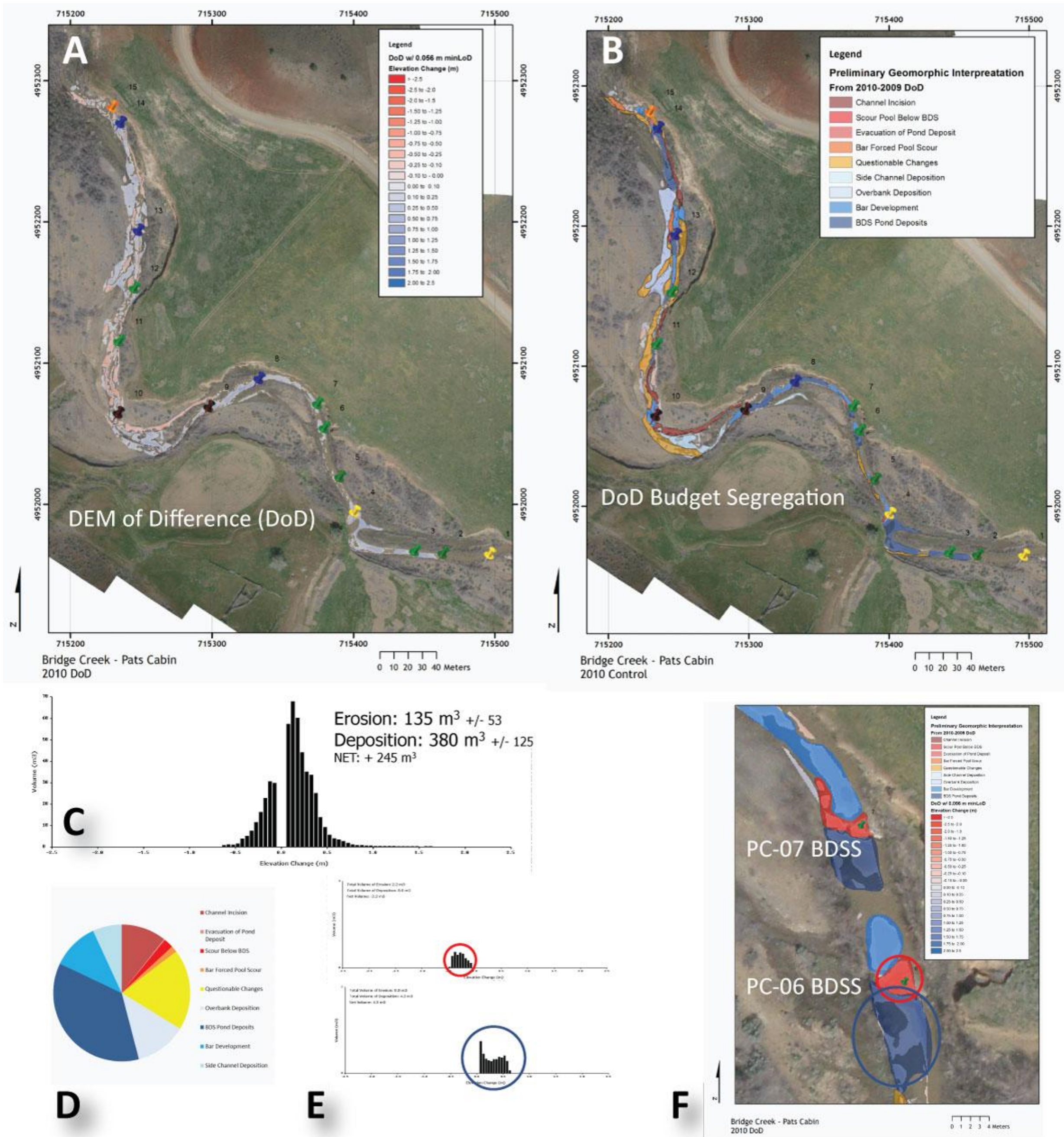

Figure 16 – Example of Geomorphic Change Detection using DEM Differencing (DoD) at Pats Cabin Reach. A. DoD of whole reach (red is erosion, blue is deposition) calculated from November 2009 to November 2010 rtk-GPS surveys. B. Segregation of DoD into specific geomorphic processes (e.g. BDS Pond aggradation, bar development, etc.). C. Elevation Change Distribution of reach showing net deposition. D. Relative magnitudes of different geomorphic processes (volumetric). E. Example elevation change distributions of BDSS Pond aggradation (bottom) and Scour in pool downstream of BDSS at PC-06. F. Budget segregation used to quantify geomorphic change at each individual BDS S.

DISCUSSION & PRELIMINARY FINDINGS

Our first year of post treatment data suggest that reinforcing beaver dams or creating beaver dam analogs (starter dams) resulted in physical changes to an incised stream that will help to restore basic functions essential to the creation and maintenance of a dynamic high quality instream and riparian habitat (Figure 16). Owing to Bridge Creek's high sediment supply, flashy flow regime, and the readily erodible nature of the alluvial valley fill Bridge Creek occupies, Bridge Creek possesses a great potential for maintaining a dynamic and diverse physical habitat. That dynamism should not be confused with the instability that lead to the incision and degradation of physical habitat into the relatively stable current system state. Instead, that dynamism is something that when combined with the room to adjust and structure provided by beaver activity can lead to relatively stable and resilient ecosystems.

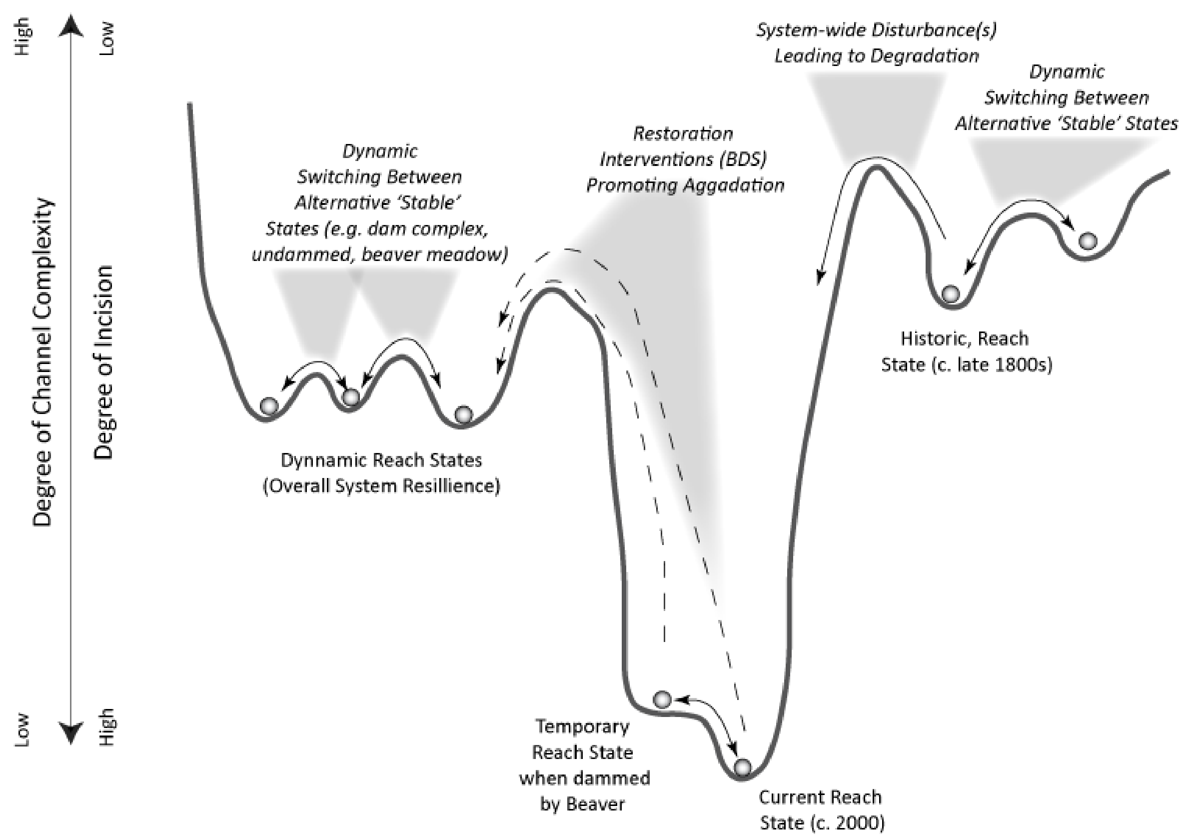

Figure 16. Conceptual Model of System States in Bridge Creek. The troughs represent persistent system states (marbles) and contrasts the inferred historic conditions (right) in contrast to current conditions (middle) and where the hypothesized system state will be in response to restoration intervention and beaver activity (left).

Structures that trapped sediment to aggrade stream beds and raised water levels high enough to disperse flow across stream-adjacent terraces improved habitat in a number of important ways. These include raising water tables, which should lead to an increase in riparian vegetation, an increase in alluvial groundwater storage and possibly an increase summer low flows; increasing the frequency, extent and depth of pool habitat; increasing stream sinuosity, stream complexity and floodplain connectivity; increased instream habitat heterogeneity (e.g. conversion of cobble-dominated plane-bed habitat to pool-riffle sequences with a mix of cobble, gravel and fine dominated substrates). Dams that did not disperse water over terraces and/or dams that did not cause upstream bed aggradation provided fewer benefits, but still improved habitat.

Most structures that were not or did not become dams generally provided fewer benefits, which in all our treatment areas combined were slightly more than half the structures. However, most of these structures still functioned to increase the quantity and quality of pools, and some trapped sediment and pushed water across stream-adjacent terraces during high flows, helping to improve groundwater recharge, provide refugia for fishes during floods, and provide opportunities for establishment of riparian vegetation. Still, many of the non-dam BDS structures will be limited in their ability to improve habitat until a dam is formed, either from beaver activity and/or the accumulation of debris.

At the treatment level, much of Lower Owens and Pats Cabin reaches have aggraded measurably throughout, enough to significantly improve floodwater access to stream-adjacent terraces in many places. In upper Lower Owens, where the incised channel was too deep to install structures high enough to push floodwaters onto stream-adjacent terraces, there has been substantial aggradation. Now, new post lines can be installed on aggraded surfaces and these will be high enough to disperse water across terraces if wicker weaves, starter dams or beaver dams are built. At Sunflower and Meyers Camp, there has still been significant aggradation, but it is concentrated where the beaver colonization and activity is concentrated.

There has been substantial aggradation throughout much of the Pats Cabin Reach above many of the BDS structures, and the photo-point series taken during two flood events (April 24, and May 23, 2010) Figure 17 show that the structures helped disperse floodwaters across stream-adjacent terraces and away from a high eroding bank. Both Pats Cabin and Lower Owens seem to have an abundant nearby sediment source in the form of exposed banks formed from erodible, alluvial deposits on wide valley floors. In contrast, Meyers Camp and Sunflower are within and downstream of more confined reaches with numerous bedrock constrictions. Though both of these reaches contain areas with wide alluvial valleys, the amount of aggradation in both these reaches was on the whole much lower and we hypothesize that this is due to a reduced upstream sediment supply. It is noteworthy that in both Meyers Camp and Sunflower, the most aggradation was upstream of the uppermost structure. Below SF1 there was little obvious aggradation until SF8 and then again until SF17. In Meyers Camp MC1 had the most aggradation followed by MC2 and then MC3. Downstream of MC3, the amount of aggradation was minimal. These observations lend support to the hypothesis that these two reaches had very little sediment recruitment within the reach and that sediment inputs upstream of these reaches were limited. Because both Lower Owens and Pats Cabin had substantial aggradation throughout and there was no downstream trend, it appears that their was ample sediment supplies from both upstream and from within the reach. The flows in Meyers Camp appeared to be more moderate and less erosive, even though there was enough terrace to erode if flows had been higher. This is in part because there are many relatively low terraces and the high sinuosity may lead to more subsurface flow. At any rate, there are few signs of erosion. In contrast, Sunflower had numerous erodible banks and evidence of scour, but the structures didn’t hold up well under high flows and this may be the reason that they did not accumulate sediment. The structures that did remain intact, many were post lines that were not colonized by beaver and that offered limited flow resistance. The PLWW that remained intact were low, generally 0.5 M in height, and many did in fact tend to accumulate sediment.

In retrospect, Meyers Camp may be an anomaly, with its gravel bedded river and meandering minimally incised channel. This illustrates the importance of identifying potential sediment sources, as many of the benefits of the restoration and in particular, the long term goal of aggrading the stream bed cannot be achieved without a sediment supply. Also it is important to note that as the stream becomes more stable and there is less bank erosion, that may reduce the rate of recovery. This points out the fact that structure is needed to keep the streams from downcutting again and getting isolated from the floodplain as the floodplain rises above the stream bed, that is, aggradation of the stream bed needs to aggrade commensurate with floodplain deposition and this is best ensured by continual addition of instream structure such as beaver dams, or where appropriate, large wood and boulder weirs.

CONCLUSIONS

The incised and degraded habitat of Bridge Creek is thought to be limiting the population of listed steelhead. We are partnering with an existing, but limited beaver population to restore geomorphic, hydrologic and ecological functions of this degraded system. The primary hypothesis we wish to test 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 and abundance of native steelhead. In 2009, 84 beaver dam support structures were installed and within one year of installation, 30% of these have been occupied. Geomorphic change detection has revealed that the occupied dams are promoting net aggradation of entire treatment reaches, increasing pool habitat and reconnecting former floodplain surfaces (i.e. terraces) and overall dramatically improving habitat conditions for steelhead. Continued monitoring will reveal whether these short-term gains can be sustained and enhanced by an expanding beaver population.

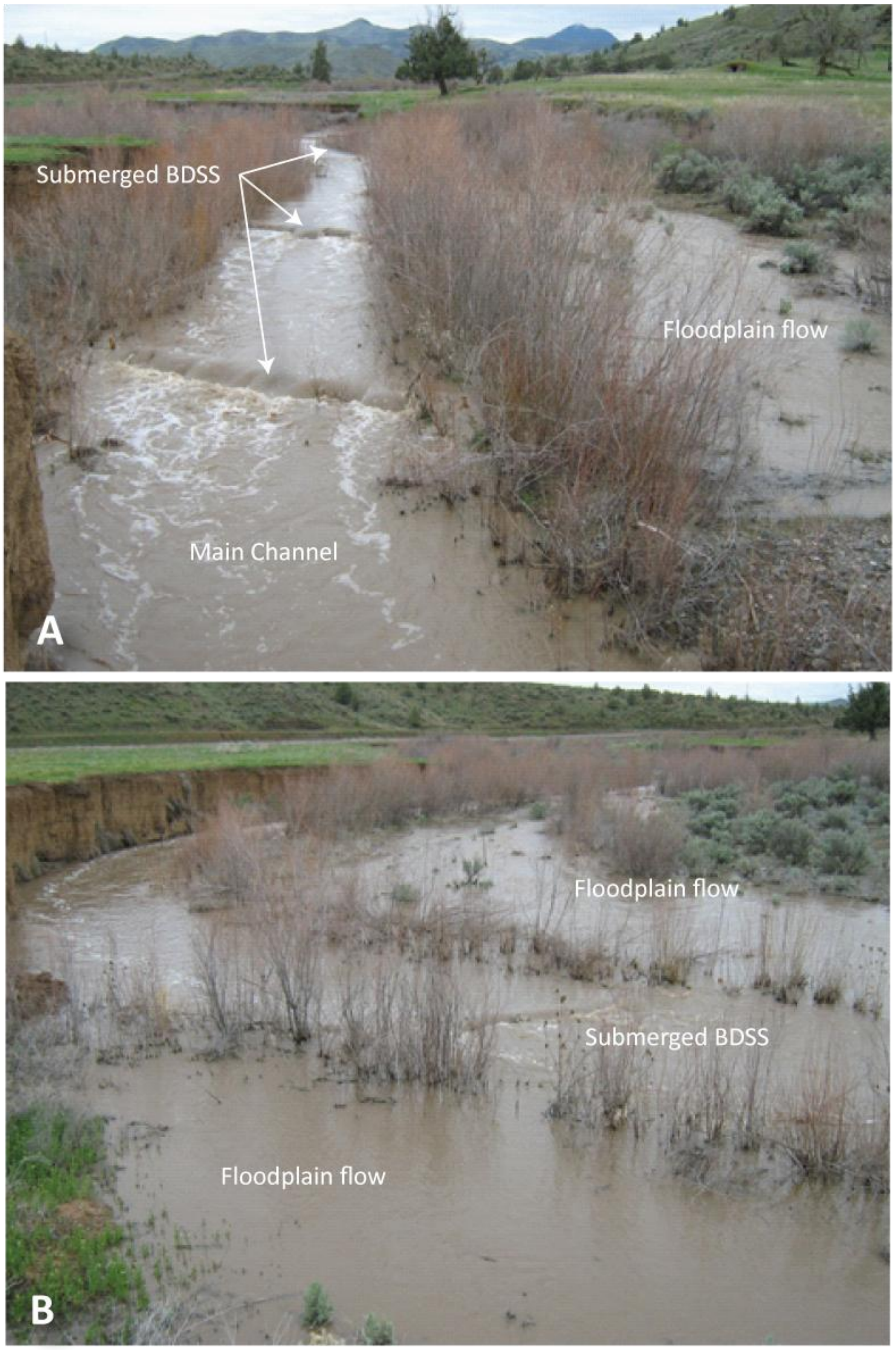

Figure 17. Two PLWWs during a high flow event in April, 2010, when flow exceeded 100CFS (A). The structures are helping to disperse flow across the river left terrace (inset floodplain) and away from a high eroding bank on river right just downstream of the structures (B).

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APPENDIX A – BDS STRUCTURE MAPS

Appendix A is comprised of 198 individual maps showing the location of the BDS structures. The maps are overlaid on two basemaps: i) a blimp aerial photography survey performed in November of 2009 by USU's ET-AL, and ii) a drone aerial photography survey performed in April of 2010. The drone imagery provides complete coverage of all BDS structure sites, whereas the blimp has some gaps in coverage in the upper part Lower Owens reach and the upper half of the Pat's Cabin reach. Maps are provided at three scales: BDSView, MidView and Overview. For each of the 84 BDS structures, two maps (one on each base) are provided (the BDSView). The Overview shows all structures within the reach and is similar to those figures shown in Figures 6-9. Finally the MidView maps divide the reaches into 2 or 3 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. As such, the Print and PDF versions of this report contain links in Table A1 to all the individual maps.

Table A1 – Hyperlinks to all the static PDF maps (by reach). Overview maps show all structures in the reach; Midview Maps show several BDS structures within the reach; BDSView maps show just individual BDS structures.

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 Blimp • 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)

A web portal for navigating to each map by browsing, through interactive maps or Google Earth *.kmz files has also been created at http://www.joewheaton.org/Home/research/study-sites/bridge-creek/2010-bds-structures, and shall be considered part of this report (Figure A1). Only ten of the MidView images are shown here for reference (Figures A2-A11). 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 A12).

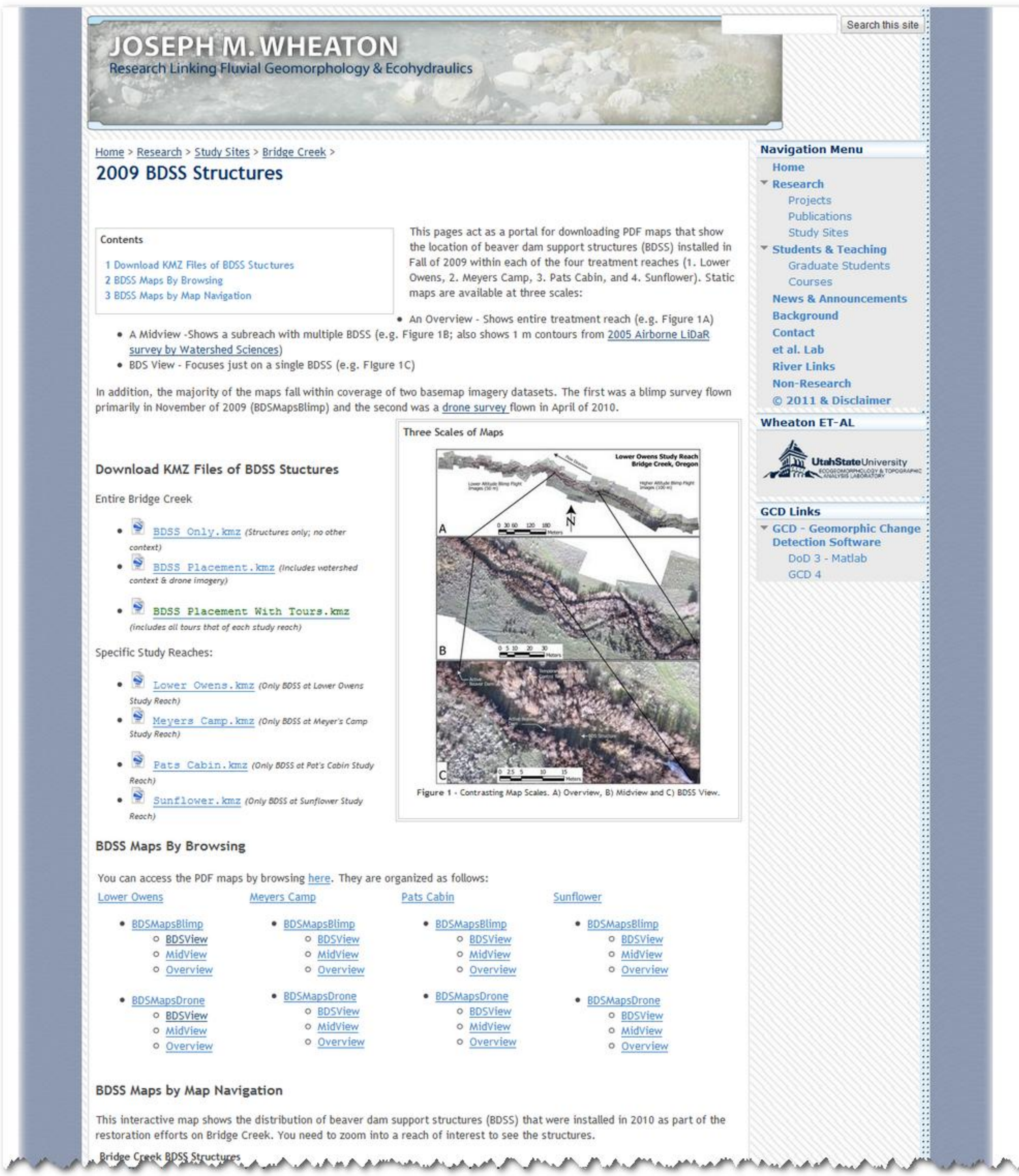

Figure A1 – Screenshot of web portal for downloading individual PDF maps and browsing interactively in Google Maps for this Appendix at: http://www.joewheaton.org/Home/research/study-sites/bridge-creek/2010-bds-structures.

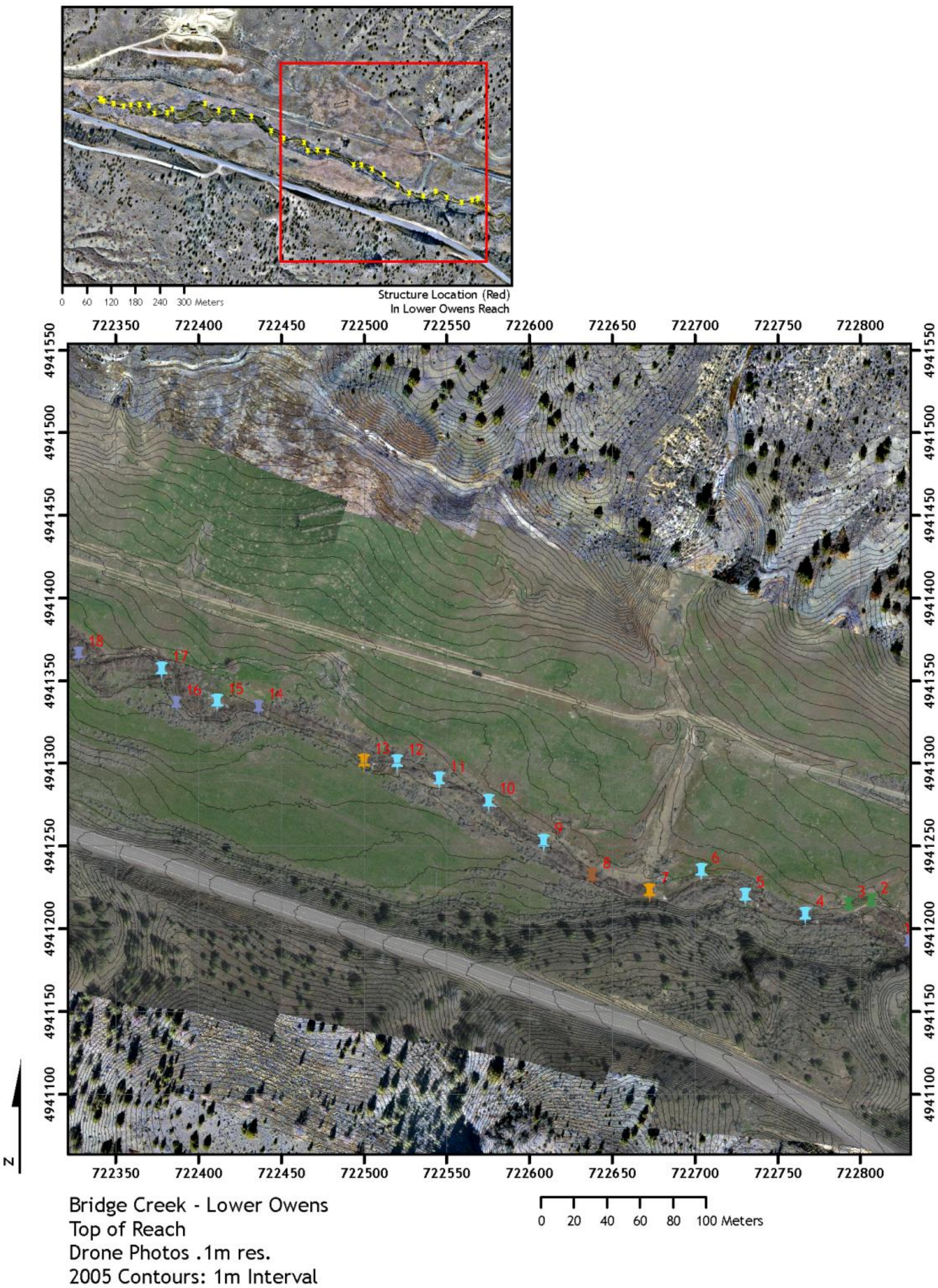

Figure A2 – Midview Map of Upper Reach at Lower Owens with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1)

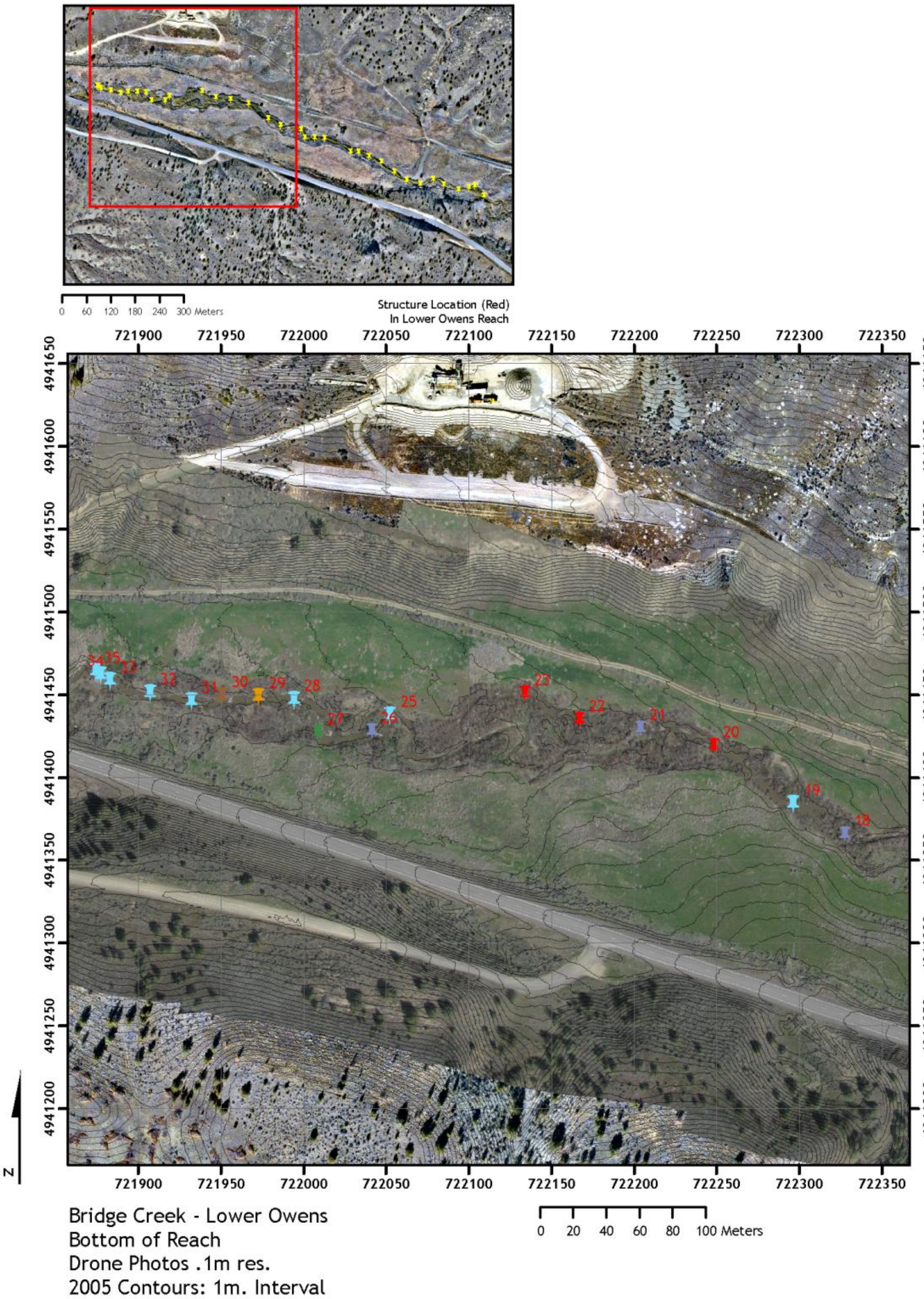

Figure A3 – Midview Map of Lower Reach at Lower Owens with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1)

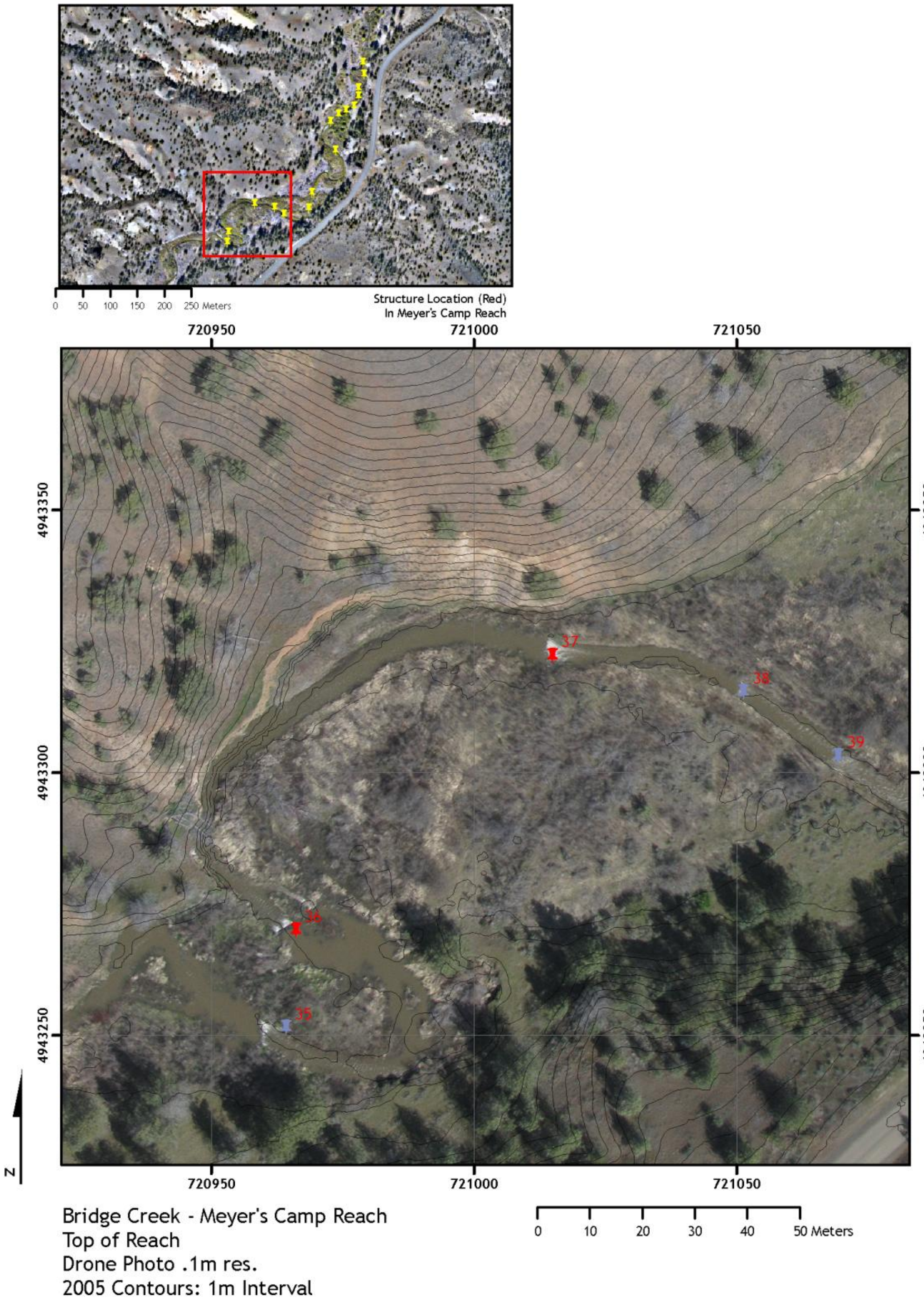

Figure A4 – Midview Map of Upper Reach at Meyer's Camp with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1)

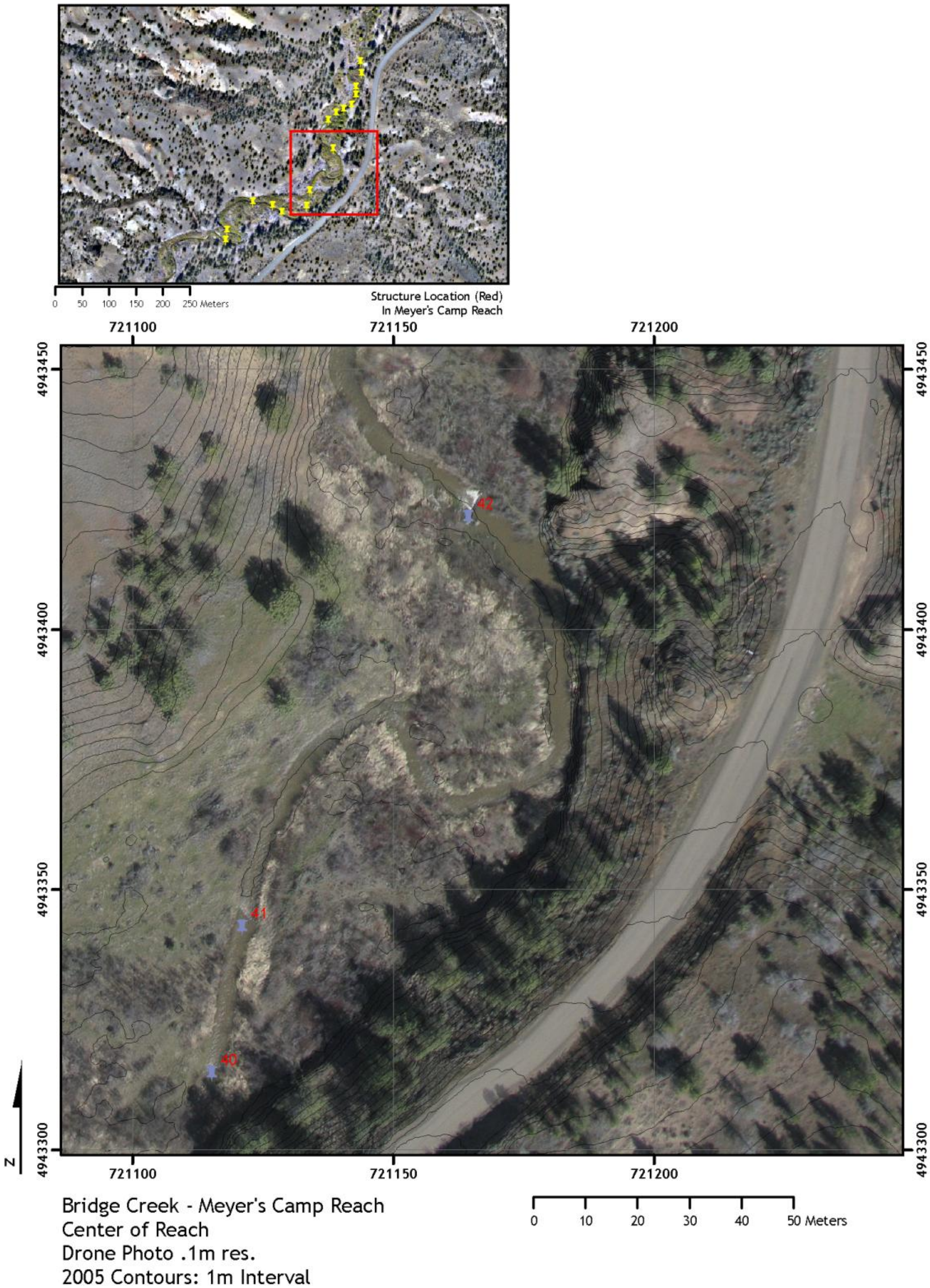

Figure A5 – Midview Map of Middle Reach at Meyer's Camp with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1)

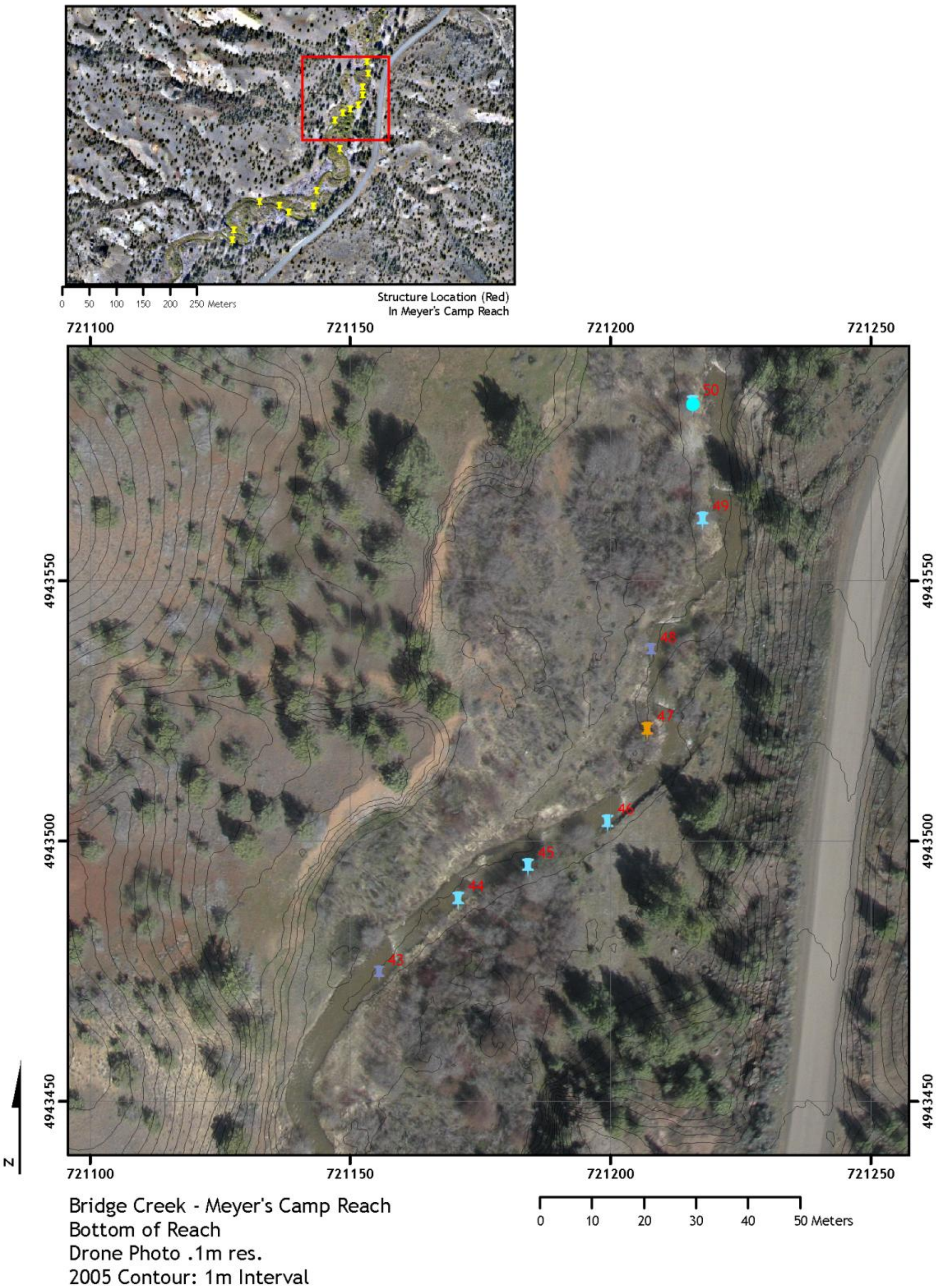

Figure A6 – Midview Map of Bottom Reach at Meyer's Camp with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

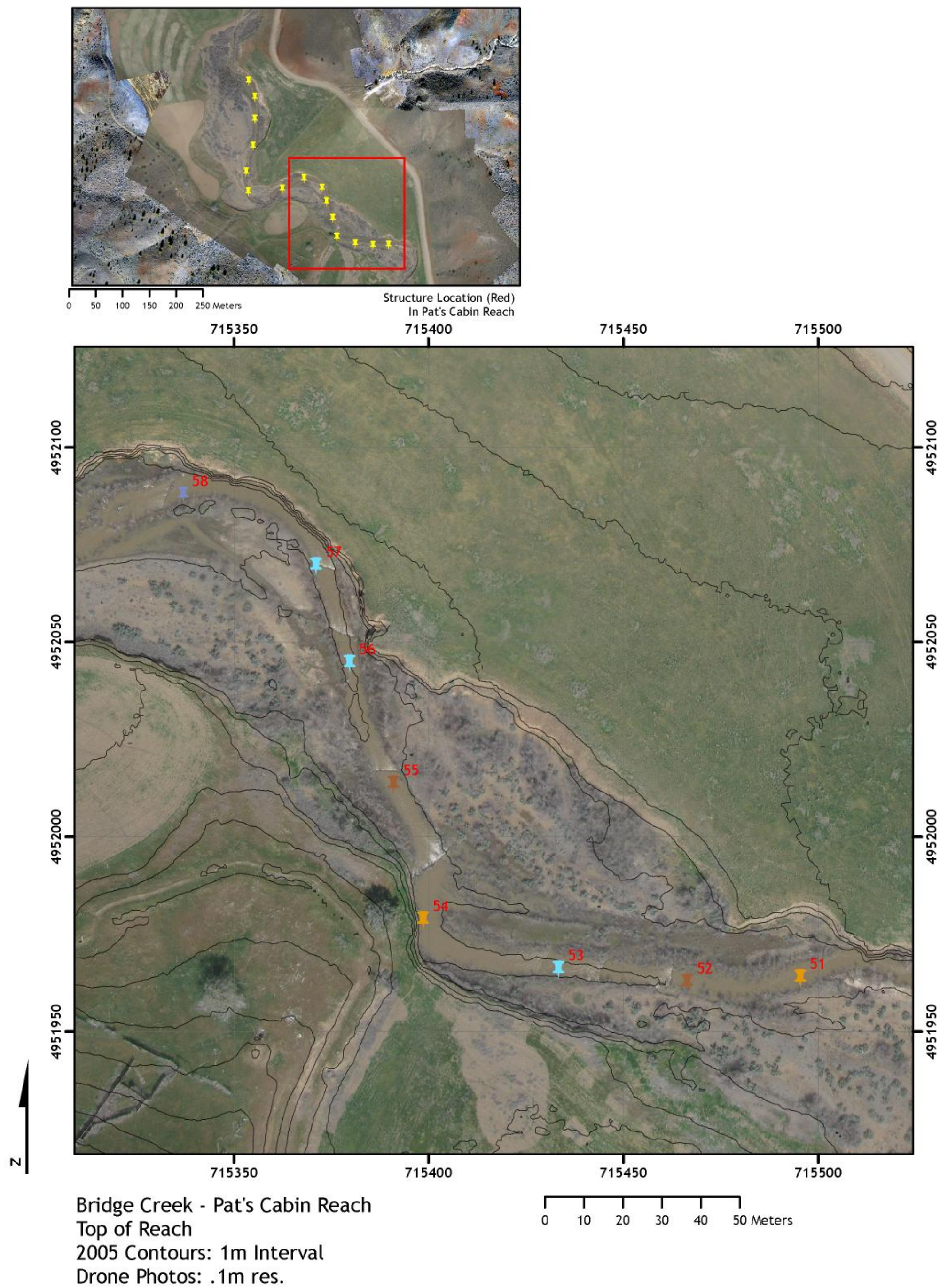

Figure A7 – Midview Map of Top Reach at Pat's Cabin with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at:
http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

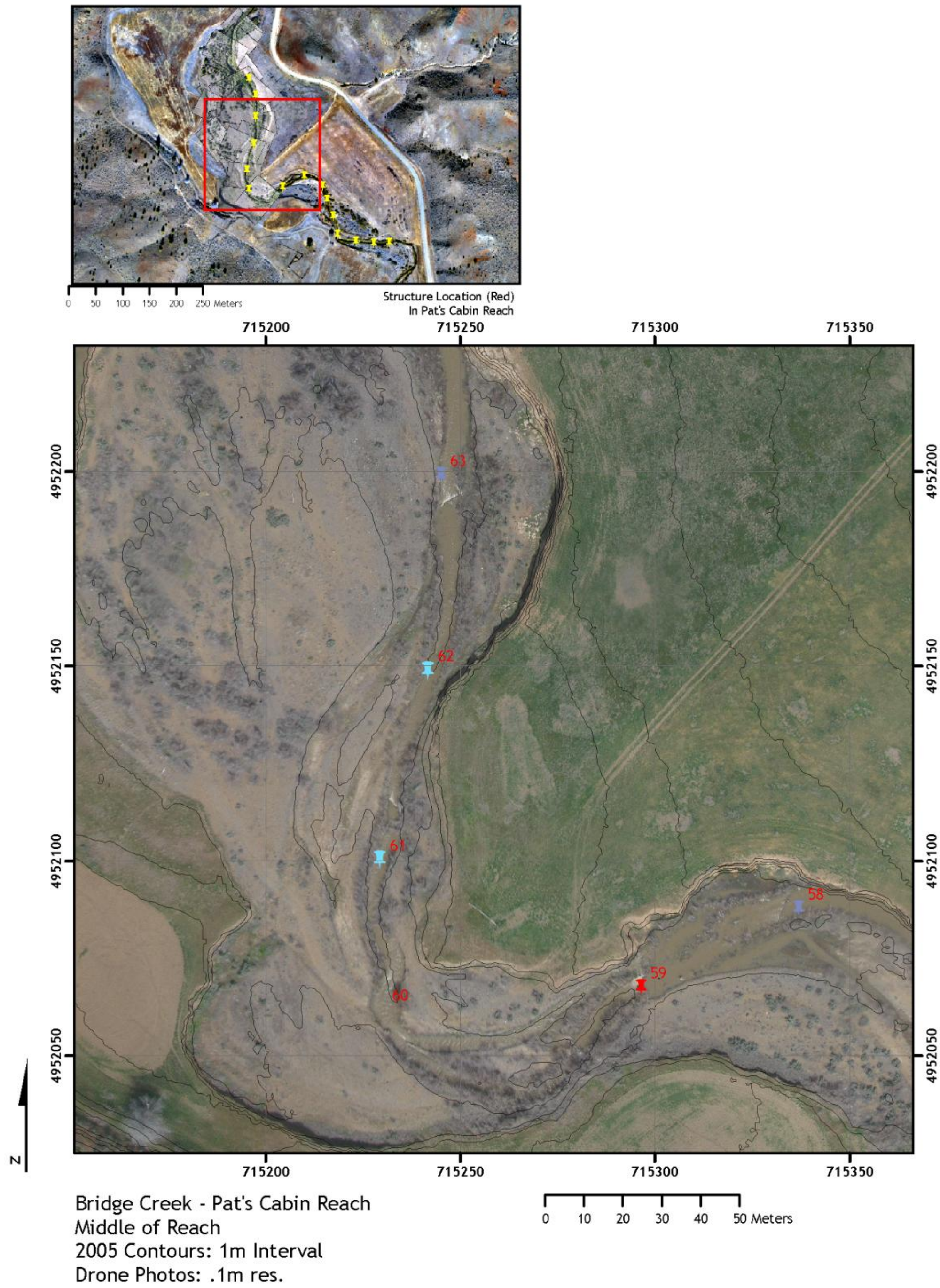

Figure A8 – Midview Map of Middle Reach at Pat's Cabin with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

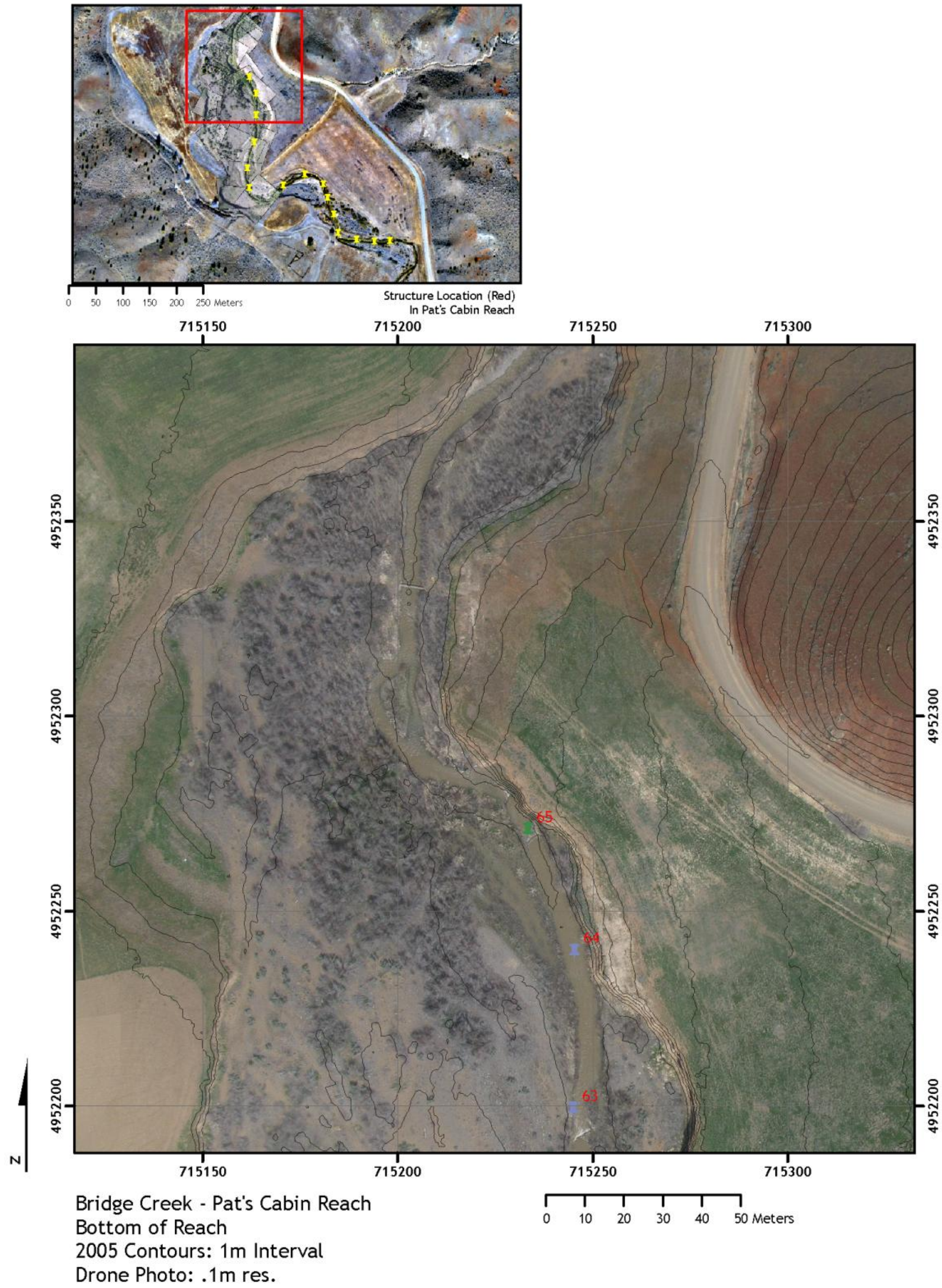

Figure A9 – Midview Map of Bottom Reach at Pat's Cabin with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

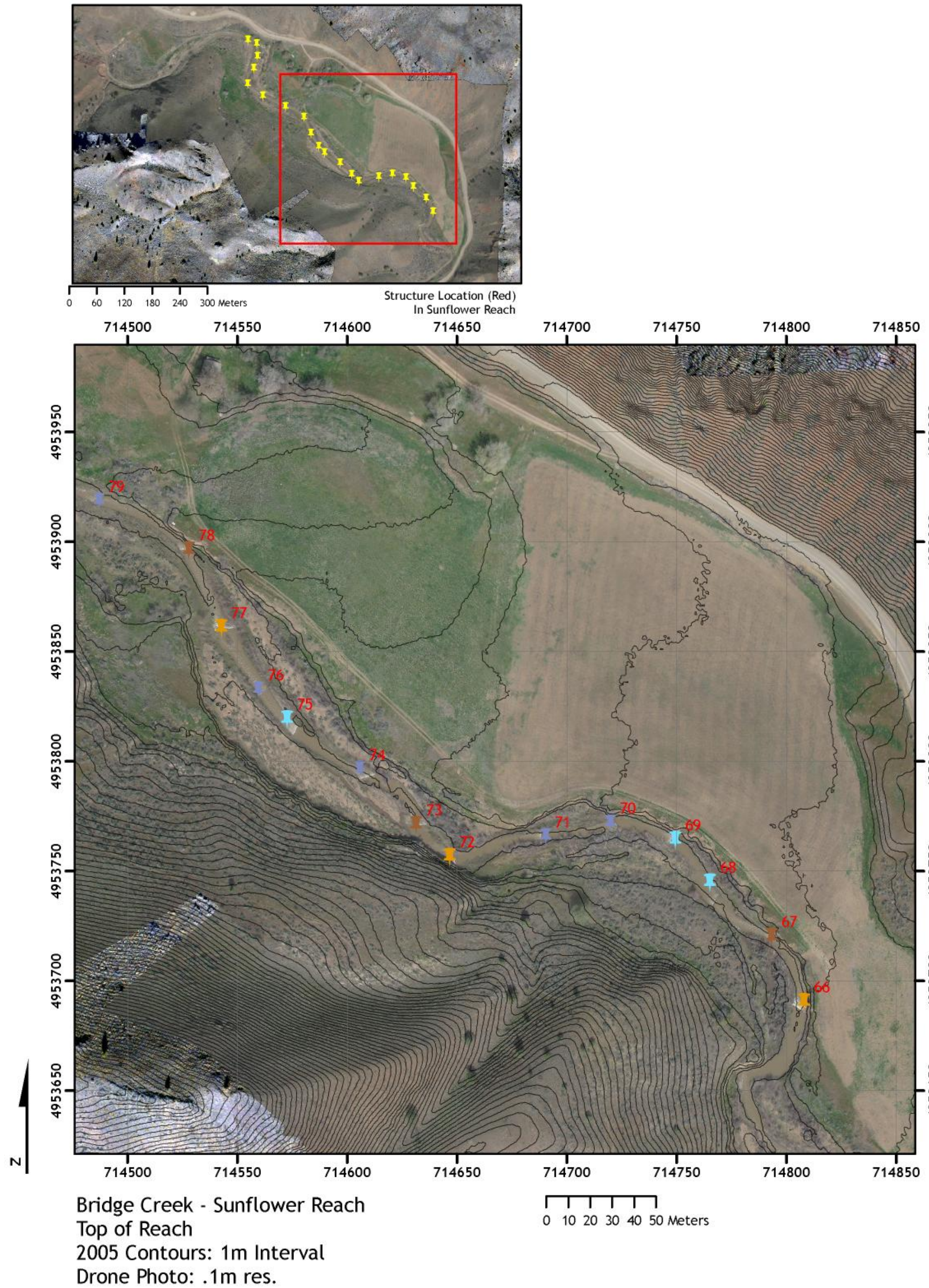

Figure A10 – Midview Map of Top Reach at Sunflower with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at:
http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

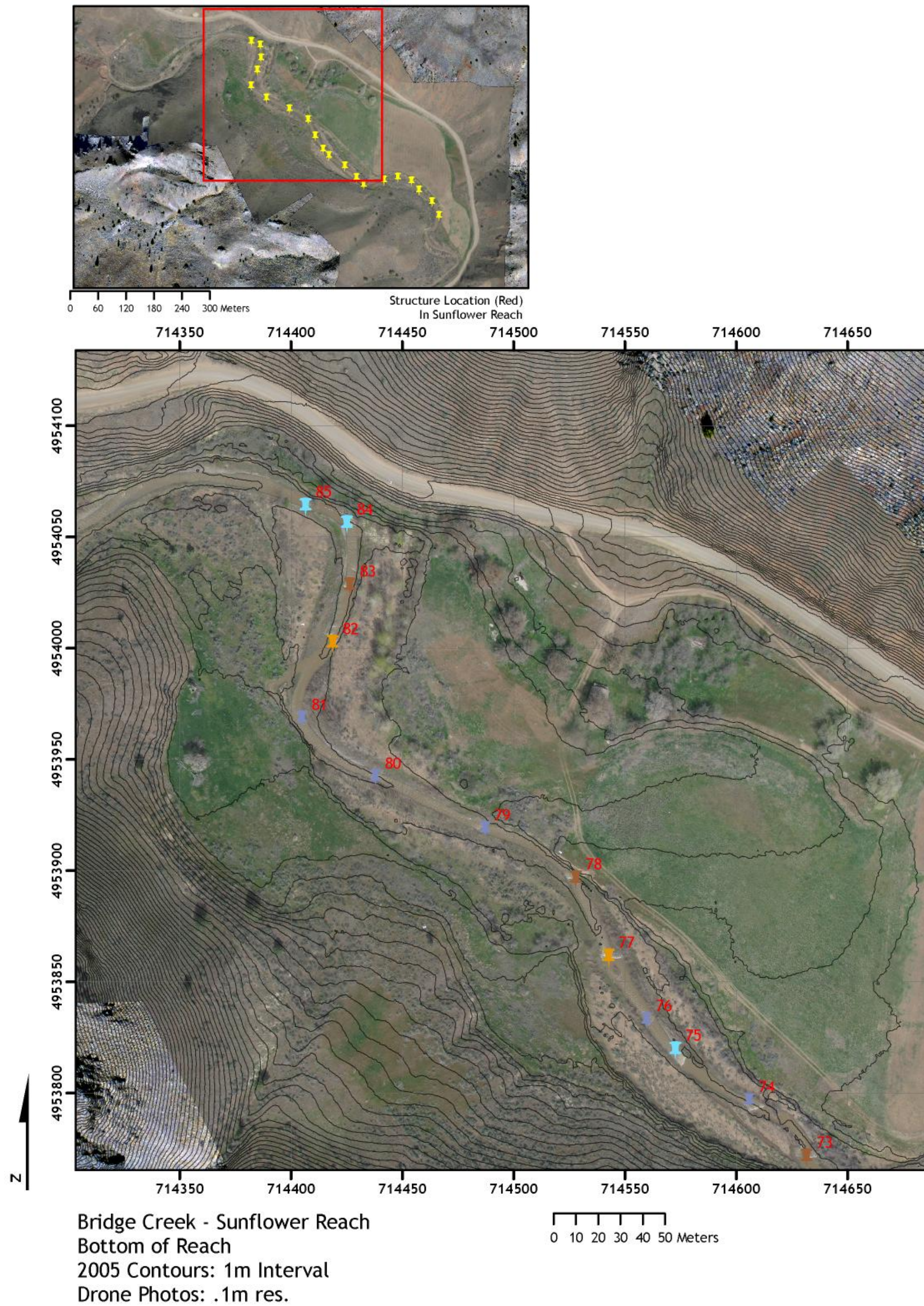

Figure A11 – Midview Map of Bottom Reach at Sunflower with April 2010 Drone Aerial Imagery as basemap and 1 m contour interval derived from 2005 Watershed Sciences LIDAR survey (available at: http://opentopo.sdsc.edu/gridsphere/gridsphere?gs_action=lidarDataset&cid=geonlidarframeportlet&opentopoID=OTLAS.102010.26910.1

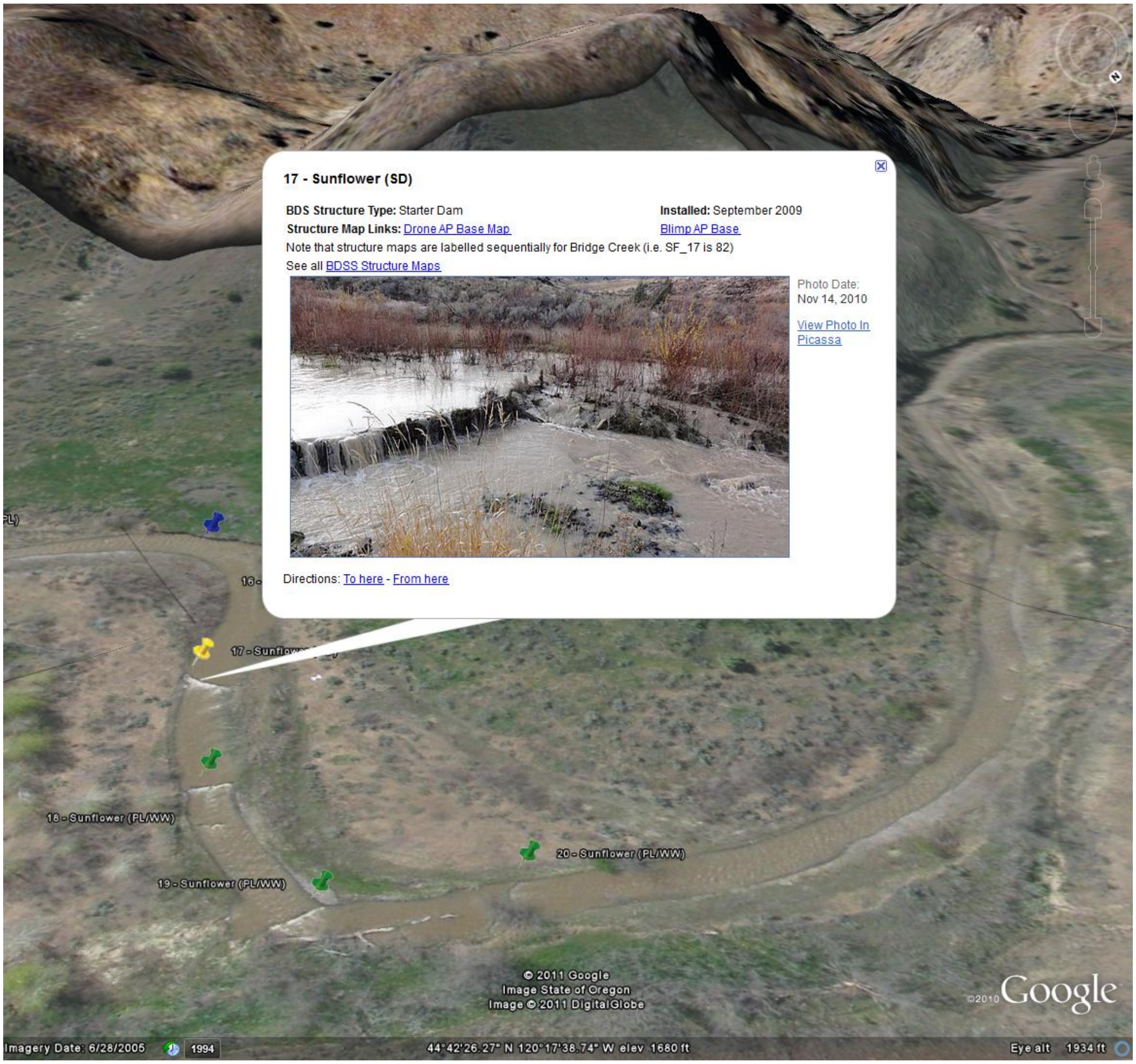

Figure A12 – Screenshot from Google Earth illustrating an example at Sunflower of the pushpins denoting each structure type and the balloons at each structure which provide links to the BDSView PDFs and links to geo-tagged Picassa albums of every structure.