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The Use of Low-Tech Process-Based Stream Habitat Restoration

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2024

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Photo credit: Marjorie Caisley, CDFW

This Fish Bulletin is dedicated to Marjorie (Margie) Caisley, who served with distinction as an engineer with the California Department of Fish and Wildlife since 2006 and is a lead author on this guidance document. She supported all facets of the Department's programs and was a beacon of light for fish passage and salmonid habitat restoration. Margie embraced the value of low-tech process-based restoration and championed the emerging field in California. She died much too young, just 4 days shy of 46 on July 4, 2022, after a courageous battle with cancer. She was a great mentor, restoration practitioner, and an all-around wonderful person who is missed immensely.

PREFACE

Widespread ongoing decline of native fish populations across the western United States indicates that the status quo pace and scale of riparian restoration is unlikely to result in significant recovery of several aquatic species (Wohl et al. 2005; Bernhardt et al. 2007). Restoration practitioners, non-governmental organizations, and government agencies all agree that low-tech process-based restoration techniques provide low-cost alternatives that are appropriate and effective in many watersheds throughout California (Ciotti et al. 2021). This document offers guidance that describes sensible assessment and planning tools, design considerations, implementation methods, and monitoring and adaptive management approaches applicable to this growing field of restoration. This report draws heavily from published works, in combination with input from California Department of Fish and Wildlife scientists and engineers, and others with experience and expertise in the restoration of riverscapes using low-tech process-based methods.

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INTRODUCTION

The California Department of Fish and Wildlife (CDFW), in cooperation with its partnering federal, state, and local government agencies, tribes, and private landowners, has invested millions of dollars to enhance and restore watershed, riparian, and instream habitat. Project types range from relatively high-cost and highly engineered fish passage and upslope sediment reduction projects to lower cost and less engineered riparian and instream habitat restoration. Even with this extensive effort, resident trout and anadromous salmonid fish populations continue to decline in most areas of the state. Climate change, anthropogenic activities, and other factors contribute to this decline in fish numbers. An extensive effort to improve natural processes in watersheds, riparian corridors, and instream habitat is needed to reverse this decline for resident fishes, anadromous salmonids, and aquatic ecosystems. This Fish Bulletin discusses low-tech process-based restoration (LTPBR) of riverscapes and draws extensively from the work of Wheaton et al. (2019) to describe low-cost restoration techniques that can improve riparian, floodplain, and instream habitat in many California streams. Riverscapes are defined as connected floodplain and channel habitats that make up the valley bottom (Wheaton et al. 2019).

In contrast to conventional restoration techniques that focus on the design and construction of specific habitat features, the LTPBR approach is process-based. Process-based restoration aims to reestablish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems (Beechie et al. 2010). The processes include erosion and sediment transport, storage and routing of water, plant growth and successional processes, input of nutrients and thermal energy, and nutrient cycling in the aquatic food web (Beechie et al. 2010). Collectively, these processes generate a suite of ecosystem services, which are renewable natural resources, such as clean water, productive soil, diverse vegetation, robust wildlife populations, and multi-faceted food chains (Vannote et al. 1980; Wohl et al. 2005; Osterkamp 2008; Thorp et al. 2010). A key element of process-based restoration is understanding that various anthropogenic activities (e.g., channelization, livestock grazing, timber harvesting, and urban development) strongly influence the rates at which various processes operate.

Wheaton et al. (2019) describe a common form of stream degradation, known as structural starvation, in which the riverscape is lacking structural elements, such as wood or beaver (*Castor canadensis*) dams. Moreover, the starvation is attributed to the "direct removal and/or disruption of processes that maintain structural inputs into the riverscape." Structurally starved systems drain water too efficiently or quickly. They tend to incise, straighten, narrow, and simplify stream channels. Channel incision severs the connectivity between the channel and its floodplain, thereby reducing ecosystem services and diverse habitat niches. Riverscapes with structure and complexity that obstruct and disrupt streamflow are healthier than those which lack these natural elements. The obstructions force hydraulic diversity, which in turn leads to geomorphic processes or erosion and deposition, which in turn create diverse habitats, greater resilience to disturbance, and a broader array of ecosystem services.

Ten principles outline the overarching strategy of LTPBR for structurally starved riverscapes (Wheaton et al. 2019):

1. Streams need space.
2. Structure forces complexity and builds resilience.
3. The importance of structure varies.
4. Inefficient conveyance of water is often healthy.
5. It is okay to be messy.
6. There is strength in numbers.
7. Use natural building materials.
8. Let the system do the work.
9. Defer decision-making to the system.
10. Self-sustaining systems are the solution.

These principles also support the goal of restoring habitat at a low cost, per mile of stream, compared to historic restoration approaches.

The LTPBR approach encompasses many different methods intended to enhance hydrologic, geomorphic, and biological processes that lead to the recovery of degraded watersheds. Stream habitat restoration techniques range from passive approaches, like cattle exclusion fencing of bankside areas to develop riparian vegetation, or levee breaches to allow streams to reoccupy historic floodplains, to active approaches, like structural interventions, which are the focus of this document. With LTPBR structural interventions, the function of the devices is to mimic natural accumulations of woody debris by constructing simple structures consisting of natural materials (e.g., logs, posts, and branches) built using hand tools primarily (e.g., post pounders, loppers, and shovels). The goal of such structural interventions is to promote a variety of physical and geomorphic processes (bank and channel erosion, sediment deposition, overbank flow, tree recruitment, wood accumulation, etc.) that lead to sustainable and resilient riverscapes. The work also tends to lengthen streamflow paths, increase water depths, and decrease flow velocity in the same manner as beaver dams and ponds, which can provide valuable habitat for anadromous salmonids, such as Coho Salmon (*Oncorhynchus kisutch*). Structural interventions provided by LTPBR can also promote channel aggradation that reduces flow capacity and thereby increases the potential for overbank flooding or floodplain connectivity. An important aspect of LTPBR is that it relies upon the stream's energy to reestablish more natural rates and magnitudes of various physical, chemical, and biological processes that support a wide range of ecosystem services (Beechie et al. 2010; Cluer and Thorne 2014; Ciotti et al. 2021).

Low-tech process-based restoration techniques provide additional tools to the restoration practitioners' toolbox. Like all stream restoration techniques, they must be implemented in the proper settings and at the appropriate scale, after thoughtful planning, and with realistic expectations as to the likely outcome of the overall project. This document describes a process of planning, design guidance, and construction techniques that will help facilitate a successful LTPBR project. The intent of this Fish Bulletin is to provide restoration professionals and practitioners, including CDFW staff and other resource agency staff, with guidance on the appropriate settings and techniques for implementing LTPBR in California. It is anticipated that adherence to this guidance will streamline notification processing for Lake and Streambed Alteration Agreements and better position a proposed project for grant funding and general permitting coverage through CDFW and other permitting agencies.

ECOLOGICAL AND HISTORICAL CONTEXT OF LOW-TECH PROCESS-BASED RESTORATION

Large wood and beaver dams provide obstructions to streamflow that alter flow depth, reduce flow velocity, promote floodplain inundation, and create a mosaic of habitat features. In California watersheds , these obstructions are primarily provided by large wood naturally recruited into the stream or placed for restoration where coniferous forests dominate, and by beaver dams where deciduous species are common. A discussion of the use of large wood in stream restoration is provided in Fish Bulletin 184, titled *The Use of Large Wood in Stream Habitat Restoration* (Flosi et al. 2024). The current document describes two effective, low-cost alternatives to provide structure to riverscapes: beaver dam analogs (BDAs), which are designed to mimic beaver dam activity, and post-assisted log structures (PALS), which mimic natural wood accumulations. The primary difference between BDAs and PALS is that local fill material (e.g., sediment from the banks and bed) is placed on the upstream side of BDAs to improve ponding, such as occurs in natural beaver dams, while PALS do not use fill material. In streams where beaver reside, their dams provide structural complexity and serve as instream obstructions that pond water and trap sediment. Beaver ponds locally recharge groundwater aquifers and raise the elevation of the water table in adjacent floodplains, which then better support the growth of riparian and wetland vegetation (Pollock et al. 2018). The ponds also provide valuable slow water rearing and refugia habitat for many fish species, including resident trout and anadromous salmonids, such as Coho Salmon and steelhead (*Oncorhynchus mykiss*) (Pollock et al. 2003; Bouwes et al. 2016).

Historically, beaver dams were widespread in small streams throughout most of the Northern Hemisphere (Pollock et al. 2003). It is estimated that prior to the arrival of Europeans, the population of beaver was between 60 and 400 million in North America. The current population is estimated to lie between 6 and 12 million (Naiman et al. 1988). The historic decline in beaver is attributed to trapping for fur and oil, and loss of habitat through stream channel alterations in valley bottom lands (Pollock et al. 2003). The range of beaver in California was described by Tappe (1942) as occurring primarily in the Klamath and Colorado River basins and in the Central Valley. This range estimate was probably conservative and reflective of what was known about beaver occupancy in California in 1942, when beaver had already been extirpated for decades from most of their native range. More recent research by Lundquist et al. (2013) and Lanman et al. (2013) greatly expands both the historic and current range of beaver in California to encompass essentially everywhere in the state that had or has enough water and dam building materials to support beaver. It is important to note that the relocation of beaver is often described in the literature as a tool for stream habitat restoration. Although carried out in other western states, such as Oregon and Washington, beaver relocation is still in its infancy in California, and therefore is not discussed further in this Fish Bulletin. The authors do recognize, however, that beaver may be far more efficient and effective at restoring streams than restoration practitioners, assuming adequate water and preferred vegetation resources are available.

Besides humans, beaver are the only other animal capable of altering the fluvial environment to suit their needs (Tappe 1942). Beaver modify stream morphology and stream hydraulics by cutting wood and building dams. Their dams are made of natural materials, such as small logs, branches, rocks, and mud. Many researchers now recognize that the widespread extirpation of beaver throughout much of their native range in North America has been a significant contributor to the widespread decline in aquatic habitat and native fish species (Darby and Simon 1999; Pollock et al. 2007; Bouwes et al. 2016; Wohl 2019).

As noted above, beaver ponds provide valuable habitat for many fish species, including resident trout and anadromous salmonids, such as Coho Salmon and steelhead. The *Recovery Strategy for California Coho Salmon* (CDFG 2004) states that "beaver ponds can create additional habitat for Coho Salmon, both in winter to avoid high flows, and in summer to avoid stranding as a result of low flows." Protecting existing beaver dams and, where feasible, promoting beaver expansion into new areas, is a cost-effective strategy for providing the structural elements needed for a self-sustaining riverscape. It is clear from the historic ubiquity of beaver throughout California, and the benefits that beaver dams confer on streams, that low-tech structures can potentially play an important role in stream restoration in California. Constructed BDAs and PALS can mimic the ecological benefits of natural beaver dams and facilitate disruption to the stream that triggers natural processes to restore form and function. However, if beaver are not present in a watershed, it may take considerably more time and effort from restoration practitioners to maintain ponded conditions behind BDAs, since beaver are known to actively maintain dams, both natural and artificial (Pollock et al. 2014).

GEOMORPHIC CONTEXT FOR LOW-TECH PROCESS-BASED RESTORATION

Streams lacking the structural elements of either large wood or beaver dams tend to become incised and disconnected from their floodplains. Channel incision can also be the result of tectonic uplift, climate change, and anthropogenic alterations (e.g., removal of large wood, forest removal, increase in impervious surfaces, channelization, diversions, and beaver extirpation). Incision accelerates the flow rate in stream channels, reduces the frequency of floodplain inundation, and lessens the occurrence, extent, and frequency of slow water habitat areas. In addition, channel incision often results in narrow riparian zones, reduction in wood recruitment, unstable streambanks, and a lowering of the water table, which has the potential to transform perennial streams into intermittent streams, or even ephemeral streams in some cases. Incised channels characterize one stage in a broader cycle of geomorphic evolution, namely a stream configuration lacking in ecosystem services.

Cluer and Thorne (2014) developed a Stream Evolution Model (SEM) that provides context for the geomorphic and ecological improvements associated with reach-scale LTPBR restoration. They describe a cycle of stream evolution that includes nine primary stages (0–8), with some stages resulting in arrested degradation (Stages 2 and 3s; Figure 1). The model shows how multi-threaded channels (Stage 0) evolve through incision to become single threaded channels and then gradually widen to allow aggradation of sediment that recreates a multi-threaded channel (Stage 8). An innovative attribute of their model is the linking, or integrating, of specific habitat and ecosystem benefits or ecosystem services to the various stages of stream evolution (Figure 2). Stages 0 and 8 exhibit multi-threaded configurations that provide the greatest range of ecosystem services, with Stages 1 and 7 also having good value. Stages 2, 3, and 4 are considered degraded, while Stages 5 and 6 may be described as on a recovery trajectory.

Cluer and Thorne (2014) also advance a method for scoring a particular stream segment in terms of its physical configuration and ecosystem services. More specifically, they provide a hydrogeomorphic attributes table and a habitat and ecosystem benefits table with which to score a particular stream segment.

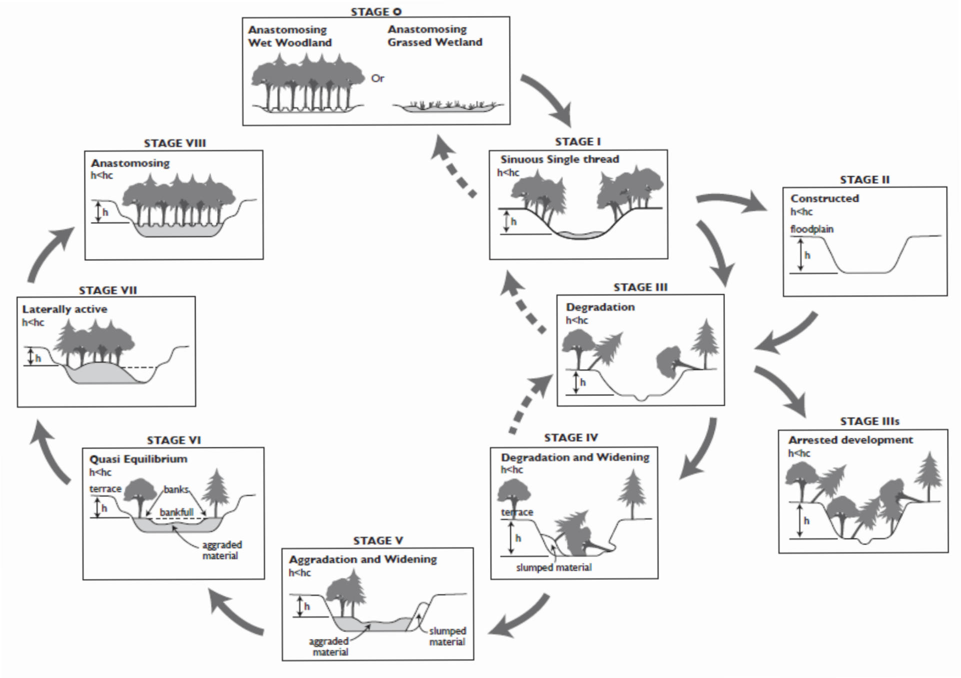


Figure 1. Stream Evolution Model (Cluer and Thorne 2014).

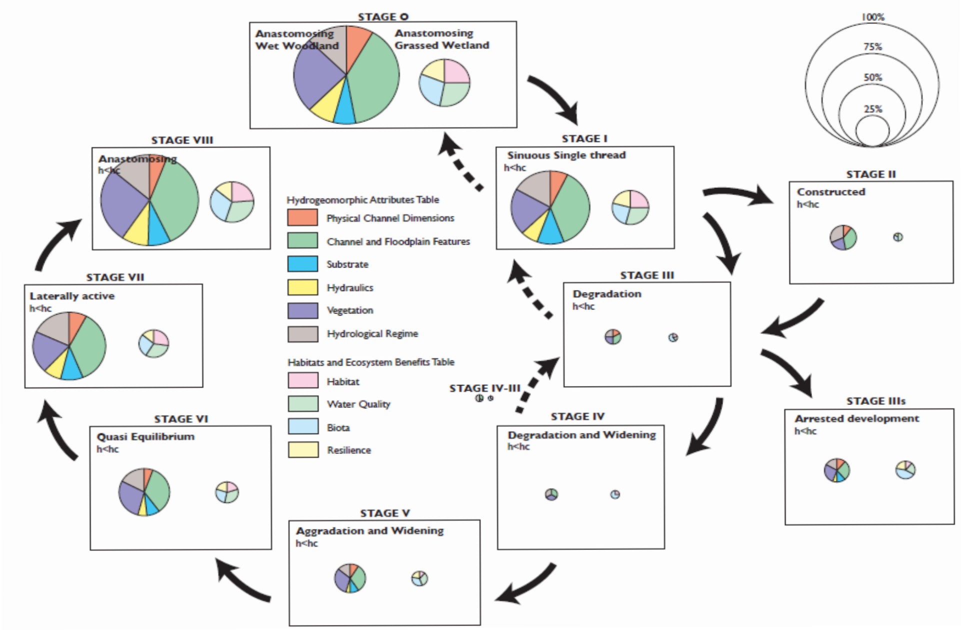


Figure 2. Habitat and ecosystem benefits provided by each stage of the Stream Evolution Model (Cluer and Thorne 2014).

Hydrogeomorphology is a branch of geomorphology that investigates the hydrologic basis of landform evolution (Dunne 1994). Hydrogeomorphology differs from fluvial geomorphology in that the latter is focused more upon the interactions between the physical shapes of rivers, surface water hydrology and hydraulics, sediment transport processes, and the landforms created. Hydrogeomorphology, in contrast, examines those various elements, in addition to exploring the linkages of groundwater flux and its role as a driver of mass-wasting and hillslope erosion (Sidle and Onda 2004).

CHANNEL INCISION, FLOODPLAIN RECONNECTION

A common objective of process-based restoration is to reconnect a stream with its floodplain or to create new floodplain surfaces. The primary goal of this work is to increase the frequency with which the floodplain is inundated. Floodplain connectivity is considered an essential element of stream channel restoration because it generates numerous hydrologic and ecological benefits, ranging from increased ecosystem diversity and complexity to attenuated flood peaks and recharged groundwater aquifers. Additionally, slow water habitat areas, such as wetlands and side-channels across the floodplain, are considered particularly valuable in terms of promoting primary production and providing rearing and refugia opportunities for various aquatic fauna (Duncan et al. 2011; Cluer and Thorne 2014). Adopting floodplain connectivity as a project objective requires an accurate identification and characterization of the active floodplain. Similarly, identifying areas near streams that were subject to fluvial processes prior to anthropogenic disturbance, or the historical process space as discussed by Ciotti et al. (2021), is important for setting appropriate riverscape restoration goals.

ACTIVE FLOODPLAIN

"Floodplain" is a relatively common term with many definitions, both formal and informal. Informally, "floodplain" can be used as a simple reference to a broad valley floor. Formally, the Federal Emergency Management Agency (Maurstad 2008) uses the phrase "100-year floodplain" as a regulatory term to designate areas subject to inundation during a 100-year recurrence interval flood, which is better defined as a flood that has a 1% chance of occurring in any given year. In contrast, Leopold (1994) defines the active floodplain of a stream as being "a level area near a river channel, constructed by the river in the present climate and overflowed during moderate flow events."

Leopold (1994) emphasizes that the active floodplain is constructed "in the present climate" because a floodplain can be abandoned and partly destroyed when the climate becomes drier. Floodplains can also be abandoned in response to tectonic uplift and anthropogenic activities that accelerate runoff to streams. An abandoned floodplain is no longer inundated by flood flows and may be referred to as a perched terrace or an elevated terrace. The channel is therefore incised and disconnected from the floodplain (Watson et al. 2002). A fluvial geomorphic term related to incision is "entrenchment," which is defined as the vertical containment of a stream and the degree to which it is incised in the valley floor (Rosgen 1994, after Kellerhals et al. 1972). Rosgen (1994) developed the entrenchment ratio metric to help characterize incision as an important attribute of a stream channel (Figure 3).

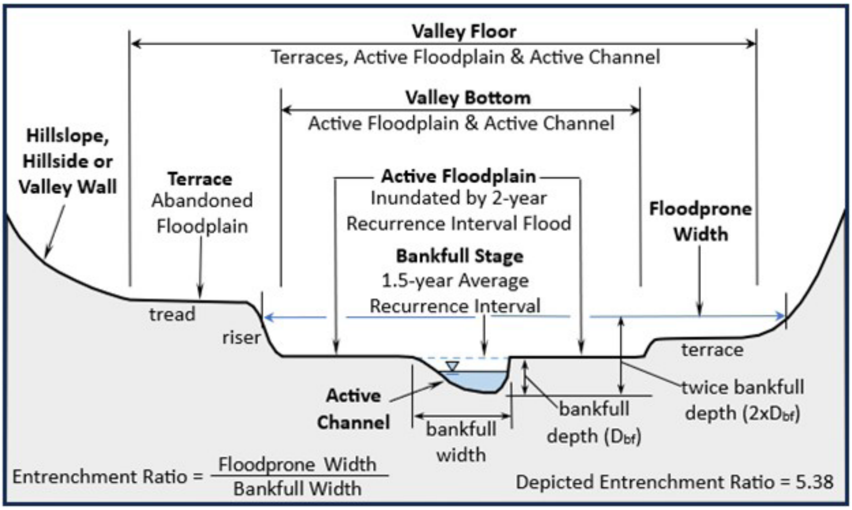


Figure 3. Diagrammatic cross-valley profile showing relationships between bankfull channel, floodplain, terraces, and valley walls. Also shown is floodprone width and the entrenchment ratio.

CHANNEL INCISION

Watson et al. (2002) describe incision as streambed lowering or degradation and erosion generated by an imbalance between the power *available* to move a sediment load and the power *required* to move a sediment load. In other words, incision may occur if the system has more power available than is necessary to move the sediment load.

As a streambed degrades, bank heights increase, a narrow incision trench forms, and the channel enlarges or deepens (Figure 4). Channel enlargement creates a positive geomorphic feedback loop in which progressively larger floods are confined within the channel, causing additional erosion and channel enlargement that will confine ever-larger flood flows capable of more erosion. Channel incision also affects the riparian corridor by lowering the water table that supplies moisture to the roots of riparian plants. The very steep side slopes associated with an incised channel commonly slough and fail, undermining and washing away riparian vegetation.

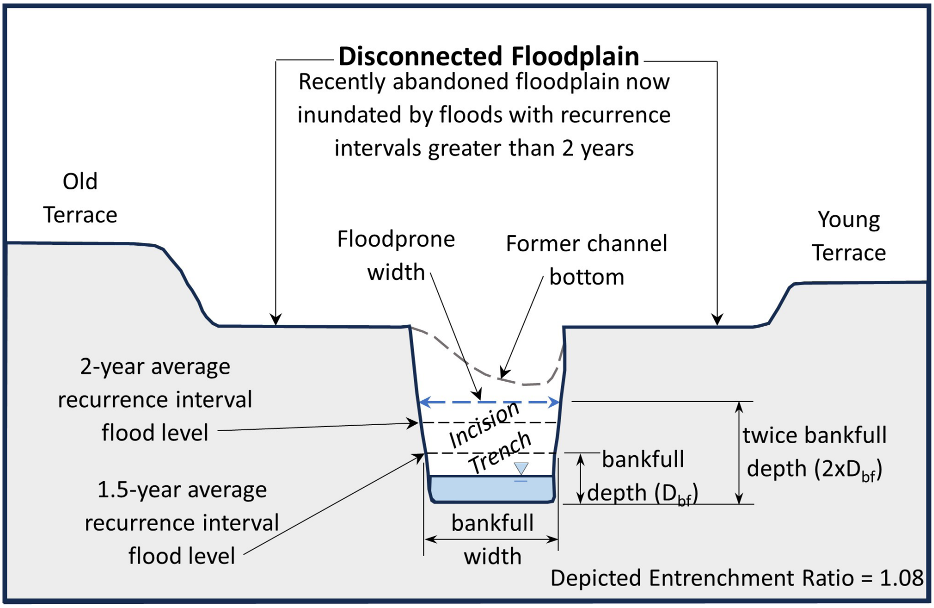


Figure 4. Diagrammatic cross-valley profile showing floodplain disconnected from the active channel and flows greater than the 2-year recurrence interval flood confined within the incision trench.

During the period of active downcutting, the term "incision trench" is used to describe the deep and degraded channel. As the incision trench deepens, the channel pattern tends to straighten such that the stream's sinuosity (channel length/valley length) is reduced (Wheaton et al. 2019). In Rosgen's (1994) classification system, the entrenched "A" type stream exhibits low sinuosity values, defined as being less than 1.2.

FLOODPLAIN RECONNECTION

Cluer and Thorne's (2014) SEM illustrates the stages, or steps, that lead to channel incision as well as floodplain reconnection via processes that promote channel aggradation or channel widening. However, the number of stages and associated stages that result in arrested degradation can be confusing (Wheaton et al. 2019). Pollock et al. (2014) reduced Cluer and Thorne's (2014) model into a four-phase incision-aggradation cycle, added a temporal scale, and named it a simplified stream succession model. Wheaton et al. (2019) modified the incision-aggradation cycle of Pollock et al. (2014) and presented the Riverscapes Evolution Model (REM; Figure 5). In the REM, one- and two-word phrases suggestive of both form and process define the four phases as: anastomosing, incised/incising, widening, and aggrading and widening. The REM, which draws upon the technical rigor of Cluer and Thorne's (2014)

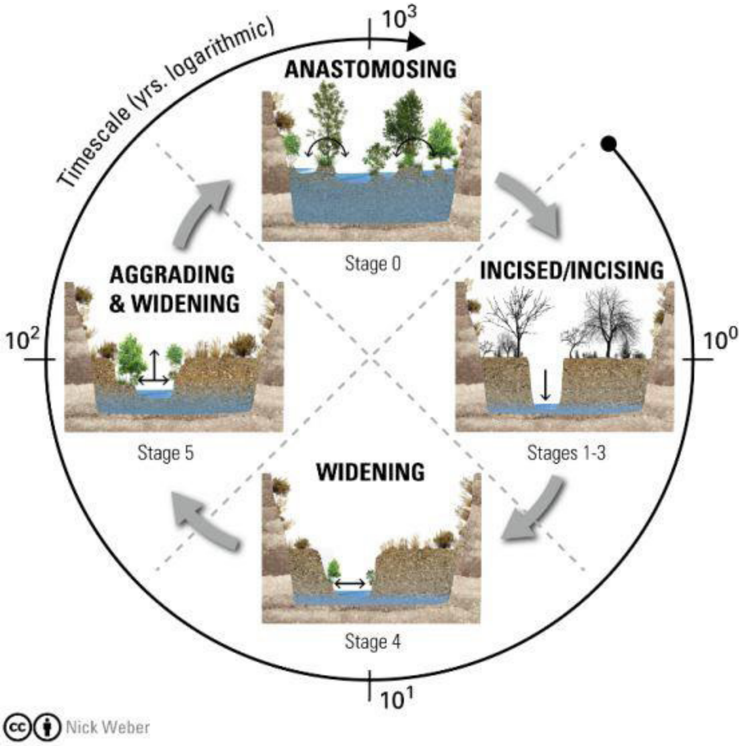


Figure 5. The four-phase Riverscapes Evolution Model (Wheaton et al. 2019).

SEM, can be used to plan restoration actions for incised streams. More specifically, understanding the existing trajectory or specific phase of the riverscapes model of a stream provides a basis for deciding whether restoration actions should aim to accelerate or change the trajectory (Pollock et al. 2014).

As per the REM and SEM, a Stage 0 or anastomosing channel system is the most resilient to disturbance, such as floods and droughts, and capable of providing the greatest diversity and productivity of ecosystem services. Anastomosing stream systems engage a broad floodplain area and include multi-thread channels with intervening vegetated islands. Flood flows are diffused across the floodplain such that peak flood events and the associated kinetic energy are effectively attenuated. Flooding recharges groundwater aquifers and maintains a generally shallow groundwater table that supports a wide variety of vegetation types and local wetlands.

During the incised and incising phase, the anastomosing channel system is reduced to a single-thread channel subject to accelerated channel erosion. At Stage 1 (Cluer and Thorne 2014), the channel and active floodplain remain connected (Figure 3). Channel sinuosity is well-established and maintained by generally stable rates of lateral migration and typical patterns of sediment transport and deposition. The groundwater table remains relatively shallow beneath the floodplain, and the system provides a broad range of ecosystem services. During Stages 2 and 3 (Cluer and Thorne 2014), the channel deepens and becomes less sinuous in response to the confinement and conveyance of relatively lower frequency and higher volume flows. This increased stream power flushes sediment out of the channel, which then more closely resembles a drainage canal in form and function, rather than a properly functioning stream channel. Floodplain inundation becomes less frequent, groundwater recharge is reduced, and the groundwater table falls. Consequently, ecosystem services that are dependent upon frequent floodplain inundation and a shallow groundwater table, such as wetland areas and riparian vegetation, diminish or collapse altogether.

A Stage 3 channel is actively incising and exhibits tall and steep banks that are geotechnically stable such that an incision trench is formed (Figures 4 and 6A). As illustrated in the REM, a Stage 3 channel is anticipated to transition toward Stage 4 and enter the phase of widening. The anticipation is based on two assumptions: a) that bed erosion will cease because sufficient resistance to continued degradation will be encountered; and b) that the steep walls of the incision trench will be eroded via a combination of mass-wasting processes and lateral hydraulic scour provided by the streamflow (Figure 6B). These are reasonable assumptions that are well-supported by many investigations and direct observations (Thorne 1991; Rosgen 1997; Simon and Rinaldi 2006; Darby et al. 2007; Florsheim et al. 2008; Williams et al. 2020). However, there are a variety of site-specific variables or geotechnical parameters that control both the rate and magnitude of such erosion. Chief among these is the composition of earth materials comprising the banks (e.g., bedrock vs. sand). More specifically, Cluer and Thorne (2014) and Pollock et al. (2014) warn that in some cases an incised stream may achieve a “state of arrested degradation” where widening does not occur. In such cases, the channel will remain in the incised and degraded state and is unlikely to widen unless a perturbation occurs or a specific action is implemented. Cluer and Thorne (2014) also warn against costly and often risky restoration efforts that over-stabilize a channelized, degrading, or widening stream, as such actions may also result in a state of arrested degradation without re-establishment of an ecologically productive floodplain.

Assuming the banks are susceptible to erosion, the widening phase will continue until the stream is unable to scour and transport away the eroded material. At that point, the channel enters the aggrading and widening phase, whereby the mass-wasted debris aggrades the bed, thereby protecting the toe of the streambank from fluvial erosion. The aggradation locally raises the bed and forces the streamflow to meander around the accumulated piles of mass-wasted debris, increasing channel sinuosity. The decrease in gradient and increase in sinuosity both tend to reduce the stream’s ability to erode and transport sediment. At the same time, streambank heights and angles also decrease, thereby improving factors affecting slope stability (Figure 6C). Collectively, the overall trend is toward less erosion and greater bank stability, which leads to the establishment and proliferation of riparian vegetation, which further stabilizes the banks and provides roughness that slows streamflow. This creates a positive geomorphic feedback loop in which the increased channel and bank stability promotes additional vegetation growth, a subsequent increase in roughness, more slow-water habitat areas, and more sedimentation that supports additional vegetation growth.

Once the widening and aggradation processes are minimized, fluvial processes dominate and rework the aggraded earth materials along the channel bottom. More specifically, bankfull discharge and moderate flood flows create and maintain a sinuous single-thread channel and re-establish an active floodplain. Cluer and Thorne (2014) assign these attributes to Stage 6, termed quasi-equilibrium (Figure 6D), although they have clarified that Stage 6 is not necessarily a desirable restoration goal. A key attribute of this stage is the re-emergence of an active floodplain connected to the bankfull channel. Because the floodplain exists along the bottom of an incision trench, it is termed an "inset floodplain."

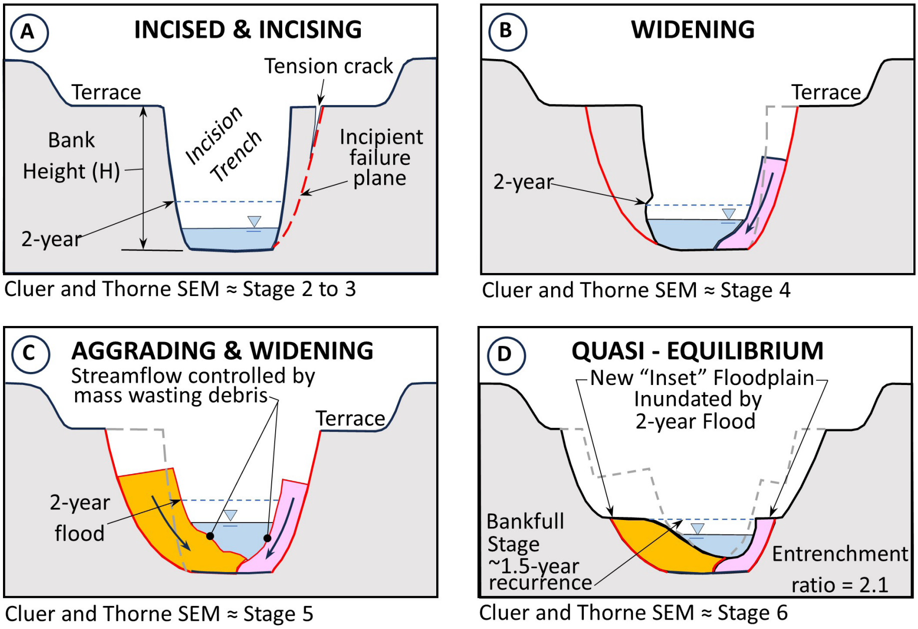


Figure 6. Diagrammatic cross-valley profiles showing the evolution of an incised stream in general accordance with the Riverscapes Evolution Model (Wheaton et al. 2019), based upon Cluer and Thorne's (2014) Stream Evolution Model.

Each of the stages summarized above has unique hydrogeomorphic attributes that aid in distinguishing one stage from another and ascertaining the current trajectory of a given channel segment on the incision-aggradation cycle. It is common for an LTPBR project intended to enhance incision recovery to exhibit multiple stages of incision-aggradation evolution within the same reach. This is largely driven by small-scale variability in stream power and sediment availability. For example, in a reach that is undergoing active incision, there is often a discrete knickpoint or series of knickpoints (i.e., a location within the active channel with an abrupt change in channel slope) that is propagated upstream. Downstream of a knickpoint the channel is incised, possibly with an inset floodplain present, and upstream of that point the channel is at a higher bed elevation and is more connected to a historic floodplain.

ROLE OF LOW-TECH PROCESS-BASED RESTORATION

From 2000 to 2007, the Surface Water Ambient Monitoring Program (SWAMP), carried out by the State Water Resources Control Board (SWRCB), assessed approximately 85,000 km of California's perennial wadable streams to determine their ability to support aquatic life (Ode et al. 2011). SWAMP used water chemistry data, physical habitat data, and benthic macroinvertebrate community composition to identify key stressors affecting water quality. The physical habitat data collected includes prevalence of excess sediments, quality of instream fish habitat, and quality of riparian habitat alongside streams (EPA 2006). Half (50%) of the stream length assessed by SWAMP was determined to be in relatively good condition, with the remaining half split approximately evenly between being degraded and very degraded. There was a strong correlation between land use and the biological conditions found in these perennial streams. Approximately 70% of the streams in forested regions (North Coast and Sierra Nevada) were determined to be in good biological condition. In contrast, none of the streams in the agricultural region of the Central Valley were found to be in good biological condition. One approach to restoring these degraded stream reaches is to construct numerous LTPBR structures to enhance the physical habitat and alter the geomorphology of the stream, thus improving floodplain connectivity and increasing the quality of aquatic and riparian habitat.

Low-tech process-based structures are similar in function to large wood structures described in Flosi et al. (2024). They provide a structural element in the stream to slow water velocities, snag additional wood, and promote sediment deposition, leading to increases in bed elevation, floodplain connectivity, channel planform, and instream geomorphic complexity and meandering. Installing numerous LTPBR structures in a stream reach will lead to complex instream habitat and improved geomorphic function. The improved functionality in turn will benefit salmonids and other stream biota by providing cover, improved water velocity, temperature refugia, an increase in available food from additional benthic macroinvertebrate productivity, and a resilient riparian zone typical of regularly inundated floodplains. A healthy, connected riverscape provides additional benefits to riparian-dependent birds, amphibians, reptiles, and mammals (Stringer and Gaywood 2016).

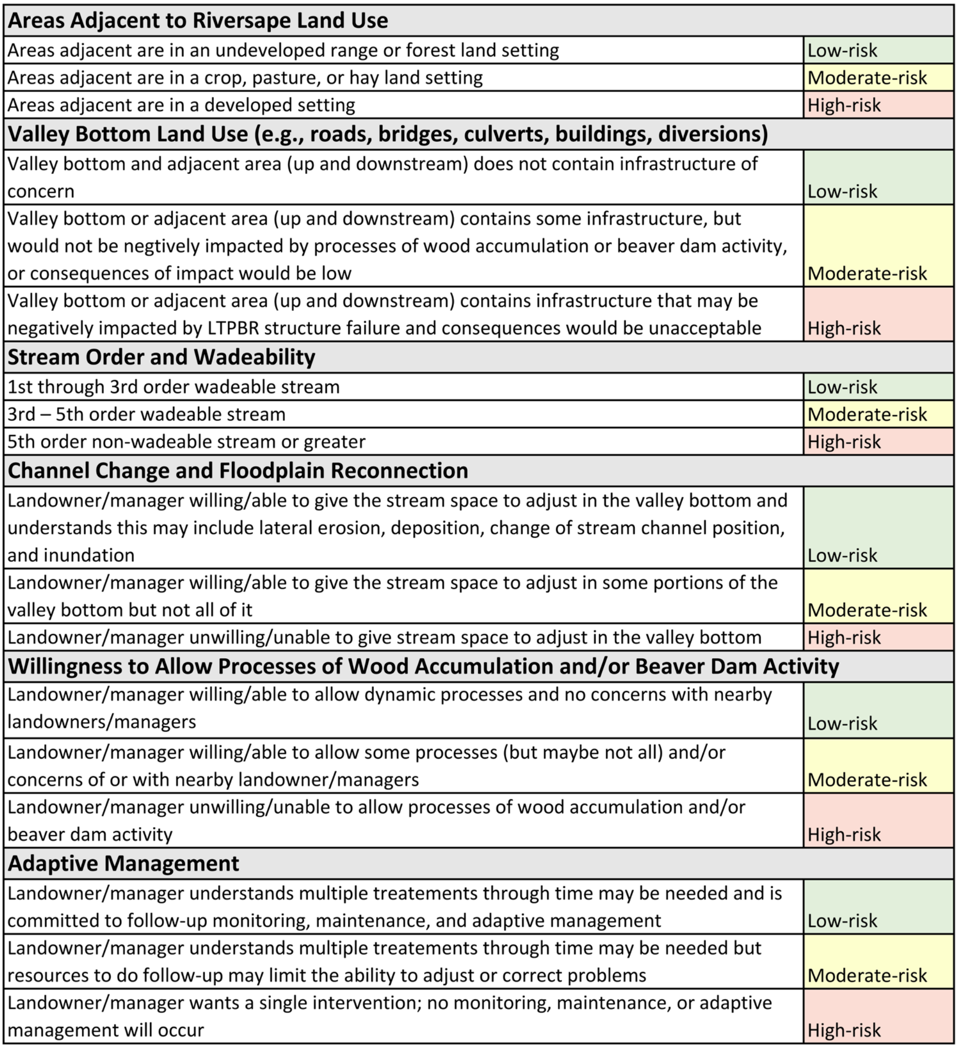
Slow water habitat areas immediately upstream of LTPBR structures create important rearing habitat for salmonids. Juvenile steelhead in Bridge Creek showed a higher preference for ponded areas compared to un-impounded reaches (Bouwes et al. 2016). Leidholt-Bruner et al. (1992) found that beaver ponds increased rearing habitat for Coho Salmon during the late summer low flow, while Swales and Levings (1989) found that beaver ponds provided valuable winter rearing habitat for juvenile salmonids. Ponded areas have slow current velocities and large edge-to-surface ratios; thus, fish expend less energy foraging than would be required in higher-velocity streams (Pollock et al. 2004). Structures that stay intact provide year-round instream habitat, which many streams lack. When numerous structures are added to a stream reach, even if some wash out or breach during high flow, the remaining structural elements are still likely to provide instream habitat and complexity.

ASSESSING RISK

For the purposes of planning an LTPBR project, potential streams and stream reaches can be categorized as either low-risk, moderate-risk, or high-risk. Low-risk reaches include streams where there is low risk to public safety, infrastructure, or private property. Moderate-risk reaches have some element of risk that can be mitigated through the planning process but may require a more detailed assessment to demonstrate how the risk is mitigated. High-risk reaches include streams in areas where public safety, infrastructure, or private property are at risk, and that risk cannot be mitigated through the planning process. Stream reaches that fall into the low- or moderate-risk category are the most appropriate for LTPBR projects.

RISK CONSIDERATIONS CHECKLIST

Bennett et al. (2019b) include a risk considerations checklist for LTPBR stream and meadow restoration (Figure 7). This checklist, although not comprehensive, covers many of the most critical risk considerations for public safety and infrastructure.



Areas Adjacent to Riversape Land Use	
Areas adjacent are in an undeveloped range or forest land setting	Low-risk
Areas adjacent are in a crop, pasture, or hay land setting	Moderate-risk
Areas adjacent are in a developed setting	High-risk
Valley Bottom Land Use (e.g., roads, bridges, culverts, buildings, diversions)	
Valley bottom and adjacent area (up and downstream) does not contain infrastructure of concern	Low-risk
Valley bottom or adjacent area (up and downstream) contains some infrastructure, but would not be negtively impacted by processes of wood accumulation or beaver dam activity, or consequences of impact would be low	Moderate-risk
Valley bottom or adjacent area (up and downstream) contains infrastructure that may be negatively impacted by LTPBR structure failure and consequences would be unacceptable	High-risk
Stream Order and Wadeability	
1st through 3rd order wadeable stream	Low-risk
3rd – 5th order wadeable stream	Moderate-risk
5th order non-wadeable stream or greater	High-risk
Channel Change and Floodplain Reconnection	
Landowner/manager willing/able to give the stream space to adjust in the valley bottom and understands this may include lateral erosion, deposition, change of stream channel position, and inundation	Low-risk
Landowner/manager willing/able to give the stream space to adjust in some portions of the valley bottom but not all of it	Moderate-risk
Landowner/manager unwilling/unable to give stream space to adjust in the valley bottom	High-risk
Willingness to Allow Processes of Wood Accumulation and/or Beaver Dam Activity	
Landowner/manager willing/able to allow dynamic processes and no concerns with nearby landowners/managers	Low-risk
Landowner/manager willing/able to allow some processes (but maybe not all) and/or concerns of or with nearby landowner/managers	Moderate-risk
Landowner/manager unwilling/unable to allow processes of wood accumulation and/or beaver dam activity	High-risk
Adaptive Management	
Landowner/manager understands multiple treatements through time may be needed and is committed to follow-up monitoring, maintenance, and adaptive management	Low-risk
Landowner/manager understands multiple treatements through time may be needed but resources to do follow-up may limit the ability to adjust or correct problems	Moderate-risk
Landowner/manager wants a single intervention; no monitoring, maintenance, or adaptive management will occur	High-risk

Figure 7. Risk considerations checklist for low-tech process-based stream and meadow restoration (modified from Bennett et al. 2019b).

RISK ASSESSMENT DOCUMENTATION

A required element of the project planning document is a written risk assessment. A project located in a low-risk reach where there is low risk to public safety, infrastructure, or private property will require little narrative. Projects in moderate-risk reaches, where public safety, infrastructure, or private property are at risk, will need documentation describing how the project proponent intends to address these issues.

As part of the risk assessment, it is suggested to use the Beaver Restoration Assessment Tool (BRAT), developed by Macfarlane et al. (2015), to identify any potential human conflicts for the project region. The BRAT can help to identify locations where there is human infrastructure in the valley bottom adjacent to an LTPBR project through the conflict potential layer. The BRAT is further described in the Project Planning section below, but one of the outputs uses GIS layers showing infrastructure (e.g., roads, urban areas, pipelines, etc.) near a given project area to determine when beaver dam building or LTPBR structures may come into conflict with human activities. This layer is intended to be a resource for assessing potential risk and is not a determinant for permitting an LTPBR project.

For all habitat restoration projects, consultation with CDFW early in the planning process, including a field visit to the project reach, is desirable. The field visit with knowledgeable CDFW staff should include a discussion of project constraints and potential alternatives.

RISK FACTORS

Like all restoration tools, LTPBR projects can have unintended negative effects. Wheaton et al. (2019) "have observed their inefficient use and misapplication in a range of settings." The rapid scaling up in the use of BDAs in various geographic areas, based largely on the data from the Bridge Creek study in Oregon (Pollock et al. 2014; Bouwes et al. 2016), suggests a potential risk of misuse owing to their simple design and low implementation costs (Davee et al. 2019).

Low-tech process-based restoration structures are not designed or built to be permanent fixtures and are not guaranteed to withstand high-flow events (Wheaton et al. 2019). Designed only to withstand a typical mean annual flood, BDAs and PALS have a design life of less than one year, although they commonly exceed that and, in some cases, have been documented to last at least 10 years. Both structure types are constructed with untreated wooden posts, with woody vegetation woven between the posts, often consisting of willow or other woody material, if this is readily available near the site. The material is buoyant, variable in quality and shape, and will deteriorate over time. When numerous low-stage structures are built within a project reach, the woody material from an individual structure that becomes mobilized is likely to be trapped by a structure downstream. For most projects, dislodged small wood is not a problem, but there is always the potential for undesirable impacts, such as the plugging of a downstream undersized culvert.

As noted above, this document does not specifically discuss the practice of beaver relocation. However, the intent of many LTPBR projects is to encourage nearby beaver to expand their colony to occupy the site and maintain the human-built structures. In low- and potentially moderate-risk reaches, this is a desirable outcome, but in high-risk reaches, this may lead to human-beaver conflicts. In the report by Davee et al. (2019), *Using Beaver Dam Analogues for Fish and Wildlife Recovery on Public and Private*

Rangelands in Eastern Oregon, ranchers with grazing permits in the Umatilla National Forest were interviewed about their concerns regarding conflicts with beaver. Ranchers worried that beaver would build dams in irrigation systems, cut down large trees, and create unwanted flooding in pastures that would turn fields into wetlands; thus the ranchers would lose the ability to work those fields. Landowners in the Scott Valley of Siskiyou County, California expressed similar concerns. Their two main concerns were that beaver would plug up irrigation infrastructure and cut down large trees (Charnley 2018). Other concerns were raised while conducting outreach for the Oregon Department of State Lands' rulemaking process to create a general permit for BDAs. These included concerns about elevated stream temperatures due to the water ponded by dams creating more surface area, the inability of fish to safely pass BDAs, and the misuse of LTPBR structures due to their low cost and simple design (Davee et al. 2019).

In Scott Valley, landowners have also observed positive impacts from beaver and beaver dams (Charnley 2018). These included slower streamflow velocity, increased water storage, elevated groundwater levels, more water available for irrigation, and increased surface water availability later into the summer. These same benefits have been observed from a variety of LTPBR projects partnering with ranchers and other rural landowners in other western states (Goldfarb 2018). Additionally, recent studies have shown that riparian corridors occupied by beaver are significantly more resistant to wildfire when compared to similar unoccupied riparian corridors (Fairfax and Whittle 2020).

A non-governmental organization (NGO) serving as an intermediary between private landowners and government agencies can increase the likelihood of project success (Charnley 2018). An NGO can work with private landowners to develop and implement the projects, seek funding, and obtain necessary permits from governmental agencies. Under this arrangement the NGO, and not the landowner, accepts responsibility for the project, including monitoring and maintenance of the structures.

The best way to avoid human conflicts with beaver is to avoid placing LTPBR structures in high-risk reaches of stream. However, it is important to understand the risk tolerance of a given landowner and the specific types of risk factors at a potential site. For example, the landowner may be comfortable with seasonal flooding of small access roads on their property and/or some unwanted beaver foraging, if that leads to the desired outcomes of the LTPBR project. In many instances, undesirable beaver behavior can be mitigated with simple, non-lethal strategies for living with beaver, as described below (Portugal et al. 2015a).

Human conflicts with beaver fall into two general categories: tree cutting and dam building (Pollock et al. 2018). Pollock et al. (2018) discuss non-lethal options for mitigating the unwanted effects of beaver. Methods to prevent beaver from cutting

Figure 8. Tree wrapped with wire fencing. Photo credit: Great Northern Corp

Figure 9. Head gate protected by wire fencing. Photo credit: Jennifer Bull

trees include surrounding trees with wire mesh cages (Figure 8) and painting the tree with a mixture of paint and sand. Methods for reducing flooding caused by dam building include installing various pond levelers or protective fences on the upstream side of culverts or head gates (Figure 9). The larger the culvert, the less likely it is to be plugged by beaver, and arch culverts or similar channel-spanning culverts are less likely than round culverts to be plugged (Pollock et al. 2018). Appendix A lists other useful resources on non-lethal beaver management strategies.

Kemp et al. (2012) conducted a systematic review of the impacts of beaver dams on fishes and fish habitat based on a meta-analysis of the literature and expert opinion. They identified 108 articles containing information on the interactions between beaver and fish. Most frequently cited positive impacts were increased fish productivity or abundance, increased fish habitat or habitat complexity, an increase in overwintering habitat, and enhanced fish growth rates. Negative impacts included barriers to fish movement, reduced spawning habitat, lower dissolved oxygen concentrations, and altered water temperature regimes.

Fish Passage. Although many studies show beaver dams and BDAs have little to no impact on fish passage (Lokteff et al. 2013; Bouwes et al. 2016; Yokel et al. 2018; Pollock et al. 2019), the potential impediment of fish movement due to constructed LTPBR projects warrants consideration. Every river system is unique and presents constraints and challenges for the survival of salmonids. Nearly every California river has been altered by human land use. Human impacts include dams, channelization, hardening of streambanks, urbanization, water diversions, and groundwater pumping for domestic use and agriculture. These impacts have resulted in reduced stream flows and higher summer water temperatures. Of concern is the upstream movement of juvenile salmonids seeking cooler water. In the Klamath River basin, juvenile Coho Salmon will move long distances when natal streams become inhospitable due to high summer temperatures and high winter flows. These juvenile salmonids will leave their natal habitat and seek non-natal rearing in cooler water tributaries and off-channel ponds (Witmore 2014). Construction of LTPBR projects must not prevent this upstream migration. Trask (2019), in evaluating BDAs constructed on the Nehalem watershed in Oregon, suggests not building BDAs within a half mile of a stream corridor exhibiting summer temperatures that exceed 18°C. In northern California, Wallace and Allan (2015) observed juvenile salmonids rearing and moving throughout the tidal portions of tributaries to enter Humboldt Bay. They state, "It is important to maintain and enhance connectivity between the streams entering the stream-estuary ecotone." These studies documenting fish movement also note the importance of the slow water habitat created by beaver dams for juvenile salmonids.

During the design phase of all stream restoration projects, including LTPBR projects, it is important that passage for all life stages of native fish be considered. Olswang (2015) monitored out-migration timing of juvenile Coho Salmon rearing in a beaver dam on Sugar Creek, a tributary to the Scott River in Siskiyou County. Olswang determined that the dam could have been a temporal barrier to fish passage depending on stream flow, and higher flows may have been necessary for downstream fish passage. Pollock et al. (2019) studied upstream fish movement at a BDA complex lower in the Sugar Creek watershed. They found that both juvenile Coho Salmon and steelhead trout moved upstream, crossing the BDA by jumping over a waterfall or swimming up a short side channel. Designing BDA projects where water from a downstream secondary dam structure is backed up to the base of the BDA structure will help facilitate upstream fish movement over the structure. Building a BDA where one side is in contact with the floodplain, providing a low-flow side channel, is another option. The more incised a channel, the greater the challenge for fish passage. As such, it is better to build numerous smaller structures instead of a few over-built, highly secured structures (Wheaton et al. 2019). Other options include installing structures that do not span the entire channel, such as bank-attached PALS or mid-channel PALS to reduce the potential for creating a barrier to fish passage. Also, building PALS instead of BDAs will help facilitate fish passage since the PALS are typically not intended to create ponded conditions. Project narratives and/or permit applications for LTPBR proposals should include a description of how the planned restoration activity takes fish passage into account.

Temperature. Depending on the circumstances, the water ponded behind beaver dams may either increase or decrease stream temperature. An increase in surface water area impounded by a dam can expand the time available for the water to be heated by solar radiation (Kemp et al. 2012). When beaver initially occupy an area, they cut down riparian trees adjacent to the stream, which reduces shade and can increase water temperatures (Pollock et al. 2018). An adult beaver can cut 200 to 300 trees a year, usually within 30 m of the water's edge (Wohl et al. 2019). Although, over time, emergent vegetation will regrow and provide shade to the ponded area.

Other studies have shown a decrease in water temperature because of the ponds associated with beaver dams. Weber et al. (2017) conducted a temperature study on Bridge Creek and concluded that a combination of increased water storage behind beaver dams, along with increased surface water and groundwater exchange in the hyporheic zone, moderates diel temperature during periods of low surface flow. They also found that there was increased heterogeneity in stream temperature in reaches with beaver dams and BDAs. Recent work by Armstrong et al. (2021) further supports this notion that a mixture of cold and warm habitats, especially for mobile species, may result in healthier overall coldwater fisheries. In a separate study, also on Bridge Creek, Bouwes et al. (2016) placed temperature loggers at the top and bottom of stream reaches with extensive beaver dams and those without beaver dams. They found that temperatures remained constant or decreased in the reaches with beaver dams, whereas temperatures increased in reaches without beaver dams. In areas where there is no hyporheic exchange of surface water with groundwater, increases in water temperature may occur in reaches with beaver dams. Ultimately, it is important that within the LTPBR project narrative, the proponents discuss potential water temperature issues identified within both the watershed and individual stream reaches proposed for restoration activities.

Property Ownership. The BRAT uses a GIS layer showing infrastructure to determine when beaver dam building (or LTPBR projects) may come into conflict with human activities. Specifically, the BRAT conservation and restoration model assesses risk by identifying the proximity of stream reaches that can support beaver dam building to human infrastructure that can be flooded or clogged and to areas with high-intensity land use (e.g., urban areas, row crop agriculture, and roads) that can be impacted by beaver activity (Macfarlane et al. 2019).

With or without beaver occupation, LTPBR projects have the potential to create landowner conflicts, as described above. Projects implemented on a single landowner's property, as opposed to several small properties, are typically easier to coordinate and pose less potential risk for landowner conflicts. The entity interested in implementing a project must identify if a proposed project reach is entirely controlled by one landowner or land manager, or if there are multiple entities involved. Property ownership for the entire project reach and the areas directly upstream, downstream, and across the stream must be determined. All private landowners and land managers who may be affected by the project should be contacted and informed about the proposed project and potential risks. Risks include the potential for beaver to inhabit the structures, which may lead to both positive and negative impacts. Landowners should be made aware that there is a suite of non-lethal beaver management techniques that can minimize damage from unwanted beaver activity (Appendix A). The project proponent should document conversations with all involved landowners and land managers, which should verify that the scope of the project and its potential positive and negative impacts have been discussed with all persons involved. All parties involved must demonstrate their project support by signing a written access permission agreement.

PROJECT PLANNING

WATERSHED AND STREAM SELECTION

The need for an LTPBR project should be based on the findings of a watershed assessment or individual stream habitat inventory. Watershed assessments are discussed in the *California Salmonid Stream Habitat Restoration Manual*, Part II (Flosi et al. 1998). Several watershed assessments specific to California coastal watersheds have been completed by the CDFW Coastal Watershed Planning and Assessment Program. Watershed assessment reports are available with background information, findings, limiting factor analysis, and improvement recommendations. For watersheds that do not have a complete watershed assessment, individual stream habitat inventories may have been completed using the methodologies described in the *California Salmonid Stream Habitat Restoration Manual*, Part III (Flosi et al. 1998). If no inventory exists, it is recommended that one be completed prior to moving forward. A local CDFW regional office can provide the most recent information on a stream of interest. Also, the CDFW Document Library[1] may contain watershed plans or stream inventories that recommend restorative actions that can be addressed using LTPBR.

The next step is to identify suitable stream reaches within the watershed or stream. Proper assessment is needed to ensure that LTPBR structures are placed in appropriate stream reaches. There are additional resources that project proponents should consult, if available for the proposed project area. The Salmon Habitat Restoration Priorities[2] (SHaRP) is a joint effort led by the National Marine Fisheries Service and CDFW in collaboration with restoration partners to identify priority locations and effective restoration actions in areas containing salmon strongholds. SHaRP planning resources should be consulted if available, and regional CDFW offices can determine their availability for particular watersheds of interest. Additionally, if Light Detection and Ranging (LiDAR) digital elevation models are available, consider using this data as part of the assessment and design process. Topographic LiDAR data do not provide ground elevations within the wetted channel due to light reflection at the water surface, but they provide typical elevation accuracies to 0.15 m for surfaces outside of the wetted channel, unless the ground surface is completely obscured by vegetation. These data are invaluable in the planning and design process and can be used for a variety of purposes, including assessments of valley bottom topography to locate existing low points in floodplains or identification of relict floodplains and overflow channels that could present potential restoration opportunities (Powers et al. 2019). The National Science Foundation hosts an open-source database of LiDAR datasets available for free download called OpenTopography (2020). OpenTopography has LiDAR data acquired from the U.S. Geological Survey that encompasses large swaths of California. Ground truthing using survey-grade real-time kinematic global navigation satellite system units is recommended to validate the accuracy of LiDAR data.

Low-tech process-based restoration techniques are intended to be used on small wadable streams (Wheaton et al. 2019). The U.S. Environmental Protection Agency (EPA 2006) defines wadable streams as perennial streams small and shallow enough to be adequately sampled by wading without a boat. Wadable streams generally fall into the first through fifth Strahler stream order (EPA 2006; Figure 10). However, Wheaton et al. (2019) do not exclude intermittent and ephemeral streams from qualifying for treatment with LTPBR structures and have documented success with LTPBR projects restoring intermittent streams to perennial stream conditions.

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[1] https://nrm.dfg.ca.gov/documents/Default.aspx

[2] https://www.fisheries.noaa.gov/west-coast/habitat-conservation/collaborating-identify-salmon-habitat-restoration-priorities

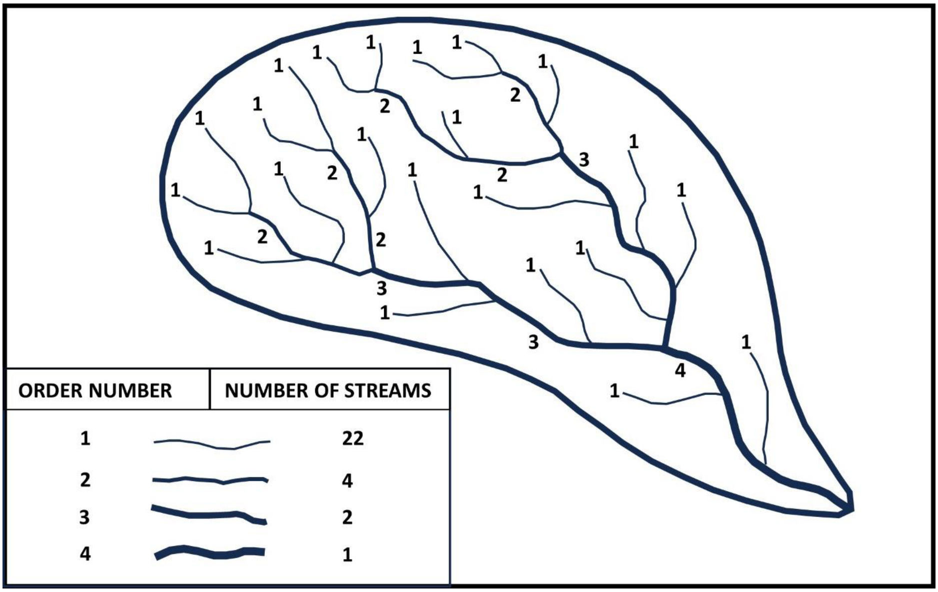

Figure 10. Strahler stream order (modified from Flosi et al. 1998).

There are several tools available to assist in identifying appropriate stream reaches for LTPBR restoration. The BRAT models the current and historic capacity of the landscape to support dam building activity by beaver (Macfarlane et al. 2015) at the 250-m reach scale. The model centers on the ability of the environment to support dams and dam building activity rather than beaver habitat suitability or beaver population estimates. The BRAT is a decision support and planning tool that can also be used to assess the potential for LTPBR projects over large geographic regions. The data used in the BRAT are from publicly available datasets based largely on remotely sensed imagery and regionally derived empirical hydrologic relationships (Macfarlane et al. 2015). Dam capacity estimates are based on seven main lines of evidence:

1. Reliable water sources
2. Streambank vegetation conducive to foraging and dam building
3. Vegetation within 100 m of edge of stream to support large beaver colonies
4. Likelihood that dams could be built across the channel during low flows
5. Likelihood that a dam is capable of withstanding typical floods
6. Stream gradient that is neither too low to limit dam density nor too high to preclude dam building or persistence
7. Suitable river that is not too large to restrict dam building or persistence

The developers of the BRAT model[3] recently completed BRAT analysis on the majority of California's streams on behalf of The Nature Conservancy (Macfarlane et al. 2019). They analyzed over 78,835 km of perennial streams in 80 hydrologic unit code 8 level watersheds within the Sierra Nevada, Cascades, Coast, and Klamath mountains to identify the most appropriate locations for beaver-assisted restoration projects and BDAs (Figure 11).

Stream reaches identified as having a high capacity for beaver dam building have most of the same characteristics as streams with a high potential for LTPBR projects, even if beaver are not currently present. The data used to generate the model includes identification of a perennial water source, locations of infrastructure, riparian and upland vegetation, base flow, 2-year peak flows, and stream gradient (Macfarlane et al. 2015). As mentioned above, LTPBR can be appropriate on intermittent and ephemeral streams. Also, LTPBR techniques can be used to jump start re-vegetation of the riparian zone by increasing the water table and decreasing unit stream power. Thus, LTPBR may be appropriate in streams that are lacking in riparian and upland vegetation. Like all models, it is important to verify the suitability of a stream reach for an LTPBR project in the field.

An additional tool available for identifying watersheds or streams suitable for LTPBR projects is provided in Pollock et al. (2018). This tool uses additional criteria not included in the BRAT to further refine where to focus LTPBR projects. *The Beaver Dam Viability Matrix: A User's Guide* is a River Restoration Analysis Tool (RiverRAT) developed to assess the likelihood that a beaver dam will persist for at least two seasons (Figure 12). The *x*-axis uses stream properties to assess overall dam viability. The *y*-axis uses factors such as project scale, land use, infrastructure, and monitoring to assess overall risk. Again, factors such as riparian corridor and beaver presence may not be as important for some LTPBR projects.

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[3] http://etal.joewheaton.org/brat-tnc.html

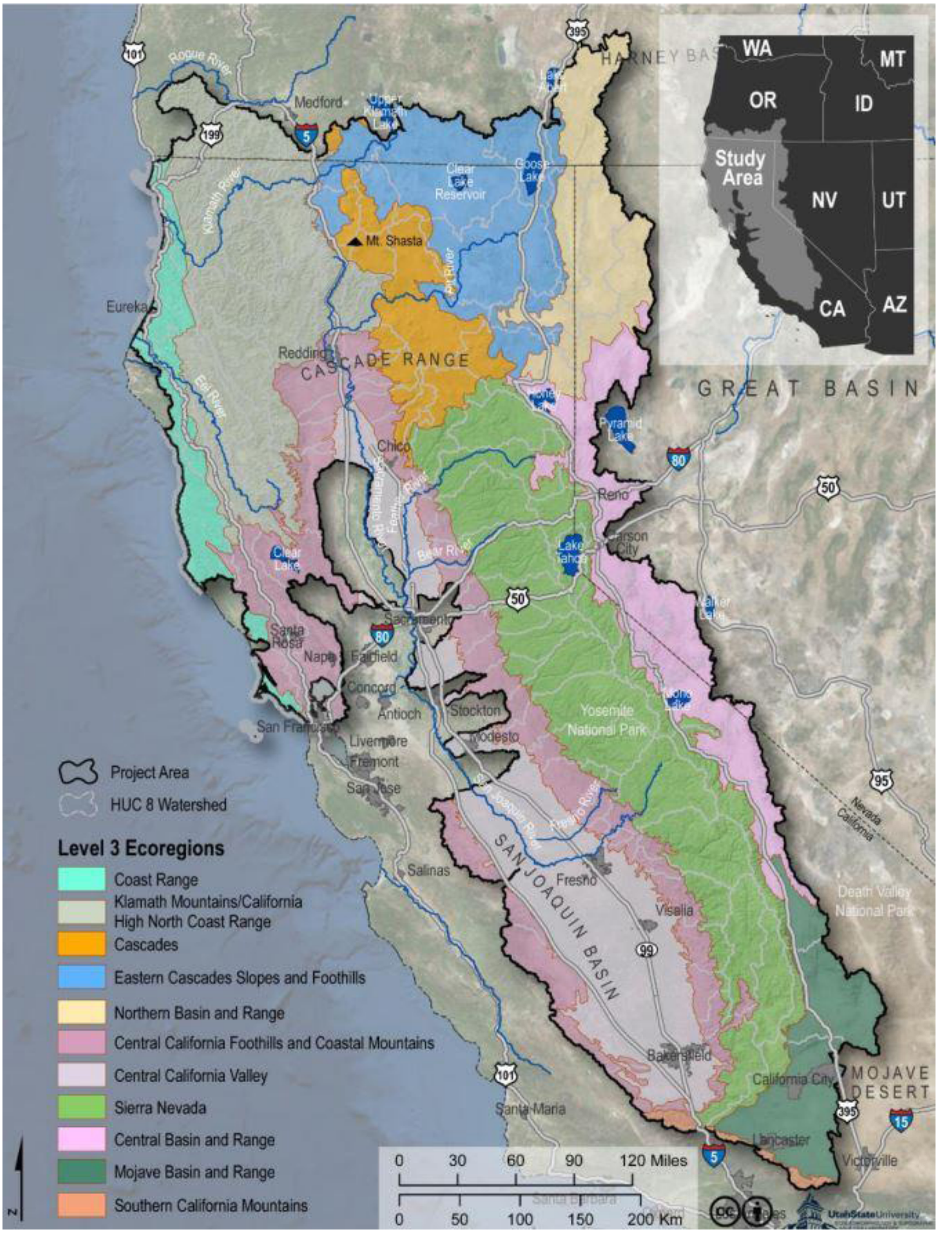

Figure 11. Extent of Beaver Restoration Assessment Tool data available in California (Macfarlane et al. 2019).

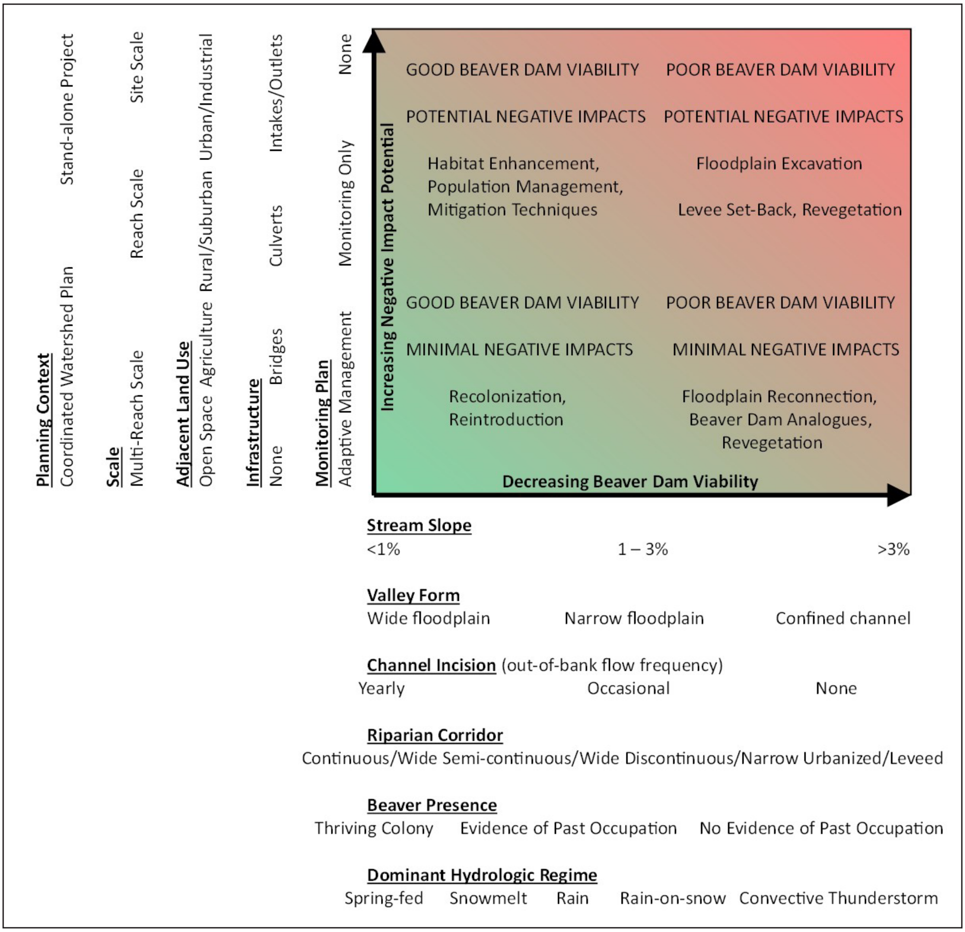

Figure 12. Beaver Dam Viability Matrix (modified from Janine Castro in Pollock et al. 2018).

SITE CHARACTERIZATION

Site Map. Low-tech process-based restoration is focused on restoring a valley bottom rather than just the stream channel and, because valley bottoms can be quite extensive, the site characterization should start with developing a site map. The site map should include the entire valley floor width and the entire length of the project site (Bennett et al. 2019b). Output from the BRAT can be used as the basis of the site map, but Google Earth aerial photography or LiDAR data-derived hillshade or color relief models can also be useful when developing a site map. Essential components of the site map include property boundaries, infrastructure locations, and locations of other constraints, such as areas that landowners do not want reconnected to the stream or floodplain (Bennett et al. 2019b). The BRAT can aid in the assessment of these features on the floodplain using the conflict potential layer that flags locations where roads and other infrastructure come in close proximity to the stream.

The site map should also delineate initial estimates of accessible floodplain, versus inaccessible terraces. Floodplains are considered areas adjacent to the stream channel that would get inundated from the current hydrologic regime, whereas terraces are areas that are too high to get flooded by the current hydrology. It can sometimes be difficult to distinguish the two when a stream is deeply incised, so areas that are in question should be considered floodplains until further evidence says otherwise (Bennett et al. 2019b). The BRAT can be used as a starting point for this task, as it contains a delineation of the valley bottoms, which identifies the boundaries of the channel and active floodplain. Additional sources of information for making this determination include historical aerial photographs, quadrangle maps, and LiDAR elevation data maps. However, it is important to note that even the earliest of these data sources tends to be from post-European settlement, so the stream channel and alignment may have already been significantly altered and constrained.

As part of developing the site map and reviewing historical information, initial hypotheses should be made on whether the stream is aggrading, degrading, static, or in equilibrium, and if it is degrading, what is causing degradation (Bennett et al. 2019b). Most streams in California are in the degradation process or have been stabilized in a degraded form. Low-tech process-based restoration is intended to alleviate degradation or to accelerate recovery from degradation, so it is beneficial to know the SEM stage of the reach. The REM, a simplified SEM, is precise enough for making this hypothesis (Figure 5). Causes of degradation can originate from within the project reach, such as berms narrowing the stream corridor, or can be larger or outside of the project reach, such as a dam upstream.

Overall channel slope for the project reach can also be determined from the BRAT or other data sources and should be recorded on the base map. Channel slope has an impact on the density of the structures proposed for the project.

Finally, vegetation at the site is an important component of LTPBR projects, and the site map should have an initial assessment of vegetation at the site (Bennett et al. 2019b). The BRAT model can inform this assessment, as one of the primary inputs is a 10-m resolution LANDFIRE (2014) dataset predicting the current and historic extent and type of riparian vegetation present. Nearby plant branches and trunks are the material of choice for building BDAs and PALS, and riparian vegetation provides ongoing input of woody material to the stream. Additionally, roots from riparian vegetation provide strength and stability to streambanks. A wide riparian buffer zone also reduces stream velocity when the flow accesses the floodplain. If the intent of the project is to have the structures occupied and maintained by beaver, a wide and well-vegetated floodplain will provide the necessary building materials and food sources (Pollock et al. 2018).

Initial Site Visit. Seasoned practitioners of LTPBR can likely combine site characterization with developing a design plan for the project site. However, new practitioners will likely need some time to contemplate the information gathered during the initial site visit before developing a design plan. The first tasks in the site visit are to verify the information on the base map, review the site constraints, and reassess the determination of floodplains versus terraces. Additionally, any significant changes in channel slope and any knickpoints in the channel bottom within or downstream of the project reach should be noted. If there are significant changes in channel slope, the project reach should be divided into subreaches of varying slopes, as slope has an impact on structure density.

The hypotheses about the stream evolution stage and sources of degradation should also be revisited while on site. Specifically, it is important to look for changes in channel geometry and condition along the reach that would suggest the reach be divided into subreaches. The initial characterization of SEM stage should be validated. Within the project reach or subreaches, signs of the channel degrading, aggrading, being stabilized in a degraded state, or being in good geomorphic condition should be observed. Signs of recent degradation or aggradation include bank failures, exposed roots on both banks, recent bar formation (looking at the age, level of imbrication, and extent of bar vegetation), and filled pools, etc. Also, signs of recent overbank flow or high flow, such as high-water marks, bent over vegetation, and fine sand deposits on floodplain surfaces, should be noted. Finally, existing structure within the reach, such as pools, wood accumulations, and beaver dams, are features that should be in all streams and are a sign of overall good geomorphic condition.

One or more cross-sections of stream should be surveyed, depending on whether there are subreaches. LiDAR and other remote sensing type surveys may not accurately capture the topography of steep, vegetated slopes and may not measure through water, so the cross-section should include the bed and banks and extend onto adjacent flat surfaces. The cross-section survey will help in deciding if more than one treatment will be necessary to adequately raise the streambed up to connect it with the floodplain, or alternatively whether to widen the channel or raise the channel bed. It may also help in estimating quantities of materials needed for the structures.

In addition to surveying one or more cross-sections, it is important to qualitatively assess the bed and bank material in each of the subreaches. The preliminary site characterization should include a description of substrate composition, i.e., sand, gravel, cobble, bedrock etc., and a qualitative assessment of scour potential, as indicated by residual pool depths and depth of alluvial cover. Small cobble, gravel, and finer bed materials are desirable if the project includes driving posts into the substrate. Large cobble or small boulder substrate can be problematic for driving posts into the substrate. Large boulders or bedrock make securing an LTPBR project with posts impractical. It is recommended that LTPBR project proponents assess the feasibility of pounding posts into the substrate in the project area by digging test holes to determine the depth to bedrock and identify if the substrate is too coarse to manually pound posts. In sand streambeds, PALS and constriction dams may be more appropriate than BDAs due to the ease with which the sand is scoured out around the posts (Shahverdian and Wheaton 2017).

The site characterization should also describe the streambank composition, including earth material stratigraphy, bedding, geometry, and potential for erosion. The more erodible the streambank, the more potential exists for an LTPBR project to induce streambank erosion or flanking of the structure. This may be an acceptable or desired outcome unless the project is in an area where streambank erosion is unwelcome. Streams with both banks armored by boulder riprap or channels confined within levees, and that need to remain that way, are generally inappropriate for LTPBR restoration projects, although LTPBR structures have been used effectively to direct flow away from armored banks in some settings. If building the structure to continue up the streambank for stability, a characterization of streambank material is important. Bedrock streambanks that extend above bankfull discharge are characteristic of high-energy streams and are unsuitable for LTPBR projects, unless the opposite bank is well-connected to the floodplain.

The type and extent of riparian vegetation that was delineated on the site map should be verified. The 10-m resolution LANDFIRE (2014) dataset can be too coarse to capture details of the vegetation at the site. It may mischaracterize the extent or type of vegetation or be out of date. It is necessary to have an accurate understanding of whether the type and amount of vegetation on site is appropriate for constructing BDAs and PALS and for beaver to utilize, should they adopt the project site. Transportation costs can be prohibitive if materials for the projects cannot be sourced locally. It is also important to be conscientious about disturbing areas with invasive plant species for fear of distributing them to a wider area.

CONSTRUCTION CONSIDERATIONS

MATERIALS USED IN CONSTRUCTION

Ideally, both PALS and BDAs are built using locally sourced natural materials to keep costs low (Wheaton et al. 2019). In most instances, LTPBR structures are built using wooden posts, although postless structures, discussed later in this report, have been constructed and seem to garner many of the same positive benefits as BDAs with posts. Postless BDAs are most appropriate in small streams with low peak flows and stream power (Shahverdian et al. 2019). If using posts, only untreated wooden posts should be used. Pressure-treated posts or any post treated with a chemical that could leach into the stream should never be used. Metal T-posts should also never be used, since LTPBR structures are meant to be temporary, and metal posts will persist in the stream beyond the life of the structure (Wheaton et al. 2019).

Wooden posts can be purchased or locally sourced if the material is readily available. Pollock et al. (2018) suggest using wooden posts made from conifer trunks. Douglas fir posts harvested onsite were used in the Upper Nehalem Creek project (Trask 2019). The Pine Creek project used lodgepole pine fence posts 3 to 4 in (1 in = 2.54 cm) in diameter (Portugal et al. 2015b). The posts should be sharpened to assist in pounding the post into the substrate. If purchasing posts, untreated peeler-core posts 6 to 8 ft long (1 ft = 30.5 cm) and 2 to 4 in in diameter are recommended (Wheaton and Maestas 2017). Smaller diameter posts may be viable for small streams with low peak flows and stream power.

Various materials have been used for the branches between the posts. Branches can either be woven between the posts or placed prior to post installation. Again, the emphasis is on locally sourced materials. Branches from willow or other deciduous species, such as cottonwood, are often recommended (Portugal et al. 2015b; Wheaton and Maestas 2017; Pollock et al. 2018). In areas where riparian vegetation is limited, it is desirable to use species that beaver do not use for food or building materials (Wheaton et al. 2019). Instead, upland woody species, such as sagebrush, pinyon, juniper, or conifer limbs, can be substituted (Shahverdian and Wheaton 2017; Wheaton et al. 2019). Vine maple and Douglas fir limbs were used as weaving material on Upper Nehalem Creek (Trask 2019). Most of the BDAs woven with vine maple failed, while all the BDAs woven with Douglas fir remained.

On the upstream side of BDAs, cobble, gravel, and fine sediment should be placed to reduce flow under the dam (Portugal et al. 2015b; Shahverdian and Wheaton 2017). Successive layers of vegetation and sediment should be added upstream of a structure to reduce flow permeability and increase upstream pool depth (Pollock et al. 2018). Sediment should be sourced from upstream of the dam, in the channel and from the banks, to limit transport distance and enhance the width and depth of the pool.

Post-assisted log structures are generally constructed using small diameter (4–12 in) and short (6–15 ft) logs or small trees and branches. Typically, no sediment is used to build PALS, and logs can be placed in three basic configurations: bank-attached, mid-channel, and channel-spanning. Wooden posts are used to secure the wood in place. In large wood projects, threaded rebar or metal cable are sometimes used to secure logs together. This is not recommended for LTPBR structures. If there is the need to secure small logs together, wooden dowels or biodegradable rope, such as hemp, should be used (Wheaton et al. 2019).

PROJECT DESIGN

There are a variety of different LTPBR structures that may be used to accomplish project objectives in different geomorphic settings within a proposed project area. Individual features may consist of channel-spanning structures intended to pond water and provide temporary rearing habitat, non-ponding structures intended to constrict the channel, or simply the addition of woody material to the reach. Portugal et al. (2015b) provide a non-exhaustive list of structure complex configurations designed to meet specific restoration objectives (Table 1). The *Low-Tech Process-Based Restoration of Riverscapes Design Manual*, Chapter 4 (Shahverdian et al. 2019) contains more examples of restoration objectives and diagrams of LTPBR structures.

TABLE 1. Incomplete list of structure complex configurations designed to meet specific restoration objectives (Portugal et al. 2015b).

Restoration Objective	Stream Process	Complex Configuration
Geomorphic complexity	Increase channel meander length, scour pool and bar formation, substrate sorting	Complex of alternating constriction dams enhancing meanders and forcing pool formation and bar deposition
Floodplain connectivity	Increase frequency, extent, and duration of floodplain inundation, channel reconnection, and groundwater elevation	Series of channel-spanning primary and secondary dams causing pond creation 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 redirecting flow
Beaver habitat	Increase lifespan of existing dams, extent of pond area providing cover, and amount of forage	Reinforcement of existing active and abandoned dams, and installation of additional channel-spanning primary and secondary dams to increase pond extents

PILOT PROJECTS

Due to the diversity of hydrogeomorphic settings within California, the history of different types of anthropogenic alterations to the riverscape, and diversity of LTPBR structure types, it is often best practice to implement a small-scale pilot or trial project prior to large-scale implementation. Pilot LTPBR projects are an invaluable tool for explicitly testing hypotheses about the most appropriate type of LTPBR structure for the hydrogeomorphic settings present in your project area. Pilots enable practitioners to gather site-specific information about sediment sources, the rate and magnitude of sediment and water flux interacting with the structures, and the level of floodplain connectivity without the use of extensive hydraulic modeling. Pilot projects usually consist of three to five different types of LTPBR structures constructed throughout the different geomorphic settings in the project area. Ideally, these structures are implemented prior to a series of high-flow events so practitioners can then return after that period to assess the efficacy of the different structures and the rate and magnitude of hydrogeomorphic response (e.g., channel widening, increased bed elevation, increased floodplain connectivity, etc.). Pilot projects are consistent with the LTPBR principle to defer critical decision-making to the riverscape and ecosystem engineers (Wheaton et al. 2019), as opposed to assuming that the riverscape is predictable in terms of project-scale hydrogeomorphic processes relative to restoration objectives.

STRUCTURE AND COMPLEX DESIGN

Low-tech process-based restoration structures are built from natural materials with the use of hand tools, and their construction does not include excavation, grading, or utilizing mechanized equipment; BDAs and PALS are not considered to be permanent features of the riverscape. As such, permitting and/or funding agencies generally do not require detailed engineering plans prepared and stamped by licensed professionals for LTPBR projects. The written project design document must provide the location and desired objective of each feature (Shahverdian and Wheaton 2017; Wheaton et al. 2019). Additionally, project narratives should demonstrate that experienced restoration professionals are involved in the process of evaluating potential LTPBR project locations from the watershed scale down to the individual proposed structure and complex scale. Each feature in the field should be flagged with a unique identifier or have its location recorded with a GPS unit. This information is necessary to monitor the feature and evaluate the need for maintenance. For example, if the feature is intended to initiate channel widening in an incised channel, and the structure is found to be flanked after winter storms, this project would be deemed a success. However, if this project were instead intended to pond water to provide rearing habitat, and it is found to be flanked after winter storms, maintenance would be needed to restore the structure to achieve the initial goal of the project. Tracking results at the structure scale can be informative to improve designs and inform subsequent treatments, but in terms of project-scale results, it is more appropriate to monitor the structure’s performance at the reach-scale or larger.

To achieve the desired goals of a project, it often takes more than one treatment over multiple years. By revisiting a project reach after high-flow events, changes to the project reach, both anticipated and unanticipated, can be observed. The designers can then implement adaptive management to lay out the next phase of the project. They should estimate how many years they anticipate it will take for the project to become self-sustaining and seek an appropriate level of funding through the expected term of required management to complete the project.

Low-tech process-based restoration structures are best when constructed in sequence (Pollock et al. 2018) to form a complex. To mimic natural beaver dams, structures are clustered, reducing the importance of a single structure and improving the stability of all the structures (Shahverdian and Wheaton 2017). Complexes are typically between 2 and 15 LTPBR structures and may be composed of a single structure type or multiple structure types. Intended to invoke a process response, LTPBR structures are not meant to remain as permanent hard structures (Pollock et al. 2014).

Weber et al. (2020) have developed a Project Implementation and Monitoring Protocol[4] for organizing and planning LTPBR designs. The program incorporates a free software application that operates on mobile devices and can be taken out in the field. It can be used to lay out the initial project design elements, subsequent monitoring, and additional maintenance and adaptive design. The program catalogues initial project objectives and helps calculate quantities of construction materials.

BEAVER DAM ANALOG DESIGN

Beaver dam analogs are channel-spanning structures intended to mimic a natural beaver dam. They can be built with or without wooden posts. A typical schematic of a first-generation BDA with posts is provided in Portugal et al. (2015b) (Figure 13).

Postless BDAs can be as stable and effective as post-assisted structures (Wheaton and Shahverdian 2018) when used in the appropriate setting (Figure 14). Not having to transport a post pounder to the construction site expands the areas in which BDAs can be built. Postless construction eliminates the need for off-site materials and reduces the cost of the project by not having to purchase untreated wooden fence posts.

Both posted and postless BDAs can serve as primary dams, with their main objective to create a pond in the active channel, or secondary dams built to support the primary dam (Portugal et al. 2015b; Table 2; Figure 15).

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[4] https://lowtechpbr.restoration.usu.edu/resources/

Primary dams are built so that their crest elevation is equal to or greater than bankfull elevation. Secondary dams have a lower crest elevation that is near or below bankfull. Beaver dam analogs typically have a straight or convex dam crest (Figure 16). Both primary and secondary dams should have a mattress built on the downstream side of the dam using sticks and logs pushed into the weave and oriented parallel to the flow. The intent of a mattress is to dissipate stream power as it pours over the dam and reduce downstream scour at the base of the dam.

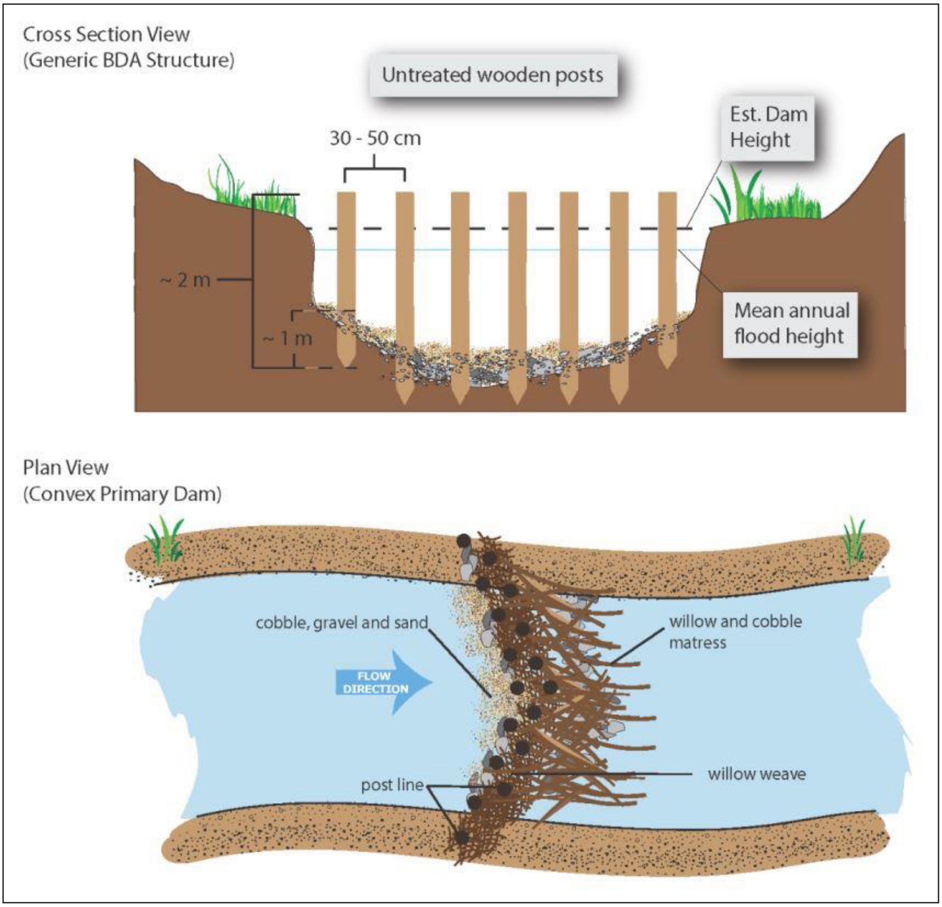
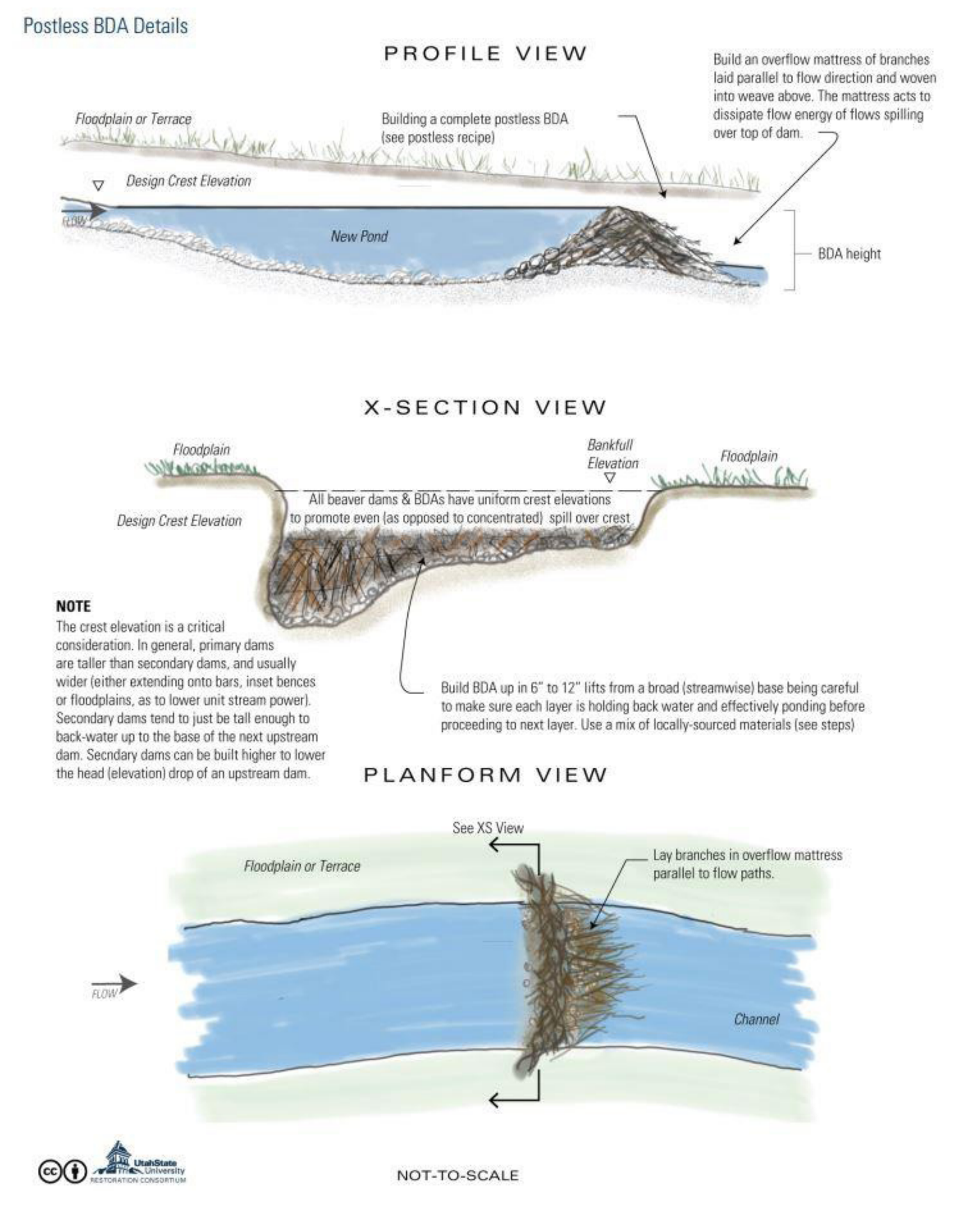


Figure 13. Above: cross-section schematic of a first-generation beaver dam analog with posts before woven fill material and a downstream mattress is added. Below: plan view showing features of a convex primary dam after woven fill and mattress is added (Portugal et al. 2015b).



Building a complete postless BDA (see postless recipe)

Build an overflow mattress of branches laid parallel to flow direction and woven into weave above. The mattress acts to dissipate flow energy of flows spilling over top of dam.

All beaver dams & BDAs have uniform crest elevations to promote even (as opposed to concentrated) spill over crest

NOTE
The crest elevation is a critical consideration. In general, primary dams are taller than secondary dams, and usually wider (either extending onto bars, inset bences or floodplains, as to lower unit stream power). Secondary dams tend to just be tall enough to back-water up to the base of the next upstream dam. Secndary dams can be built higher to lower the head (elevation) drop of an upstream dam.

Build BDA up in 6" to 12" lifts from a broad (streamwise) base being careful to make sure each layer is holding back water and effectively ponding before proceeding to next layer. Use a mix of locally-sourced materials (see steps)

Lay branches in overflow mattress parallel to flow paths.

Figure 14. Typical schematic sketches of a postless beaver dam analog (Shahverdian et al. 2019).

TABLE 2. Summary of typical hydraulic, hydrologic, and geomorphic effects of beaver dam analogs (Shahverdian et al. 2019).

Type	Hydraulic	Hydrologic	Geomorphic
Primary BDA	Create deep slow water	Increase frequency and magnitude of overbank flow, increase hyporheic flows	Channel aggradation upstream, bar formation, bank erosion (if breached on ends), sediment sorting
Secondary BDA	Create deep slow water	Increase frequency and magnitude of overbank flow, increase hyporheic flows	Channel aggradation, channel avulsion, bank erosion, dam pool formation, bar formation

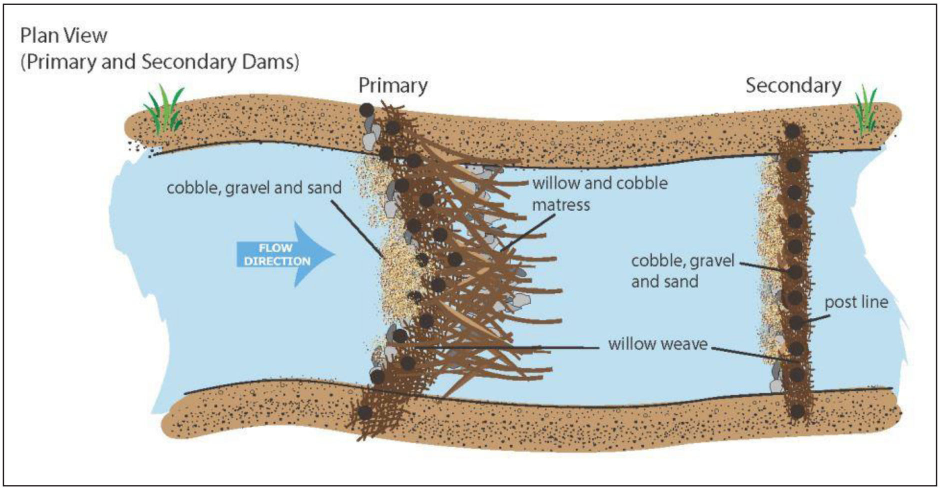
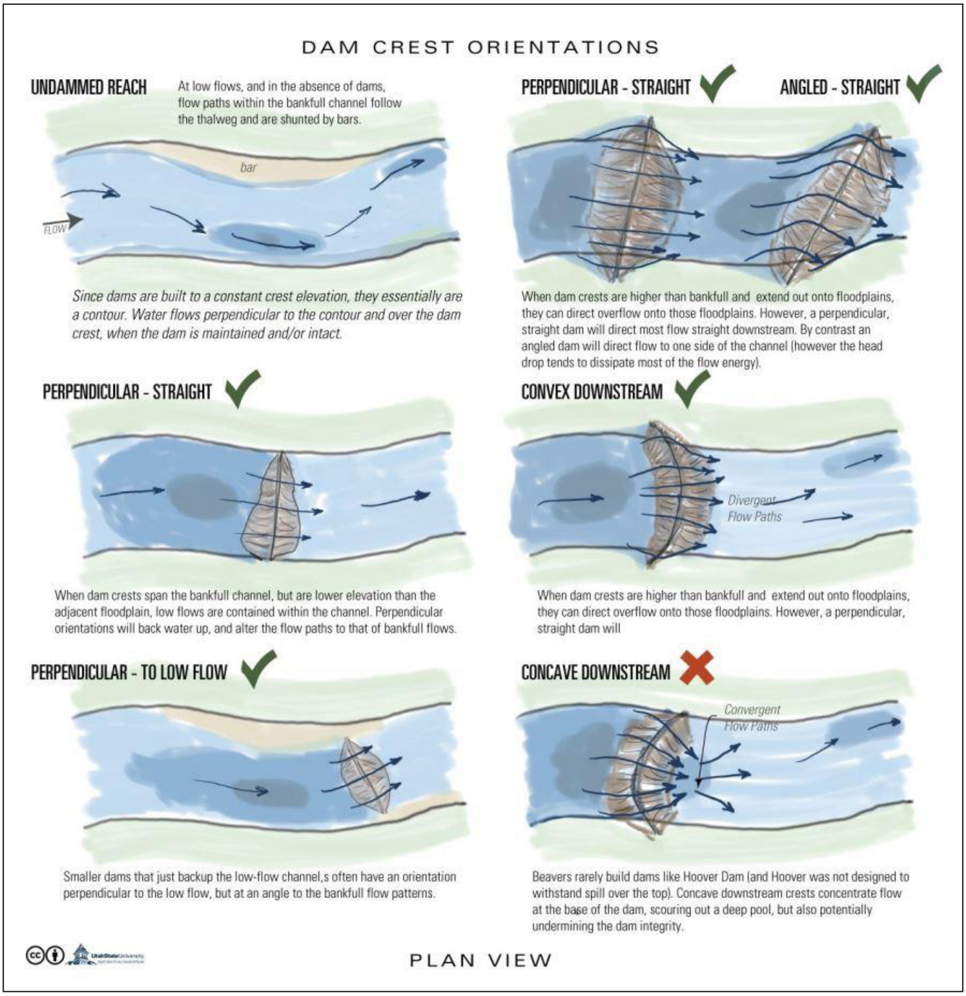


Figure 15. Plan view schematic of primary and secondary dams working in concert (Portugal et al. 2015b). Note: secondary dams can also have a convex planform and should also include a downstream mattress.



At low flows, and in the absence of dams, flow paths within the bankfull channel follow the thalweg and are shunted by bars.

Since dams are built to a constant crest elevation, they essentially are a contour. Water flows perpendicular to the contour and over the dam crest, when the dam is maintained and/or intact.

When dam crests are higher than bankfull and extend out onto floodplains, they can direct overflow onto those floodplains. However, a perpendicular, straight dam will direct most flow straight downstream. By contrast an angled dam will direct flow to one side of the channel (however the head drop tends to dissipate most of the flow energy).

When dam crests span the bankfull channel, but are lower elevation than the adjacent floodplain, low flows are contained within the channel. Perpendicular orientations will back water up, and alter the flow paths to that of bankfull flows.

When dam crests are higher than bankfull and extend out onto floodplains, they can direct overflow onto those floodplains. However, a perpendicular, straight dam will

Smaller dams that just backup the low-flow channel,s often have an orientation perpendicular to the low flow, but at an angle to the bankfull flow patterns.

Beavers rarely build dams like Hoover Dam (and Hoover was not designed to withstand spill over the top). Concave downstream crests concentrate flow at the base of the dam, scouring out a deep pool, but also potentially undermining the dam integrity.

Figure 16. Dam crest orientation (Shahverdian et al. 2019).

Since BDAs are channel-spanning structures intended to pond water, they are likely to be impacted by high flows. These impacts may be anticipated and not require maintenance or repair, or unanticipated and require some action on the part of the entity responsible for the project. Again, it should be reiterated that it is far more efficient and effective for beaver to maintain BDAs. The level of practitioner maintenance will largely depend on the goal of the project and its potential for unintended impacts on private land or infrastructure. High flows may result in a total blow-out of the structure, flanking or breaching of the dam, or filling the dam with sediment so it is no longer ponding water. If a BDA occupied by beaver is flanked or breached, it will likely not need maintenance from restoration practitioners. It is also common for damaged structures to continue to function. If the intent of the project is to provide rearing habitat, then sites that have filled in with sediment or have breached to the degree that they are no longer ponding water will need to be rebuilt or abandoned. Aggraded sediment in an incised channel provides opportunities for a new channel to form with better floodplain connections.

Spacing for channel-spanning structures is dependent upon stream gradient and width. Spacing of BDAs should mimic natural spacing of beaver dams, generally between one and two channel widths (Portugal et al. 2015b). The dam crest height will also influence the spacing of structures, dependent upon their function. Portugal et al. (2015b) found the typical height range for natural beaver dams in Pine Creek to be between 0.5 and 1 m high. If natural beaver dams are present, dam heights should be measured to inform BDA height. Primary BDAs have a crest height equal to or greater than bankfull elevation, creating large ponds, while secondary dams have lower crest elevations and create smaller ponds (Wheaton et al. 2019). For the secondary dam to reduce the hydraulic gradient in support of the primary dam, it must be built close enough to the primary structure to achieve that goal. Specifically, the ponded water upstream of the secondary dam should extend upstream to the base of the primary dam.

The dam crest of a structure can be angled to direct the flow. Water flows over a dam perpendicular to the structure. In a straight dam, most of the flow will be directed downstream. An angled dam will direct the flow towards one of the banks. Beaver dam analogs should be built either convex or straight. Convex dams have the U-shape pointing downstream and concave dams have a U-shape pointing upstream. Convex dam crests are most similar to how beaver construct dams and provide the greatest stream power dissipation over the crest by spreading high flows over the structure. Concave structures should be avoided, as the flow over the crest of the dam will concentrate and form a deep pool, potentially undermining the structure (Shahverdian et al. 2019; Figure 16).

In streams where there is concern over the ability of an LTPBR structure to persist through annual peak flows, structures can be stabilized using wooden posts (Shahverdian and Wheaton 2017). Commercially purchased posts are usually either 6 or 8 ft long. Posts should be driven into the substrate as deep as possible, with a minimum of 25% to 33% of the post below ground (Bennett et al. 2019a). Typical post spacing is between 0.5 and 0.8 m apart (Portugal et al. 2015b). Posts can be placed in either a single row or a staggered double-staged row. For BDAs with posts, a double row of posts is stronger, provides for a wider base, and eliminates the need for building a wall (Shahverdian et al. 2019). Posts should be installed either straight or angled slightly upstream. Posts angled downstream may weaken the structure (Shahverdian et al. 2019). With a double-staged row, the upstream row should be angled downstream and the downstream row upstream (Figure 17). Posts should be cut to the desired height of the structure. This will keep debris from accumulating on the structure and prevent beaver from building on the excess post height, which both create structural instability (Yokel et al. 2018).

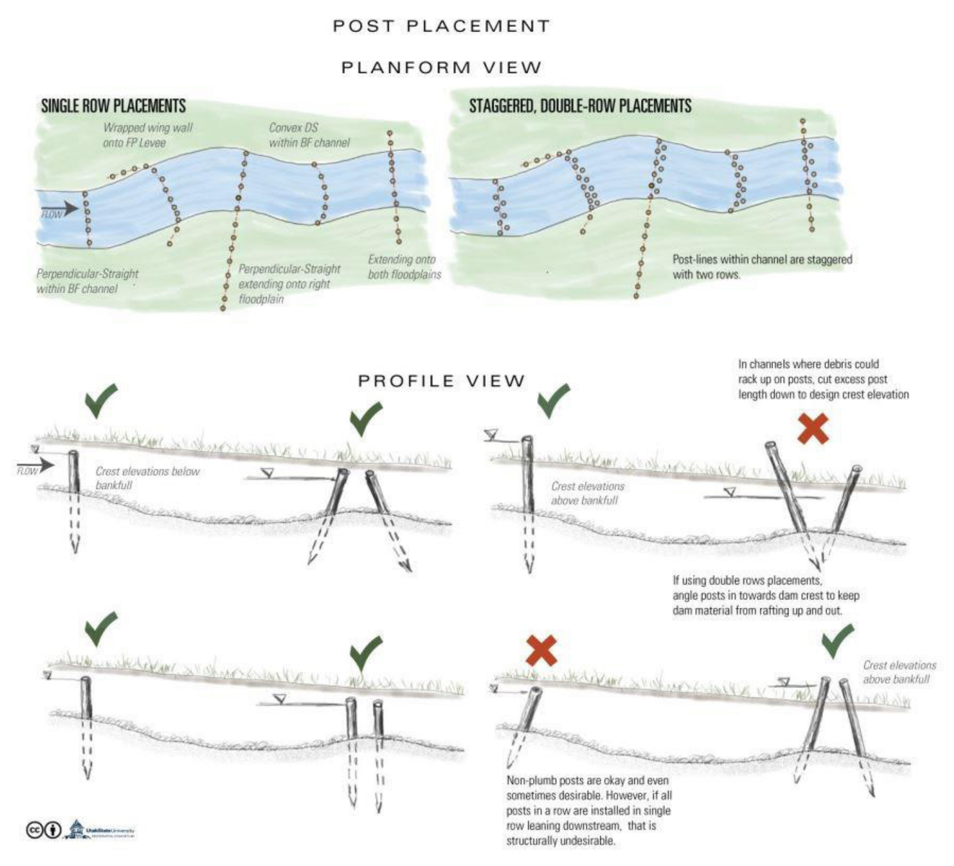


Figure 17. Post placement (Shahverdian et al. 2019).

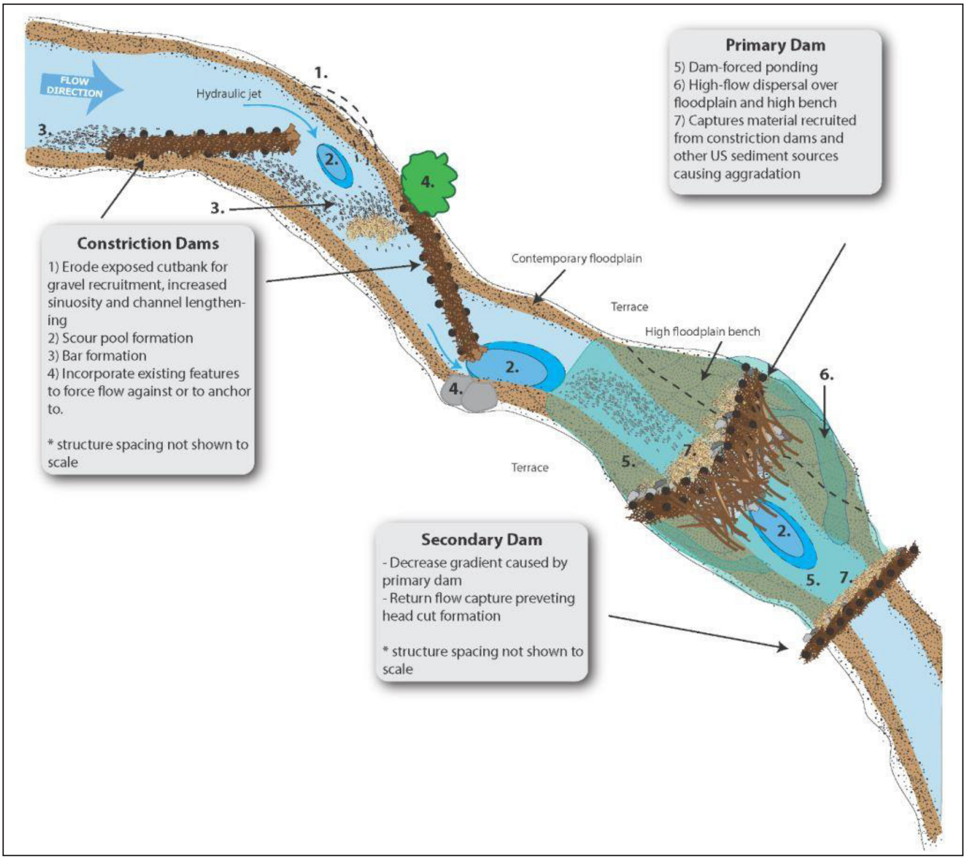
Another option is to reinforce an existing beaver dam using wooden posts to stabilize the structure. In this case, no new structure is built. The purpose is to increase the longevity of an existing dam that is actively maintained by beaver or abandoned dams that are still intact (Portugal et al. 2015b; Pollock et al. 2018). Appendix E of Shahverdian et al. (2019) includes descriptions and typical drawings of postless BDAs, post-assisted BDAs, post-line wicker weave BDAs, and double post and mattress BDAs.

POST-ASSISTED LOG STRUCTURE DESIGN

Both PALS and BDAs are permeable, temporary structures built using natural materials. The construction of PALS and BDAs is similar, with the main difference being that the upstream side of a BDA is sealed to a certain degree in order to create a pond, while PALS are built with only woody material.

There are various ways to construct PALS. Since the goal is to mimic natural wood accumulations, larger diameter and longer logs are used in the construction of PALS than in BDAs. Construction does not include sealing the upstream side of the structure. Depending on the goals of the project, PALS can span the channel, be attached to one bank to constrict the channel (Figure 18), or be placed mid-channel or on the floodplain.

As opposed to BDAs, which influence flows at all flow stages, PALS typically effect geomorphic change to the channel during moderate to high flows. “Hydraulic purchase” refers to the ability of PALS to influence flows at different flow stages and is an important concept to consider when designing and building PALS (Shahverdian et al. 2019). The geomorphic changes that PALS can initiate are determined by stream flow rates. During high flows, PALS can trap woody material and bedload.



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

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

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

* structure spacing not shown to scale

Figure 18. Simplified schematic demonstrating how bank-attached/constriction post-assisted log structures and primary and secondary beaver dam analogs work in concert as part of a structure complex (Portugal et al. 2015b).

Mid-channel and bank-attached PALS may trap enough woody material to become channel-spanning structures, creating unintended or intended bank erosion and flooding. Adjustment or maintenance of the structure is only required if it affects private property or infrastructure. If not, the project should be evaluated on the overall change to the project reach rather than to the individual structure.

Determining which type of LTPBR structure to use depends on the goals of the project, since hydraulic, hydrologic, and geomorphic effects vary with different structure types. Table 3 describes how different types of PALS influence these processes.

For all LTPBR structures, regular inspection to assess the performance of individual structures and, more importantly, changes to the stream reach are essential. The entity responsible for the project must be willing to take responsibility for the project and adjust as necessary to ensure success.

Typical schematics for PALS are presented in Appendix D of Shahverdian et al. (2019). These schematics are intended to give general guidance on the construction of PALS, rather than serve as engineered drawings to be followed for each project. Appendix D includes descriptions and typical drawings of bank-attached, mid-channel, and channel-spanning PALS.

TABLE 3. Summary of typical hydraulic, hydrologic, and geomorphic effects of post-assisted log structures (Shahverdian et al. 2019).

Type	Hydraulic	Hydrologic	Geomorphic
Channel-spanning PALS	Create upstream backwater or pond, create plunge hydraulics downstream	Increase frequency and magnitude of overbank flow, increase hyporheic flows	Channel aggradation, channel avulsion, bank erosion, dam and plunge pool formation, bar formation
Bank-attached PALS/Constriction dam	Force convergent flow (deeper and faster), create eddy behind structure	Force overbank flows	Bank erosion, scour pool formation, bar formation, sediment sorting, channel avulsion
Mid-channel PALS	Force flow separation, create eddy behind structure	Force overbank flows	Bank erosion, scour pool formation, bar formation, sediment sorting, channel avulsion

LOW-TECH PROCESS-BASED RESTORATION STRUCTURES AND FLOODPLAIN CONNECTIVITY

Floodplain connectivity is often the stated goal of an LTPBR project. The best opportunities for floodplain connectivity are in stream reaches where the elevation difference between the channel and the floodplain is minimal. Locating LTPBR structures in these stream reaches may result in additional benefits, such as a more robust riparian zone, increased connection with the hyporheic zone, and groundwater recharge. In reaches with poor floodplain connectivity, LTPBR structures will be subject to a greater portion of high flows, increasing the probability of the structure being flanked or completely blowing out.

PROJECT IMPLEMENTATION

PERMITTING

A variety of permits may be required to complete an LTPBR project. A discussion of potential permits is included in the *California Salmonid Stream Habitat Restoration Manual*, Part VI (Flosi et al. 1998). Opportunities exist for simplified and streamlined permitting requirements for certain restoration activities. For example, some LTPBR projects may qualify for expedited approvals from CDFW under the Habitat Restoration and Enhancement Act[5] of 2014 (Fish & G. Code §§ 1650-1657) if they meet certain requirements, including eligibility for SWRCB's Order for Clean Water Act, Section 401 General Water Quality Certification for Small Habitat Restoration Projects. More recently, on August 16, 2022, SWRCB adopted an Order for Clean Water Act, Section 401 Water Quality Certification and Waste Discharge Requirements for Restoration Projects Statewide (Statewide Restoration General Order[6]) and consolidated the Program Environmental Impact Report that will further expand coverage for LTPBR activities.

Projects that alter the streambed or streambank or divert or obstruct natural streamflow generally require a CDFW Lake and Streambed Alteration Agreement[7] (LSAA). Some streamlined permitting pathways (e.g., Habitat Restoration and Enhancement Act eligible projects noted above) incorporate LSAA requirements by design. The LSAA includes species protection measures, oil spill protection and reporting requirements, and several other conditions that must be followed. Heavy equipment decontamination protocols must be followed prior to any heavy equipment entering a stream. The CDFW Invasive Species Program website[8] provides general information about preventing the spread of invasive species. Field guidance

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[5] https://wildlife.ca.gov/Conservation/Environmental-Review/HREA

[6] https://www.waterboards.ca.gov/water_issues/programs/cwa401/generalordersunderdev.html

[7] https://wildlife.ca.gov/Conservation/Environmental-Review/LSA

[8] https://wildlife.ca.gov/Conservation/Invasives

and decontamination protocols are provided in CDFW's Aquatic Invasive Species Decontamination Protocol (CDFW 2022) and the U.S. Bureau of Reclamation's *Inspection and Cleaning Manual for Equipment and Vehicles to Prevent the Spread of Invasive Species* (DiVittorio et al. 2012). Short-term negative impacts from construction work to the stream are inevitable. These include, but are not limited to, increased turbidity and disturbance of riparian vegetation. To minimize impacts, the project should be implemented when the reach is dry or at its lowest summer flow. Sediment generated by the project must be confined to as small an area as possible to reduce downstream impacts to invertebrates, fish, and other vertebrate species.

HAND CREW LABOR

For most LTPBR projects, construction can be completed by hand crew labor. Sources of this labor include restoration practitioners and other natural resources professionals, volunteers, and the California Conservation Corps (CCC). Safety is the number one concern on any project site. Restoration practitioners and the CCC should come to the work site with proper safety gear, such as hard hats, gloves, and eye and ear protection. If using volunteers, the entity organizing the project is responsible for providing essential safety gear.

A variety of hand tools (hand saws, pruners, etc.) are necessary to gather and prepare the woody material and construct LTPBR projects. Specialized tools, such as portable lever-operated hoists and chainsaws, are valuable for maximizing efforts in securing woody material. It is more efficient to employ established restoration practitioners or CCC crews that have the necessary tools, with crew members already trained and certified in the use of specialized project tools. Volunteers are valuable in completing tasks that do not require specialized training, such as moving materials to the worksite, packing and weaving woody material, and securing and placing substrate to seal BDAs.

Harvesting trees or downed logs near the project site is the most cost-effective way to collect the materials needed to construct LTPBR projects. It is important to discuss and receive permission from the landowner or land manager prior to harvesting any trees or downed logs.

Depending on the site and the availability of local materials, it may be necessary or more cost-effective to purchase the posts needed for the project instead of sourcing them locally. This will require a truck, trailer, or all-terrain vehicle to haul the posts to the sites. Staging materials as close to the site as possible makes the actual construction faster and more efficient. For some projects, using a small boat, raft, or canoe to move construction materials and equipment between sites is useful (Bennett et al. 2019a). Using a plastic-bottom boat rather than a metal boat is suggested, since they slide more easily over the streambed and are less prone to cracking or puncturing in shallow water.

When using posts, some form of post driver is needed to drive the posts into the substrate. This can range from a very simple sledgehammer or manual post driver to a much more expensive and efficient hand-operated hydraulic-powered post driver. If only building a few LTPBR structures in an area where pounding the posts into the substrate is not too difficult, then a manual post driver is probably adequate. If many LTPBR projects requiring posts are planned, then acquiring a hand-operated hydraulic-powered post driver is desirable. This is a specialized piece of equipment, which is heavy to move, and requires trained crew members to operate it safely. Bennett et al. (2019a) covers various types of post pounders and their proper use in detail.

HEAVY EQUIPMENT

Heavy equipment may be used to drive wooden posts into the substrate, though this is not a preferred option, given the cost and associated impacts with operating heavy machinery in a riparian environment. Heavy equipment with an attached post pounder or an excavator modified with a vibrating pad can be used to drive these posts into the substrate (Pollock et al. 2018).

The decision of when and where to use heavy equipment is largely dependent on the site and site conditions. An advantage to using heavy equipment is that the posts can be quickly and deeply driven into the substrate, depending on the skill and expertise of the operator. Heavy equipment should only be used where there is an existing road to access the site, so damage to existing riparian vegetation can be avoided, and if it will be less expensive than using hand crew labor.

If heavy equipment is used, at the end of the project, disturbed project roads should be hydrologically disconnected from streams, as best as feasible. All temporarily opened project roads and skid trails should be treated with locally generated slash to minimize surface erosion and promote volunteer revegetation. The slash should be track-walked and compacted into the ground. If using mulch, only weed-free mulch should be used to reduce the possibility of importing invasive weeds to the area.

EVALUATION, MAINTENANCE, AND MONITORING

EVALUATION

Low-tech process-based restoration structures consisting of either PALS or BDAs are not intended to be permanent stationary structures. Their intent is to add numerous individual structures within a project reach, functioning in concert at the complex scale, that partner with the stream to improve riverscape ecological function. With most restoration projects, success or failure is evaluated at each individual structure. Projects involving LTPBR structures must be evaluated differently. They are considered a success if the project meets the overall design objectives, even if some of the individual structures do not perform as anticipated. More broadly, the goal of most LTPBR projects in a structurally starved setting is to enhance the processes of wood accumulation and/or beaver dam activity and become self-sustaining over time. It is important in the design process to acknowledge that it is likely that not all structures will meet their design objective and that structures will need some maintenance. To achieve the overall goal of a healthy sustainable riverscape, it may take several years of annual maintenance, construction of additional structures, or removal of structures not performing as anticipated. The entity responsible for the project will need to perform these tasks unless beaver occupy the stream reach. The most cost-effective LTPBR strategy is to have beaver take over the maintenance of the reach and construction of any additional structures.

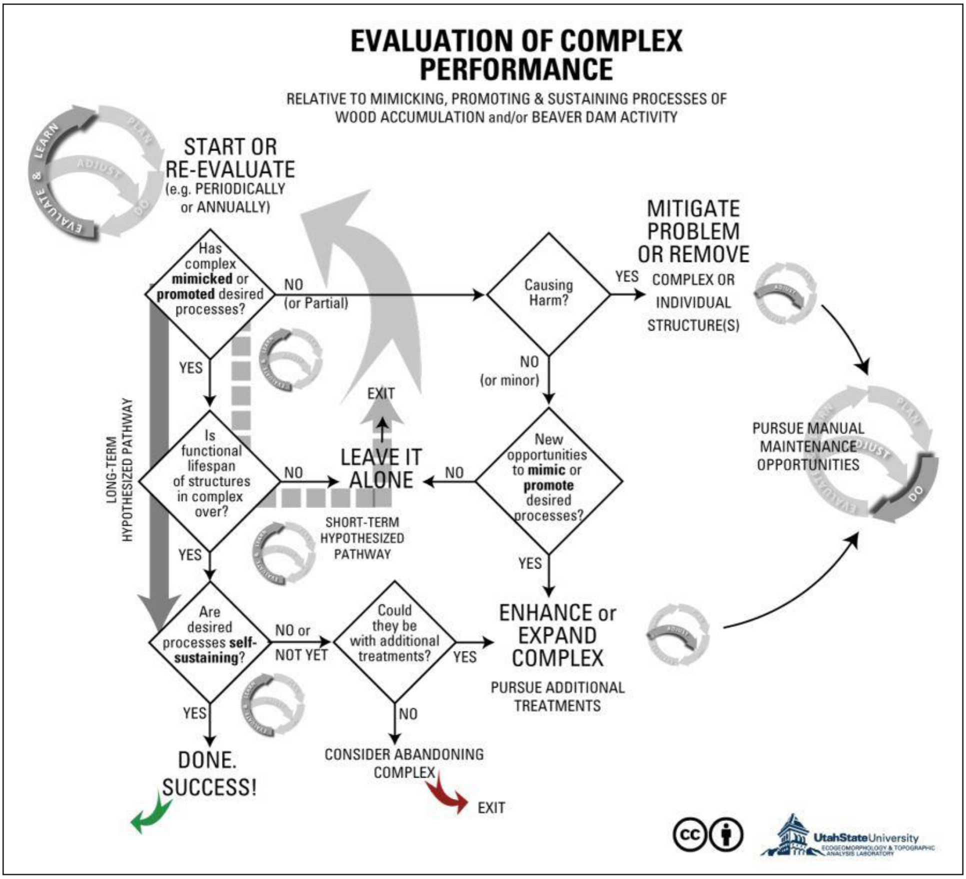

Figure 19. Adaptive monitoring and maintenance for evaluation of low-tech process-based restoration structure complexes (Wheaton et al. 2019).

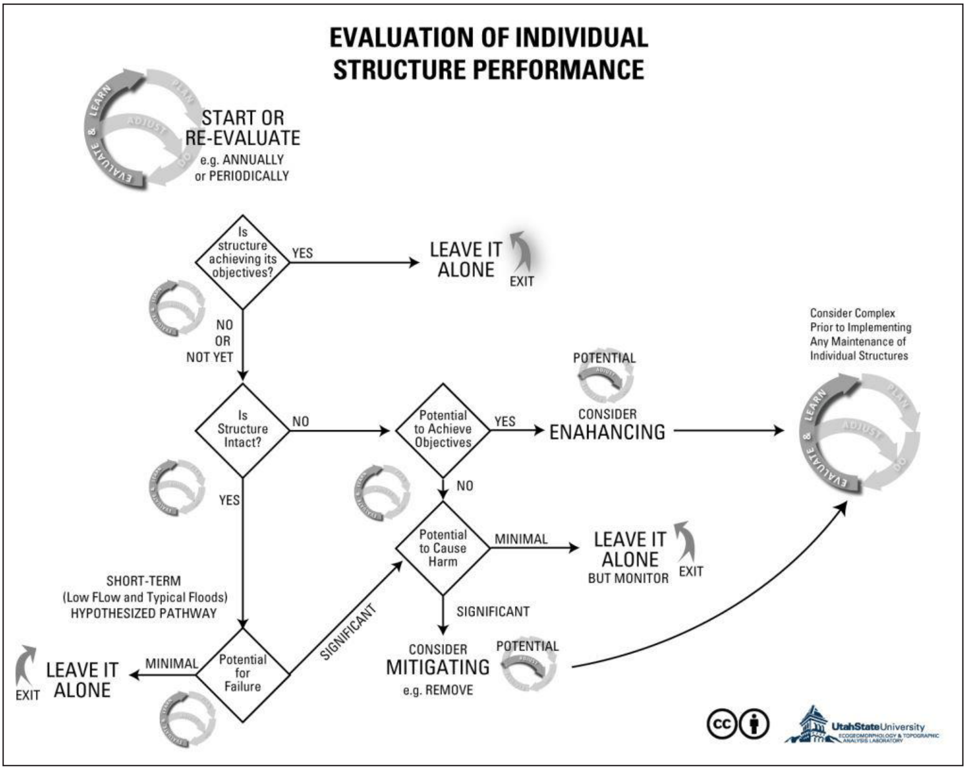

Figure 20. Adaptive monitoring and maintenance for evaluation of individual low-tech process-based restoration structures (Wheaton et al. 2019).

To evaluate an LTPBR project, the goals of the project must be well-defined, and the current conditions of the stream reach selected for treatment well-described. Low-tech process-based restoration structures are typically not engineered, nor do they have detailed drawings like other restoration projects. By the very nature of their construction and the natural materials used, they are not intended to be permanent fixtures. Figures 19 and 20 provide examples of how to evaluate LTPBR complexes and individual structures using a simple adaptive management framework. The primary evaluation of project success is based on whether the stated goals have been attained at the complex or larger project scale, not at the scale of individual structures.

MAINTENANCE

Maintenance plans and schedules should be presented in project support documentation. They will vary based on the structure types, restoration objectives, and hydrogeomorphic setting of the project. Typically, channel-spanning structures designed to pond water will require more maintenance, in order to maintain the ponded water extent, than other structure types if beaver are not actively maintaining them. If resources allow, an annual assessment and structural maintenance should be conducted prior to the high-flow period, and another assessment should be conducted during the recession to summer baseflow conditions. The high-flow period is when the most geomorphic work is accomplished through the hydraulic interaction of high flows with the structures.

Other types of typical maintenance of BDAs and PALS are listed below and explained in more detail in Chapter 3 of Wheaton et al. (2019). Maintenance can continue until the stream reach achieves the goals of the project or beaver occupy the reach in adequate numbers to maintain the reach.

Typical PALS maintenance:

- Adding more wood to existing structures
- Adding posts to existing structures
- Building new structures where other structures have been washed downstream
- Adding wood either by hand or falling trees in treatment areas and allowing the system to rearrange the wood

Typical BDA maintenance without beaver present:

- Adding more posts to reinforce a dam
- Repairing minor breaches
- Building out the BDA further onto the floodplain or raising the crest elevation to increase the size of the pond
- Adding more fill to seal the dam and raise the water level
- Building new BDAs if previous BDAs aggraded or the channel migrated

MONITORING

There are many ways to monitor an LTPBR project, from simple post-project implementation monitoring as described below, to spatially explicit, high-resolution change detection using repeat digital elevation models generated from topographic surveys and hydraulic models. The development of an effective monitoring plan for a given project and the level of monitoring are based primarily on an accurate summary of existing conditions, a clear articulation of project objectives, and the availability of funding for monitoring.

Minimally, photo points should be established before construction, and photos should be repeated after bankfull storm events for an established length of time to monitor the project and ensure that project goals are attained. Additionally, simple metrics should be included related to the specific restoration objectives that can either be collected in the field with a depth rod and tape measure or remotely in GIS using repeat aerial images or digital elevation models. For example, in an incised setting, the restoration objective may be to increase the rate of channel widening to allow for development of an inset floodplain. In this case, a series of bankfull width measurements can be collected throughout the project reach pre- and post-implementation. Post-implementation widths should be collected after a series of high-flow events to assess if widening has occurred. In an example in which the LTPBR project goal is to create deeper pools, a series of residual pool depth measurements can be collected pre- and post-implementation as described above to assess if habitat quality has improved.

Additionally, both the project description provided in the project design and the design objectives articulated at the structure and complex scale can be used to determine if the features meet the stated objectives. The evaluation must be adequate to determine if maintenance is needed on existing features, if additional features should be added, or if an individual feature or the overall project has resulted in unintended consequences. If funding is available, the following components should be included in a monitoring plan for LTPBR projects (Appendix B provides a more detailed list of potential attributes to include in the following surveys):

1. **Rapid monitoring and repeat photos of structures:** a field survey to characterize the distribution and dynamics of natural and artificial LTPBR structural elements

2. **Survey of channel attributes:** a field survey to document characteristics of the geomorphic habitat units (e.g., pools, bars, and riffles) and produce metrics that evaluate restoration effectiveness and in-channel habitat quality and quantity

3. **Image analysis of floodplain, vegetation, and channel change:** a desktop process to identify and quantify characteristics of the valley bottom, including vegetation, floodplain connectivity, and floodplain habitat quantity from aerial imagery

Bennett et al. (2019b) and Weber et al. (2020) provide free resources, including field and desktop data collection protocols and instructional videos, field design and monitoring apps, and databases for planning, designing, monitoring, and evaluating LTPBR projects at multiple spatial scales. The design, maintenance, and monitoring field collection apps and associated protocols are supported by trainings and a database accessible to other LTPBR practitioners throughout the world. These tools are a means for LTPBR practitioners to apply a standardized and consistent approach to the design, maintenance, monitoring, and analysis of LTPBR projects. Implementing this approach using a standardized process will advance the art and science of LTPBR practices and support widespread and common tasks for project development, regulatory compliance, and regular monitoring and reporting requirements from land management agencies like CDFW.

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APPENDIX A

NON-LETHAL BEAVER MANAGEMENT RESOURCES

- Beaver Solutions[9]– specializes in resolving human/beaver conflicts with non-lethal techniques; lots of free resources, including beaver management plans

- *Wildlife in a Managed Forest: The American Beaver* (Coe et al. 2016)

- *Beaver Management Technical Paper #1: Beaver Management Tools Literature Review and Guidance* (King County 2018)

- *How to Keep Beavers from Plugging Culverts* (Nolte et al. 2005)

- *Living with Wildlife: American Beaver* (ODFW, no date)

ADDITIONAL LOW-TECH PROCESS-BASED RESTORATION RESOURCES

- Low-Tech Process-Based Restoration of Riverscapes Resources[10]– free LTPBR references and training resources (LTPBR manual and pocket guide, self-paced modules and materials, LTPBR workshops and classes, primary literature on LTPBR, and LTPBR talks and webinars); free LTPBR tools and protocols (Implementation and Monitoring Protocol, Riverscape Consortium Models and Tools, and LTPBR Design App); LTPBR examples and community resources (BDA explorer map and list of LTPBR projects, case studies and reports, LTPBR adaptive management examples, and LTPBR recipes)

- Occidental Arts and Ecology Center[11]– a plethora of non-lethal beaver management resources and planning, design, and assessment guidance on LTPBR in general

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[9] https://www.beaversolutions.com

[10] https://lowtechpbr.restoration.usu.edu/resources/

[11] https://oaec.org/publications/beaver-in-california/

APPENDIX B

MONITORING SURVEY METHODS AND ATTRIBUTES

The following suggestions are taken from Weber et al. (2020) with more details and resources available in that document. Specifically, all the survey attributes listed below are described in the protocol and included in the field monitoring application.

1. **Rapid monitoring and repeat photos of structures:** a field survey to characterize the distribution and dynamics of natural and artificial LTPBR structural elements

   Components to include: Field Survey Event Attributes (e.g., reach name, survey date, survey start and stop coordinates, survey valley length, survey flow, survey notes, surveyed by, observation ID, etc.), Structure Source (e.g., natural or artificial), Structure Notes, Dominant Low-Flow Type, Lateral Response (e.g., dispersion, erosion, or no response), Elevational Response (e.g., depositional, erosional, equilibrium, or no response), Beaver Maintenance, Fish Passage Risk, Dam-Specific Attributes (e.g., dam length, maximum hydraulic height, minimum jump height, dam integrity, etc.), Jam-Specific Attributes (e.g., artificial jam condition, length, width, height, wood count, etc.)

2. **Survey of channel attributes:** a field survey to document characteristics of the geomorphic habitat units (e.g., pools, bars, and riffles) and produce metrics that evaluate restoration effectiveness and in-channel habitat quality and quantity

   Components to include: Geomorphic Unit Attributes (e.g., unit type, structure forced, unit notes, unit coordinates, primary channel, primary unit, length, width, depth, percent wetted, etc.)

3. **Image analysis of floodplain, vegetation, and channel change:** a desktop process to identify and quantify characteristics of the valley bottom, including vegetation, floodplain connectivity, and floodplain habitat quantity from aerial imagery

   Components to include: Riverscape Survey Event Attributes (e.g., image date, image source, image flow, riverscape survey notes, GIS files, etc.), Measures of Active Channel Network Length (e.g., primary and non-primary channel length, wetted channel length, etc.), Measures of Riverscape Feature Area (e.g., active channel area, active floodplain area, riparian vegetation area, etc.)

The following tables were taken from Weber et al. (2020) and are intended to support the analysis of the data collected during the three surveys using the field monitoring app. They are a set of indicator metrics to evaluate project effectiveness specific to project objectives articulated in the design process. They also list the monitoring surveys used to create the metrics, calculation of metrics, and interpretation of the metrics' relationship to the objective.

Table B1. Indicators of trench widening (Weber et al. 2020).

METRIC	SURVEY	EXPORT AS	CALCULATION AND INTERPRETATION
% STRUCTURES LATERALLY EROSIVE	Field	calc_LateralErosionPercentTotalStructures	% of total structures causing or that have caused lateral erosion of banks, disconnected floodplain and/or terrace surfaces, or valley walls leading to widening of the active channel or inset floodplain.
% STRUCTURES DEPOSITIONAL	Field	calc_DepositionalPercentTotalStructures	% of all structures that are net aggradational, indicating reduced stream power, increased channel elevation, and potential for inset floodplain development.
PRIMARY CHANNEL LENGTH	Field, Riverscape	calc_ChannelLengthPrimary, PrimaryChannelLength	Sum of primary channel unit lengths following the thalweg. Increasing channel length suggests a widening of the incision trench creating space for channel meanders and a more complex channel planform.
NON-PRIMARY CHANNEL LENGTH	Field, Riverscape	calc_ChannelLengthNonPrimary, NonPrimaryChannelLength	Sum of non-primary unit length measured along the thalweg. The occurrence or increase in non-primary channel length suggests formation of an inset floodplain and more complex channel planform.
ACTIVE CHANNEL AREA	Field, Riverscape	calc_ChannelAreaTotal ActiveChannelArea	In incised channels the area of the active channel is often a direct measure of channel confinement.
ACTIVE FLOODPLAIN AREA	Riverscape	ActiveFloodplainArea	Presence and increase of an inset active floodplain are indicative of widening incision trench.
RIPARIAN VEGETATION AREA	Riverscape	RiparianVegetationArea	The presence and extent of riparian vegetation is evident of inset floodplain development.

Table B2. Indicators of floodplain connectivity and expansion (Weber et al. 2020).

METRIC	SURVEY	EXPORT AS	CALCULATION AND INTERPRETATION
% STRUCTURES LATERAL DISPERSAL	Field	calc_LateralErosionPercentTotalStructures	% of total structures causing or that have caused lateral dispersal of flow onto active and/or disconnected floodplain or terrace surfaces indicating increased floodplain connectivity and expansion.
% STRUCTURES DEPOSITIONAL	Field	calc_DepositionalPercentTotalStructures	% of all structures that are net aggradational, indicating increased channel elevation, and potential for inset floodplain development.
PRIMARY CHANNEL LENGTH	Field	calc_ChannelLengthPrimary, PrimaryChannelLength	Increasing channel length through creation of a more complex planform is indicative of a wandering channel with a high degree of floodplain connectivity.
NON-PRIMARY CHANNEL LENGTH	Field, Riverscape	calc_ChannelLengthNonPrimary, NonPrimaryChannelLength	Sum of non-primary unit length measured along the thalweg. The occurrence or increase in non-primary channels throughout floodplain surfaces is indicative of a channel with a high degree of floodplain connectivity.
ACTIVE CHANNEL AREA	Field, Riverscape	calc_ActiveChannelArea ActiveChannelArea	Active channel area will increase as a product of increased primary and non-primary channel length.
ACTIVE FLOODPLAIN AREA	Riverscape	ActiveFloodplainArea	Floodplain area provides a direct measure of floodplain connectivity and expansion.
RIPARIAN VEGETATION AREA	Riverscape	RiparianVegetationArea	Increased floodplain inundation frequency and groundwater elevations contribute to expansion of riparian and wetland vegetation extent.

Table B3. Indicators of riparian vegetation abundance and extent (Weber et al. 2020).

METRIC	SURVEY	EXPORT AS	CALCULATION AND INTERPRETATION
ACTIVE FLOODPLAIN AREA	Riverscape	ActiveFloodplainArea	Increased active floodplain extent creates conditions and often provides the mechanism contributing to riparian vegetation establishment.
RIPARIAN VEGETATION AREA	Riverscape	RiparianVegetationArea	Increased floodplain inundation frequency and groundwater elevations contribute to expansion of riparian and wetland vegetation extent.

Table B4. Indicators of in-channel habitat quantity and quality (Weber et al. 2020).

METRIC	SURVEY	EXPORTED AS	CALCULATION AND INTERPRETATION
POOL FREQUENCY	Field	calc_DensityUnitsPools	Concave unit density (pools / km) based on the survey length measured along the center of the valley bottom. Increased pool frequency is indicative of a dynamic channel and offers critical cover and holding habitat for fish at all life-stages.
POOL DEPTH RANGE	Field	calc_DepthPoolsRange	Range (max. – min.) of depth measurements from cancave units. An increased range of pool depths suggests higher habitat complexity.
BAR FREQUENCY	Field	calc_DensityUnitsBars	Convex unit density (bars / km) based on the survey length measured along the center of the valley bottom. Increased occurrence of bars indicates a more dynamic channel and often provides substrate variation critical to adult spawning salmonids.
POND AREA	Field	calc_WettedAreaPonds	Sum of the wetted area of pond unit types. Pond habitat often creates thermal refugia, drought refugia, and slow-water rearing habitat for many aquatic species.
WOODY DEBRIS FREQUENCY	Field	calc_DensityJams	Woody debris accumulation density per. km scaled to the survey length measured along the center of the valley bottom. Increased woody debris provides cover and flow velocity refugia for many aquatic species.
WETTED CHANNEL AREA	Field	calc_WettedAreaTotal	Sum of unit wetted areas. Wetted channel area provides a measure of habitat quantity that will increase with pond formation, channel lengthening, and non-primary channel creation.

Table B5. Indicators of beaver habitat creation (Weber et al. 2020).

METRIC	SURVEY	EXPORTED AS	CALCULATION AND INTERPRETATION
% INTACT DAMS	Field	calc_DamIntegrityPercentIntact	Percent of dam structures surveyed marked "intact". Intact dams allow pond cover for beaver, increase likelihood of beaver colony establishment, or indicate beaver maintenance of existing dams.
% ARTIFICIAL DAM MAINTENANCE	Field	calc_BeaverMaintDamArtificialPercent	Percent of artificial dam structures being actively maintained by beaver. Beaver maintenance on artificial structures provides direct evidence of beaver occupation.
COUNT NATURAL DAMS	Field	calc_CountDamsNatural	The number of natural dams provides direct evidence of beaver colony establishment.
POND AREA	Field	calc_WettedAreaPonds	Sum of the wetted area of pond unit types. Greater pond area provides cover for beavers and increases the likelihood of beaver colony persistence.
AVERAGE POND DEPTH	Field	calc_DepthPondsMean	Average depth of pond unit types (only considers ponds with depths > 0). Deeper ponds provide cover for beavers and increases the likelihood of beaver colony persistence.
NON-PRIMARY CHANNEL LENGTH	Field, Riverscape	calc_ChannelLengthNonPrimary, NonPrimaryChannelLength	In larger systems non-primary channels often exhibit a lower stream power more suitable to natural dam establishment.
RIPARIAN VEGETATION AREA	Riverscape	RiparianVegetationArea	Expansion of woody riparian and wetland vegetation provides increased forage for beaver.