Planning for Groundwater Recharge Using Instream Biotic Structures (BDAs and Post-Assisted Log Structures (PALS) – Field Tour Handouts

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This material is supplemental information to accompany the Salmonid Restoration Federation's (SRF) Coho Confab (August 24-26th, 2017 in Petrolia, CA) field tour and workshop titled: Beaver Dam Analogues and Groundwater Recharge Planning in the Mattole Headwaters presented by Tasha McKee (Sanctuary Forest) and Elijah Portugal, MS (RCAA). Much of this material is derived from a draft version of a comprehensive restoration design manual following a design approach promoted by the Fluvial Habitat Center at Utah State University. For more information about this design approach and examples of its use please refer to the literature mentioned in this document.

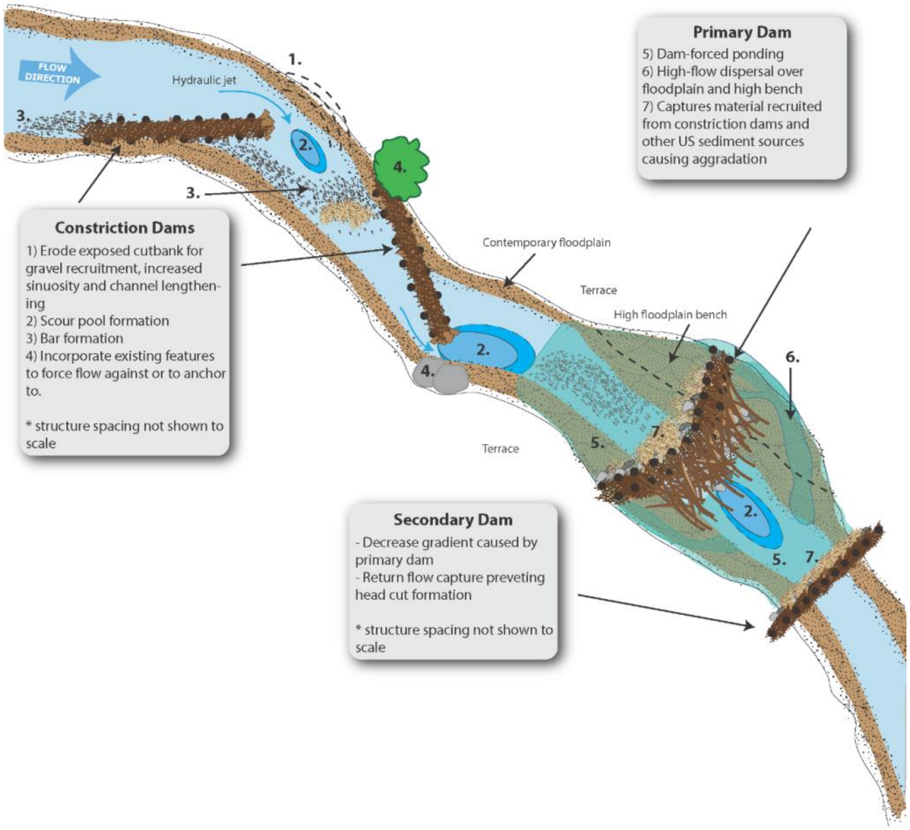


Figure 1 – Simplified schematic demonstrating Beaver Dam Analogues (BDAs) functioning as part of a structure complex. Source: Elijah Portugal (2015a)

Contents

Fundamentals of Process Based Restoration

(Beechie et al., 2010; Roni et al., 2002):

(1) Restoration actions should address the root causes of degradation. A baseline geomorphic/ecological conditions assessment and/or geomorphic classification method should be conducted to identify causes of impairment.

(2) Actions must be consistent with the physical and biological potential of the site. This requires a historical context for actions with some ability to predict the range of future conditions expected from the proposed actions.

(3) Actions should be at a scale commensurate with environmental problems. When a watershed-wide project is unfeasible, reach-scale actions should be prioritized within a larger context of clearly articulated restoration objectives within the watershed.

(4) Actions should have clearly articulated expected outcomes for ecosystem and geomorphic dynamics. This includes a clear assessment of uncertainty and risk associated with restoration actions. Monitoring the response to restoration actions is necessary to assess if project goals were met.

(5) Restoration specific to recovering fish populations should conform to the principles above and the following guidelines: 1) protect areas with intact processes and high-quality fish habitat, 2) reconnect isolated high-quality fish habitat, 3) restore hydrologic, geologic, and riparian processes (e.g., road/culvert decommissioning, exclusion of livestock, riparian planting), 4) instream habitat enhancement (e.g., addition of LWD and/or BDA structures). Instream habitat enhancement should be a last priority after attempting to restore natural processes or if short-term improvements in habitat are needed for endangered species recovery.

Watershed/Geomorphic Context

A watershed assessment to inform restoration planning can take many different forms but minimally should include a desktop and field-based hydrological, geomorphic and ecological assessment of existing conditions and recovery potential. If beaver are to be included in the restoration plan then the watershed assessment should address their habitat needs. The scope and detail of a watershed assessment for a given project will likely be determined by the projects budget and existing data. Increasingly there are existing reports, data sources and GIS resources to draw on that can inform your assessment (i.e., 'don't reinvent the wheel' if a sufficient watershed assessment has already been done). For example, in Utah the beaver restoration assessment tool (BRAT) (explained below) outputs are available for the entire state (Macfarlane, 2014) and provides a host of information relevant to beaver restoration planning that can be incorporated into a watershed assessment. To access the complete report on the Utah BRAT effort see:http://etal.usu.edu/Downloads/BRAT/UTAH_BRAT_FinalReport.pdf. There are many existing methods for conducting a watershed scale assessment to inform restoration planning (See section below). One such method is the River Styles Framework (Brierley and Fryirs, 2005) though many other geomorphic/hydrologic/ecologic assessment methods exist and can be used and may be more appropriate depending on the scale and scope of the restoration project (Kasprak et al., 2015)

The River Styles framework is a hydrologic and geomorphic classification system which provides tools for interpreting river character, behavior, geomorphic condition, and recovery potential. A full-scale assessment consists of a series of four stages that includes 1) an identification of the unique suite of River Styles (i.e., reach types) within the watershed, 2) an assessment of the current condition of the watershed, given the historical context, 3) predictions about the recovery potential and finally 4) implications for watershed management and restoration planning. This framework is widely used by watershed managers in Australia, New Zealand and is gaining traction in the Columbia River Basin. For more information about River Styles see: (Brierley and Fryirs, 2005; Fryirs and Brierley, 2012; Portugal et al., 2016; Portugal et al., 2015b; Portugal E.W., 2015). A watershed assessment following the River Styles framework includes all of the parameters explained below. We recognize that logistical constraints limit the scope of any watershed assessment and it is possible to conduct a scaled down version of River Styles assessment that still provides critical information for restoration planning (for examples of scaled down River Styles assessments see Portugal et al., 2015 and Portugal et al., 2016). Regardless, we advocate that a watershed assessment minimally addresses the following parameters explained below **(climate and hydrology, geomorphology, riparian vegetation, condition and recovery potential, and an assessment of the ability to support dam building by beaver).**

Existing Watershed Assessment Protocols

The following are vetted watershed assessment protocols, which can be used to accomplish the objectives of a watershed assessment to inform cheap and cheerful restoration. Some of these protocols can also be used to develop a monitoring plan for restoration effectiveness:

Hydrology and Geomorphology – The River Styles framework ((Brierley and Fryirs, 2005): http://www.riverstyles.com/outline.php) provides a useful organizational structure to conduct a watershed-scale geomorphic and hydrologic assessment. It has explicit stages that cover condition and recovery potential.

Aquatic Habitat - The Columbia Habitat Monitoring Program (CHAMP) (Bouwes et al., 2011): https://www.champmonitoring.org/Program/Details/1#tab-protocol~#protocol2020 is a comprehensive habitat status and trend monitoring program which utilizes high-resolution topographic mapping to make reach-scale digital elevation models of the river. Pacfish/Infish Biological Opinion (PIBO) ((Heitke et al., 2010): http://www.fs.fed.us/biology/resources/pubs/feu/pibo/pibo_stream_sampling_protocol_2012.pdf) is another aquatic habitat effectiveness monitoring program. Both CHaMP and PIBO have extensive monitoring data-sets within the Columbia River Watershed available to the public. As of writing, the Fluvial Habitat Center is developing a rapid habitat monitoring program that draws on existing protocols (e.g., CHaMP and River Styles) and will be made available to the public following completion.

Riparian Vegetation - Riparian vegetation can be assessed effectively using modified rangeland and forestry protocols ((Winward, 2000): http://www.fs.fed.us/rm/pubs/rmrs_gtr047.pdf), specific protocols for identifying vegetation water use ((Cooper and Merritt, 2012):http://www.fs.fed.us/rm/pubs/rmrs_gtr282.pdf)), wetland delineation methods ((ACOE, 1987):http://el.erdc.usace.army.mil/elpubs/pdf/wlman87.pdf), large river protocols ((Scott et al., 2012):http://etal.usu.edu/Reports/Big_Rivers_Final_Report_2012.pdf), or remote sensing products including LANDFIRE and MODIS vegetation products. While we cannot cover the range of available methods for assessing vegetation in this brief manual, we advise practitioners to consult with appropriate protocols for measuring vegetation in the type of ecosystem they wish to restore.

Network Tools to Support Watershed Assessments and Restoration Planning

With publically available, national GIS datasets there are increasing resources to leverage to conduct a watershed assessment to inform restoration planning. The following is a description of a novel, freely available network based model that the authors of this manual developed.

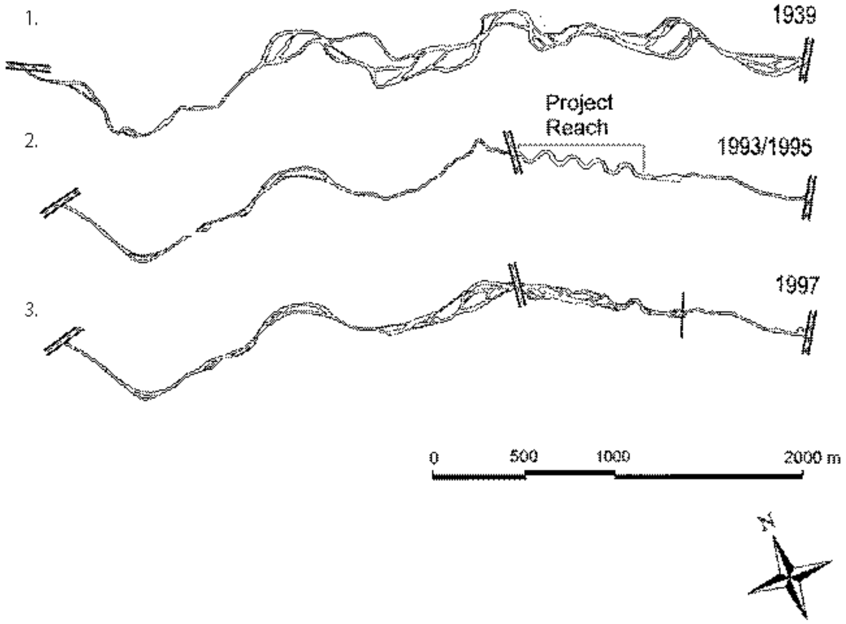
R-CAT: Riparian Condition Assessment Tool (http://etal.joewheaton.org/rcat) – The Riparian Condition Assessment Tool is a riparian area (valley bottom) mapping, condition assessment and recovery potential tool intended to help researchers and managers assess riparian condition and recovery potential over large regions and watersheds. R-CAT is a systematic stream network based model that uses uniform, spatially explicit data with a consistent spatial scale to produce continuous variable outputs for each reach (~500 meters) throughout the entire network. The R-CAT models can be run with nationally available, existing GIS datasets or high resolution landcover and DEM datasets and are designed to delineate valley bottoms, assess riparian vegetation condition, evaluate floodplain condition and estimate recovery potential of riparian areas. Valley bottom delineation is a necessary first cut to identify the area where instream and floodplain restoration will take place. The stream network models consist of the following: the **Valley Bottom Extraction Tool (V-BET)**, **Riparian Vegetation Departure (RVD)** from historic condition tool, **Riparian Condition Assessment (RCA) tool** and **Riparian Recovery Potential (RRP)** tool. These network models were first developed and implemented across the Colorado Plateau Ecoregion and the state of Utah and at the time of writing are now being run for the entire Interior Columbia River Basin. For more information see the website listed above and upcoming publications (Gilbert et al. 2016. V-BET: A GIS tool for delineating valley bottoms across entire drainage networks. (In preparation). For submission to: Computers and Geosciences; Macfarlane et al. 2016. Assessing riverine riparian vegetation departure from historic condition across entire drainage networks. (In preparation). For submission to: Riparian Ecology and Conservation; Macfarlane et al. 2016. Region wide riparian and floodplain condition assessment for sustainable river management. (In preparation). For submission to: Journal of Environmental Management.

Climate and Hydrology

A basic understanding of the sources, amount, timing and delivery of water through the project watershed is critical for restoration planning. Minimally, the following questions should be addressed: Does the majority of precipitation fall as snow or rain and when? When is the timing of peak runoff event(s)? When and for how long are base flow conditions? Is stream temperature limiting the species of restoration concern, if so when are the warmest months? The scale and scope of the project will determine the detail of the hydrologic assessment. The BRAT model incorporates hydrology in the form of regional curve predictions of stream power associated with high and low flow events which is critical to identifying if beaver assisted restoration is possible and where it should occur, but additional hydrologic analysis is recommended. Minimally, a hydrologic analysis should include the following information contained in the Appendix:

Geomorphology

It is essential to establish geomorphic context for any cheap and cheerful restoration project for the following reasons. A geomorphic assessment can: 1) identify the root causes of river degradation (Beechie et al., 2010), 2) provide evidence for historic river condition and, 3) establish realistic expectations for river recovery potential. A common complaint in peer-reviewed restoration literature about traditional restoration projects is they lack adequate geomorphic and hydrologic context to justify restoration actions (Palmer et al., 2005). This has led to projects that seek to establish a static or stable river form which is inappropriate for the geomorphic and/or hydrologic setting and ultimately fails. For example, Kondolf et al., (2001) and Smith (1997) documented two cases where adequate geomorphic and hydrologic context was not provided and an inappropriate channel form (in this case, symmetrical meander bends) was imposed on two rivers that did not have the necessary geomorphic or hydrologic processes to maintain the single-thread meandering channel form. In both cases, high flow events caused massive failure (Figure 2).



1) Historic river form was multi-threaded and dynamic

2) Geomorphic and hydrologic context was not adequately considered. Restoration project imposed a static single-threaded symmetrical meandering river form

3) Restoration project fails at high flow and returns to the multi-threaded river form that is supported by the geomorphic and hydrologic processes present

Figure 2 – Example of restoration failure because an adequate geomorphic and hydrologic assessment was not conducted. Source: Modified from Kondolf et al., (2001).

Rivers look and behave the way they do primarily because of the relationship between channel gradient (i.e., slope) and water discharge, balanced by the amount and size of sediment supplied to the channel. Structural elements (e.g., LWD, beaver dams) and riparian vegetation also play a substantial role in determining river form. A basic understanding of the fundamental drivers of river form is important to consider when conducting cheap and cheerful restoration. E.W. Lane (1954) first described this fundamental relationship and it has been used since as a conceptual tool to identify the main drivers of river form. Fundamentally, this relationship illustrates that changes in any one of the variables (e.g., amount and/or size of sediment supply or timing and magnitude of water delivery) directly affects the others such that they adjust to maintain the most efficient channel gradient to convey the given supply of sediment and water (Figure 3). In the example illustrated in Figure 2, they did not adequately consider the relationship between sediment and water supplied to the stream and disaster ensued.

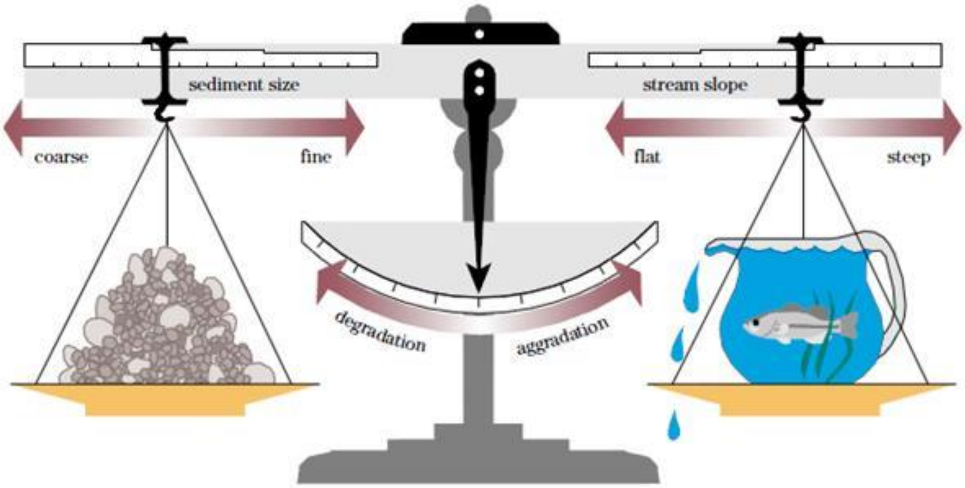
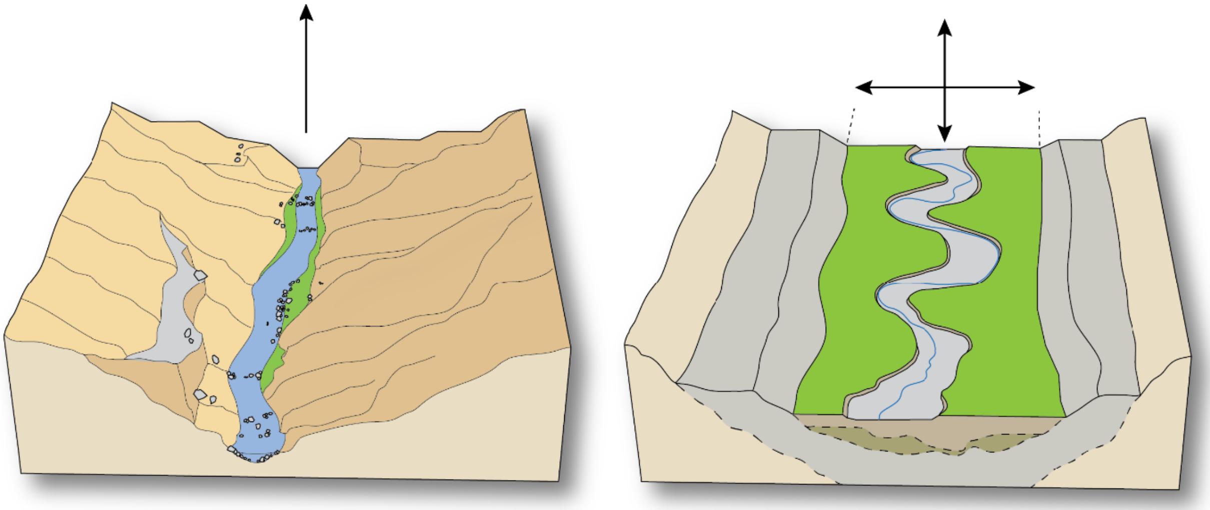


Figure 3 - Lane's Balance. A conceptual diagram linking water discharge and channel gradient (i.e., transport capacity) with the quantity and size of sediment supplied to the channel. Fundamentally, this relationship is responsible for the form of the channel which is the physical template of instream aquatic habitat. Source: From Rosgen (1996) adapted from Lane (1954).

The scale of a geomorphic assessment will likely be determined by funding constraints but ideally would be conducted at the watershed scale. Rivers at all scales are controlled by geomorphic and hydrologic processes that occur at the watershed scale. Similarly, many aquatic and riparian organisms, (e.g., fish and riparian trees) require favorable habitat at the watershed scale. Consequently, watershed-scale analysis is best to identify the limiting factors that can be addressed at the smaller scale of the restoration project.

Minimally, a geomorphic assessment should include the following parameters:

1) **Valley Setting and Channel Confinement:** The ability of a river to adjust and respond to restoration treatments is variable throughout a watershed. For example, river reaches that are laterally confined and/or dominated by bedrock are generally poor candidates for restoration because the natural capacity for geomorphic adjustment (e.g., lateral or vertical migration or sediment storage) is very low. In contrast, streams that are partly-confined (i.e., confined on one side) or unconfined in semi-alluvial or alluvial settings have a high natural capacity for adjustment and are typically good candidates for restoration. Oftentimes, unconfined areas are more degraded relative to a more confined setting because, i) the presence of floodplains accommodates intensive human land-use (e.g., grazing, farming) and ii) these areas have a high natural capacity for adjustment leaving them sensitive to the effects of land-use. In areas that have been heavily modified by human activities, oftentimes the current confining features are levees, berms, roads and other artificial features as opposed to natural confining features (e.g., bedrock, hillslopes, terraces, alluvial fans). It is important to recognize the difference because there may be some ability to remove the artificial confinement but not the natural.



Confined valley setting

Laterally unconfined valley setting

Figure 4 – Differences in the natural capacity for adjustment and restoration potential, comparing a river reach in a confined valley setting (Left) with low adjustment potential and within a laterally unconfined valley setting (Right) with high adjustment potential. Arrows denote the directions of adjustment and floodplain extents are shown in green. Source: O'Brien (2014).

2) **Channel Planform:** The example from Figure 2 underscores the need to consider the historic and current channel planform when planning restoration. Channel planform is the number of channels and the sinuosity of those channels when viewed in planform. The amount and sinuosity of channels is a reflection of the behavior of a river (i.e., dynamic versus stable, relative amounts of sediment supply compared to water supplied, relative amounts of wood loading, etc.) when the river is in an alluvial (i.e., self-formed) setting. When a river is laterally confined by bedrock or other confining features, the planform and sinuosity is influenced or controlled by the confining features and not by the behavior of the river itself. A simple assessment of historic and current channel planform provides invaluable information about river condition and river recovery potential.

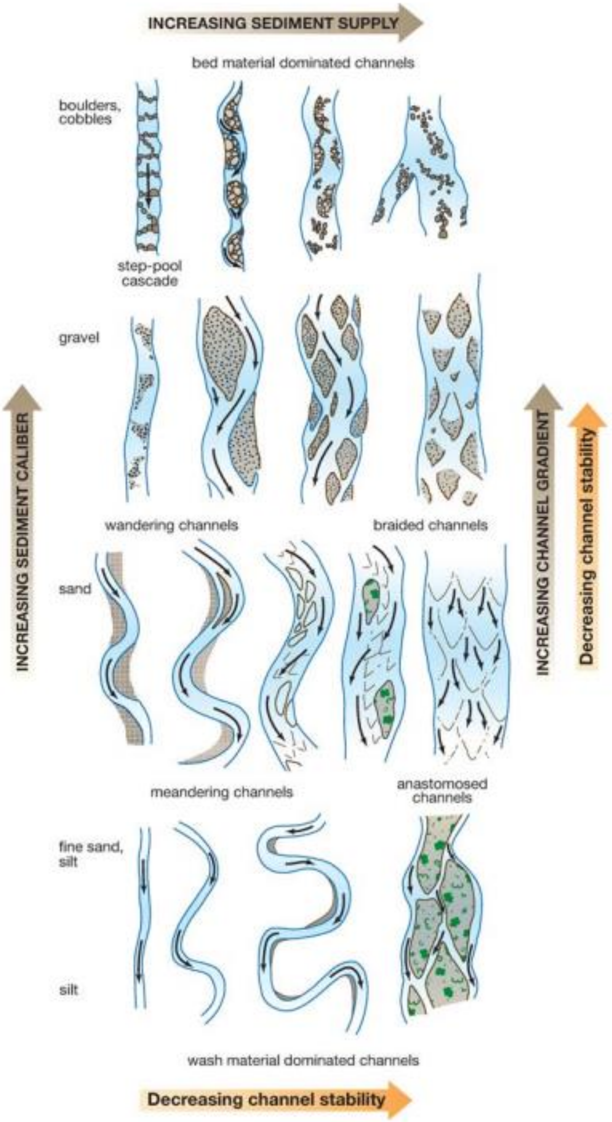


Figure 5 – Diagram showing different types of channel planform and sinuosity in alluvial (i.e., self-formed rivers) rivers. The common factors that govern different planforms are shown with brown arrows and common attributes of those rivers are highlighted with orange arrows. Source: Church (2006) modified from Church (1992).

3) **Floodplains:** Valley setting determines if there is enough lateral accommodation space for floodplains to develop. Typically, floodplains attain the most developed form (i.e., largest spatial extent and depth) lowest in the watershed where the decreased gradient (~ <1%) and lateral valley space allow for their development. Floodplains serve as critical buffers for the river where sediment is deposited during high flows events. Energy is dissipated during high flows when the river has access to its floodplain which is critical for downstream flood control and protection of infrastructure. The buffering function of floodplains is also important for water quality and quantity as sediment and water settles out on the receding limb of high flow events. This elevates the water table locally and helps to replenish groundwater. Riparian communities rely on the occasional inundation of floodplains for reproduction and growth. For example, in Utah

cottonwoods are a critical part of a healthy riparian community and are often the target of restoration actions. They rely on floodplain connectivity for reproduction during seed dispersal. Cottonwood seeds are deposited on the floodplain during high flow events leaving them outside of the active channel to develop while continuing to receive water and nutrients from the slowly receding water table beneath the floodplain. Riparian plant communities and the animal species reliant on riparian habitat (e.g., birds, reptiles, amphibians, and beaver) require floodplain connectivity.

The characteristics of floodplains (e.g., low gradient, high quality soil for agriculture or grazing) are also favorable for human land-use and consequently floodplain impairment and disconnection is common. A geomorphic assessment should locate where floodplains naturally occur and if the river currently has connection to these surfaces during high flow events. Often contemporary floodplains and abandoned floodplains (i.e., terraces) retain relict features like paleo channels that can provide information about historic river condition which can help to set realistic restoration objectives. These features can be identified using high-resolution Digital Elevation Models and historic imagery which is increasingly available for many watersheds (Figure 13).

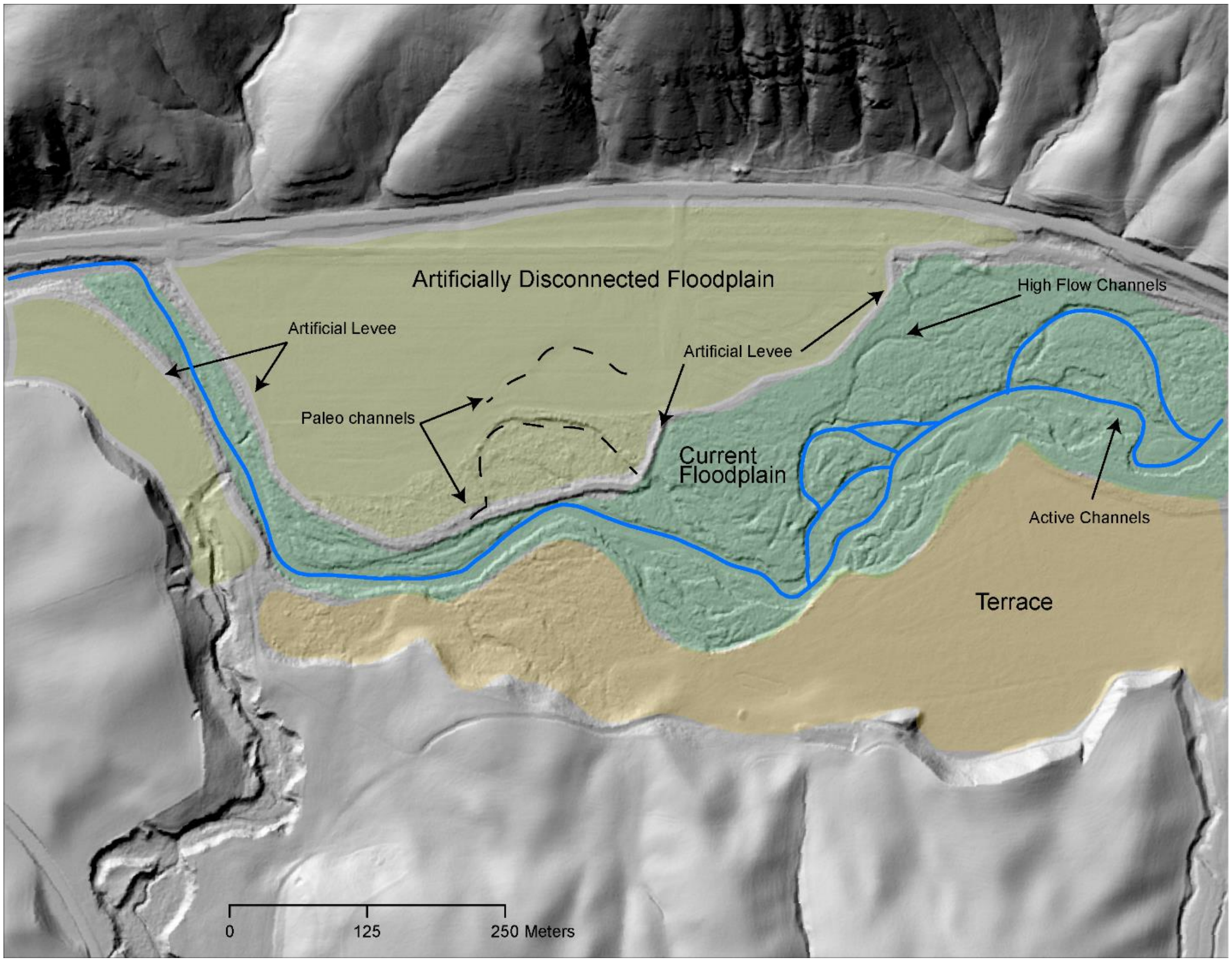


Figure 6 – Examples of floodplains. The current floodplain is shown in forest green, note how the channel planform is multithreaded and considerably more sinuous on the right compared to the straight single-threaded channel planform on the left where artificial levees restrict

floodplain access. A terrace (i.e., abandoned floodplain) is shown in brown and the artificially disconnected floodplain is shown in light green.

4) **Bed Material:** Changes in the size and shape of the dominant sediment composing the channel bed can be indicative of changes in the hydrologic or geomorphic processes operating within the watershed. For example, bed material is typically coarse in the upstream, higher gradient portion of the watershed where increased stream power winnows away fine sediment and narrow valleys contribute coarse material directly from the hillslopes. In contrast, it is typical for the lower gradient portions of the channel to be composed of finer material because of the decreased gradient and the processes of abrasion and sorting. Abrasion occurs as sediment travels downstream and is worn down through transport. Sorting occurs during sediment transport because different water velocities are needed to transport different grain sizes. It is important to identify the dominant bed material within a proposed restoration area because the size of the bed material relative to the dominant flows will control the rate and magnitude of the geomorphic response to restoration treatment. For example, if the dominant bed material is boulders or bedrock it may be inappropriate to attempt to scour a pool in this region for fish habitat. Conversely, if the dominant bed material is unconsolidated sand and silt (e.g., sand bedded rivers in southern Utah) the expected geomorphic response to BDA structures will be much more rapid then in a coarse-bedded river.

5) **Sediment Supply:** It is important to identify the dominant sources of sediment of various sizes supplied to a stream because it will allow for a better prediction about the rate and magnitude of response to restoration. For example, in many incised streams the restoration goal is to aggrade the bed to enable hydrological reconnection to a former floodplain. If there is an ample supply of gravel available to the degraded stream, liberating this material from the banks will aggrade the bed more rapidly compared to sand or finer material. Additionally, gravel-sized sediment is necessary for bar development which is an important component of instream aquatic habitat.

6) **Geomorphic Units:** The assemblage of instream (e.g., pools, bars, runs, etc.) and floodplain (e.g., contemporary floodplain, bench or ledge, terrace) geomorphic units reflects the rivers behavior within different portions of the stream network. For example, a fresh point bar deposit on the inside of a meander bend with an adjoining freshly cut bank opposite the point bar are the geomorphic units that reveals the behavior of the rivers lateral adjustment. The assemblage of geomorphic units is often indicative of the quality of the aquatic habitat. Typically, a higher number of different kinds of geomorphic units represents higher quality aquatic habitat. Geomorphic units can be formed by instream structural elements like LWD and beaver dams that force variations in water flow which creates variability in erosional and depositional processes leading to high quality aquatic habitat. Many degraded streams have much lower rates of LWD recruitment and beaver dams compared to historic conditions. This results in a diminished, uniform assemblage of geomorphic units with poor quality instream aquatic habitat.

   The following questions should be considered when planning for restoration: What types of geomorphic units are currently present or absent? Given the geomorphic setting within the watershed what types of geomorphic units were present prior to human disturbance? What types of sediment are the geomorphic units composed of? Are they being created and reworked under the current flow regime or under a past regime?

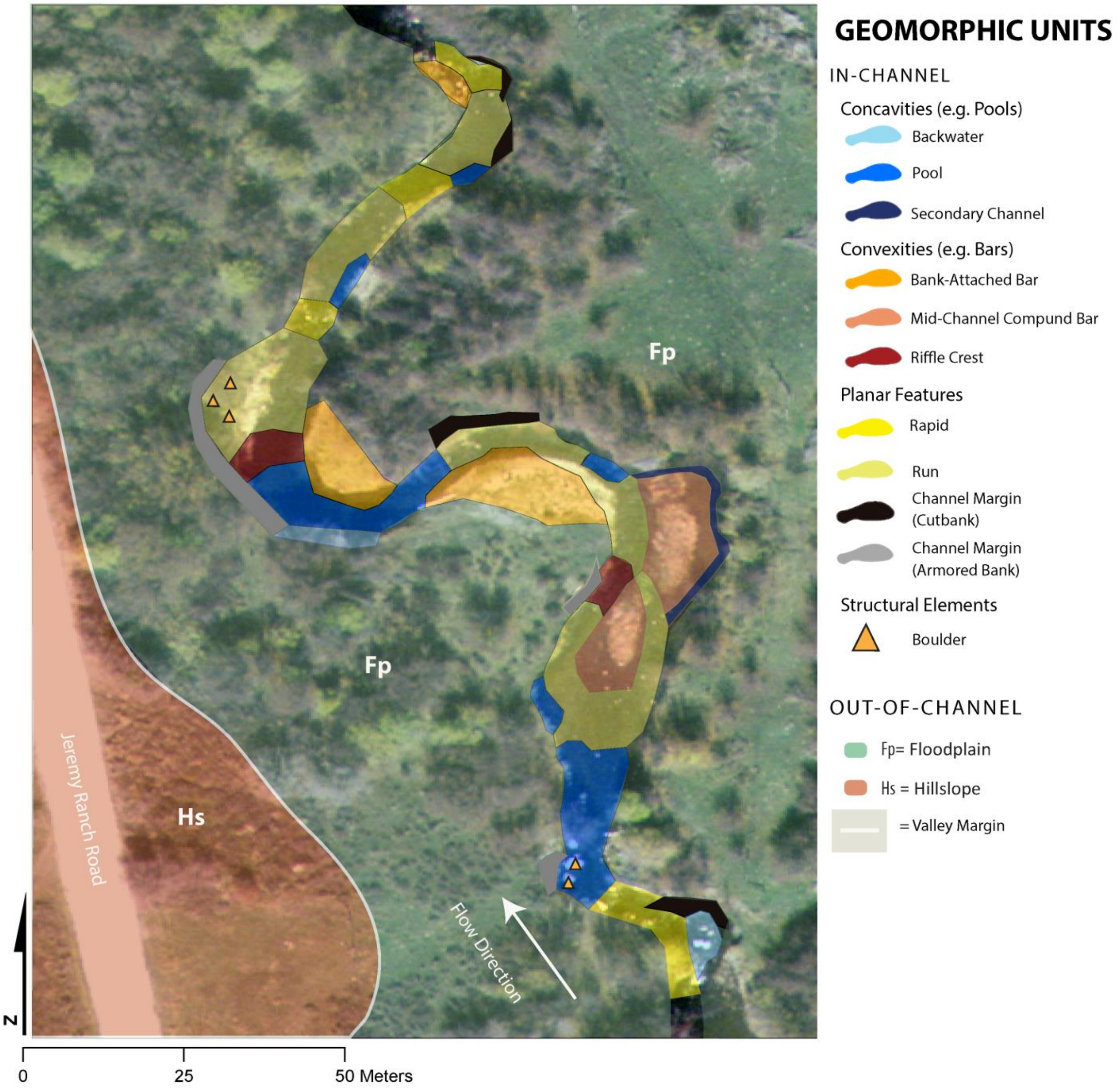


Figure 7 – Example of instream and floodplain geomorphic units from the Weber River Watershed River Styles Report (Portugal et al., 2016)

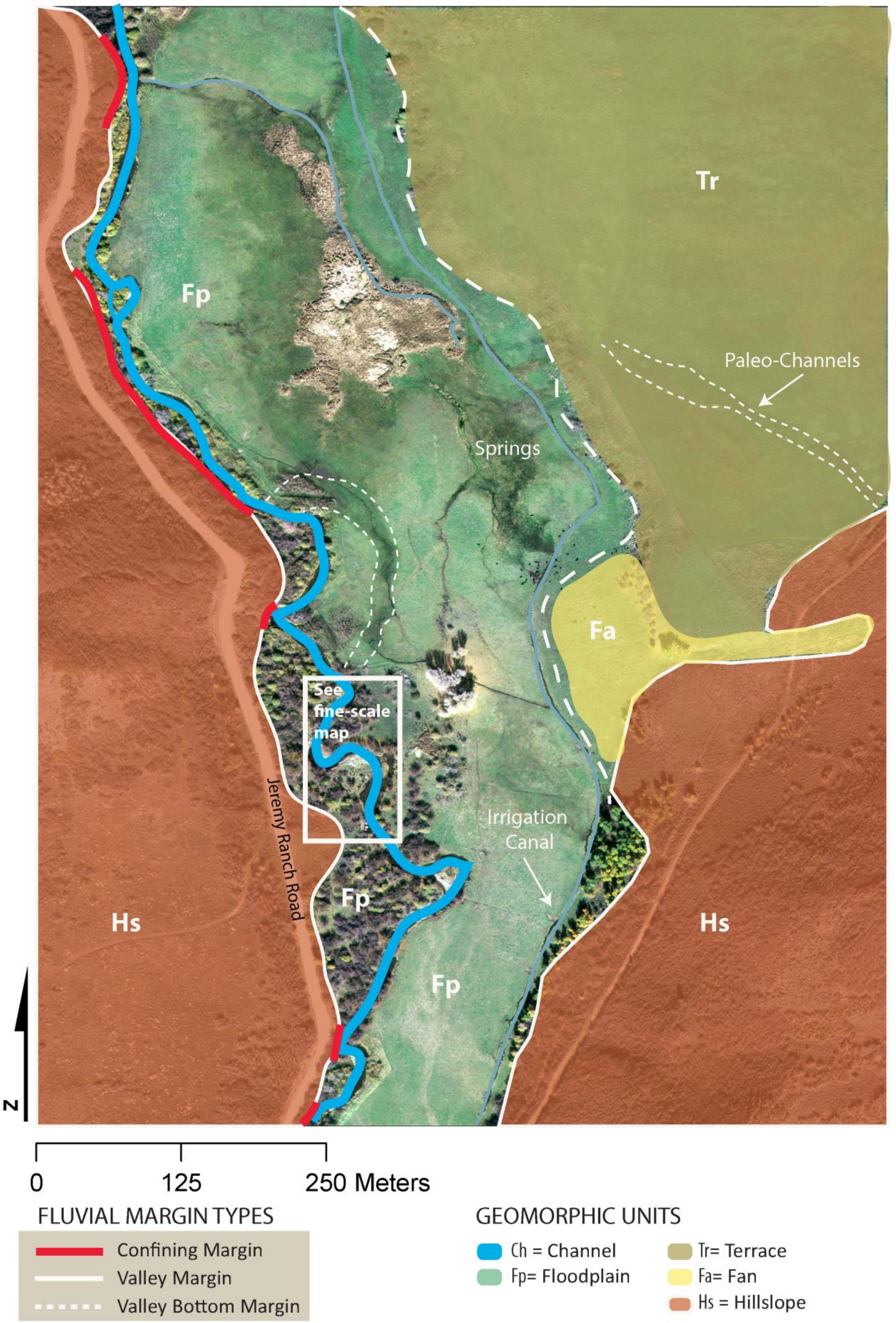


Figure 8 – Example of floodplain geomorphic units from the Weber River Watershed River Styles Report (Portugal et al., 2016)

Where in the Watershed Can Beaver Build and Maintain Dams? -Beaver Restoration and Assessment Tool (BRAT)

The Beaver Restoration Assessment Tool (BRAT – http://brat.joewheaton.org) is a decision support and planning tool intended to help researchers and resource managers assess the potential for beaver as a stream conservation and restoration agent over large regions and watersheds (Macfarlane et al., 2015). The BRAT model is run with widely available existing data sets (e.g., LANDFIRE vegetation layers, NHD stream layers, USGS regional hydrologic curves, NED DEMs) and used to identify opportunities, potential conflicts and constraints, and identify beaver management zones through a mix of assessment of existing resources and scenario-based assessment of potential futures. The primary backbone to BRAT is a spatially- explicit network model that predicts the capacity of riverscapes to support dam-building activity by beaver (Macfarlane et al., 2015). The model predicts the maximum density (in dams/km) of beaver dams the channel can support in each 250 - 300 m reach on the drainage network. It also provides dam capacity estimates based on historic conditions which can be a benchmark for restoration objectives. Additionally, the model provides predictions of the potential for human/beaver conflict and beaver management zones over the network scale (Figure 9).

Beaver management zones (BMZs) are extremely helpful in planning beaver assisted restoration and have been generated for the entire state of Utah (Macfarlane, 2014). BMZs are derived in the following manner: the model leverages the BRAT capacity model to calculate both existing and historic capacity based on the derived current and modeled historic condition of the LANDFIRE riparian vegetation. These data are leveraged to estimate riparian condition and recovery potential based on the contrast of existing and historic capacity. This information is combined with the outputs of the Human-Beaver Potential Conflict Model to differentiate streams segments into seven different management categories. The seven stream categories that the inference system uses are: 1) Low-hanging Fruit, 2) Quick Return, 3) Long-term Possibility, 4) Naturally Limiting, 5) Anthropogenically Limiting, 6) Living with Beaver (high source), and 7) Living with beaver (low source). The BMZ category definitions are available in Mcfarlane et al., (2014) (http://etal.usu.edu/Downloads/BRAT/UTAH_BRAT_FinalReport.pdf).

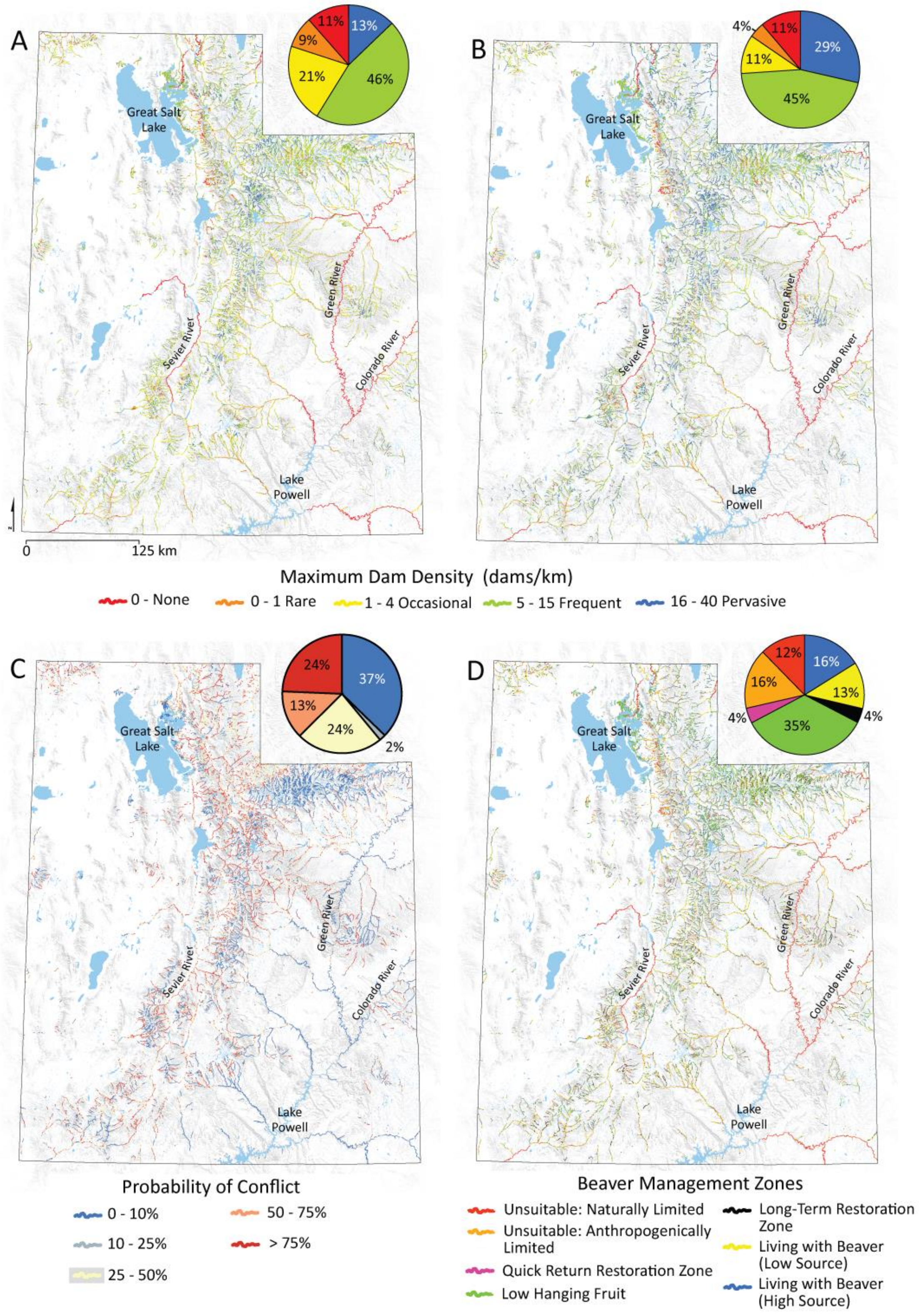


Figure 9 – Map of Utah statewide BRAT outputs that includes A. existing beaver dam capacity, B. historic beaver dam capacity, C. probability of potential conflict, and D. beaver conservation and restoration zones (i.e., Beaver Management Zones). For a definition of Beaver Management Zones see MacFarlane et al. (2014). Figure Reprinted from MacFarlane et al. (2014)

Restoration Objectives

The watershed assessment provides the necessary information to develop well-informed, specific, and measurable **restoration objectives at multiple scales**. The specific type of river impairment identified during the watershed assessment (e.g., incision, disconnected floodplain, lack of LWD, uniform assemblage of geomorphic units, etc.) will determine the broad-scale restoration objectives. **In general, the primary cheap and cheerful restoration objective is to initiate or enhance hydrologic, geomorphic and ecological processes that create and maintain dynamic, high quality instream and riparian habitat**.

There are many valid restoration objectives, many of which are mandated by state and federal laws pertaining to threatened and endangered species. It is important to develop restoration objectives that are supported by a watershed assessment so that the geomorphic, hydrologic or ecological processes operating in the watershed fit with the restoration objectives. Figure 2 again provides an example of how an inadequate watershed assessment led to poorly defined restoration objectives that were not supported by the inherent stream processes operating at the restoration site. Restoration objectives should be specific and quantifiable so that restoration actions can be monitored to assess if the objectives were met. An example of a specific and measureable restoration objective would be, to increase the survival and growth rates of juvenile steelhead by 30% over the next five years following restoration. This is a clearly defined restoration objective that can be measured by fish population sampling before and after restoration.

Once the broad-scale restoration objectives have been defined it is important to articulate restoration objectives at the scale of the restoration action. For example, the authors recently completed a pilot cheap and cheerful restoration project on an incised stream in Oregon (Portugal et al., 2015a). Here the broad-scale restoration objective was to partner with a beaver population to restore geomorphic, hydrologic and ecological processes to improve habitat for aquatic and riparian biota within the incised portions of the stream. The broad objectives were refined by the information from the watershed assessment to include specific restoration objectives at the reach scale. Figure 10 shows specific restoration objectives at the reach scale that differ based on the variability of current geomorphic and hydrologic condition relating to incision recovery (Figure 14).

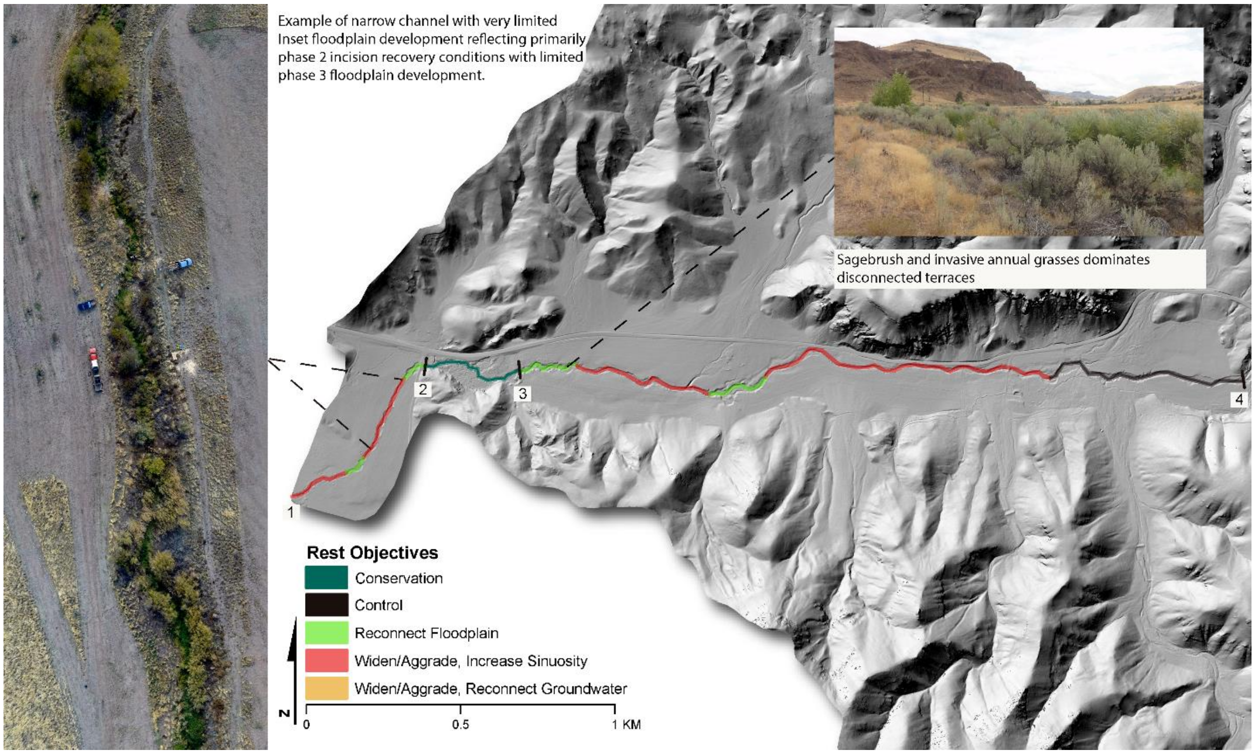


Figure 10 - Restoration objectives for lower Pine Creek. Dominant objectives are displayed while additional secondary objectives are assumed (e.g., enhance instream geomorphic complexity, elevate the water table and groundwater levels and expand the riparian area). Reach breaks are also displayed, with the reach id indicating the beginning of the reach. Inset photos show examples of current condition.

Conceptual Models to Inform Restoration Objectives

We conduct watershed assessments to understand the current geomorphic, hydrologic and ecological processes in a degraded watershed. The assessment also identifies the historic process regime prior to degradation and an envisioned future condition following restoration. With this information we develop conceptual models about system function, both current and historic. Conceptual models provide essential information to develop specific and measurable restoration objectives and hypotheses. The following are two examples of conceptual models developed for cheap and cheerful restoration projects in the Asotin Creek IMW (Wheaton, 2012) and the Bridge Creek IMW (Pollock, 2012)

Example 1 - Asotin Creek IMW Conceptual Model to Inform Restoration

Our assessments and other regional assessments (ACCD, 1995; ACCD, 2004; Bennett, 2012; SRSRB, 2005) support the conclusion that there is less LWD in the stream channel of Asotin Creek and its tributaries than historically. The lack of LWD, combined with a history of land use that has included extensive logging in the upper reaches of the study creeks, over-grazing, channel straightening, and riparian degradation in the lower reaches, has led to straighter, shallower, and more homogeneous channels with relatively few deep pools. A cursory inspection of riparian conditions along the study creeks suggests a relatively healthy riparian corridor providing adequate cover and shading to help regulate stream temperatures. However, a closer inspection reveals that most of Charley, large stretches of the South Fork and portions of the North Fork have a fairly stable, rather homogenous riparian age and species structure, which likely reflects a steady recovery following cessation and/or reduction in some of the previous land uses (e.g., logging, grazing). Unfortunately, this recovery has taken place around a relatively homogenized channel, and has acted to stabilize the degraded condition of the channel. The majority of the stream consists of homogenous habitat dominated by plane-bed runs and glides and characterized by a notable absence of large pools and large woody debris despite a riparian corridor that is well established and provides good cover. The current process regime supports the stability of this somewhat degraded state. However, there are encouraging remnants of a more diverse age and species structure in the riparian corridor (especially in the North Fork) and in these areas the channel is often more diverse.

The ball and cup diagram on the left hand side of Figure 12 illustrates the fate of the current condition in the study creeks. The study creeks are currently locked in a state of low channel complexity, whereby the system parameters are fixed by a combination of a stable riparian corridor, an armored bed, and relatively modest mean annual floods that lack the capacity to shift the streams into a different state and/or to modify the system parameters. Even when rare large floods do occur, as noted by the historical discharge record of Asotin Creek, the streams quickly revert back to degraded conditions. Despite this current scenario, rapid geomorphic assessments highlighted that the study creeks are capable of a higher degree of complexity and complexity seems largely related to the degree of hydraulic heterogeneity in flow width and flow patterns, which in turn are directly influenced by how much LWD is present.

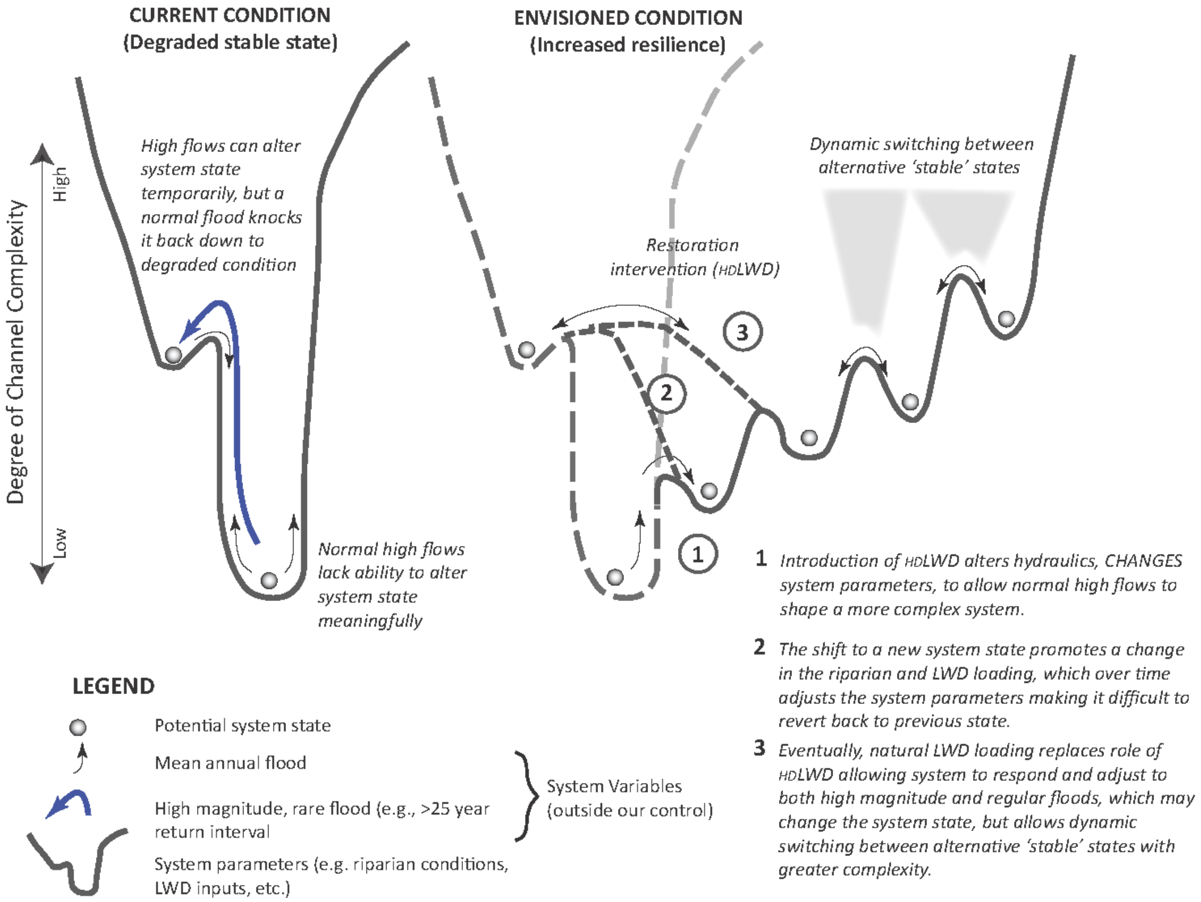


Figure 11 - Conceptual model of current condition (left) and envisioned condition (right) post restoration in response to the introduction of $_{\text{HD}}$LWD. In this instance, we can't change the system variables (e.g., hydrology), but we can change the system parameters by increasing the loading of LWD, which we hypothesize will shift the stream into more complex system states, which can dynamically switch between alternative stable states.

Example 2 – Bridge Creek IMW Conceptual Model to Inform Restoration

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. 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.

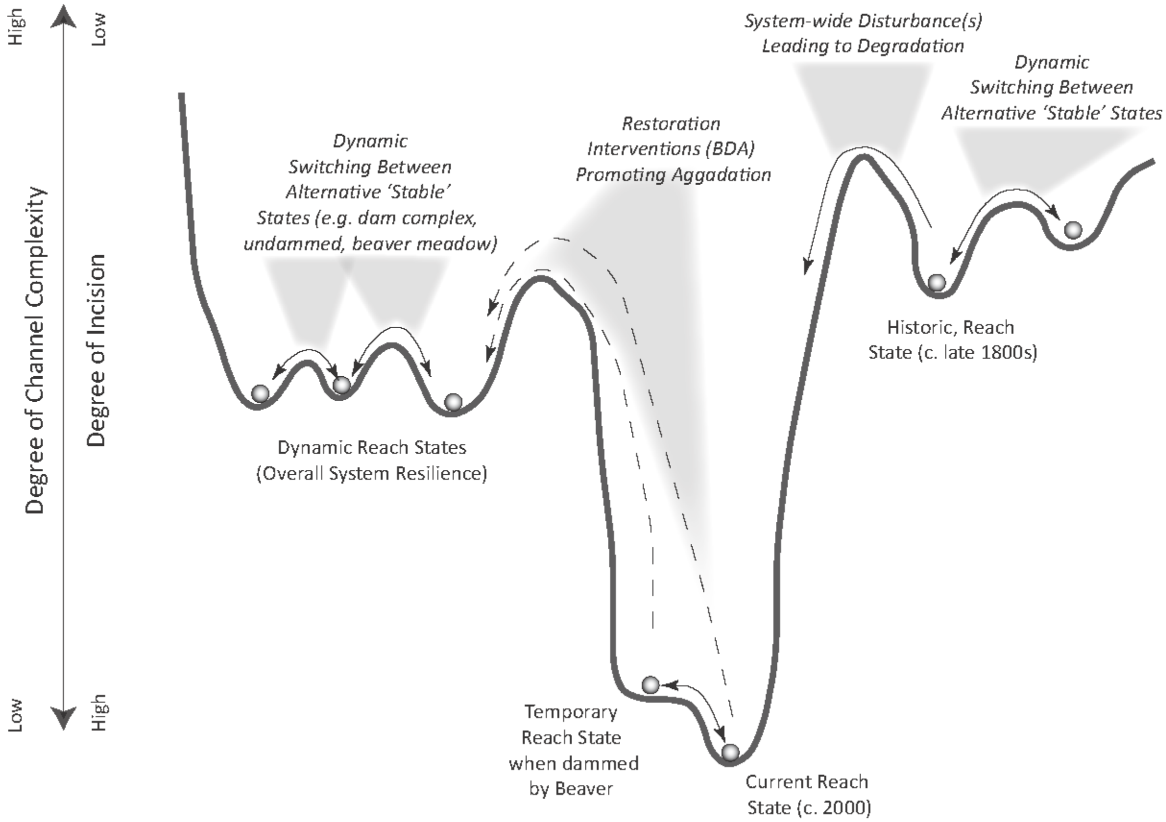


Figure 12 - Conceptual Model of System States in Bridge Creek. The troughs represent persistent system states (marbles) and contrasts the inferred historic conditions (right) in contrast to current conditions (middle) and where the hypothesized system state will be in response to restoration intervention and beaver activity (left).

Restoration Design Plan

After the conceptual model and restoration objectives have been defined based on the information gained during restoration planning all the necessary pieces are in place to develop a restoration design plan. The design plan is, 'where the rubber meets the road' in that the actual restoration actions are developed in this phase. The following are critical components of a cheap and cheerful design plan:

Scope of the Plan: Both in terms of the size of the project and the time period over which the project will occur (e.g., multiple treatments). This will likely be determined by the projects budget.

Pilot Projects: We can't emphasize enough the importance of using pilot projects to inform the larger-scale restoration design. The results of the pilot project provides invaluable information to maximize the effectiveness of the design plan.

Identify Reference or Target Conditions: If possible, locate portions of the watershed that are in relatively better condition compared to the proposed treatment areas. It is best if these areas share a similar geomorphic setting as the proposed treatment area. This will help to develop the target conditions that the restoration actions will attempt to create. Additionally, these areas do not need to be treated by the restoration action and can be left alone to act as a source area for riparian vegetation and beaver if present.

Controls and Conservation Reaches: To effectively monitor the results of the restoration actions identify areas within the watershed that share a similar geomorphic setting as the proposed treatment areas. These untreated reaches can act as a comparison against the treatment reaches for monitoring purposes. If the project includes multiple treatment phases control reaches can be changed into treatment reaches as the project expands over time. Conservation reaches are untreated reaches that are in better condition compared to the treatment areas. Oftentimes these reaches also serve as the reference or target conditions if they share a similar location in the watershed and geomorphic setting as the treatment areas.

Prioritize Treatments: Depending on the specific restoration objectives, some areas are more important to treat immediately compared to others.

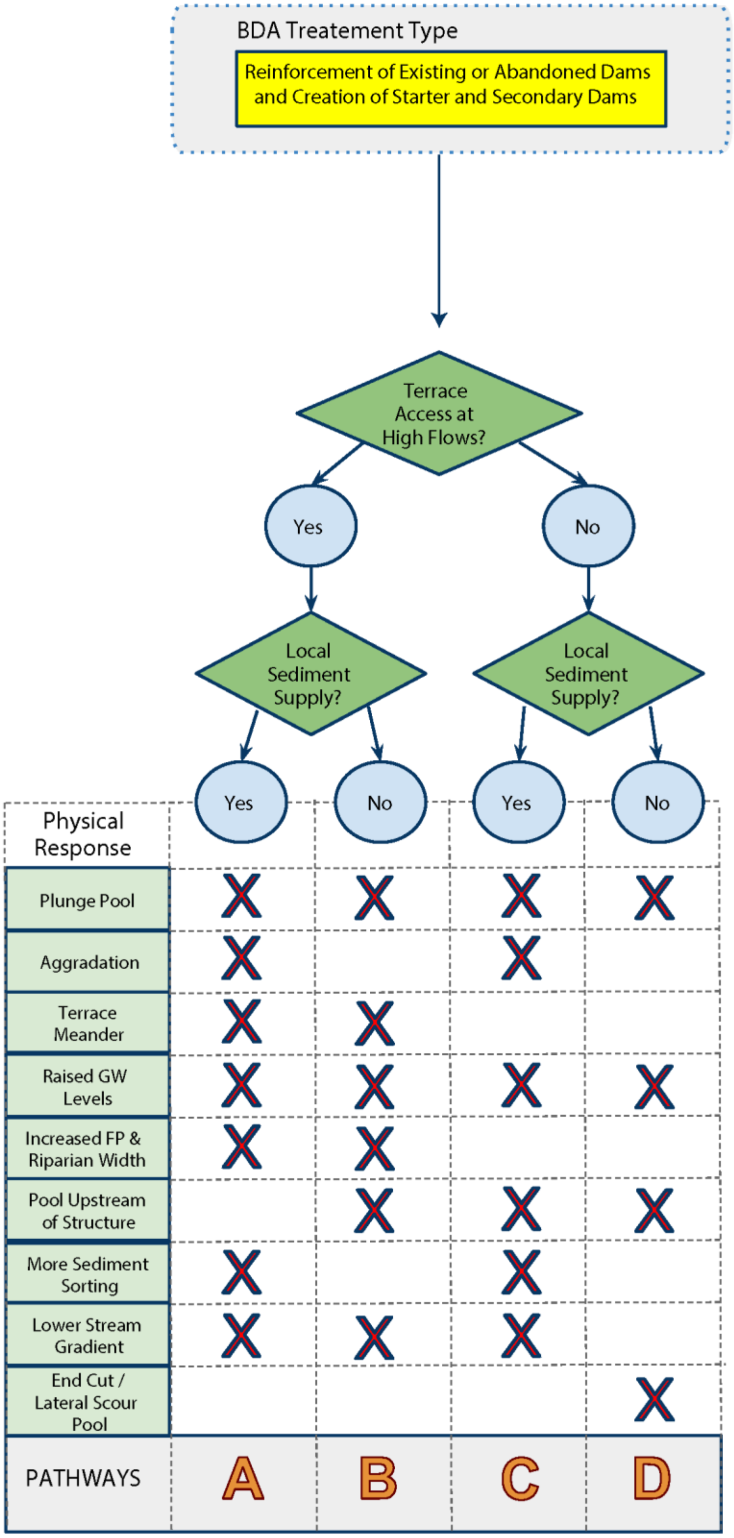
Experimental Design: A cheap and cheerful restoration design plan should have experimental design hypotheses and anticipated responses at multiple spatial scales to maximize the opportunities to learn from the restoration actions. For example, in Bridge Creek, Oregon where beaver-assisted restoration was developed the researchers articulated design hypothesis at three 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.

Example Design Hypothesis at Watershed Scale: Can we concentrate enough restoration activity within a single watershed such that there is a measurable population-level change in the steelhead that utilize the system?

Example Design Hypothesis at Reach or Restoration Structure Complex Scale: Can we 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? The BDA 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). 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.

Example Design Hypothesis at Individual Structure Scale: Each type of BDA structure has specific hydrogeomorphic objectives, as to how the structure is likely to respond depending on which type of structure was installed and what stochastic processes (e.g., high flow event) occur after installation. For example, a reinforced active dam or starter dam 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 secondary dam, 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 13).



Physical Response	Yes	No	Yes	No
Plunge Pool	X	X	X	X
Aggradation	X		X	
Terrace Meander	X	X		
Raised GW Levels	X	X	X	X
Increased FP & Riparian Width	X	X		
Pool Upstream of Structure		X	X	X
More Sediment Sorting	X		X	
Lower Stream Gradient	X	X	X	
End Cut / Lateral Scour Pool				X
PATHWAYS	A	B	C	D

Figure 13 – A Beaver Dam Analog (BDA) structure can follow multiple pathways (A-D) depending on the type of BDA 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. Note that not all BDA structure types are featured in this figure. Source: Joe Wheaton.

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.

Incision Recovery/Groundwater Recharge

Channel incision has been identified as a serious problem in many streams throughout the western United States (Beechie et al., 2008; Shields et al., 1999). Vertical channel incision lowers the groundwater table, reduces the extent of historic wetlands, lowers summer base flows, creates warmer water temperatures, and generates a loss of physical habitat diversity (Darby and Simon, 1999; Pollock et al., 2007). Additionally, incision causes significant loss of riparian vegetative communities, and population declines in fish and other aquatic organisms (Pollock et al., 2014). Typically, incised streams will not recover naturally for decades or even centuries without restoration actions (e.g., Pollock et al. 2014). The immediate necessity to improve habitat conditions for threatened or endangered species warrants active restoration of incised streams.

Incision recovery of alluvial streams generally progresses through four basic successional phases (Figure 14) (Cluer and Thorne, 2014; Elliott et al., 1999) rapid incision lasting from years to decades where sediment outputs are greater than inputs; 2) widening of incision trench with continued high sediment outputs; 3) slow aggradation which can last hundreds of years where sediment input is greater than output; and 4) dynamic equilibrium where sediment input and output are approximately equal. Beechie (2008) offers an alternate incision recovery model for narrow, deeply incised channels that lack the adequate stream power to accomplish significant widening prior to aggradation. This is due to the accumulation of bank failure deposits at the base of the incision trench which limits lateral channel migration and inset floodplain development.

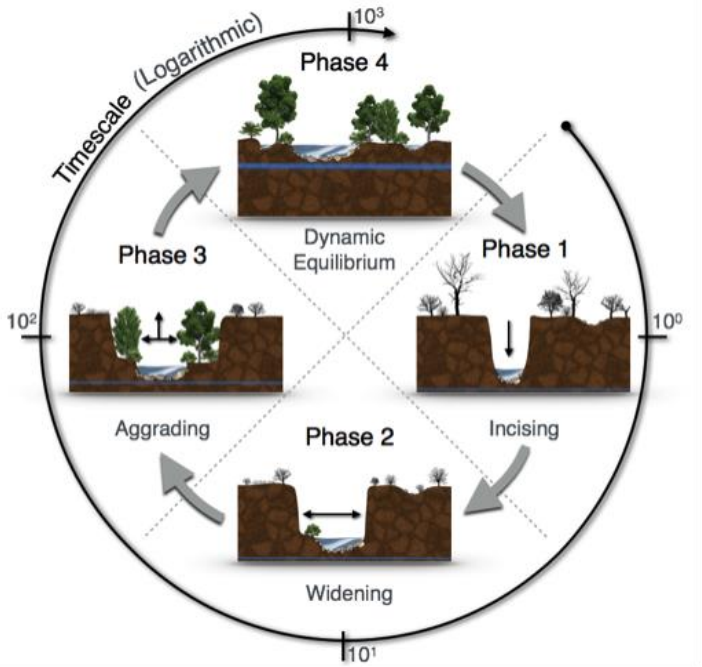


Figure 14 - A simplified succession model typical conditions for incision-prone streams. Highlighted are the dominant physical processes forcing each phase and typical timescales of recovery. Small arrows illustrate the direction of erosion or deposition and the dashed line signifies the water table elevation. Source: reproduced from Cluer and Thorne (2014) and Pollock et al. (2014).

Regardless of the incision recovery model, the recovery process can be accelerated by the presence of riparian vegetation, natural dam building activities of beaver (Burchsted et al., 2010; Pollock et al., 2003) and by mimicking dam building with Beaver Dam Analogs (BDAs) (Pollock et al., 2014) and $_{HD}$LWD . BDAs and $_{HD}$LWD can accelerate the trench widening phase (2) by directing flow against banks enhancing bank erosion and by reinforcing existing dams the functional life of a dam is increased. The rate of aggradation during phase 3 is also accelerated by natural and artificial beaver dam impoundment. In addition to aggradation vertically increasing the channel and floodplain, it also increases the rate and duration of floodplain inundation. The presence of dams also increases the quality and quantity of aquatic habitat during phases 2-3. Figure 4 illustrates a typical incision succession model for incision prone streams with the presence of BDAs.

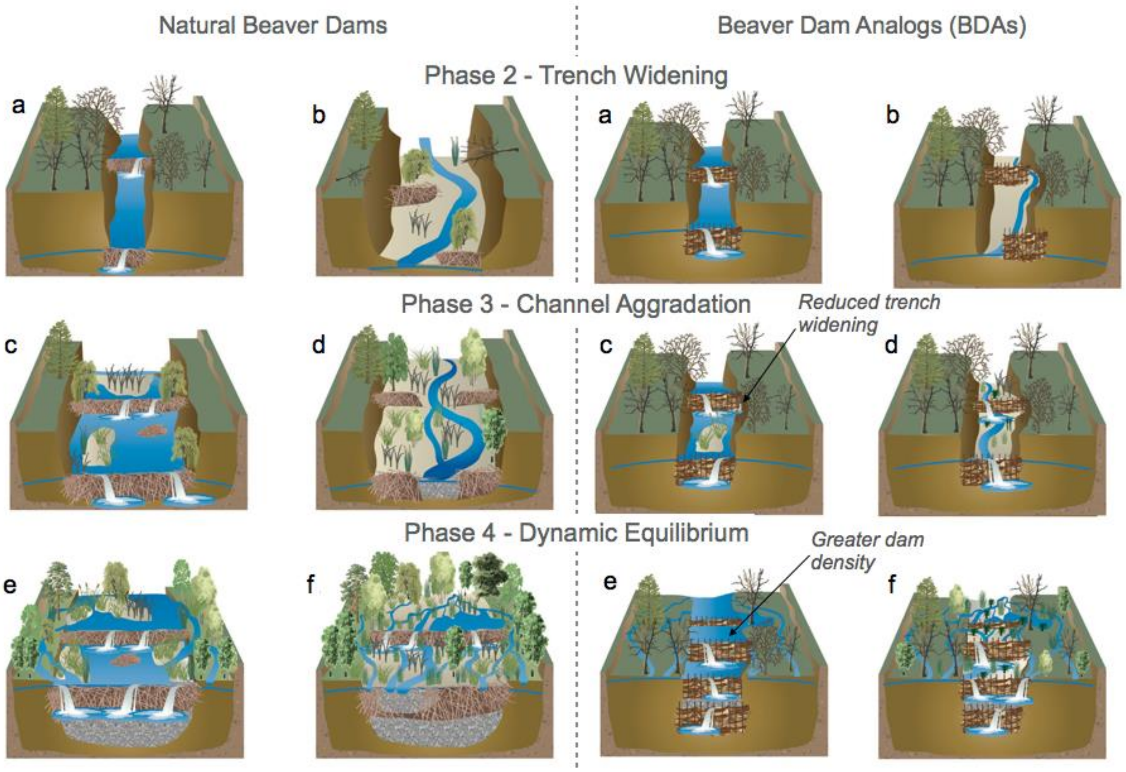


Figure 15 - Recovery sequence for incision prone alluvial streams comparing natural beaver activity to beaver dam analogs (BDAs). BDAs withstand greater stream power than many natural dams. BDAs can be strategically placed to maximize widening or aggradation to enhance the rate of recovery and provide benefits to aquatic and riparian habitat during recovery. Source: reproduced from Pollock et al. (2014).

Restore Streams with a Wood Deficit

Many streams suffer from low volumes of large wood recruitment compared to historic conditions (Bryant, 1983; Hough-Snee et al., 2014; Meredith et al., 2014). A wood deficit leads to simplified and degraded aquatic habitat. Cheap and cheerful restoration methods can be used to restore this type of impaired stream. Specifically, the $_{HD}$LWD technique can be used to increase instream roughness and introduce enough LWD to rival historic wood loading rates (Bennett, 2012) . High-density LWD increases the instream geomorphic complexity by creating a larger diversity of instream geomorphic units (e.g., pools and bars), can enhance floodplain connectivity, and increases aquatic habitat quality.

Restore Hydrologic Connectivity

Many degraded streams suffer from a lack of surface, groundwater and floodplain hydrologic connectivity. This is particularly true for incised streams or streams with limited floodplain connection. Disruptions in water connectivity limit the extent of aquatic habitat, raise water temperatures, and reduces the extent of wetland and riparian habitat. Cheap and cheerful restoration can address this problem with the use of beaver, BDAs and $_{HD}$LWD. Dam building by beaver has been shown to influence stream hydrology in a number of important ways primarily by altering the amount, and timing of delivery of water and sediment (Gurnell, 1998; Pollock et al., 2003).

Surface and Groundwater Connectivity

Surface water ponding upstream of beaver dams elevates the water table and groundwater levels (Woo and Waddington, 1990) locally. With a high density of beaver dams it has been shown that dam impoundments can attenuate water table decline during the dry season, elevating base flow (Burchsted et al., 2010; Westbrook et al., 2006) and alleviating the effects of drought (Hood and Bayley, 2008). Additionally beaver dam building can create and maintain large wetland areas (Wright et al., 2002). Beaver dam analogs can also be used to garner many of the same benefits of natural beaver dams (Pollock et al., 2014).

Structure Types: Beaver Dam Analog Structure Complexes

The general goal of a beaver-assisted restoration project is to broadly mimic the dam building activities of beaver to then restore hydrological and geomorphic processes. However, there is a deliberate strategy in how and where structures are built to most effectively induce these processes that may be beyond the strategies by which beavers build dams and dam complexes. We employ a variety of Beaver Dam Analogs (BDAs) (Pollock et al., 2014) structure types to achieve different functions, some of which mimic the types of functions of natural beaver dams, and some which create conditions that increase the probability that beaver dams and other BDAs will persist. Individual BDA structures used in isolation are unlikely to achieve a goal of restoring a process that is self-sustaining and must be used in concert with other BDAs to form a complex. Finally, for the larger restoration effort, the family of complexes must be viewed at even coarser resolution such as the reach or watershed scale to ensure that non-localized processes do not prevent localized goals (e.g. sediment delivery, discharge, vegetation communities etc.).

Much in the way beaver build dam complexes, individual BDA structures are designed to function as part of a structure complex. In general, structure complexes consist of 2- 8 BDA structures configured to achieve clearly defined goals for channel and riparian rehabilitation. The functional objective(s) for a complex are articulated during the design process and determine the types and configuration of structures comprising a complex. Many of the same landscape features discussed below for individual structure types (e.g., incision trench width, channel gradient, morphology, features to exploit, etc.) are also considered when designing a complex, and each structure is configured to support the overall complex objectives. Depending on the length of the restoration project, restoration goals, and the effectiveness of individual structures over time, the functional objectives for structures within a complex may be updated and reprioritized.

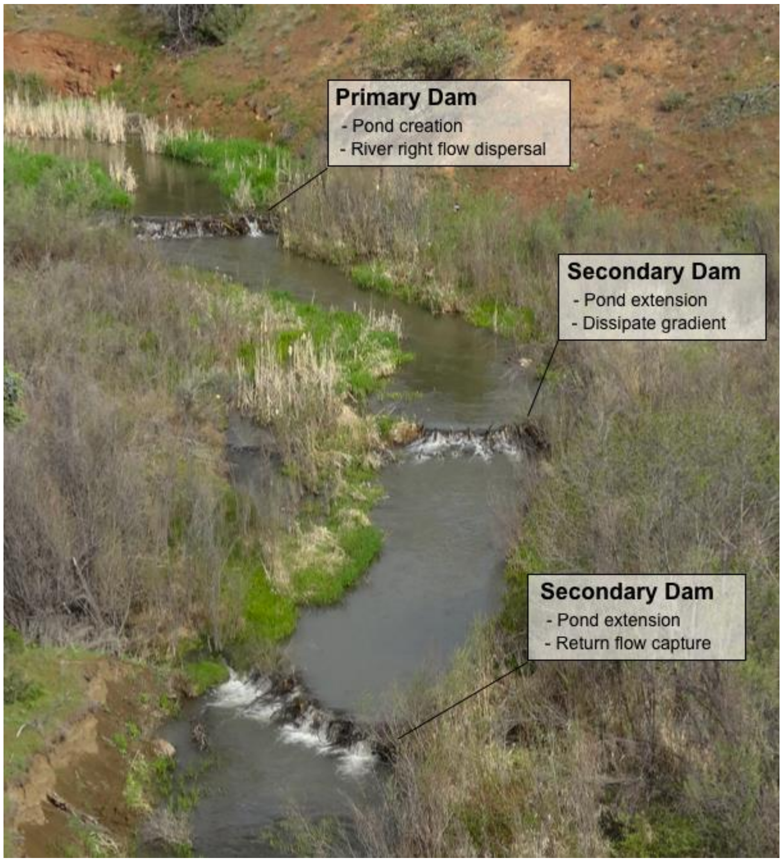


Figure 16 - Structure complex on Bridge Creek, OR. A starter dam is shown at the top of photo which has led to ponding upstream and downstream flow over the floodplain. Two secondary dams are shown downstream, extending the length of the ponded area and encouraging additional flow onto the RR floodplain. Not visible in the photo is a high-flow side channel on RL that is now regularly inundated due to ponding from the upstream secondary dam pictured in the middle of the photo. (Figure from Weber et al., (2015))

**Structure complexes can be configured to create and maintain a diversity of hydrogeomorphic processes. For vertically incised streams that
processes. For vertically incised streams that have lost historic floodplain connection BDA structure complexes have been designed to mimic
complexes have been designed to mimic the role that beaver complexes play in expediting the transition between the evolutionary phases
between the evolutionary phases (Cluer and Thorne, 2014; Pollock et al., 2014; Schumm et al., 1984) of incised stream channels.
incised stream channels. Representative complex configurations designed to support rapid transitions between the evolutionary phases of
between the evolutionary phases of incised streams are listed in Table 1. The following section provides a short narrative and accompanying
tables (Table 1 and**

Table 2) to explain the restoration objectives, evolutionary phase transitions/stream processes influenced, and design considerations specific to the different types of restoration complexes.

Widening/Increase Instream Geomorphic Complexity: This structure complex is intended to increase the width of a vertically incised, narrow section of stream channel. This is accomplished through increased bank erosion which accelerates the evolutionary recovery phase transition from Phase 1, following rapid vertical incision to Phase 2, trench widening. Incision trench widening is necessary for the recovery of incised streams to first create accommodation space for subsequent channel and floodplain aggradation. Focused bank erosion increases channel length and can lead to development of a more sinuous channel planform and a reduction in channel gradient. Lowered channel gradient encourages higher rates of aggradation from upstream sediment mobilization, accelerating the recovery process. Widening decreases instream stream power by providing high flow dispersion out of the active channel onto incipient, inset floodplain surfaces. High flow dispersion also extends the functional life of beaver dams and/or beaver dam analogs by the reduction in stream power acting on the dam itself which leads to fewer dam failures.

Though the primary restoration objective for this complex type is to accelerate the rate of widening there are additional benefits garnered to aquatic and riparian habitat that occur during the widening process. Focused bank erosion creates a local sediment supply that is then redeposited as instream bar and inset floodplain features within the incision trench further downstream (Schumm et al., 1984). This increases the geomorphic and aquatic habitat complexity by providing a diversity of flow paths and velocities within the active channel during base flow and on developing inset floodplains during high flow. Strategically mobilizing a variety of grain-sizes present in the banks increases the variability in substrate composition within the active channel which is important for aquatic biota. The increase in incision trench width and reduction in stream power also allows for riparian corridor expansion. For a more thorough explanation of incision trench widening see Pollock et al., (2014).

Widening and increasing geomorphic complexity can be accomplished through a complex of constriction dams with an occasional channel spanning primary and secondary dams located downstream of the constriction dams to capture the eroded bank material. Alternatively, a series of channel spanning dams can be used that are designed to preferentially fail in a chosen direction. The following channel attributes should be present to initiate the design of this type of structure complex though not all attributes need be present in one location. The contemporary stream channel is vertically incised and laterally confined by hydrologically disconnected terraces or alluvial fans. There is limited to no inset floodplain present on either side of the contemporary stream. The walls of the confining incision trench are primarily composed of erodible material (i.e. not bedrock). Typically, channel planform sinuosity is low and channel gradient is relatively higher compared to less laterally confined sections. There is extremely limited instream geomorphic complexity (i.e. plane-bed geomorphic units are dominant) and a relatively homogenous distribution of grain-sizes within the active channel.

Aggradation/Floodplain Connectivity: This structure complex is primarily intended to create new inset floodplain, expand the area, and enhance the rate of connectivity with existing floodplain surfaces during the incision recovery process. This is accomplished through increasing the rate of channel aggradation with a series of channel spanning dams, which accelerates the evolutionary recovery phase transition from Phase 3 slow aggradation to Phase 4 dynamic equilibrium (Cluer and Thorne, 2014; Pollock et al., 2014; Schumm et al., 1984). It should be noted, that incision and recovery of incision prone streams in alluvial settings does not typically follow a completely linear trajectory everywhere and because of this, some reaches possess channel attributes representative of multiple phases of recovery that may require a structure complex that both encourages additional widening while also enhancing floodplain connectivity.

During the trench widening phase accommodation space is created to allow for development of inset floodplains. Additionally, it is common in incised streams to have high flow floodplain benches and ledges within the boundaries of the existing incision trench which is reflective of the stochastic process of past channel incision. These relict and contemporary floodplain surfaces can be targeted for flooding and lateral expansion with this type of structure complex. By increasing the rate, duration and inundation of floodplain surfaces this elevates the water table during both low and high flow conditions (Woo and Waddington, 1990), increases groundwater recharge (Westbrook et al., 2006) which can lead to an increase in the diversity of riparian vegetation (Wright et al., 2002) and an expansion of the riparian corridor (Westbrook et al., 2011). Additionally, high flow paleo-channels on existing inset floodplain surfaces can be activated during relatively lower flow events which provides flow refugia for juvenile salmonids. The rate of floodplain creation, inundation and expansion is elevated by accelerating the rate of sediment aggradation through channel spanning dam impoundments. Ponding upstream of beaver dams and beaver dam analogs slows water velocity encouraging deposition of a range of sediment both instream and on the floodplain (Butler and Malanson, 1995; Pollock et al., 2007) while also creating high-flow dispersal onto existing surfaces.

Design consideration for these structure complexes depends on the height and area of the existing floodplain surfaces (i.e. there must be inset floodplain surfaces present to initiate design of this complex type. In most cases, several primary dams will be required to raise the crest elevation above the inset floodplain level. Higher dam crest elevations, require a higher number of secondary dams to prevent upstream head cutting. BDAs with higher crest heights may also require more maintenance or multiple stages of treatment to reach the desired height of regular inundation. Beavers are the most effective at maintaining dams and so encouraging their establishment should be considered. Thus, areas with riparian vegetation necessary to support beavers may be given higher priority. In some circumstances, the primary dam may need to extend laterally across the part of the floodplain intended for flooding, to ensure the flooded pond accesses low points, such as paleo-channels. Spacing between channel spanning dams will largely depend on channel gradient, but is generally within 1 – 2 channel widths. A larger spacing may be necessary (2-4 channel widths) if including constriction dams as flowing water is needed to force a more powerful hydraulic jet. Consideration should be given to creating a continuous ponded area or if it is desirable to leave some free-flowing riffle conditions for fish habitat.

Restore Hydrologic Connectivity: This restoration objective can be accomplished through the same type of structure complex explained in the previous section (Aggradation/Floodplain Connectivity) in that it is composed of channel spanning dams. As has been previously discussed, dam building by beaver has been shown to influence stream hydrology in a number of important ways primarily by altering the amount, and timing of delivery of water and sediment (Gurnell, 1998; Pollock et al., 2003). Ponding upstream of beaver dams elevates the water table and groundwater levels (Woo and Waddington, 1990). With a high density of beaver dams it has been shown that dam impoundments can attenuate water table decline during the dry season, elevating base flow (Burchsted et al., 2010; Westbrook et al., 2006) and alleviating the effects of drought (Hood and Bayley, 2008). It should be noted that the elevation of base flow is also influenced by the composition of the underlying aquifer and its effectiveness at releasing groundwater recharged by the dam impoundments.

Design considerations differ from the Aggradation/Floodplain Connectivity structure complexes. Aggradation is not an objective, thus locating sediment sources for dam impoundment and including secondary dams as grade stabilization is irrelevant. Instead, a series of channel spanning primary dams compose this complex. It may be necessary to extend the length of the primary dams laterally onto the floodplain to ensure adequate capture of surface and shallow sub-surface flow. Ideally, locate valley wide constriction points for dam placement. Extra emphasis may also be placed on creating impermeable dams by using additional fill material.

Create Beaver Habitat: The primary objective of this complex type is to create favorable habitat conditions for existing or relocated beaver. Beaver build dams to create ponds that provides protection from predators, expands forage area, stores food over winter, and provides thermal refugia (Westbrook et al., 2011). As has been mentioned previously and should be obvious, beaver are experts at building and maintaining their own dam complexes. To maximize the restoration benefits from the hydrogeomorphic processes influenced by dam building it is preferential to let beavers do the work. This structure complex is composed of a series of channel spanning primary and secondary dams but the design considerations differ from the two other complexes also comprised of channel spanning dams in the following ways. Emphasis is placed on creating deep pools by flooding existing pools with dam ponds. Pond extent should be maximized by locating areas with low floodplain present. Proximity to suitable riparian forage material is necessary. A complex designed primarily as beaver habitat can have secondary objectives of enhancing aggradation, floodplain and/or hydrologic connectivity.

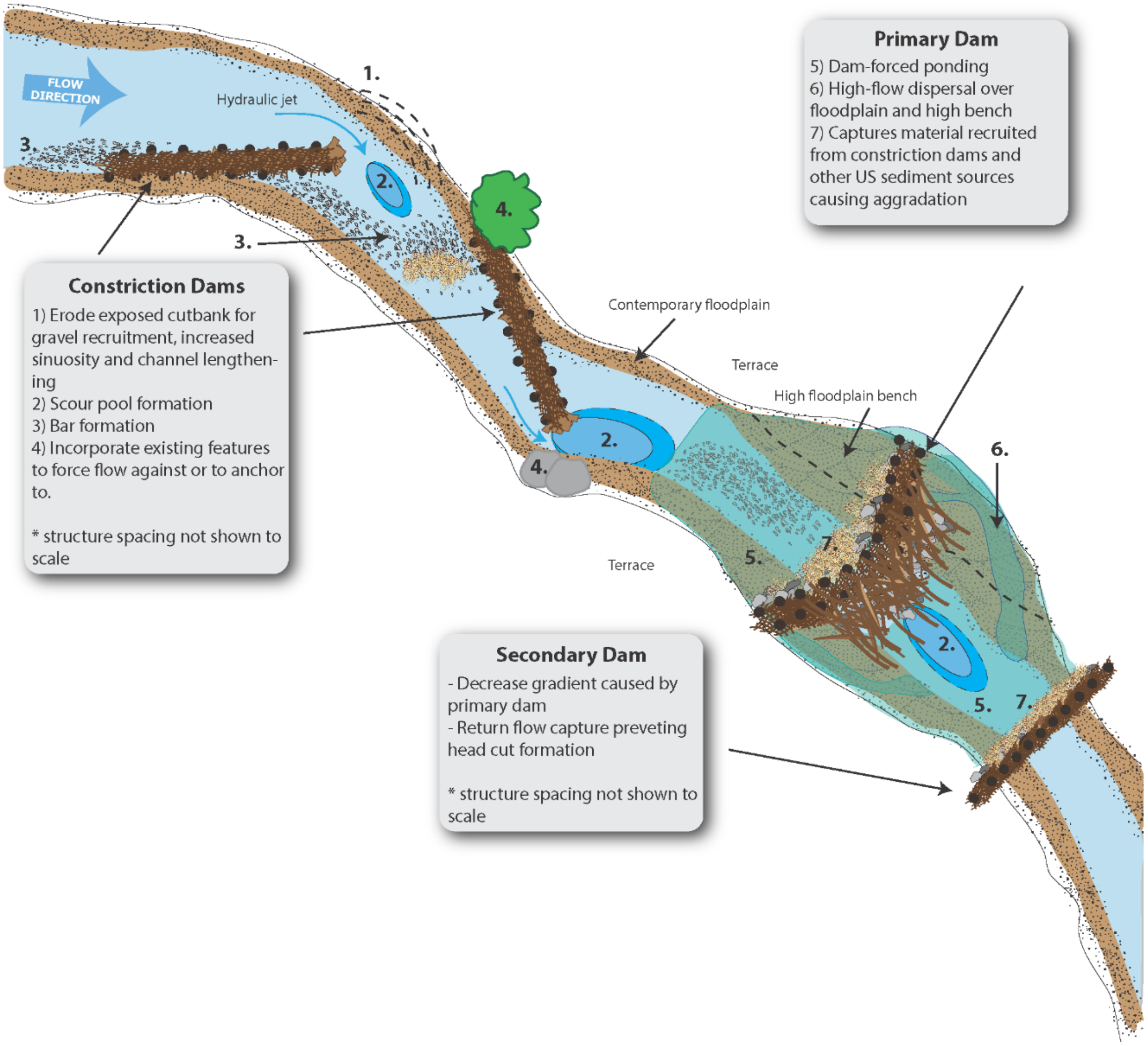
Table 1 - Representative complex configurations designed to expedite the evolutionary phases of incised stream channels.

Evolutionary Phase Transition	Stream Process	Complex Configuration
Phase 1 rapid incision to Phase 2 trench widening	Reduce stream power and sediment output by introducing roughness elements that widen the incision trench, reduce gradient, and increase channel length	Series of constriction dams for bank erosion and widening of the incision trench and increasing sinuosity and secondary dams to reduce water surface gradient and encourage deposition within the incision trench
Phase 2 trench widening to Phase 3 slow aggradation	Continue widening of the incised channel, increase sinuosity and inset floodplain formation	Constriction dams to widen the incision trench, increase sinuosity, and mobilize material for aggradation and bar development followed by primary dams designed for channel aggradation. Secondary supporting dams lower gradient below and provide stability for primary dams and increase extent of ponding and channel aggradation
Phase 3 slow aggradation to Phase 4 dynamic equilibrium	Floodplain reconnection, increased groundwater elevation, and riparian expansion	Primary dams creating extensive pond formation and dispersing flow onto disconnected terraces and benches. Downstream secondary supporting dams decrease gradient, capture return flow, and increase pond extent

Table 2 - Incomplete list of structure complex configurations designed to meet specific restoration objectives.

Restoration Objective	Stream Process	Complex Configuration
Geomorphic complexity	Increase channel meander length, scour pool and bar formation, increase substrate composition diversity	Complex of alternating constriction dams accentuating natural meanders and forcing scour pool formation and bar deposition
Floodplain connectivity	Increased extent and duration of floodplain inundation, secondary	Series of channel spanning primary and secondary dams causing pond creation

	channel reconnection, and groundwater elevation	and flow dispersion
Hydrologic connectivity	Increase water storage, pool/pond extent, and groundwater elevation and exchange	Series of channel spanning primary and secondary dams causing extensive pond creation
Infrastructure protection	Direct flow away from areas of concern	Series of constriction dams designed to redirect flow
Beaver habitat	Increase life-span of existing dams, extent of pond area providing cover, and amount of forage	Reinforced existing active and abandoned dams, and install additional channel spanning primary and secondary dams to increase pond extents



Constriction Dams
1) Erode exposed cutbank for gravel recruitment, increased sinuosity and channel lengthening
2) Scour pool formation
3) Bar formation
4) Incorporate existing features to force flow against or to anchor to.

* structure spacing not shown to scale

Primary Dam
5) Dam-forced ponding
6) High-flow dispersal over floodplain and high bench
7) Captures material recruited from constriction dams and other US sediment sources causing aggradation

Secondary Dam
- Decrease gradient caused by primary dam
- Return flow capture preveting head cut formation

* structure spacing not shown to scale

Figure 17 - Simplified schematic demonstrating how constriction, primary, and secondary structures work in concert as part a structure complex. Source: Elijah Portugal (2015a)

Beaver Dam Analog Structure Design

In general, the design and installation of BDA structures is a relatively simple, cost effective, and non-destructive restoration approach. BDA structures are constructed of untreated, sharpened lodgepole fence posts, approximately 3-4" diameter, driven into the active channel and inset floodplain using a hydraulic post pounder. Posts extend no more than 1 m above the active channel bed, which is within the 0.5 to 1.5 m typical height range of natural beaver dams. For a single structure posts will be spaced approximately 0.5 - 0.8 m apart, and driven to a depth of approximately 1 m into the streambed. Following installation of the post line, willow stems are generally woven in between the posts to create a semipermeable structure that closely resembles a natural beaver dam. The willow weaving acts as a dam, but is also designed to be passable to fish, and is consistent with the adult and juvenile fish passage criteria provided in NOAA's Anadromous Salmonid Passage Facility Guidelines (2004) and consistent with the Aquatic Resources Biological Opinion for restoration actions on federal lands in Oregon and Washington. In addition to weaving willow among the post line, BDA structures will be reinforced by placing cobble, gravel, and fine sediment at the base of the structure, a technique very similar to the way beavers build natural dams. Reinforcing the base of BDA structures prevents flow from scouring under the dam, and speeds up pond formation and associated processes. Beaver Dam Analogues should last until the pool behind the dam fills with sediment and is colonized by woody riparian vegetation (< 5 yr). The spacing between structures will be consistent with the dam layout of a natural beaver colony, which is approximately 30 - 100 m apart, depending on stream gradient and width.

There are four major BDA structure types:

- Primary Dams
- Secondary Dams
- Constriction Dams
- Reinforced Existing Dams

While not always mutually exclusive, specific structure types vary with respect to their function, design, and construction, and are strategically placed to mimic the form and function of beaver dam complexes. Each structure is designed with defined objectives for triggering and/or maintaining geomorphic and hydraulic processes leading to channel and floodplain rehabilitation.

Table 3 – Four major restoration structure types. Constriction dams are classified as both BDA and PALs structure types

Structure Type	Function	Design	Construction
Primary Dam	Primary flow impounding structures maximize pond extent, water storage, channel aggradation, flow dispersion, and groundwater exchange	Channel spanning dams built adjacent to and extending laterally onto floodplains, benches, and terraces. Crest elevation greater than bankfull	Convex post-line with wicker weave. Upstream impermeable sediment wedge for pond creation, downstream willow mattressing scour prevention

Secondary Dam	Downstream gradient control and return flow capture of primary dams. Increase extent of ponding, aggradation, and habitat complexity	Channel spanning dams installed downstream of primary dams. Crest elevation at or below bankfull	Post-line with wicker weave. Less extensive upstream sediment wedge and little to no downstream mattressing
Constriction Dam	Creation of hydraulic jet to increase capacity for geomorphic work of bank erosion, sediment recruitment, pool and bar formation	Partial channel spanning dam oriented downstream and at an angle to flow. Enhance natural flow constrictions at meanders and in-channel structural elements	Staggered post-line securing locally available fill material such as LWD, cobbles, gravels, sand, and/or willow weave
Reinforced Existing Dam	Increase resistance of active dams to high flow events and extend functional life of abandoned dams. Increase likelihood of stable colony establishment	Active and abandoned dams in areas lacking established beaver colonies	Post-line installation extending along the width of and just downstream of natural dam crest

Primary Dams

Primary dams closely resemble and share many of the design features and functions of natural beaver dams. Primary dams are designed to do the majority of the geomorphic work associated with channel aggradation and facilitate water storage, groundwater recharge, and floodplain reconnection.

Function

In general, primary dams can be differentiated from other structure types in that their main objective is to create immediate upstream pond formation in the active channel, kick-starting many of the positive benefits associated with stable pond formation. These dams are built to a higher elevation than secondary and constriction dams, which increases the potential elevation of channel aggradation and promotes flooding of adjacent channel surfaces, such as abandoned inset benches and terraces. Functions of primary dams include:

- Provide immediate deep-water cover to increase likelihood of beaver colonization.
- Decrease rate of dam failure by reducing water surface gradient and dissipating high flows onto adjacent floodplain and terrace features.
- Provide immediate deep-water cover for fish during low-flow periods, and flow refugia during high flows.
- Increase instream habitat complexity through increased geomorphic and hydrologic complexity.
- Increase groundwater exchange thereby providing thermal refugia for fish and increasing the extent of riparian plant communities.
- Elevate water table leading to increased surface water connectivity and riparian vegetation recruitment.
- Enhance the rate of channel aggradation by capturing material as suspended and bed-load.

- Increase and enhance floodplain connection through ponding and flow dispersal across terraces.

Figure 18 - Example of a primary dam on Bridge Creek, OR after construction (left panel) and extensive flooding onto adjacent floodplain surfaces the following spring (right panel). Source: Nick Weber.

Design

Major design considerations for primary dams include the placement of the structure within the channel and the specification of a dam crest elevation. Crest elevation refers to the vertical distance posts extend above the current bed elevation.

Structure placement is primarily concerned with local channel morphology and the presence and size of adjacent channel features, which include:

- Incision trench width. Areas that offer more accommodation space within the incision allow a greater amount of ponding and flow dispersion without the requirement of a higher dam that can be prone to breaching.
- Channel width. Natural constriction points are good locations for primary dams.
- Channel gradient. Lower channel gradients increase the upstream extent of ponding and aggradation and are also less prone to dam breaching.
- Presence of inset floodplain, high floodplain benches and terrace surfaces which can be inundated. Flooding of these surfaces immediately increases floodplain reconnection and allows flow dispersion at high flows.
- Presence of disconnected high flow channels. Adjacent abandoned high flow channels can be easily flooded and speed up the process of floodplain reconnection.
- Bank composition. In confined channels, banks that are armored by vegetation or large substrate decrease the likelihood of endcut breaches around the dam.

Dam crest elevation is also dictated by local channel attributes. A number of local channel attributes should be considered when specifying primary dam crest elevations including:

- Desired elevation of the aggraded channel. This elevation may be equal to the surrounding disconnected high floodplain bench or terrace, or at an elevation in which the accommodation space between the confining features of the incision trench are greater.
- Elevation of inset high floodplain benches and terraces. Crest elevations designed slightly above the elevation of adjacent high floodplain benches and terraces cause immediate surface flooding within the upstream pond, and promote high and low dispersed flow downstream.
- Width of the incision trench and channel gradient. Narrow and steep channels require a lower crest elevation in order to prevent dam breaching at high flows.

Figure 19 - Example of primary dam structure installed by the Oregon Department of Fish and Wildlife in 2012 on Beach Creek in the Upper Mainstem John Day River. Structures were designed to support greater habitat complexity and increase water storage during low base flow conditions. Source: Nick Weber

Construction

Local channel features ultimately determine dam construction elements (e.g., the presence of anchoring features like bedrock or roots). General construction elements employed in the installation of primary dams include:

- Post line installation. Post lines provide support for the dam. Similar to natural dams, primary dam post lines should have a convex shape to dissipate high flows preventing excessive scour below the dam.
- Willow weave. Green willow (preferably sourced locally) is tightly woven in between posts working up from the active channel bed to the desired crest height elevation.
- Construct impermeable base. Similar to natural beaver dam building techniques, cobble, gravel and sand is placed directly upstream of the dam abutting the posts and willow-weave. This prevents head cutting of the structure and immediately increases the impermeability of the dam causing immediate pond formation.
- Mattress construction. Directly downstream of the primary dam and within the active channel a ‘mattress’ is constructed of cobble, gravel, sand, and willow placed parallel to flow. Parallel willow placement mimics the natural dam building activity used by beaver and can be interspersed among the perpendicular willow weave to increase structure stability. This ‘mattress’ prevents excessive scour below the structure thereby reducing potential failure due to head cutting and undermining downstream of the dam.
- Post lines trimming. Following construction, post heights should be trimmed just above (~20) above the height of the dam crest elevation.

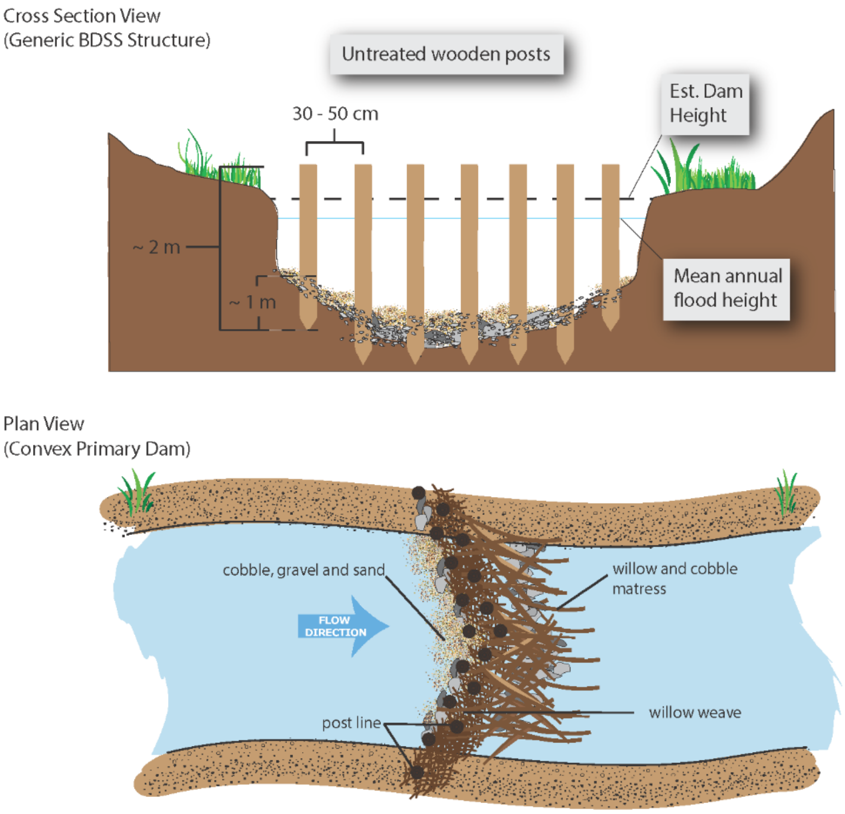


Figure 20 - Cross section schematic (above) of general beaver dam analog (BDA) without fill material. Plan view (below) showing the features of a convex primary dam. The hypothesized geomorphic and hydraulic responses (e.g., ponding, bar and pool formation, etc) are not shown in this figure. Source: Elijah Portugal (2015a)

Secondary Dams

Secondary dams share many similarities to primary dams, and to a lesser degree initiate many of the same geomorphic and hydrologic responses. However, the primary objective of secondary dam is to be designed and positioned as support structures for primary dams.

Function

Secondary dams are channel spanning structures that are generally installed downstream of larger primary dams. Support is provided by lowering the water surface gradient created by primary dams, which prevents excessive scour and potential head-cutting downstream of the primary dam. In addition, flow impounded by secondary dams increases pond area, expanding refugia for beavers and increasing the likelihood of beaver colonization within a dam complex. Functions of secondary dam structures include:

- Gradient control. Dissipating the gradient created by primary dams increases dam stability by decreasing the likelihood of head-cutting and dam undermining.
- Return flow capture. Raised water levels behind secondary dams reduces the potential for head-cutting of dispersed flow channels across floodplains, benches, and terraces.
- Trench aggradation. Reduced velocities behind secondary structures begin aggradation of the active channel within the incision trench.
- Fish habitat complexity. Creation of upstream pond and downstream scour pool and depositional bar increases fish habitat complexity

- Beaver colonization. Increased pond extent and stable dam building structures increase the likelihood of beaver colony establishment and persistence.

Figure 21 - Overhead view of primary dam causing extensive ponding and river left overflow (large dam center) and downstream secondary supporting dam functioning as a gradient break. Bridge Creek, OR. Source: Nick Weber

Design

Design considerations related to incision depth, width, and presence of floodable surfaces outlined above for primary dams also apply to the design of secondary dams. However, they are generally installed with a lower crest elevation and a width that remains primarily within the active channel and therefore a few additional design features are considered, including:

- Spacing for gradient control. Dams serving as gradient control should be close enough to impound flow to the base of an upstream primary structure, and far enough downstream to maximize pond area and extent of channel aggradation. Distance downstream will largely depend on channel gradient, but is generally within 1 – 2 channel widths below a primary dam.
- Placement as return flow capture. Structures designed to capture return flow should be placed a short distance (~ 1 channel width) downstream of the overflow channel reentry point. In many cases this will depend on the presence of existing natural or artificial dams creating overflow channels or the specific design response of a primary dam. Examining terraces, benches, and floodplains downstream of primary dams for the presence of abandoned channels or areas of low elevation adjacent to the active channel can help to predict where overflow channels and reentry points may develop.
- Placement for habitat complexity. Secondary dam placement designed to increase habitat complexity should allow enough space so that downstream structures do not impound flow to the base of the next upstream structure. Increasing the space between structures maximizes flow velocity complexity promoting the formation of downstream forced pools and depositional bars.

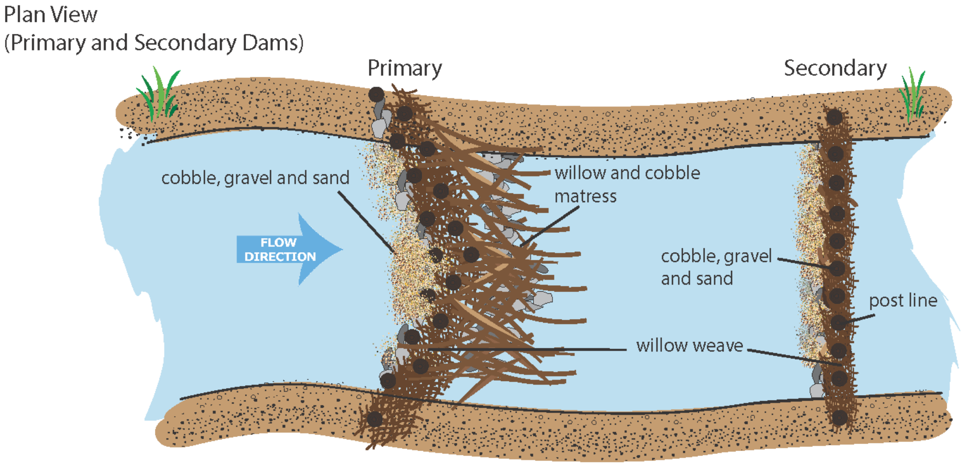


Figure 22 - Planview schematic of primary and secondary dams working in concert. The hypothesized geomorphic and hydraulic responses (e.g., ponding, bar and pool formation, etc) are not shown in this figure. Source: Elijah Portugal (2015a)

Construction

Construction techniques for secondary dams are largely analogues to those described for primary dams and require the same materials and method explained above. However, because secondary dams generally have lower crest elevations and support less extensive ponds, several of the measures used to ensure the stability of primary dams can be relaxed when constructing secondary dams.

- Dam profile. Dam profiles can be straight as opposed to convex as flow dissipation below structures with low crest heights is less of a concern.
- Impermeable surface. Less extensive base of cobble, gravel and sediment needed during construction.
- Mattress construction. Less extensive or no construction of a downstream mattress of cobble and willow.

Reinforced Existing Dams

In some areas it's possible to capitalize on beaver dams that are actively maintained or abandoned dams that are still intact and reinforce them with fence posts to increase dam longevity.

Function

Continued dam failure will often cause beavers to abandon location before a colony can establish a stable dam complex. Reinforcing intact dams with wooden fence posts can greatly reduce the likelihood of active dam failure during high flow events, and also serves to extend the functional life of abandoned dams. Reinforcing existing active dams can also increase the chances of beaver colony persistence and establishment of stable natural beaver dam complexes, or can lead to reoccupation of dams when local food supplies may be sufficient to support a beaver colony.

Figure 23 - Reinforced abandoned dam that has been reoccupied on Lower Owens, Bridge Creek. Source Nick Weber

Design

Reinforcing existing dams does not involve construction of new structures so the principal design considerations are selecting suitable active and abandoned dams to reinforce:

- Some portion of the dam should be intact.
- Consider evidence of the current or past geomorphic effectiveness of the dam (e.g., flooding and flow dispersion across high floodplain or terrace surfaces).
- Choose abandoned dams with suitable forage material close by to encourage beaver colonization.
- If designing a complex with a specific objective, find complementary locations for new dam structures in close proximity to the dam(s) to be reinforced.

Construction

Reinforcing existing or abandoned dams consists of pounding wooden fence posts directly downstream of the dam crest or within a structural gap or breach of active or abandoned dams. In addition to the fence posts, willow weave and cobble, gravel and sand can also be used to patch breaches. The materials and construction methods are the same as the construction of primary dam structures.

Constriction Dams AKA Bank-Attached Post Assisted Log Structures (PALS)

Constriction dams or bank-attached PALS are distinct from primary and secondary dam structures in that they span only part of the active channel and are designed either 1) mimic failed or breached beaver dams and also the role of natural dam failure within the evolutionary cycle of incised streams (Pollock, 2014) or 2) a piece of LWD that has naturally recruited into the stream and is oriented with one side on the bank and the other in the stream. Constriction dams are common to both the BDA and PALS restoration structures.

Function

Constriction dams function to partially impinge flow and facilitate the immediate creation of a hydraulic jet. Hydraulic jets have a higher stream power relative to unimpeded flow, and can be strategically directed towards erodible banks or existing structural elements (e.g. bedrock or tree roots) to increased rates of geomorphic instream work (i.e. scour and deposition). Constriction dams can be used to increase instream geomorphic and aquatic habitat complexity in number of ways:

- Sediment recruitment. Flow can be directed towards erodible banks with coarse deposits (i.e., cobble, gravel, sand) to mobilize material for bar development and downstream deposition and channel aggradation behind dams.
- Erosion prevention. Flow can be directed away from erodible banks to prevent erosion and protect existing infrastructure such as roads or private property.
- LWD recruitment. LWD can be recruited by eroding banks where LWD is present.
- Scour pool/bar creation. Flow can be directed towards non-erosive in-stream structural elements (i.e., bedrock, boulders, LWD, roots) forcing pool scour and bar development.
- Widening of incision trench. Strategic erosion of banks can be used to widen the incision trench in incised channels allowing increased high flow dispersal and increasing dam persistence.
- Channel lengthening. Dissipate stream power by increasing channel sinuosity, channel length, and decreasing slope.

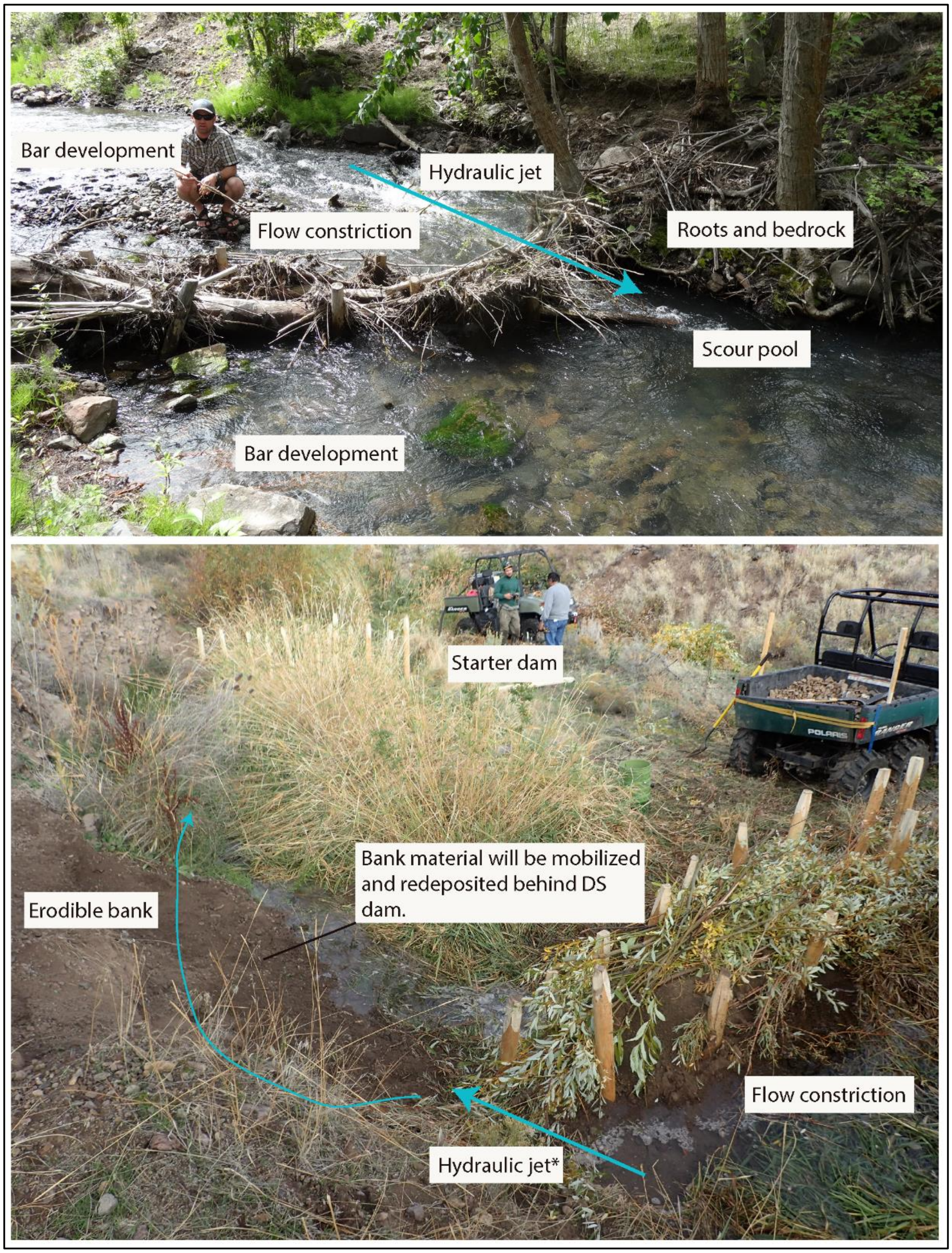


Figure 24 - Examples of constriction dams. Above panel shows a 2 year old constriction dam on Asotin Creek WA. Structure is oriented towards bedrock and roots forcing scour pool formation and bar development. Below panel shows a constriction dam from Pine Creek, OR just after installation. Structure is designed to mobilize material from an erodible bank to enhance bar formation and aggradation rates behind the downstream primary dam shown in the top of the picture. Source: Elijah Portugal

Design

Design considerations will differ slightly by the intended function of each constriction dam. However, most constriction dams will be attached to either the right or left bank and oriented downstream at roughly a 120° angle in order to constrict flow and create a hydraulic jet. Other design considerations specific to constriction dams include:

- Existing flow constrictions. In many cases, constriction dams can be designed to enhance existing flow convergence zones created at meander bends or by other in-channel structural elements (i.e. boulders, bedrock, vegetation, roots).
- Gradient and stream power. Reaches with relatively high gradients will have a greater stream power and ability to do geomorphic work.
- Amount of channel constricted. A greater portion of the channel should be constricted when stream power is low and/or the intended geomorphic response is high (90 – 95%). On larger streams with high stream power constriction dams may accomplish the specified design objectives with constriction ranging from 50-70 %.
- Non-erosive elements. Constriction dams that force a hydraulic jet into non-erosive in-channel elements can have a higher capacity for the geomorphic work associated with pool formation and bar deposition.
- Anchors. In-channel structural elements such as bedrock, boulders, or LWD can be incorporated into the structure itself serving to anchor and add support.
- Bank armoring. Structures designed to initiate lateral bank erosion should consider bank armoring from vegetation that may impede lateral mobility.
- Bank material. Location of desired sediment size range to mobilize from erodible banks (e.g., gravels for bar development or sands and fines for deposition behind downstream dams).
- Bar formation. To enhance the rate of bar formation locate existing bar surfaces and force sediment mobilization upstream through a constriction dam.

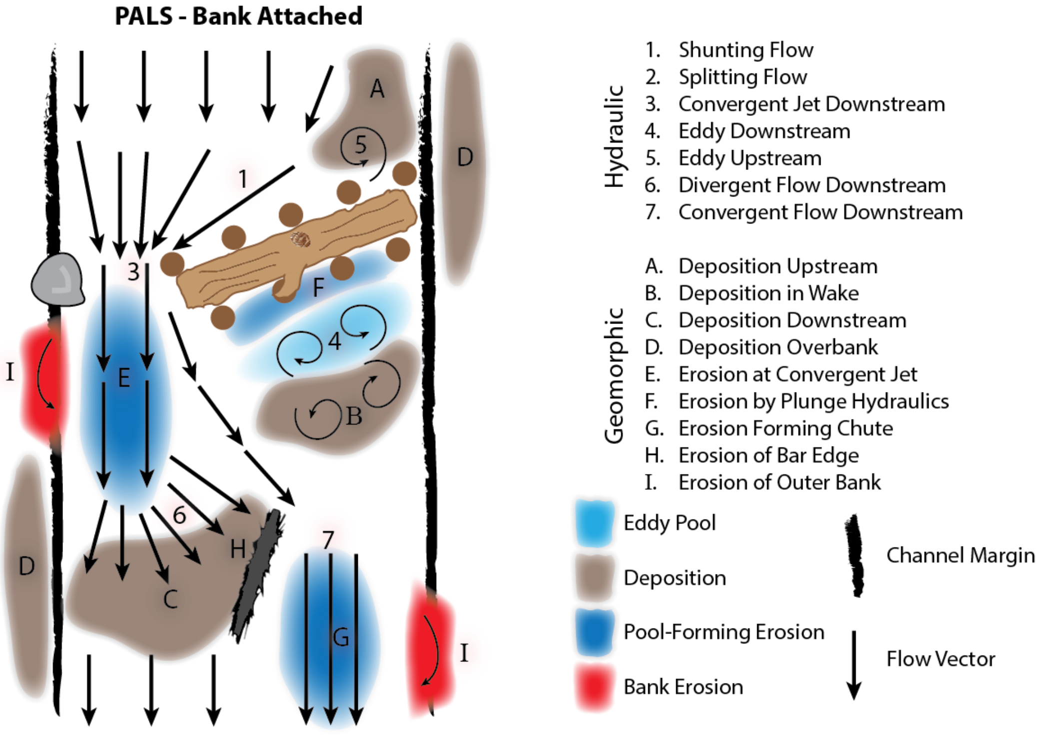


Figure 25 – Potential hydraulic and geomorphic responses after the installation of a constriction dam (aka bank-attached PALS). Source Reid Camp

Construction

Typically a large amount of LWD will be required to build numerous constriction dams (aka bank-attached PALS) and thinned seed trees lots, second growth forests, or juniper removal projects can provide an almost perfect source of this material. Trees should have branches still intact and be 10-40 cm diameter near the base and no longer than 10 m to aid transport. Pieces required for construction will depend on the width of stream, accessibility of the site (e.g., how far wood needs to be carried), and availability of materials. The best structures can be built with a variety of size pieces of LWD. Large logs are good for the base of the structure, while medium and small pieces are good for building up the structure height and complexity.

- The structure profile is straight but typically oriented 120 degrees downstream into flow.
- Not channel spanning (80-95% constriction often optimal).
- Post placement. Two rows of posts are often staggered to add stability to the structure and create a place to secure LWD and fill material.
- Place large piece of LWD on the stream bottom to maximize the redirection of flow and force of concentrated constriction jet towards the opposite side of the channel.
- Remove branches from one side of each piece of LWD to facilitate building a more densely packed structure (i.e., lay piece with removed branches nearest the ground)
- Place some LWD up on the bank to prevent water from flowing around structure on the side it is being built from.
- Post placement. Once LWD is placed in the stream use posts to secure the wood in place. Use two rows of posts staggered to add stability to the structure and create a place to secure LWD and fill material.
- Use removed branches to fill in gaps on structures and help force flow towards constriction
- Fill material. A combination of LWD, cobble, gravel, sediment, and woven willow is secured within the structure to decrease its permeability.
- Slope structure height slightly downwards from the bank it is being built from
- Don’t make the structure too pretty; irregularity will help recruit more LWD moving downstream during high flows

High-Density Large Woody Debris Design Considerations

The general goal of the $_{HD}$LWD restoration approach is to increase the LWD density over a large area (several km) to broadly mimic the densities of LWD found in undisturbed or reference conditions. Numerous small LWD structures (secured and unsecured) are built primarily by hand to mimic trees that would have naturally fallen into the stream from riparian areas and nearby upslope areas. $_{HD}$LWD structures are not built in complexes in quite the same rigorous fashion as BDAs because trees fall more randomly than beavers build dams. However, groups of LWD structures can be used to create certain outcomes including reconnection of floodplain and abandoned channels, increasing sinuosity, or encouraging tree and sediment recruitment (see below). We use three main structure types in the $_{HD}$LWD approach: post-assisted log structures (PALS), key pieces, and seeding.

PALS are built using similar methods to BDAs in that wooden fence posts are used to build all natural structures. Unlike BDAs, PALS are generally built to simulate natural trees that would fall in the stream and increase hydraulic and geomorphic complexity. Key pieces are large trees that can be added using heavy machinery where access to the stream permits, and there will be little impact to the existing riparian area. Key pieces are intended to act as buffers to large floods and potentially help create large debris jams by collecting added LWD and naturally occurring LWD during high flows. Seeding is simply adding pieces of LWD by hand to provide more wood to the stream that can be trapped on PALS or key pieces creating more complexity. Typically, seeding wood is added to areas that are geomorphically complex, with the primary goal of keeping LWD densities high. All of these types of LWD are intended to last in the system for 5-10 years depending on stream gradient, width, and magnitude of flood events. Depending on the condition of the existing riparian habitat, natural LWD inputs may be restored by a single treatment of $_{HD}$LWD if recruitment of LWD and interaction between the channel and floodplain is sufficiently increased.

There are three major PALS types and three LWD types used in $_{HD}$LWD:

- Bank-attached PALS (this is the same structure as the Constriction DAM BDA explained above)
- Mid-channel PALS
- Debris jams PALS
- Spanner
- Seeding
- Key pieces

Each PALS vary with respect to their function, design, and construction, and are strategically placed to mimic the form and function of natural accumulations of LWD. Each structure is designed with defined objectives for triggering and/or maintaining geomorphic and hydraulic processes leading to channel and floodplain rehabilitation (Figure 29 and Table 6).

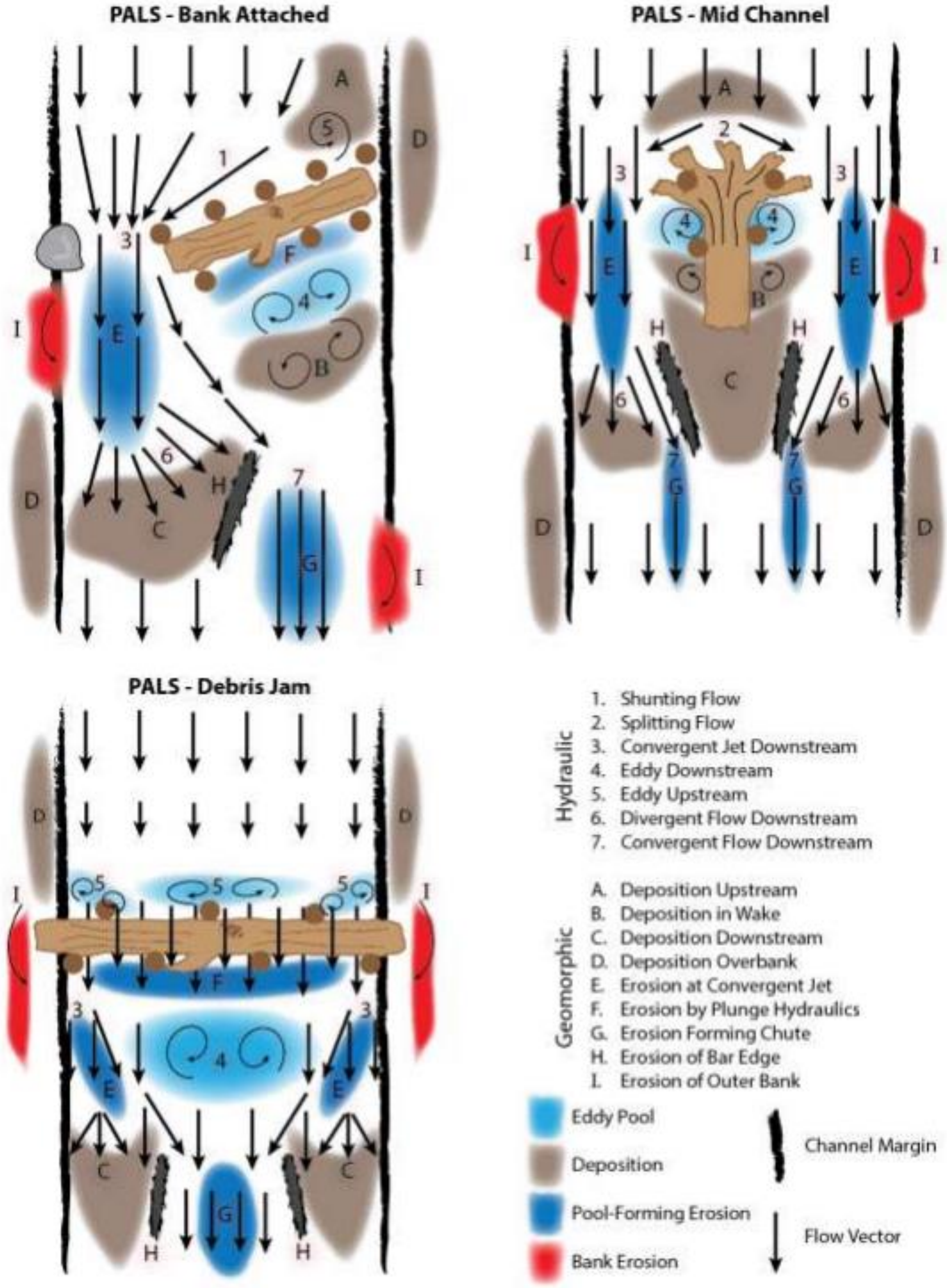


Figure 26 - Potential hydraulic and geomorphic responses associated with bank-attached (aka constriction dam), mid-channel, and debris jam PALS. Source: Reid Camp

Table 4 - Large woody debris structures used in the $_{\text{HD}}$LWD approach to increasing wood frequency in wadeable streams. Constriction dams are classified as both BDA and PALS structure types

Structure Type	Function	Design	Construction
Bank attached PALS	Explained in Table 5		
Mid-channel PALS	Split flow in wide shallow areas to increase depth variability and hydraulic diversity. Create two scour pools on either side of structure, mid-channel bar downstream of structure.	Intended to simulate a tree with a root wad. Large face upstream to split flow with long tapered truck parallel to the flow. Block 40-80% of the flow in mid-channel.	Use large log perpendicular to flow at upstream end. Build head of structure 2-4 layers high. Extend downstream parallel to flow with several long logs
Debris jam PALS	Flow impounding structure that can also be intended to force channel avulsion into disconnected side channel or floodplain area. Water storage, channel aggradation, flow dispersion, and groundwater exchange	Channel spanning PALS built adjacent to and extending laterally onto floodplains, benches, and terraces. Crest elevation greater than bankfull	Straight post-line securing LWD pieces. Built to span the entire bankfull channel if possible.
Spanner	Force flow under a log to create a mid-channel scour pool, possible location of log jam formation and act as source of LWD	Place a large log (preferably 3 x length of bfw) perpendicular to flow to simulate tree falling across the stream. Use existing vegetation to keep log in place	Use machinery to place or several people to carry large log into place
Key pieces	Act as less mobile LWD by being longer and larger diameter than pieces of LWD used for PALS. Increase LWD diversity and potentially act as starting points for large natural log jams	Install where access permits and damage to existing riparian is minimal.	Install with heavy machinery, several people, or draft horses
Seeding	Provide additional LWD for building more complex structures after high flow events, and to keep LWD densities high.	Add opportunistically and as LWD source permits	Can be left on existing bars or on the floodplain depending on objectives

Example 65% Design Plans: McKee Creek

In the **McKee Creek Colluvial Hillslope and Inset Floodplain Streamflow Enhancement Project** we will use a high density of three different types of instream structures meant to influence geomorphic and hydrologic processes in slightly different capacities depending on the structure type and the natural process that is being mimicked. Generally, all the instream structures are intended to mimic natural accumulations of High Density Large Woody Debris (HDLWD (Bennett et al., 2016; Wheaton, 2012)) within the channel and inset floodplain but each individual structure is strategically placed to take advantage of existing channel and floodplain features (e.g., presence or height of inset floodplain, anchoring features) and has a corresponding specific hypothesized geomorphic response at the structure level (e.g., bar formation upstream and downstream and adjacent pool formation). The response of each individual structure, though important, is of less concern than the larger-scale geomorphic and hydrologic response to the grouping of structures that are meant to function together to achieve restoration objectives leading to enhanced streamflow.

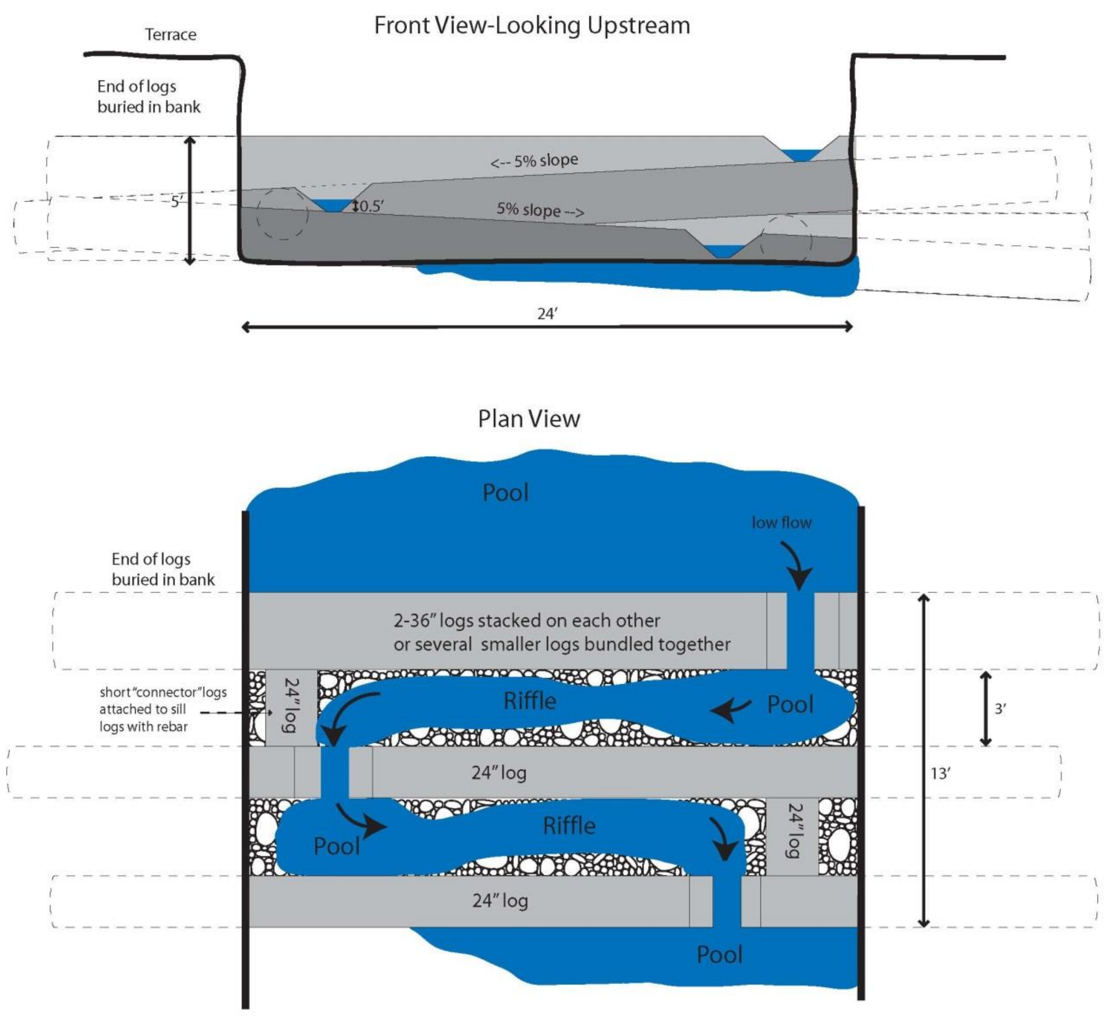
1) Log and boulder weirs

Channel spanning structures installed such that they immediately elevate the bed elevation leading to increased sediment and water retention, increased instream pool habitat, and increased floodplain access. These structures will be placed strategically to enhance the rate of existing floodplain connectivity, and to reconnect historic high floodplains and side channels leading to an increase in groundwater recharge. The structures will incorporate fish passage utilizing a step pool design that mimics naturally occurring bedrock and wood structures in Mattole streams. Non-channel spanning instream structures will be installed upstream and downstream of the log and boulder weirs to provide scour protection and increased cover and complexity. Over the long term, the channel spanning log structures will promote natural processes of aggradation such that the streambed elevation will increase and the pools immediately upstream of the structures will likely fill in. Though the upstream pools will be temporary features the increased instream complexity due to the structures will influence hydraulics to promote and maintain a higher amount of pool habitat compared to current conditions. Similar to beaver dams and LWD jams, the structures are designed to promote formation of complex streams with higher sinuosity, floodplain connectivity and wood recruitment as the streambed elevation increases.

Construction

Structures will be anchored into the streambanks using excavated and backfilled trenches or placed against larger, standing trees where conditions allow. Gravel to be used as backfill against the weirs will be excavated on site from strategically selected high points in the existing floodplain, where excavation will facilitate increased floodplain access. Fish passage design will provide for either passage through a structure, in the case of a debris jam, or creating a structure with a maximum 6” jump height to accommodate juvenile passage (Figure 1). Heavy equipment and hand labor by the CCC’s will be used to install the structures. Equipment access will be accommodated by selecting routes that reduce the amount of ground and vegetation disturbance and utilizing existing logging roads where feasible. Upon completion of equipment access, trails will be covered with debris to eliminate future vehicle access. Any exposed soil will be mulched with weed-free straw or native mulch.

Conceptual design for a 5′ x 24′ log weir with fish passage



Design Notes:

- -All logs should be conifer, preferably redwood or Douglas-fir
- -Lower two sills and connector log should be 24″ diameter. If not available, smaller logs will need to be bundled with cable.
- -Bury logs > 6-10′ into banks, or use epoxy and rebar to attach to bedrock
- -Space between log sills should be filled with coarse gravel (4″ diameter) mixed with small cobble , sufficient to allow for some scour
- -Dimensions of trapezoidal channel cut through top sill log is approximately 6″ wide at base and 3′ wide at top.
- -Low flow assumed to be 6″ deep in trapezoidal channels. If lower or higher, dimensions of trapezoidal channel should be adjusted accordingly
- -Dimensions should be adjusted on site to ensure a maximum 6″ drop from water surface to water surface at low flow. A low flow notch may be needed.
- -Scale: 1″ = 4′

Figure 27 – Conceptual diagram of a log and boulder weir with fish passage. (Source: Sanctuary Forest)

2) Channel spanning post-assisted check dams

The post-assisted check dams will be channel spanning, mostly impermeable structures composed of wooden posts driven in the bed and bank supporting bundles of brushy fill material sourced locally. The dams closely resemble Post Check Dams described in the California Department of Fish and Wildlife Salmonid Stream Habitat Restoration Manual (2002) and share similarities to Beaver Dam Analog (BDAs) (Pollock et al., 2014) though are not meant to mimic natural beaver dams. Instead the check dams will mimic natural accumulations of large wood, and serve as grade control structures. The structures will be placed at a high density, rivaling historic wood loading rates. They will elevate the bed elevation through trapping sediment and will create pools upstream, increasing groundwater recharge in the channel bed alluvium and in the toe of the hillslopes in a steep intermittent tributary, located above anadromy.

Construction

The structures typically consist of a somewhat porous dam that minimally spans the channel, and often extends out onto adjacent floodplain, bench and/or terrace surfaces (depending on crest elevation used). The structures are often supported by a series of un-treated wooden fence posts driven into the bed, banks and floodplain surfaces which provide some anchoring for dam fill materials such as willow or other brush weaves, woody debris, mud, rocks, and brush mattresses (Figure 2). In general, the design and installation of these structures is a relatively simple, cost effective, and non-destructive restoration approach. Structures are constructed of untreated, sharpened lodgepole fence posts, approximately 3-4" diameter, driven into the active channel, banks and floodplain using a hydraulic post pounder. Posts typically extend no more than 1 m above the active channel bed. For a single structure, posts will be spaced approximately 0.5 - 0.8 m apart, and driven to a depth of approximately 1 m into the streambed. Following installation of the post line, willow stems or other locally sourced brush is generally woven in between the posts to create a semipermeable structure. In addition to weaving willow among the post line, the structures will be reinforced by placing cobble, gravel, and fine sediment at the base of the structure. Reinforcing the base of the structures prevents flow from scouring under the dam, and speeds up pond formation and associated processes. The structures should last until the pool behind the dam fills with sediment and is colonized by woody riparian vegetation (< 10 yr.). The spacing between structures will be consistent with the gradient and stream width but is typically 8 - 30 m apart, depending on restoration objectives. In McKee Creek the structure spacing will be approximately 6-8 m apart.

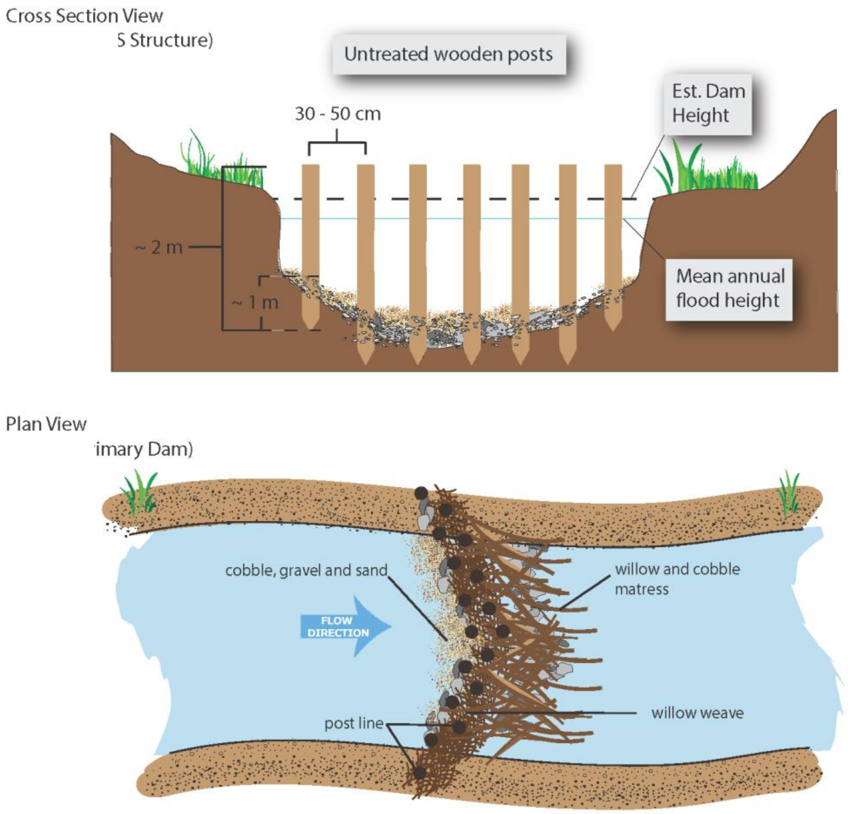


Figure 28 – Conceptual diagram of a generic channel spanning post-assisted check dam. (Source: Elijah Portugal)

3) Non-channel spanning instream structures (unanchored wood and post-assisted constriction dams)

The non-channel spanning instream structures are designed to facilitate fish passage and will be a mix of strategically placed unanchored LWD, and post-assisted constriction dams. These structures will support the log and boulder weirs with grade control, influence instream hydraulics increasing instream complexity and floodplain accessibility as well as providing cover and increased instream habitat (Wheaton, 2012). The structures are intended to mimic the behavior of natural LWD recruited to the channel and initiate the same benefits listed above. These are inexpensive treatments installed primarily using hand labor at a high enough density to rival historic rates of wood recruitment before disturbance (Bennett, 2012). The fate of an individual treatment (i.e., structure) is not as important as the larger-scale dynamic response of all structures working in concert over the project length. As such, structures are designed rapidly without hard engineering (i.e. static) which saves time and money. Each structure is typically composed of wood carried by hand to the site, which limits the size of each individual structure. The size limitation forces the design to emphasize many small structures instead of a few large ones. This spreads the beneficial geomorphic and hydraulic responses over a larger area increasing the likelihood of the restoration action addressing the root cause of river degradation.

Unanchored LWD will be added to the channel in strategic locations where natural wood accumulation is expected given channel properties and hydraulics. The LWD will be trees sourced locally from proposed forest thinning in upper McKee Creek and will be primarily put in place by hand crews with some heavy machinery assistance if logistically feasible and warranted. Depending on the size of the LWD, 3-10 pieces may be placed in the same location to create a small wood jam.

The non-channel spanning post assisted constriction dams are similar to the channel-spanning post-assisted check dams except the dam crest does not extend all the way across the channel and typically LWD is used as the primary dam fill material with some additional brushy material (Figures 3,4,5). Constriction dams function to partially impinge flow and facilitate the immediate creation of a hydraulic jet. Hydraulic jets have a higher stream power relative to unimpeded flow, and can be strategically directed towards banks, inset floodplains, or existing structural elements (e.g. bedrock or tree roots) to accomplish increased rates of geomorphic instream work (i.e. scour and deposition), and increased floodplain connectivity during high flow. Constriction dams can be used to accomplish restoration objectives in a number of ways:

- Sediment recruitment. Flow can be directed towards erodible banks with coarse deposits (i.e., cobble, gravel, sand) to mobilize material for bar development and downstream deposition and channel aggradation behind dams.
- Erosion prevention. Flow can be directed away from erodible banks to prevent erosion and protect existing infrastructure such as roads or private property.
- LWD recruitment. LWD can be recruited by eroding banks where LWD is present.
- Floodplain inundation. During high flow increased channel roughness and jet formation causes a higher magnitude and rate of floodplain inundation
- Scour pool/bar creation. Flow can be directed towards non-erosive in-stream structural elements (i.e., bedrock, boulders, LWD, roots) forcing pool scour and bar development.
- Widening of incision trench. Strategic erosion of banks can be used to widen the incision trench in incised channels allowing increased high flow dispersal and increasing dam persistence.
- Channel lengthening. Dissipate stream power by increasing channel sinuosity, channel length, and decreasing slope.

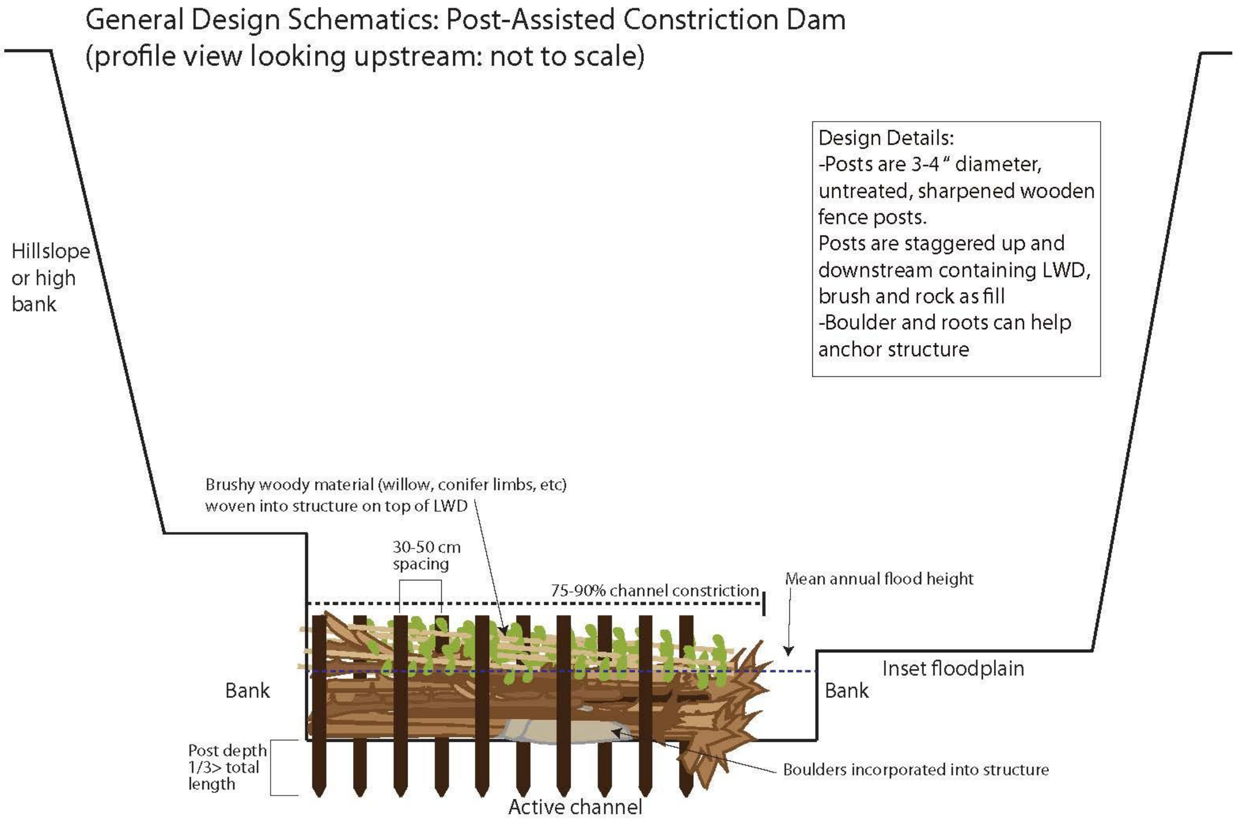


Figure 29 – Design schematic for a typical post-assisted constriction dam. View is in profile looking upstream. Source: Elijah Portugal

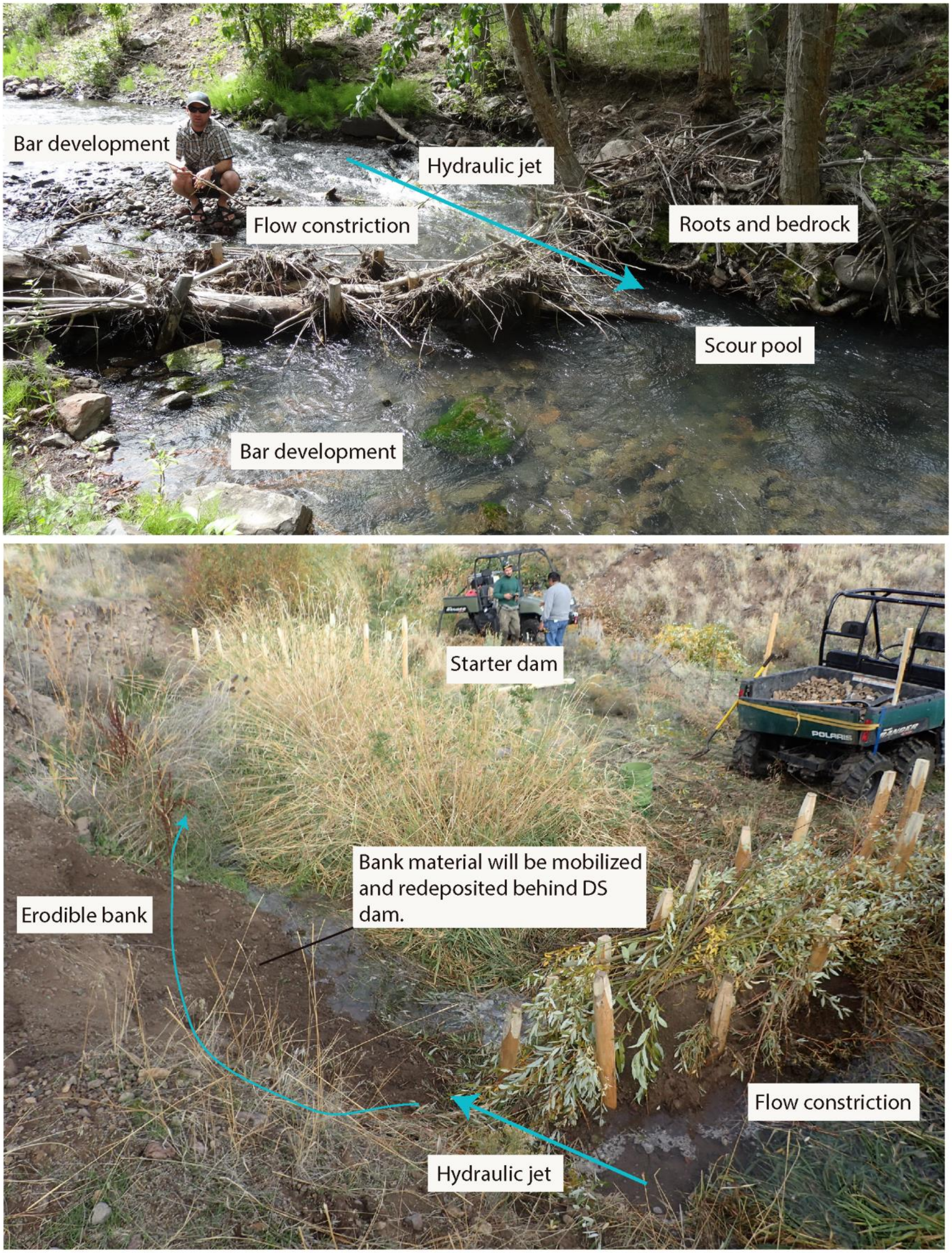


Figure 30 - Examples of constriction dams. Above panel shows a 2 year old constriction dam on Asotin Creek WA. Structure is oriented towards bedrock and roots forcing scour pool formation and bar development. Below panel shows a constriction dam from Pine Creek, OR just after installation. Structure is designed to mobilize material from an erodible bank to enhance bar formation and aggradation rates behind the downstream channel-spanning starter dam shown in the top of the picture. (Source: Elijah Portugal)

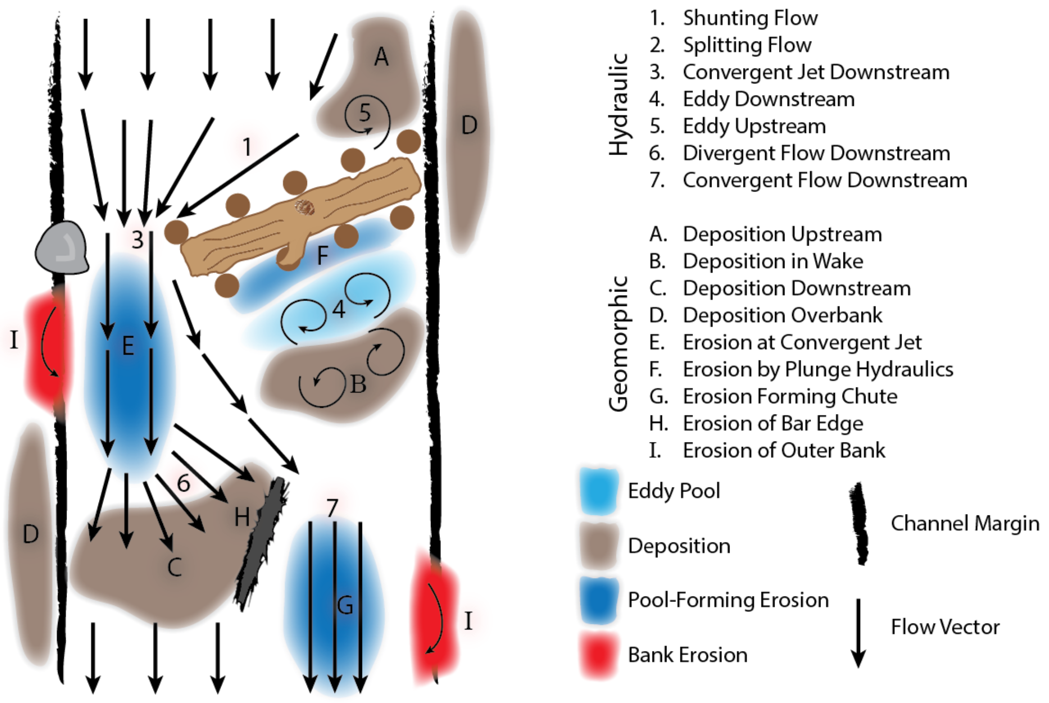
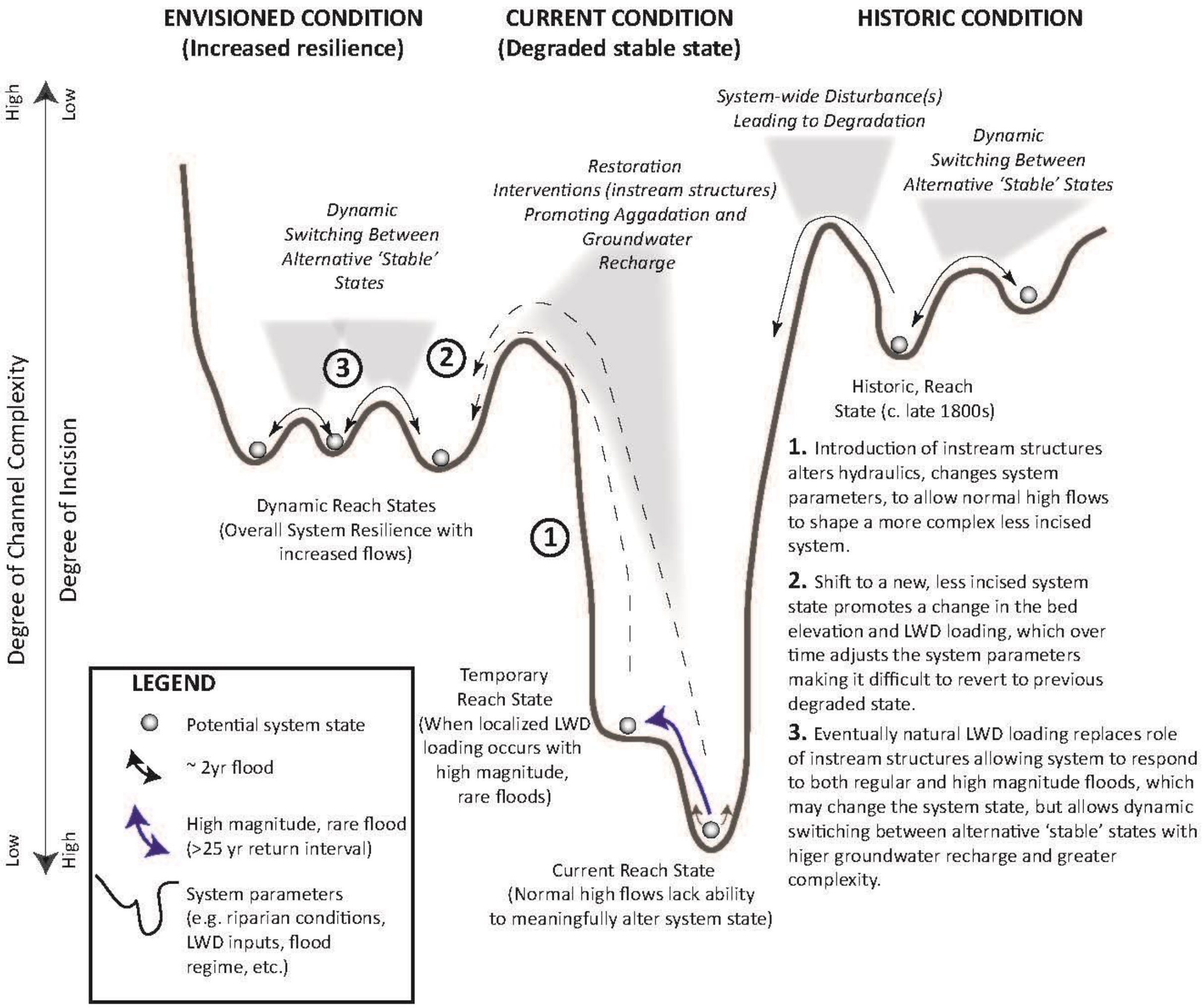


Figure 31 – Predicted hydraulic and geomorphic responses after the installation of a non-channel spanning post-assisted constriction dam. (Figure credit Reid Camp (2015).

Construction

Typically a large amount of LWD will be required to build numerous constriction dams and we plan to use LWD generated from the proposed upslope thinning project. Trees will have branches still intact and be 10-40 cm diameter near the base and no longer than 10 m to aid transport. The best structures can be built with a variety of size pieces of LWD. Large logs are good for the base of the structure, while medium and small pieces are good for building up the structure height and complexity. The following construction methods will be used:

- The structure profile is straight but typically oriented 120 degrees downstream into flow.
- Not channel spanning (80-95% constriction often optimal).
- Post placement. Two rows of posts are often staggered to add stability to the structure and create a place to secure LWD and fill material.
- Place large piece of LWD on the stream bottom to maximize the redirection of flow and force of concentrated constriction jet towards the opposite side of the channel.
- Remove branches from one side of each piece of LWD to facilitate building a more densely packed structure (i.e., lay piece with removed branches nearest the ground).
- Post placement. Once LWD is placed in the stream use posts to secure the wood in place. Use two rows of posts staggered to add stability to the structure and create a place to secure LWD and fill material.
- Use removed branches and other brush to fill in gaps and help force flow towards constriction
- Fill material. A combination of LWD, cobble, gravel, sediment, and woven willow is secured within the structure to decrease its permeability.
- Don't make the structure overly uniform; irregularity will help recruit more LWD moving downstream during high flows



1. Introduction of instream structures alters hydraulics, changes system parameters, to allow normal high flows to shape a more complex less incised system.

2. Shift to a new, less incised system state promotes a change in the bed elevation and LWD loading, which over time adjusts the system parameters making it difficult to revert to previous degraded state.

3. Eventually natural LWD loading replaces role of instream structures allowing system to respond to both regular and high magnitude floods, which may change the system state, but allows dynamic switching between alternative 'stable' states with higer groundwater recharge and greater complexity.

Figure 32 – Conceptual diagram of McKee Creek Colluvial Hillslope and Inset Floodplain Streamflow Enhancement Project.

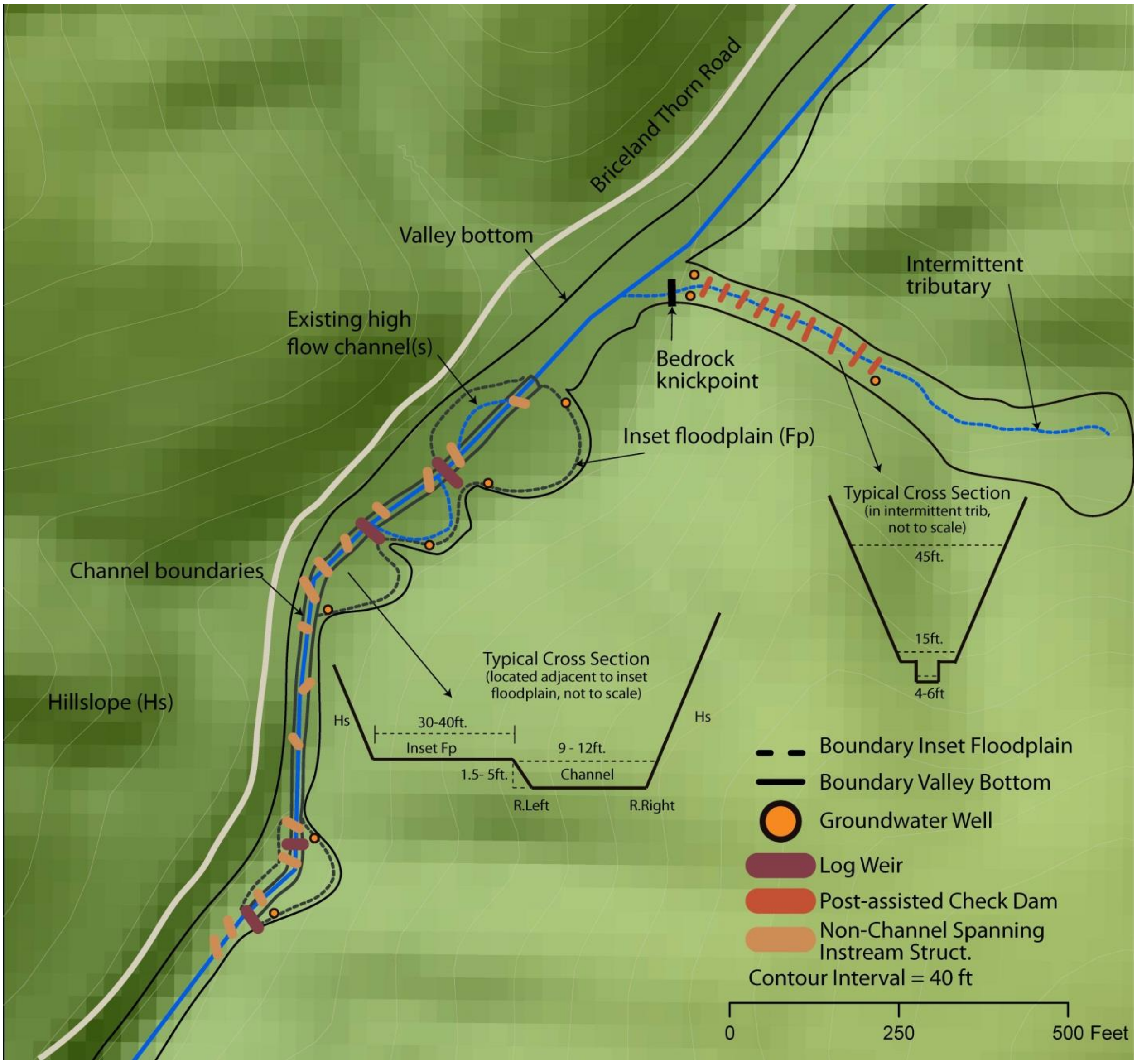


Figure 33 –65% design plans for McKee Creek Colluvial Hillslope and Inset Floodplain Streamflow Enhancement Project.

Additional BDA Resources

Fluvial Habitat Center: http://etal.joewheaton.org/home

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BDA Chapter in Beaver Restoration Guidebook

Pollock, M.M., Weber, N.P., and Lewallen, G. 2015. Beaver Dam Analogs. *In* The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains. Portland, Oregon. pp. 82–97.

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BDAs and Channel Incision Recovery

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V-BET – Valley Bottom Extraction Tool

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Appendix: BDA Post Pounder Summary

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BDA Post Pounder Summary

Brand **Atlas Copco** Cost $ **9000**

Minimum Crew **2** Maximum Post Diameter **3.8**

	Driver	Power Supply
Type	**Hydraulic**	**Gas Generator**
Weight lbs.	**75**	**250**
Example Model	**LPD-T HBP**	**LP-13-30 P**

Application

Largest and most powerful system that has worked in most situations. Can be challenging to move in heavily vegetated or steep systems.

Comments

in larger streams a cheap plastic canoe ($100) cab be used to transport the system and posts downstream; Larger tires and handles can also be added to the power pac to make it easy to move/carry

URL **https://www.atlascopco.com/en-us**

Brand **Skidrill** Cost $ **5000**

Minimum Crew **2** Maximum Post Diameter **4**

	Driver	Power Supply
Type	**Hydraulic**	**Gas Generator**
Weight lbs.	**70**	**100**
Example Model	**HP 20**	**P38**

Application

Will drive most posts in most situations except in difficult situations such as large embedded cobble and hard clay

Comments

in larger streams a cheap plastic canoe ($100) cab be used to transport the system and posts downstream; Larger tires and handles can also be added to the power pac to make it easy to move/carry

URL **http://skidril.com**

BDA Post Pounder Summary

Brand **Rhino** Cost $ **2000**

Minimum Crew **1** Maximum Post Diameter **4 - 6**

	Driver	Power Supply
Type	**Pneumatic**	**Compressor**
Weight lbs.	**50 - 100**	**None**
Example Model	**PD 55**	**None**

Application

Pneumatic units require air compressor

Comments

We have not used these but could be useful in some situations such as with larger posts in easy access situations.

URL **https://www.airpostdrivers.com/air-post-driver-parts.htm**

Brand **Redi** Cost $ **1500 - 2500**

Minimum Crew **1** Maximum Post Diameter **3**

	Driver	Power Supply
Type	**Gas**	**Gas Engine**
Weight lbs.	**40**	**None**
Example Model	**Redi Classic**	**None**

Application

Good for small projects in relatively easy situations; very portable but does NOT have the power for difficult sites or driving hundreds of post/day

Comments

Handy for T-posts and maintenance of structures.

URL **https://redidriver.com/all-about-redi-driver-inc/**

BDA Post Pounder Summary

Brand **Kiwi & others** Cost $ **2500 - 10,000**

Minimum Crew **1** Maximum Post Diameter **> 6**

	Driver	Power Supply
Type	**Tractor**	**Air/Hydraulic**
Weight lbs.	**> 100**	**> 500**
Example Model	**HP1000**	**NA**

Application

Good for tough jobs when road access is available

Comments

URL **http://www.kencove.com/fence/Post+Drivers_products.php**