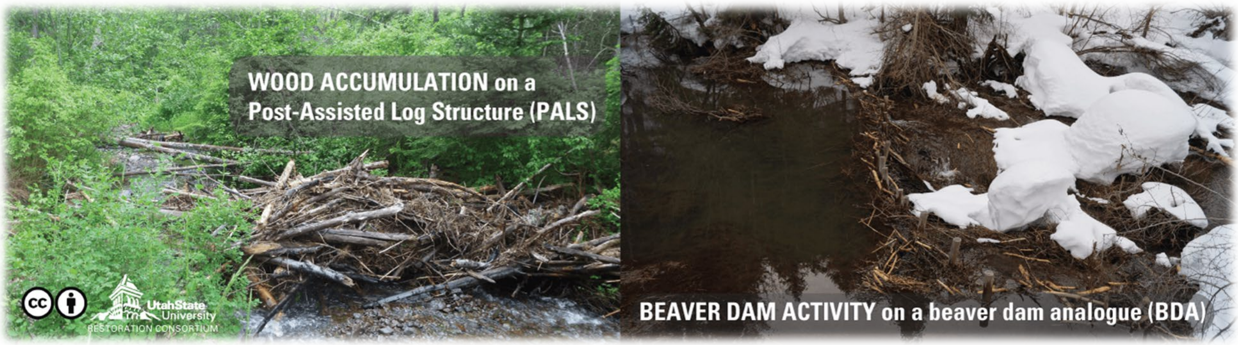
Chapter 4 – MIMICKING & PROMOTING WOOD ACCUMULATION & BEAVER DAM ACTIVITY WITH POST-ASSISTED LOG STRUCTURES & BEAVER DAM ANALOGUES



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IMPLICATIONS FOR PRACTICE

- Post-assisted log structures (PALS) and beaver dam analogues (BDAs) are hand-built structures. PALS mimic and promote the processes of wood accumulation; whereas BDAs mimic and promote beaver dam activity.
- PALS and BDAs are permeable, temporary structures, built using natural materials.
- BDAs differ from PALS in and that BDAs create ponds using a variety of fill materials; PALS are built with only woody material, which tends to be larger diameter than the woody material used for BDAs.
- PALS and BDAs are both intended to address the broad impairment of structural starvation in wadeable streams, but can also be used to mitigate against a range of more specific impairments.
- PALS and BDAs can be built using a variety of natural materials, and built to a range of different shapes, sizes and orientations.
- PALS and BDAs are most likely to achieve restoration goals when built in high numbers.
- Some PALS and BDAs are likely to breach and/or lose some wood, but when many structures are installed, that material will accumulate on downstream structures or in natural accumulation areas leading to more complexity.

INTRODUCTION

The systematic and widespread removal of large woody debris (LWD) and beaver has resulted in simplified and degraded riverscapes (Wohl, 2005; Wohl, 2013). Historically, large woody debris and beaver dams were ubiquitous throughout North American riverscapes (Naiman et al., 1988). Beaver dams exert a major influence on streams by influencing hydrologic and geomorphic processes and have been shown to elevate water tables (Westbrook et al., 2006), maintain channel-floodplain connectivity (Burchsted et al., 2010), increase riparian areas (Cooke and Zack, 2008), attenuate peak flows and elevate baseflow (Nyssen et al., 2011), and increase sediment retention (Butler and Malanson, 1995). Large woody debris has been shown to influence hydrologic and geomorphic processes in similar ways to beaver dams by creating fish habitat and spawning areas and promoting sediment and nutrient retention (Gurnell et al., 2002; Roni et al., 2015; Wohl, 2014). Importantly, many of the processes beaver dams and large woody debris influence are often directly related to stream restoration goals (Beechie and Bolton, 1999). The introduction of habitat structures has been practiced for at least a century (Thompson and Stull, 2002), with restoration focused on the creation of discrete habitat features, often pools for fish, rather than emphasizing how structures could enable and promote processes.

Figure 1 – The vision that guides the use of post-assisted log structures (PALS) and beaver dam analogues (BDAs) is 'Stage 0,' where large wood accumulation and beaver dams force the floodplain connectivity, multiple channels and complex physical instream and riparian habitat.

To address the scope of degraded streams (Chapter 1: Shahverdian et al., 2019a), cost-effective and scalable restoration methods are critical. The approach to restoration described throughout this manual, and the design of low-tech process-based restoration projects described in this chapter is informed by the vision of physically complex valley bottoms and multi-thread channels described as 'Stage 0' (Cluer and Thorne, 2014, Figure 1).

We describe the design process for two types of low-tech structures, post-assisted log structures (PALS) and beaver dam analogues (BDAs). PALS are woody material of various sizes pinned together with untreated wooden posts driven into the substrate to simulate natural wood accumulations. BDAs are channel-spanning, permeable structures, with a uniform crest elevation, constructed using woody debris and fill material, to form a pond and mimic natural beaver dams. We introduce the term complex to describe a group of low-tech restoration structures designed to achieve specific objectives. A complex may be composed of a single type of structure, or a mix of structure types. In general, complexes range in size between 2 – 15 structures. Complex design is described in Chapter 5 (Shahverdian et al., 2019b).

First, we discuss some of the key low-tech restoration principles that inform the use and application of PALS and BDAs; next we detail the form, function and design considerations for PALS and BDAs; then we describe how PALS and BDAs are likely to change through time, as well as trade-offs associated with each structure type. We conclude by outlining some of the common misconceptions and pitfalls that practitioners may encounter when employing the use of PALS and BDAs. This chapter does not address large-scale planning and assessment that is required in order to determine if low-tech restoration structures are an appropriate restoration technique (Chapter 3: Bennett et al., 2019b) or complex-level design (Chapter 5: Shahverdian et al., 2019b). A history of the recent development and use of PALS (Appendix B) and BDAs (Appendix C) can be found in the Appendix.

KEY PRINCIPLES FOR DESIGNING POST-ASSISTED LOG STRUCTURES AND BEAVER DAM ANALOGUES

While the use of instream restoration structures, often referred to as habitat structures, is not new, we contend that an explicit linking of the how structural additions are conceptualized within a process-based framework is lacking, and has led to their misapplication (see Chapter 1: Shahverdian et al., 2019a). Here we briefly review the key low-tech process-based restoration principles (Chapter 2: Wheaton et al., 2019) that inform the design of PALS and BDAs.

Strength in Numbers – Focus on the Treatment, Not the Structure

Low-tech restoration structures are intended to be implemented in high numbers (Figure 2). The importance of any individual structure is limited when understood in the context of an entire project. As such, the emphasis is not on any particular structure, but rather the total number of structures and density at which they are built. Maintaining a focus on the larger context helps practitioners reduce the time and resources spent designing individual structures. The design of individual structures is a rapid (3-5 minutes) process that does not require high resolution hydraulic, topographic or hydrologic data.

It's Okay to be Messy

The beaver dams and large woody debris that low-tech restoration structures emulate are diverse, characterized by a range of shapes and sizes. There is no 'ideal' restoration structure. At the scale of an entire restoration project, there should be a range of PALS and BDAs shapes and sizes. Different structures shapes, sizes and locations can be designed to promote specific outcomes at the structure scale. Building a diversity of structure types accommodates variability and uncertainty in stream flows and is more likely to encourage the recovery of degraded processes (e.g., erosion, deposition, overbank flow) that are crucial to meeting restoration goals. Different structures can be designed to affect different processes during different flow conditions (i.e., baseflow vs high flow). Low-tech restoration structures are designed in the field, most often built using locally available materials, and intended to have lifespans similar to the natural features they mimic, whether beaver dams or large woody debris.

DEFINITIONS

Post-Assisted Log Structures (PALS) – woody material of various sizes pinned together with untreated wooden posts driven into the substrate to mimic natural wood accumulations.

Beaver Dam Analogues (BDAs) – a permeable, channel-spanning structure with a constant crest elevation, constructed with a mixture of woody debris and fill material to form a pond and mimic a natural beaver dam.

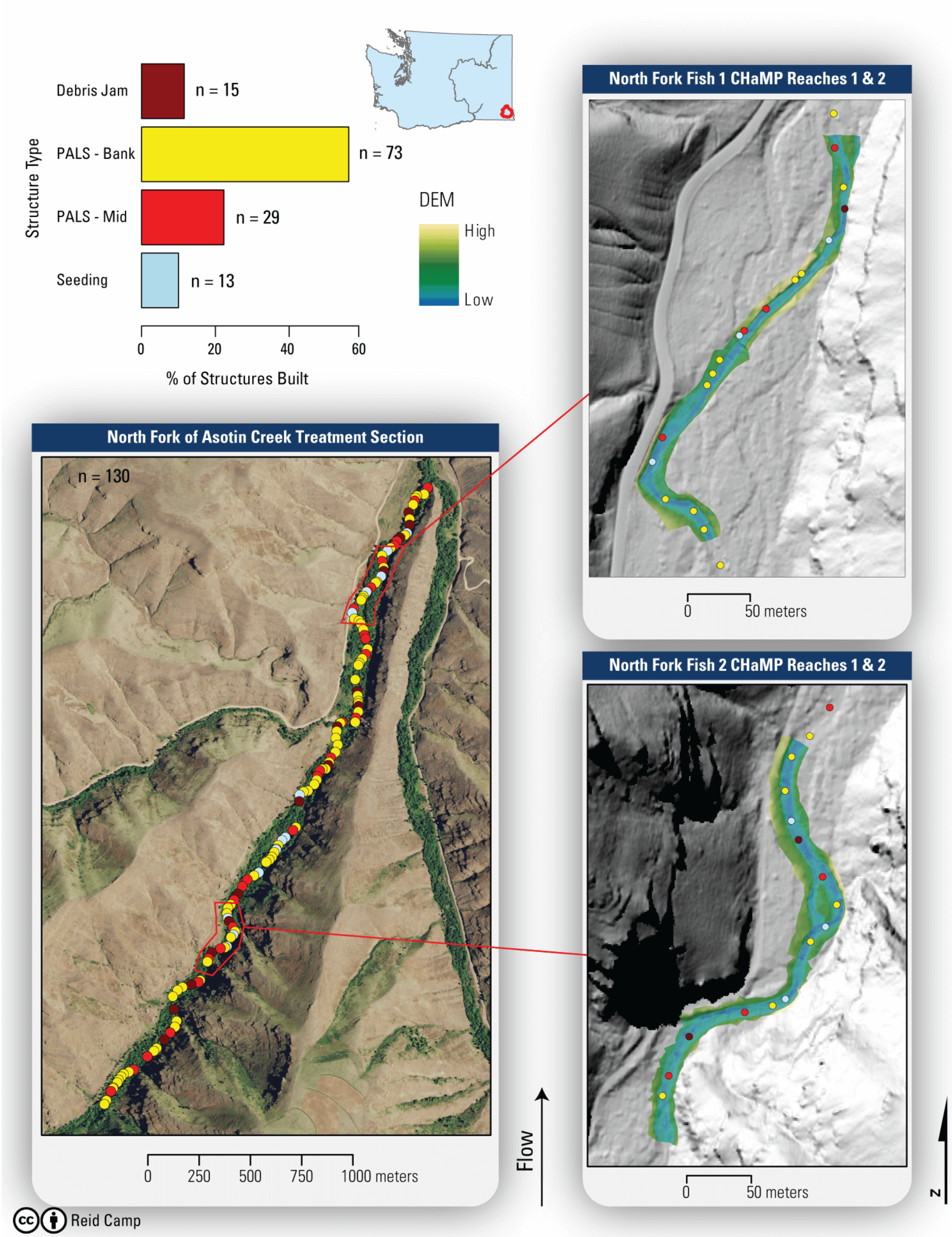


Figure 2 – An example of typical density of structure placement shown at the reach scale (upper and lower right) and at the riverscape scale in lower left. Not only are a high number of structures built, a diverse mix of structure types are used to achieve complex-level objectives (see Chapter 5 for design: Shahverdian et al., 2019b) Figure adapted from Camp (2015a).

POST-ASSISTED LOG STRUCTURES (PALS) & BEAVER DAM ANALOGUES (BDAS)

Post-assisted log structures (PALS) are a low-tech restoration structure that mimic and promote accumulation of large woody debris (LWD) and are designed to influence hydraulic, hydrologic and geomorphic processes (Figure 3). PALS are designed to influence hydraulics across a range of flows, and depending on the design, may force the creation of an upstream pond. While PALS influence hydraulics at all flows, they are most likely to force geomorphic change during high flows and as such require posts to provide temporary stability. PALS can be built in a range a shapes and sizes, best described by their location within the channel and desired function, but in general consist of larger diameter and longer length material than used in the construction of BDAs. PALS can be used to achieve a range of restoration outcomes including: creating high flow refugia for aquatic species; increasing channel-floodplain connectivity at high flows; increasing physical complexity by altering patterns of erosion and deposition; and promoting channel incision recovery by forcing channel widening and aggradation.

Figure 3 – A post-assisted log structure (PALS) so buried in wood accumulation and sediment, it is hard to recognize.

Beaver dam analogues (BDAs) are man-made structures that mimic the form and function of natural beaver dams. BDAs are temporary, permeable structures built with or without posts using a combination of locally available woody material sediment and fill material. The design and implementation of BDAs is a simple, non-destructive and cost-effective method to restore the processes that are responsible for physically complex channel and floodplain habitat. They can be used to support existing populations of beaver by increasing the stability of existing dams; create immediate deep-water habitat for beaver translocation (Figure 4); or they can be used to promote many of the same processes affected by natural beaver dams (e.g., increased channel-floodplain connectivity).

Figure 4 – An example of using beaver dam analogues to mimic the deep water cover provide by a natural beaver dam and provide a safe release site for a colony of four beaver (2 shown in A). The beaver are immediately comfortable and curious with the safety of water in their new suggested home. These beaver expanded this and another BDA complex within a few months of their release. From: Shahverdian and Wheaton (2017).

Below we first describe the form of the various low-tech structures to provide context and terminology necessary to discuss their function. Next, we describe the functions of PALS and BDAs.

Form: Structure Type, Dimensions, and Material

Types of PALS are differentiated by their position in or relative to the channel. We define PALS types as channel-spanning, bank-attached, mid-channel, and on the floodplain (Figure 5). Unsecured wood ("seeding") can also be added within groups of PALS to increase wood density but defer to the system where the wood will accumulate (Chapter 5: Shahverdian et al., 2019b). The size and height of the structure can vary depending on specific objectives. PALS are built to a height that is necessary to achieve a certain objective (e.g., create a scour pool or reconnect a floodplain- see next section). The orientation of structures (relative to flow) can be as varied as natural wood accumulations but generally channel-spanning and mid-channel PALS are built roughly perpendicular and bank-attached PALS are built angled upstream, perpendicular, or downstream. PALS are generally built with woody material that can be moved and placed by one to four people (i.e., shrubs, branches, logs, and/or trees 1-1.5 ft (30-45 cm) diameter and 10-16 ft (3-5 m) long). Generally, a wide range of sizes are used; large pieces are positioned first and pinned in place with medium and small pieces used to fill in gaps and make the structure less porous. This simulates natural racking of small material on a natural log jam.

Figure 5 - PALS can be built in a range of shapes, sizes and in different channel locations. (A) bank-attached, (B) mid-channel, (C) channel-spanning, (D) channel-spanning, (E) mid-channel, (F) channel-spanning, (G) bank-attached, and (H) channel-spanning.

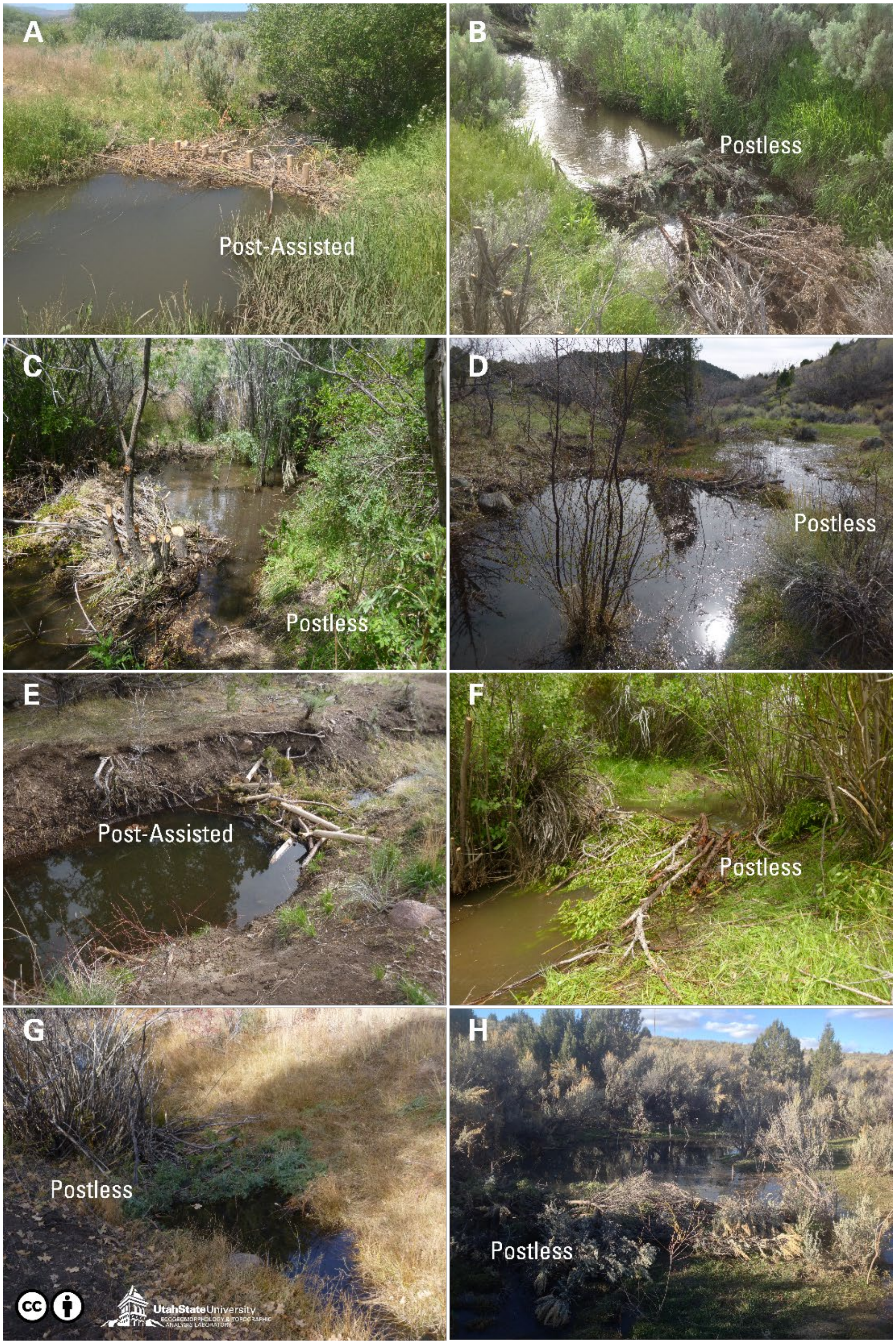


Figure 6 - Representative photos of the diversity of possible BDA shapes, sizes, locations, and building material. (A) post-assisted and willow weave (B) postless, sage and juniper (C) postless willow, using existing willow for stability (D) postless, juniper (E) post-assisted and juniper (F) postless willow and juniper (G) postless juniper (H) postless sage.

Like natural beaver dams, BDAs can be built in a range of environments and in a variety of shapes and sizes using a range of natural materials. We define primary BDAs as a relatively taller structure meant to mimic a beaver primary dam that is used to create a pond that supports and underwater entrance to their lodge and food cache (woody winter food storage). Often their crest elevation is equal to, or greater than bankfull elevation. They may be completely within the bankfull channel or extend onto the adjacent floodplain. Secondary dams mimic beaver dams that extend deeper water to other foraging locations or back up water to the base of a primary dam to reduce the hydraulic head created by the primary dam. They generally have a lower crest elevation, near or below bankfull. BDAs have a uniform crest elevation such that water flows equally over the entire crest rather than concentrating flow in a particular location. The crest planform may be straight or convex. BDAs may be constructed with or without untreated wooden posts driven into the streambed (Figure 6). They can be built from a range of woody material including riparian species such as willow and cottonwood, as well as upland species such as juniper and sagebrush. In all cases, BDAs incorporate locally sourced sediment ranging from silt and sand to coarse cobble, placed on the upstream face of the structure to protect the base of the structure from scour. Although rarely approaching a true beaver dam, this sediment reduces dam permeability and forces upstream pond formation. While the height and length of BDAs may vary according to location and objective, all BDAs share a common cross-sectional form that resembles a pyramid. Rather than a vertical wall, BDAs should have a broad base which promotes stability by reducing the potential for scour as water moves through and over the structure.

Function: How PALS and BDAs Influence Hydraulic, Hydrologic and Geomorphic Processes

Here, we distinguish the processes that are influenced by low-tech structures into three categories: hydraulic, hydrologic and geomorphic. Hydraulic refers to the changes in the depth and velocity of water, which ultimately drive both hydrologic and geomorphic responses. Hydrologic refers to changes in the timing and magnitude of the movement of water through the streams and ultimately watershed. Geomorphic refers to the characteristic topographic forms created from the changes in patterns of erosion and deposition that result from altering hydraulics. The manner in which structures influence hydraulic, hydrologic and geomorphic processes depend on their specific form and location. Here we describe how structures influence hydraulic, hydrologic and geomorphic processes in a general sense. For clarity, we address hydraulic, hydrologic, and geomorphic processes separately, however in practice the hydraulic response to low-tech structures forces both hydrologic and geomorphic responses (Figure 7 and Figure 8).

*Table 1 – Summary of typical hydraulic, hydrologic and geomorphic effects of post-assisted log structures (PALS) and beaver dam analogues (BDAs). *indicates that influence may be minor compared to other structure types.*

Type	Hydraulic	Hydrologic	Geomorphic
PALS Channel-spanning	create upstream backwater or pond, and 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
PALS Bank-attached	force convergent flow (deeper and faster), create eddy behind structure	force overbank flows*	bank erosion, scour pool formation, bar formation, sediment sorting, channel avulsion
PALS Mid-channel	force flow separation, create eddy in lee of structure	force overbank flows*	bank erosion, scour pool formation, bar formation, sediment sorting, channel avulsion
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

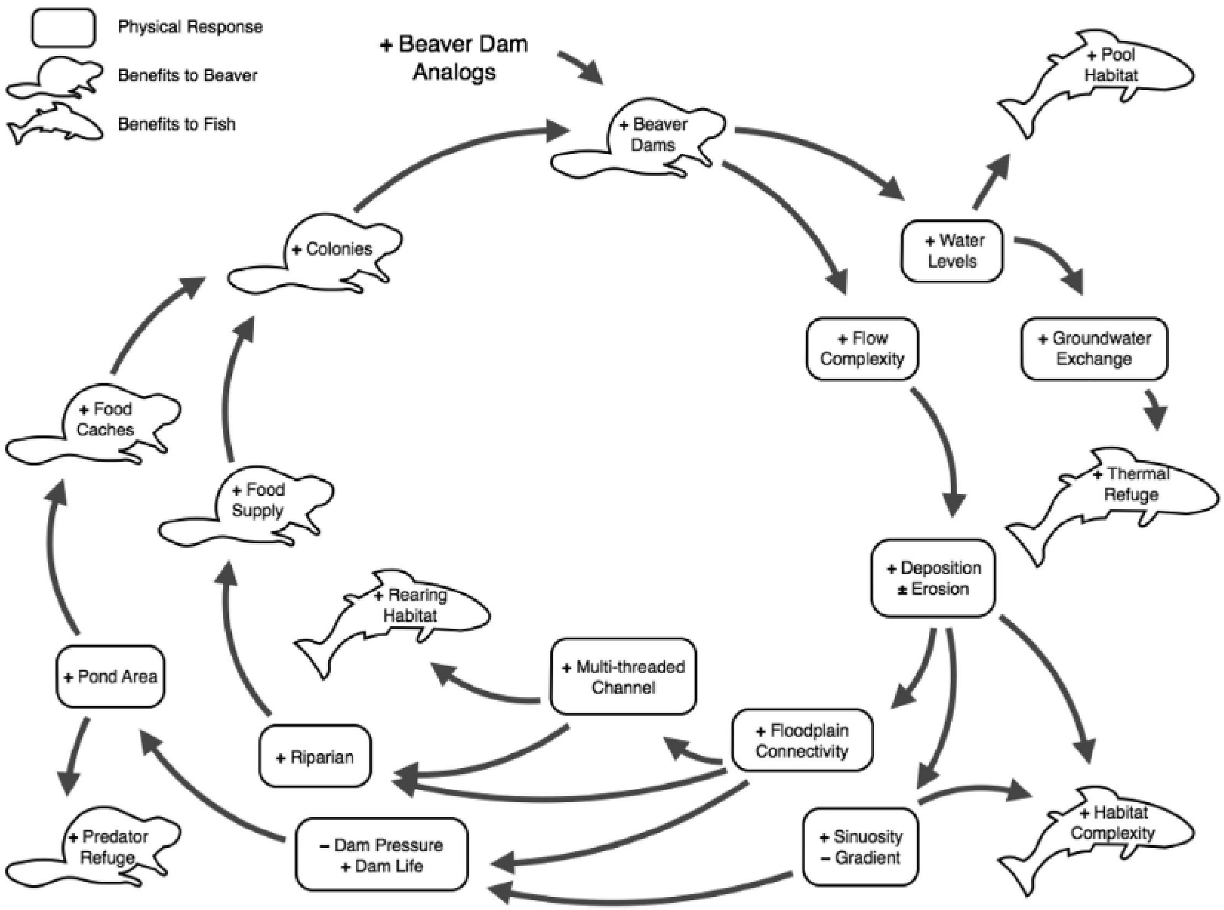


Figure 7 - From Bouwes et al. (2016b): Expected changes following the installation of beaver dam analogues (BDAs). Beaver-made dams and BDAs slow and increase the surface height of water upstream of the dam. Beaver ponds above, and plunge pools below dams change the plane bed channel to a reach of complex geomorphic units providing resting and efficient foraging opportunities for juveniles. Deep pools allow for temperature stratification and greater hydraulic pressures forcing downwellings to displace cooler groundwater to upwell downstream, increasing thermal heterogeneity and refugia. Dams and associated overflow channels produce highly variable hydraulic conditions resulting in a greater diversity of sorted sediment deposits. Gravel bars form near the tail of the pond and just downstream from the scour below the dam, increasing spawning habitat for spawners and concealment substrates for juveniles. Complex depositional and erosional patterns cause an increase in channel aggradation, widening, and sinuosity and a decrease in overall gradient, also increasing habitat complexity. Frequent inundation of inset floodplains creates side channels, high-flow refugia and rearing habitat for young juveniles, and increase recruitment of riparian vegetation. Flows onto the floodplain during high discharge dissipates stream power, and reduces the likelihood of dam failure. The increase in pond complexes and riparian vegetation increases refugia for beaver and their food supply and caching locations, resulting in higher survival and more persistent beaver colonies. Beaver will maintain dams and the associated geomorphic and hydraulic processes that create complex fish habitat.

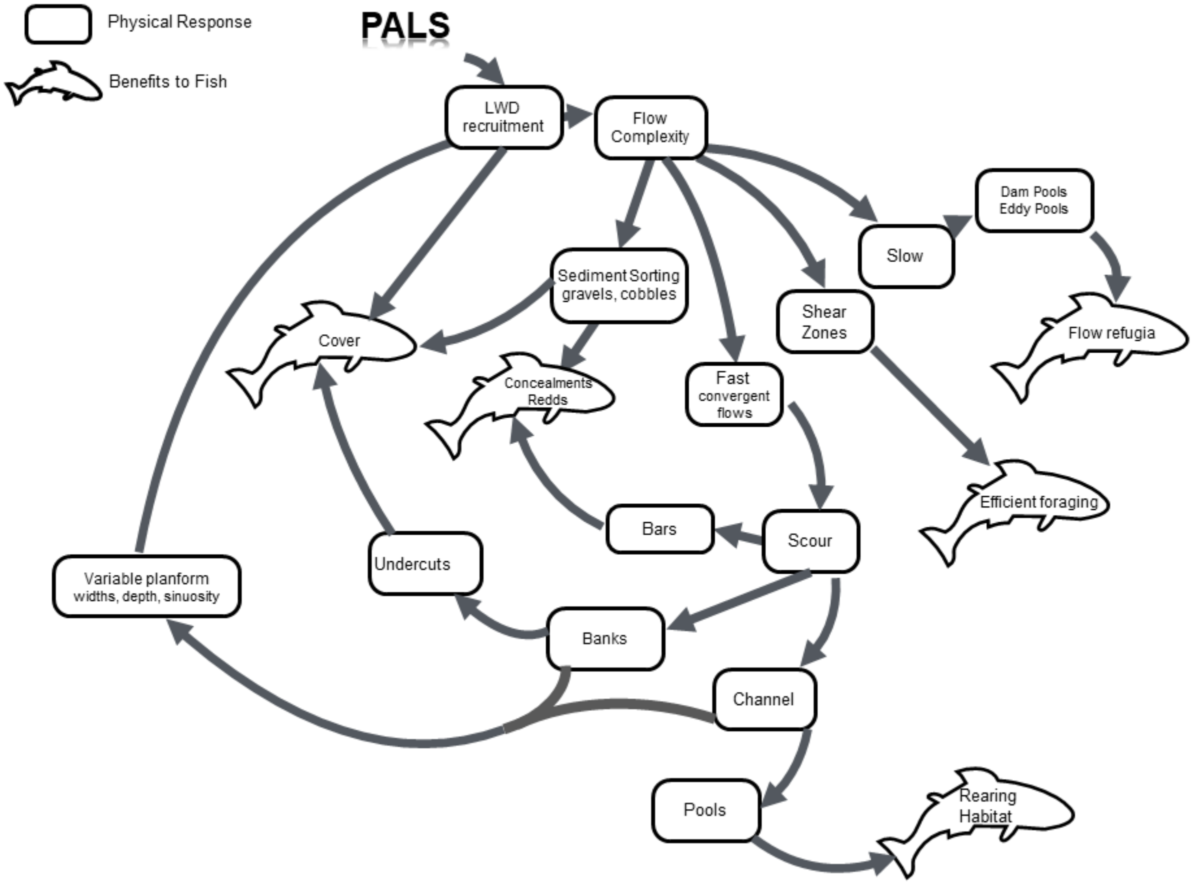


Figure 8 - Conceptual model used in the Asotin Intensively Monitored Watershed (IMW) study of the expected geomorphic and steelhead responses of adding post-assisted log structures (PALS). The increase wood loading by adding PALS is expected to increase flow complexity, creating: deposit and erosion of different substrates sizes; areas of slow water above and behind structures provide resting areas; fast water where convergent jets can scour bottom substrate creating pools or undercut banks; and shear zones at the interface between fast and slow water that is energetically efficient for juvenile steelhead foraging. The deposition of gravels from scour or changes in water velocity provides areas where juveniles can hide and adults can build redds. Wood and undercut banks also provide steelhead cover from predators. The increase in geomorphic complexity including changes in the number and diversity of geomorphic units, channel sinuosity, overbank flows, variables widths is expected to move the stream from a degraded stable state that was locked in by dense young riparian vegetation, to a dynamic stable state (Stage 0) that is capable of recruiting more wood and maintain more complex fish habitat.

Hydraulic

PALS and BDAs influence hydraulics in diverse ways and during multiple flow conditions. Changes in depth and velocity are the foundation for changes in hydrologic and geomorphic changes. The primary hydraulic impact of BDAs is to create slow-moving, deep water upstream of the structure. Although seemingly simple, the complex topography this creates (Bouwes et al., 2016b) (Figure 9), including the formation of gravel bars, is easily observed following the breaching of a BDA or beaver dam. In a plane bed channel previously dominated by large cobble, pond deposits behind the BDA are sorted from larger to smaller as water approaching the dam face slows diminishing the capacity to suspend larger sediment sizes. This deposition also leads to channel aggradation. Along homogenized and simplified streams, deep-water habitat (e.g., pools) is often limited. BDAs force dam pools that provide flow and temperature refugia for fish (Bouwes et al., 2016b). Furthermore, by immediately creating deep water, BDAs can create an important habitat feature for successful beaver translocation (McKinstry and Anderson, 2002).

PALS create more variable flow patterns and force areas of high and low velocity and shallow and deep water (Camp, 2015a). Channel-spanning PALS can force deeper, slower velocity water upstream of the structure and increase velocity as water flows over the top of the structure. Channel-spanning PALS can rack up material that reduces their permeability and can provide a similar function as a BDA. Mid-channel PALS force flow to split into two separate flow paths, and often create eddies in the lee of the structure (Figure 10). Water split around a mid-channel structure is often faster and shallower initially, but may force scour pools on either side of the structure or channel widening. Bank-attached PALS shunt flow to the opposite side of the stream from the bank it is attached to causing water to converge, increase in velocity and depth. As flow moves past a bank-attached structure, flow diverges and forms eddies, where low is slower and often shallower. The force of these hydraulic responses will be influenced by the size, shape, degree of channel constriction, and orientation of the PALS (i.e., form). Diverse hydraulics provide important habitat characteristics (e.g., energy refugia, predation refugia, prey delivery, oxygen delivery) for fish and other aquatic species that enable them to satisfy their specific life-stage needs.

In general, as flows become constricted, the energy dissipated on the stream bed or bank becomes higher per unit area (i.e., increase in unit stream power), increasing the ability of the water to scour. These constricted flows, such as what can be accomplished with a bank-attached PALS, can be further accentuated by forcing flows to a hard surface such as boulder, making the constriction smaller. Taller, less porous structures create a greater hydraulic head. This potential energy can be focused through a constriction or alternatively, this energy can be dissipated over a structure to prevent scouring, such as in a channel-spanning PALS or BDA. Structures also increase stream roughness, slowing water, and promoting bar development.

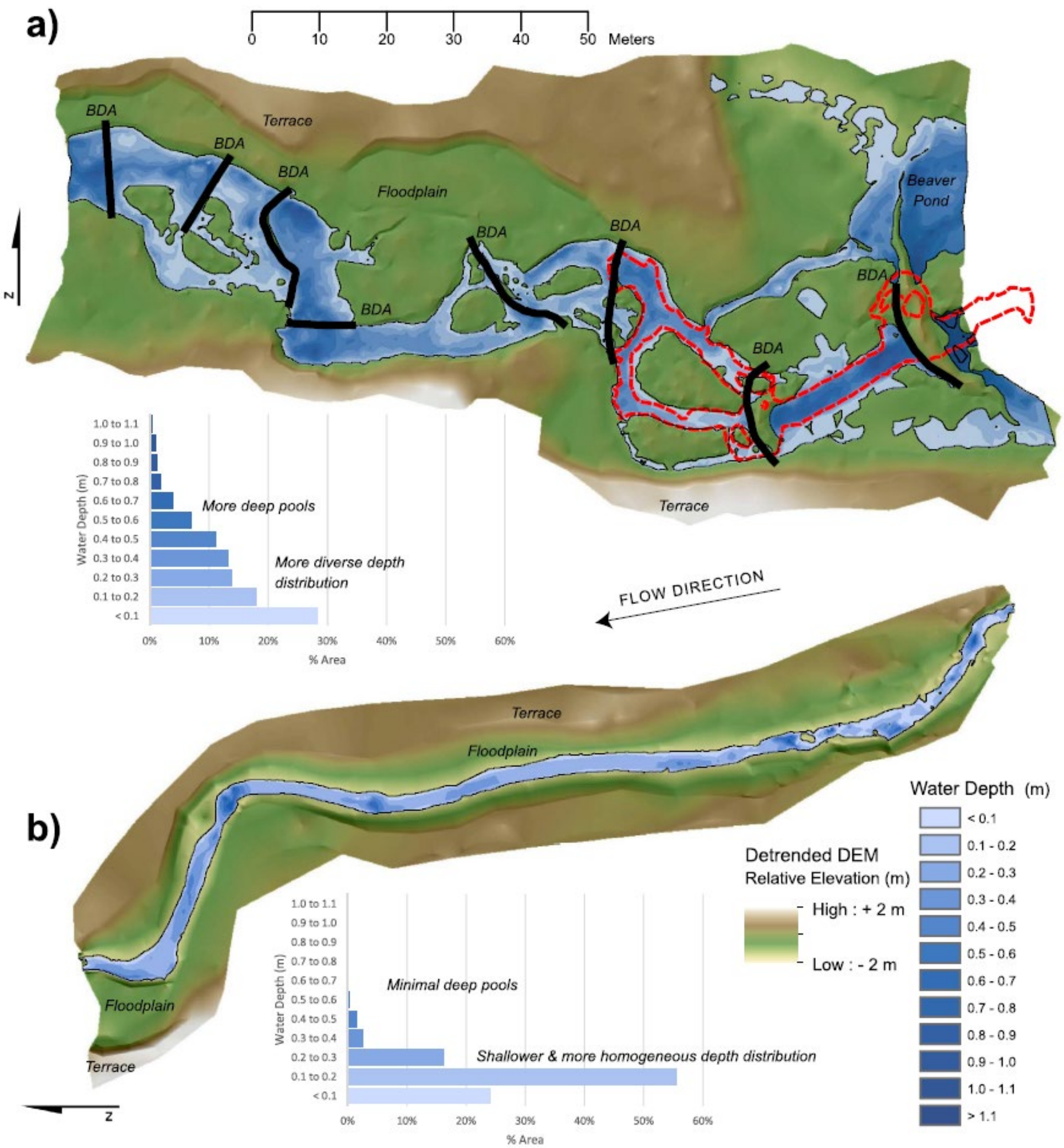


Figure 9 - Digital elevation models (DEMs) and water depth distributions for a A) typical reach with beaver dam analogues (BDAs) (i.e., successfully mimicking and promoting beaver dam activity) and B) without BDAs (i.e., structurally-starved control) from Bouwes et al. (2016b). Treatment area with BDAs has more channels and greater water depth variability than the control area without BDAs. Note: the red dashed line delineates the extent of a temperature experiment.

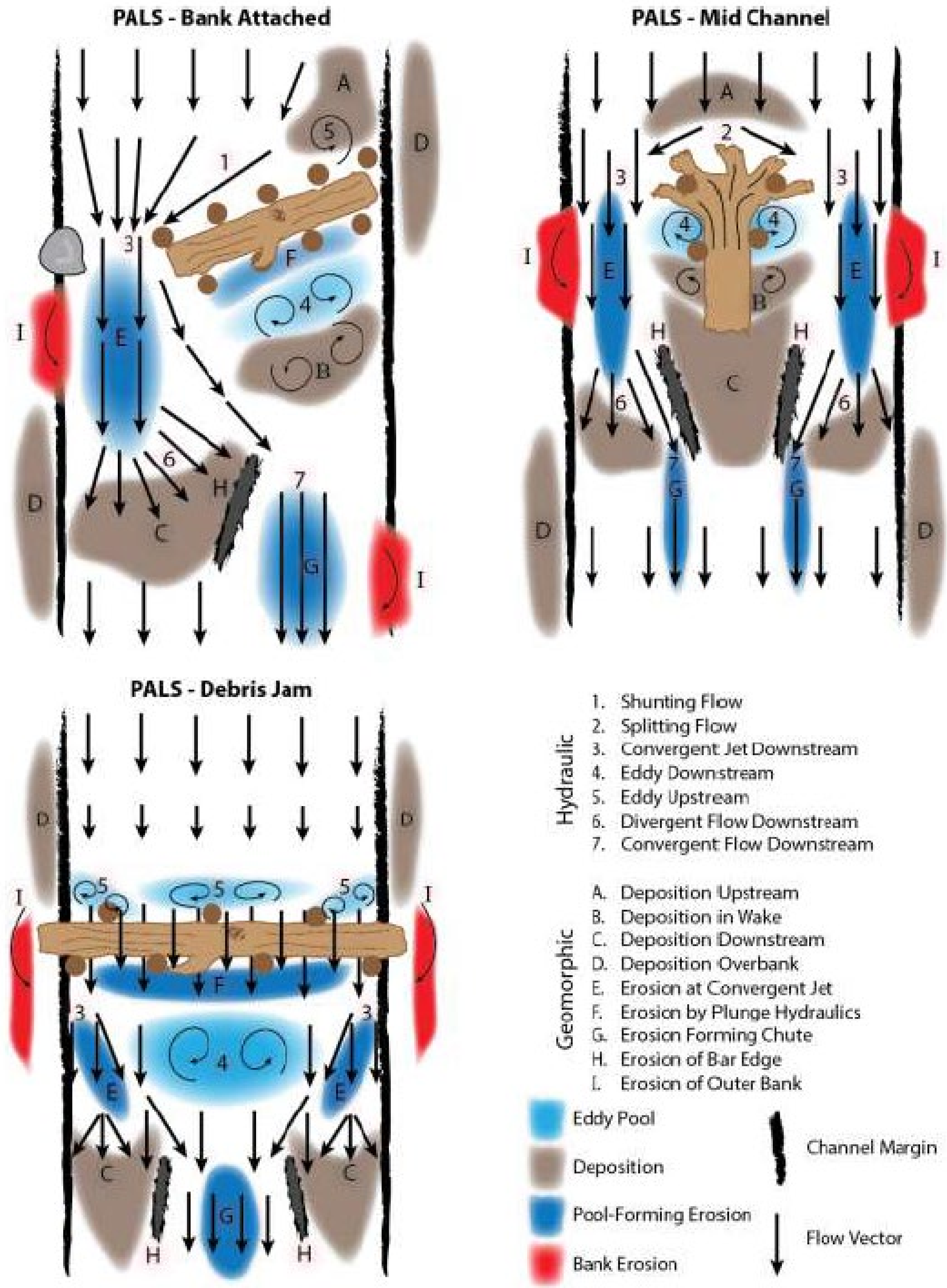


Figure 10 - Hypothesized hydraulic and geomorphic responses associated with bank-attached, mid-channel, and debris jam post-assisted log structures (PALS) from Figure 3.5 from Camp (2015a). Note: what is labeled as 'debris-jam' is referred to in this chapter as 'channel-spanning'.

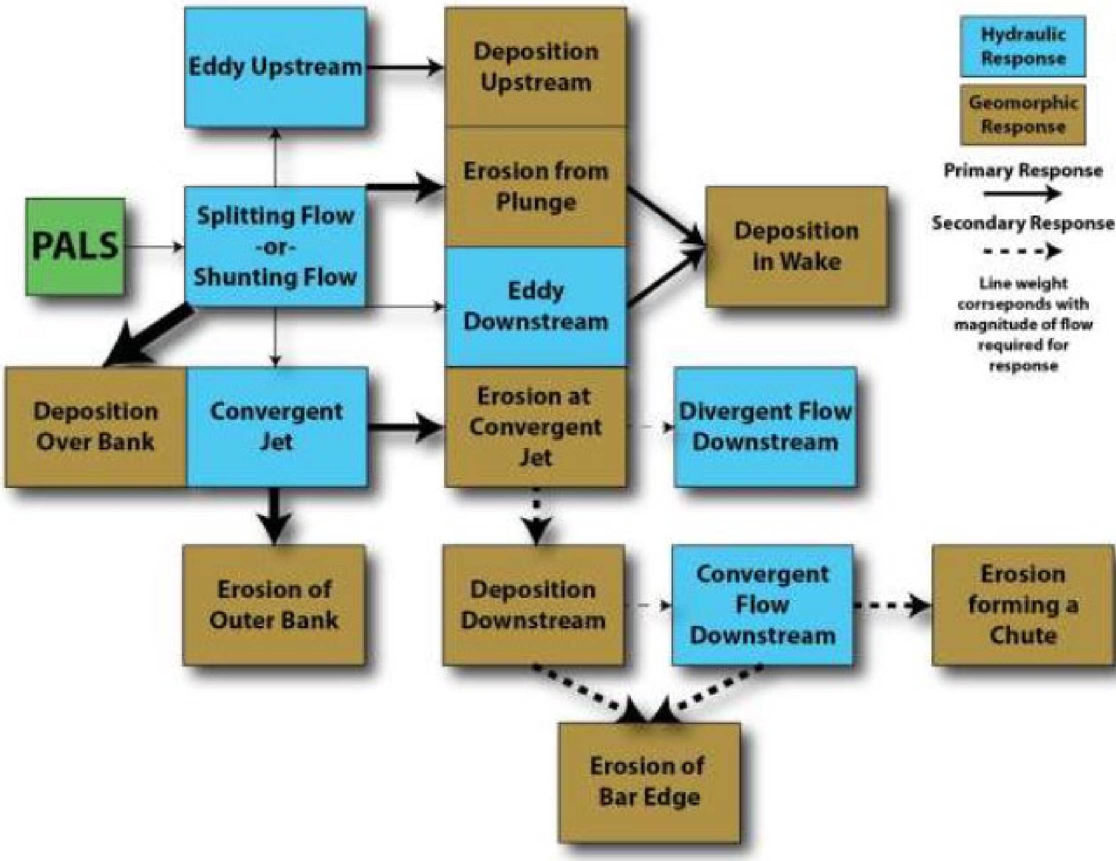


Figure 11 - Observed hydraulic and geomorphic responses associated with deflector and mid-channel PALS relative to the magnitude of flows from Camp (2015a). Deflectors (bank-attached) PALs shunt flow, and mid-channel PALS split flow (channel-spanning PALS not depicted). The thickness of the arrows (responses) signifies the magnitude of flow required to initiate observed responses (thin – low flow; medium – typical flood; thick – large flood) based off of empirical findings of their prevalence.

Hydrologic

BDAs alter the timing and magnitude of water delivery by forcing temporary storage in ponds and groundwater. BDAs can increase channel-floodplain (i.e., lateral) connectivity by influencing the frequency, duration, and extent of overbank flows. BDAs may increase overbank flows both by channel aggradation and increased instream roughness raising surface flows (Figure 12). BDAs can also be strategically placed to activate side channels or high flow channels (i.e., diversifying residence time of water). Depending on local geomorphic setting and BDA design, BDAs can produce channel-floodplain connectivity and overbank flows during baseflow conditions or during high flow conditions. Increased overbank flow can recharge ground water and raise the water table, providing the water resources necessary to promote riparian expansion; attenuate peak flows and increase baseflow. Water recharge and an increase in the hydraulic head of surfaces waters, may also force water through hyporheic pathways that can produce cool zones of upwelling that provide temperature refugia (Weber et al., 2017).

PALS influence stream hydrology by increasing instream roughness, which promotes channel-floodplain connectivity. Like BDAs, PALS can be used to divert flows into side-channels or high-flow channels. By increasing water depth or diverting flows into stream banks, PALS may also force increased hyporheic flow and exchange and produce areas of upwelling downstream by slowing water and increasing water depth (i.e., surface water and groundwater exchange). The hydrologic impact of PALS are most likely more pronounced during high flow conditions (i.e., flow attenuation (see Riverscapes Principle 4 – "inefficient conveyance of water is often healthy" in Chapter 2: Wheaton et al., 2019));

however, channel-spanning PALS that have sufficiently racked up material to decrease porosity similar to a BDA may be able to force overbank flows even at low discharges.

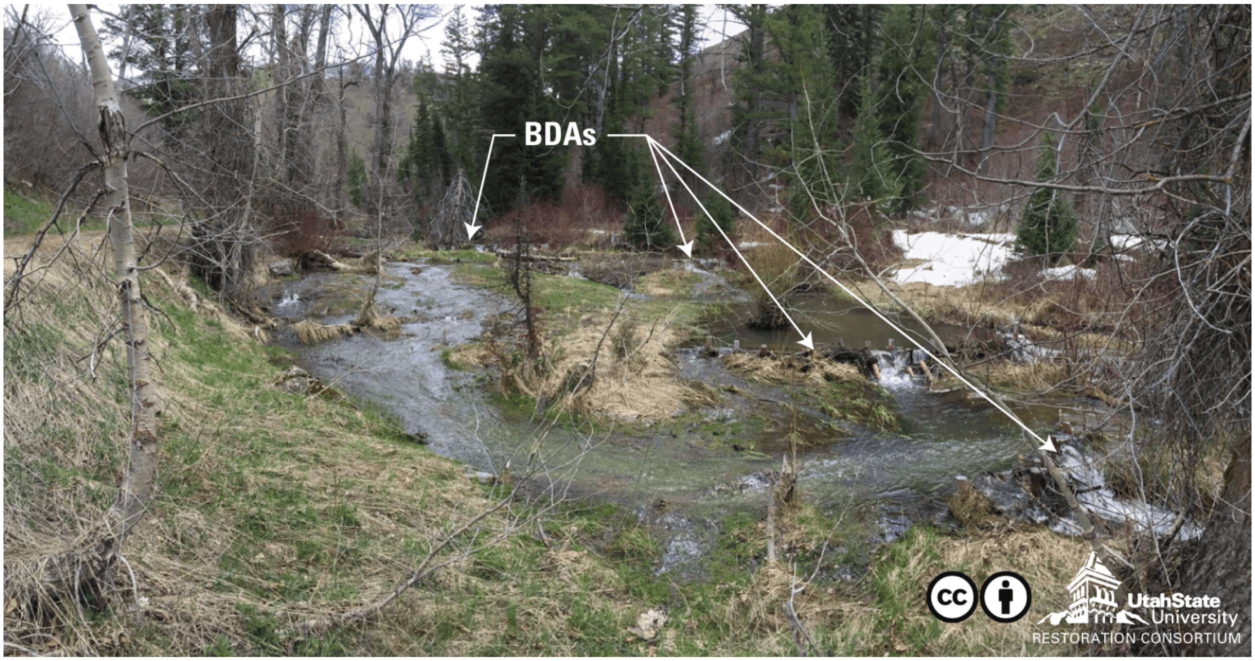


Figure 12 – Complex of four BDAs forcing overbank flows and inundation of the floodplain where the project goal was to restore the stream to perennial flows. The same magnitude flows (spring-runoff here) prior to installation of these BDAs had no overbank flow.

Geomorphic

By altering local hydraulics, PALS alter patterns of erosion and deposition (Figure 10 and Figure 11). These patterns of erosion and deposition create a greater diversity of geomorphic units. Depending on the specific location and structure type, PALS can force: bank erosion, channel widening, lateral migration, channel avulsions, scour pools, plunge pools, bar creation, sediment sorting, and channel aggradation. Some processes, such as channel avulsions and bank erosion are essential processes for the ongoing recruitment of natural large woody debris necessary to sustain physical complexity.

BDAs can lead to increased sediment retention, channel aggradation, and sediment sorting. Increased sediment retention, especially of fine sediment, can increase water quality. Deposition of sediment behind the dams can cause channel aggradation leading to increased channel-floodplain connectivity and accelerated channel incision recovery. BDAs that breach can also lead to geomorphic changes such as increase in channel width and sinuosity (Pollock et al 2014; Figure 13). Additionally, BDAs can not only quickly connect relic channels, but also create new channels. BDAs can force additional pathways onto a floodplain surface that can eventually result in the formation of another channel when return flows head-cut back to the structure. If BDAs are occupied by beavers, these geomorphic processes are likely accentuated, but, additionally, beavers mechanically create their own channels and tunnels that can lead to further side channel formation.

The geomorphic complexity that is added by the addition of structures is critically important in improving habitat quality for flora and fauna. Perhaps equally important is the increase quantity of aquatic and mesic habitat that structure creates by increasing surface and subsurface water area (Bouwes et al., 2016b).

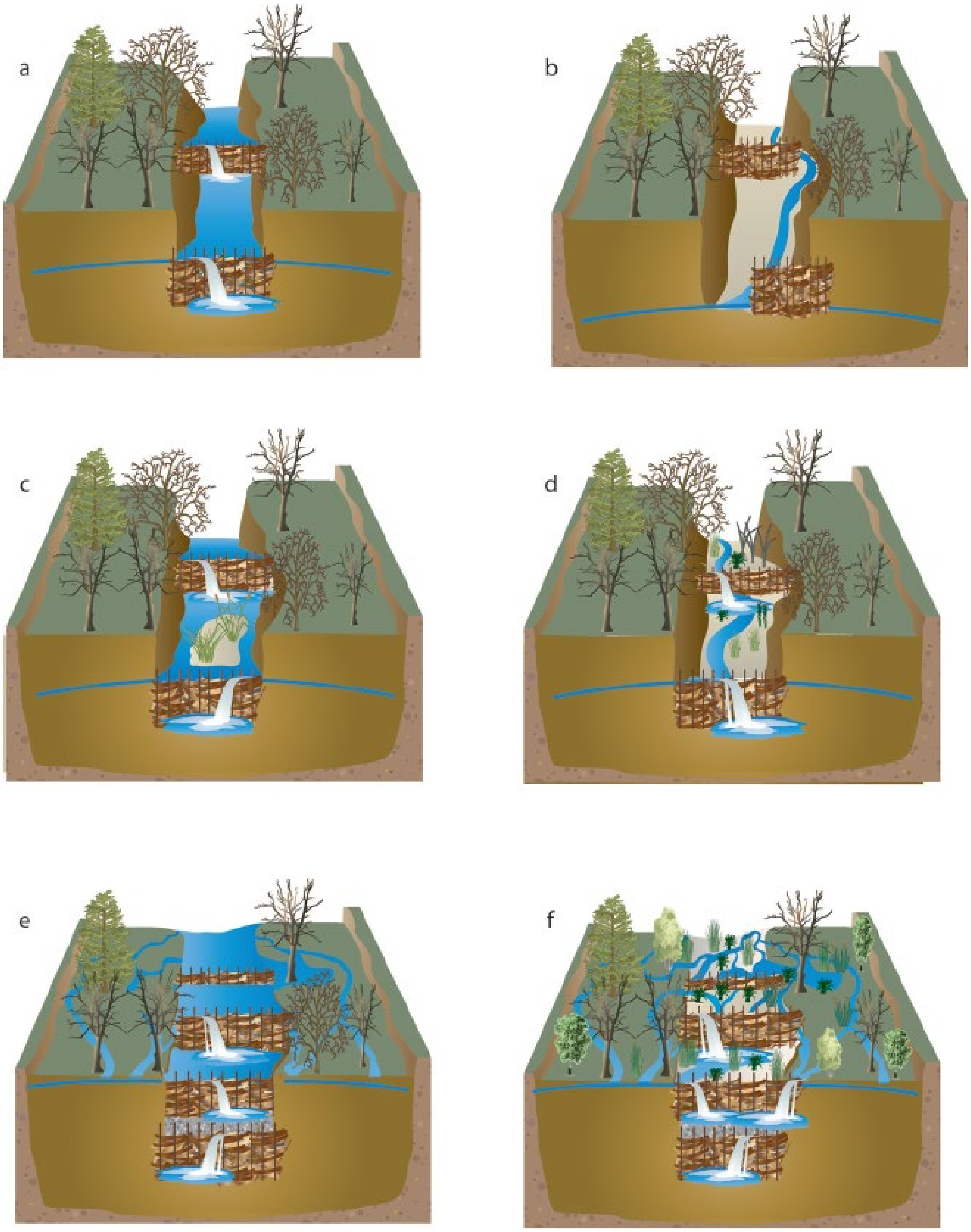


Figure 13 – Expected geomorphic responses following the Cluer and Thorne (2013) channel evolution model (from Stage 3 to 0) after the installation (a) of BDAs, their initial 'failure' by end-cutting (b), subsequent repair (c) and aggradation leading to floodplain reconnection in an incised system. Figure from Pollock et al. (2014). In practice, PALS can force the same processes of channel-widening and aggradation as BDAs.

Structure Location

Unlike traditional restoration, which is often characterized by a limited number of instream structures, or stream miles treated, low-tech restoration structures can, and should, be implemented over the maximum possible spatial extent (Chapter 1: Shahverdian et al., 2019a). This means working across a range of geomorphic settings and flow regimes, including incised channels, channels with extensive floodplain, and channels at various stages in their channel evolution (Cluer and Thorne, 2014). The location of a structure constrains what processes it can promote and therefore the structure type that will be most effective (Figure 14). Below, we discuss how the structure setting can influence their performance as well as outline the variables practitioners need to consider when designing an individual structure.

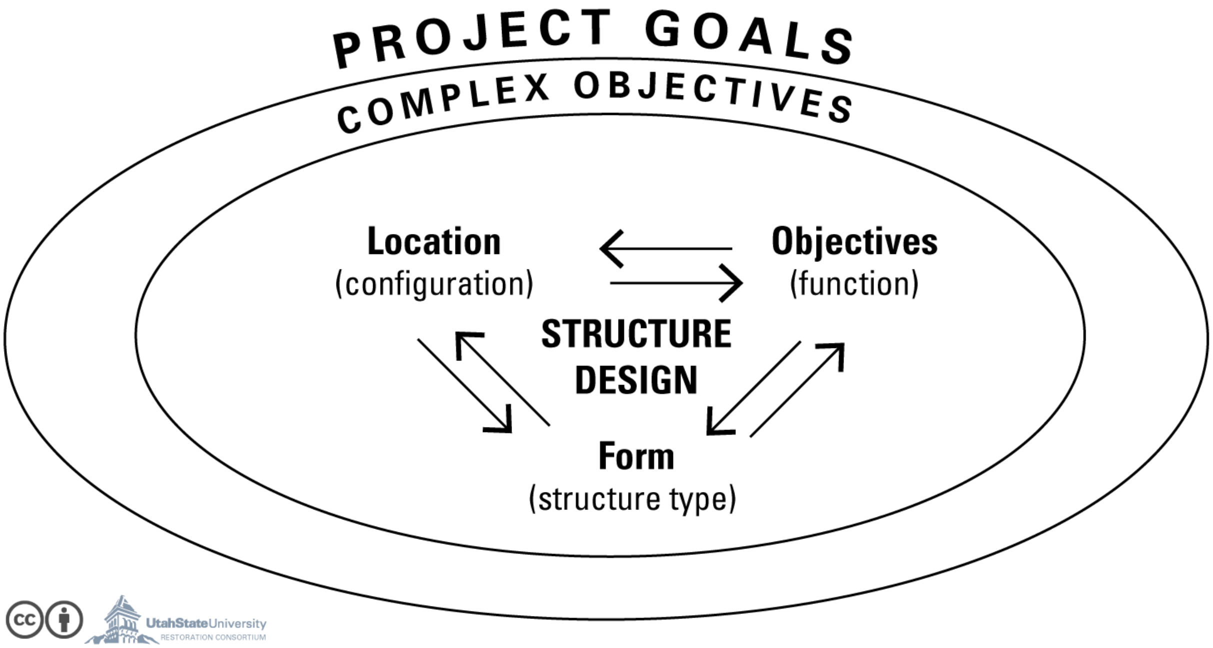


Figure 14 - Structure design is informed by relative location, (i.e., structure configuration within a complex), structure objectives (the function) and form (structure type, size, shape).

The natural variability between riverscapes as well as within riverscapes suggests that there are innumerable forms that PALS and BDAs can take. In other words, no single structure is 'right', and the entire treatment (number of structures, or miles treated) is more important than individual structures. However, project managers should consider multiple factors when designing an individual structure. Recognizing and working with these attributes will increase the ability of structures to promote the "system to do the work." Below we discuss some general attributes to consider when designing low-tech structures.

Table 2 - General flow, geomorphic, and vegetation attributes to consider when designing PALS and BDAs.

Characteristic	Importance
Flow	
Existing flow patterns	Enhancing natural flow convergences and divergences using existing geomorphic features such as bars and meander bends is more cost-effective than working against such patterns
Stream power	Stream power (a product of discharge and slope) is a useful metric that represents how much power a stream has to do geomorphic work. Higher slopes and higher discharge will be able to do greater geomorphic work, but also put more physical pressure on the structure
Geomorphic	
Channel width	Wider channels will require more material to build geomorphically effective structures, but are often natural areas of deposition
Bank susceptibility to erosion	Highly resistant banks, whether because of vegetation or lithology, are less likely to erode and provide a source of material or promote increased sinuosity. Structures that force convergent flow against highly resistant banks are more likely to force scour of the channel bed
Channel bed substrate	Sand bedded streams and rivers have more highly mobile and erodible channel beds, making the PALS and BDAs more vulnerable to scour
Bank material	Locate structures adjacent to banks with specific grain sizes (e.g., gravel to support spawning habitat) if composition of bars (downstream) is important to initiate different geomorphic processes (e.g., aggradation)
Bank height	If sediment recruitment is a goal to promote channel aggradation, taller banks will provide more sediment per unit length eroded than shorter banks.
Vegetation	
Presence/absence and type	Vegetation may increase resistance to bank erosion and channel widening, but it may also be an important target when recruiting large woody debris into the system. Directing flow at well-vegetated banks may help create undercut banks and provide good fish cover

Flow Regime

The flow regime within the project area is important information generally obtained during the planning phase that helps inform the design of individual structures. The flow regime is useful when estimating the forces that will be exerted on any given structure to provide some guidance on how stable a structure needs to be. Additionally, estimating the bankfull height (1-2 year recurrence interval flood) will help determine how tall a structure needs to be to meet some structure objectives (e.g., floodplain access). A cursory survey of the project area can reveal the effects of previous floods – key in on those indicators and use PALS to replicate the results.

Local Sediment Sources

PALS tend to induce more geomorphic change when there is a local sediment source upstream. Whether it is in the form of a bar, erodible bank, sediment slug, or caused by erosion from upstream structures, PALS cannot accumulate and sort sediment if it is not being delivered.

Channel Geometry, Planform, Slope

Because the width, depth, and slope of a channel will influence the forces exerted on the structure, consider the materials and time required to construct a structure, and also what objectives are realistic. In general, structures built in a high gradient narrow channel with high banks (e.g., incised channels) will experience greater force than those built in wider channels with low banks. The forces exerted on a structure also depends on the height and amount the structure constricts or spans the channel, regardless of the channel geometry.

These considerations are also important for considering spacing of structures. If BDAs or channel-spanning PALS are used to pond water, the height of the structure and the channel slope will determine where an upstream BDA becomes redundant. In higher gradient channels BDAs will need to have higher crest elevations to create larger ponds.

The sinuosity and number of channel threads are important considerations when planning locations for structures. Straight, single-thread channels require less consideration for structure placement because the imposed forces are relatively homogenous. The forces (e.g., shear stress) in a sinuous area are more variable. For example, the amount of force will be higher on the outside of a meander bend than the inside. Use this distribution of forces to your advantage when placing a structure to increase their effectiveness and stability. For example, PALS can be placed at the head of side channel junctions to encourage flow path separation, or small PALS can be quickly built to improve side channel habitats.

Channel-Floodplain Connectivity

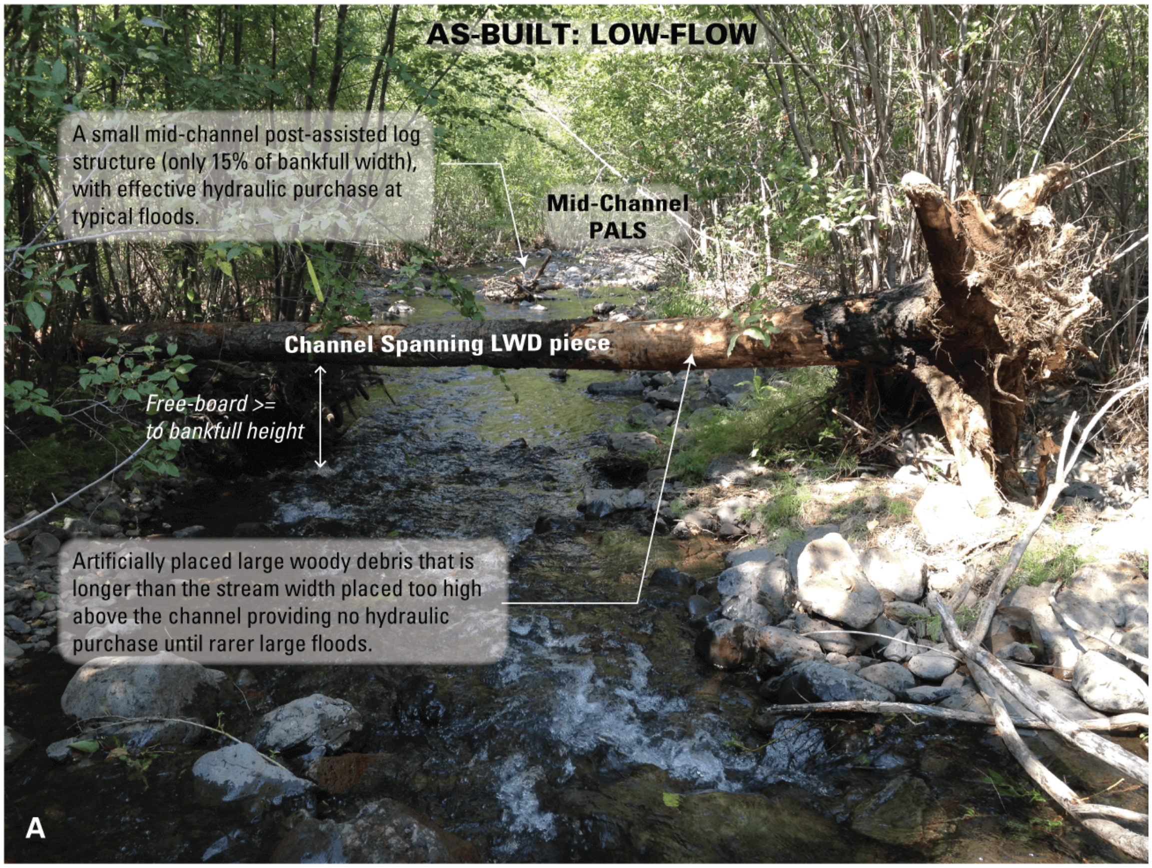
The degree of channel-floodplain connectivity influences the force exerted on a structure at high flows. Where channel-floodplain connectivity is high (i.e., minimal elevation distance between the channel and floodplain) and flows reach or exceed the bankfull elevation frequently, high flows will disperse across the floodplain, increasing flow width and decreasing the force on any given structure. Where channel-floodplain connectivity is limited, and flows are incapable of dispersing, high flows will exert their full force on the structure, increasing the probability of a breach, blowout, or movement downstream. Because restoring channel-floodplain connectivity is a common restoration goal, locating opportunities (e.g., low bank, relic channels) where structures may increase connectivity to promote groundwater recharge, off-channel habitat creation, or riparian expansion is often a major consideration.

Some of the factors listed above are consistent at the scale of entire projects (e.g., flow regime) while others may vary over short length scales (e.g., channel geometry). Some of these factors can be evaluated remotely, while others require field visits.

Structure Design

The design of individual PALS and BDAs depends on the site-specific conditions outlined in the previous section. Based on those considerations there are a number of structure attributes practitioners must decide upon, including: structure type, height, width (both laterally and longitudinally), orientation to flow, percent constriction (PALS only), and whether to use posts for additional stability (Table 3). A specific consideration when building PALS is the hydraulic purchase of the structure (Figure 15). Hydraulic purchase refers to the different flow stages at which a PALS will be able to influence flow (BDAs influence flow at all stages). What geomorphic changes PALS are able affect depends on what flows they are capable of interacting with.

ILLUSTRATIONS OF HYDRAULIC PURCHASE AT DIFFERENT STAGES



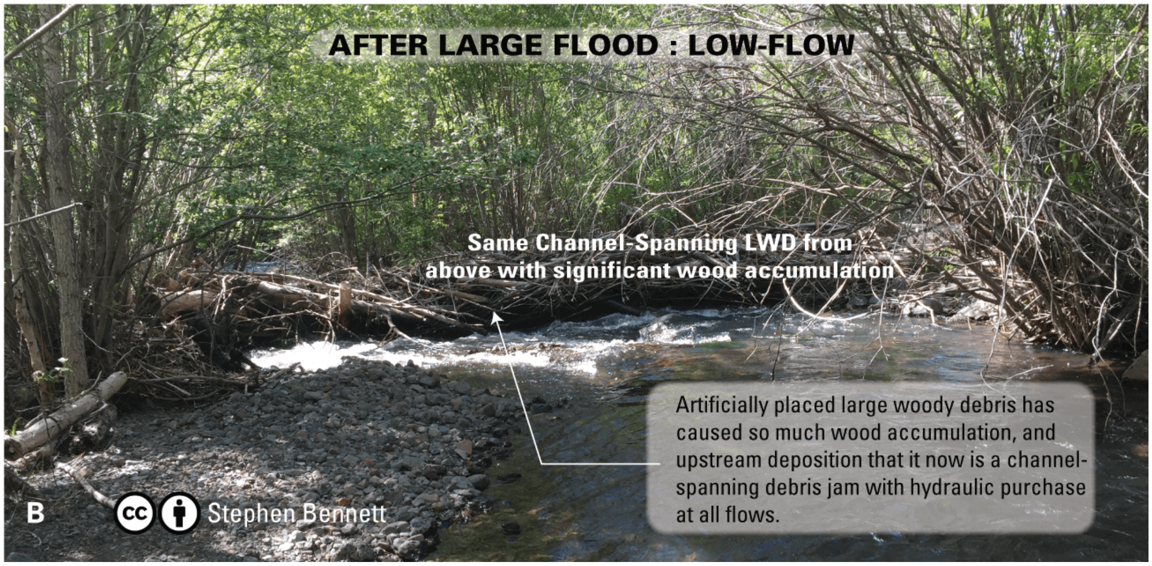


Figure 15 – A key placement consideration is defining at what flow stage the structure will engage with hydraulics or obstruct flows (i.e., hydraulic purchase). At the design stage, there is a choice about whether to build for immediate (i.e., low-flow) hydraulic purchase (e.g., mid-channel PALS in background of A), or only to activate at typical floods or rarer floods (e.g., channel-spanning piece in A). Wood that is long enough that it spans past the entire width of the channel, will only be engaged in overbank flows. Here, there was no wood accumulation for three years through typical floods, but a larger rare flood eventually came through and impressive responses associated with wood accumulation resulted.

Table 3- Design decisions for individual PALS and BDAs.

Design Decisions	Description
Location/type	The location of PALS and BDAs constrains the influence they are able to have
Percent constriction (PALS only)	The percent of the channel constricted by a PALS influences its ability to force convergent flow and do geomorphic work
Size	The height, width, and thickness of any given structure determines how much of the flow it is able to influence, shunt or back up water, as well as its stability
Orientation	How a structure is oriented with respect to the flow will influence hydraulic and geomorphic response
Posts	The number of posts used is an important logistical consideration that influences the time and resources required to build a particular structure. It also influences the overall stability of the structure

PALS and BDA Complexes

All low-tech restoration structures should be designed as part of a larger-scale project. While individual structures (PALS and BDAs) may have local influence, they are unlikely to achieve restoration goals unless they are part of a more widespread effort (Chapter 1: Shahverdian et al., 2019a; and Chapter 2: Wheaton et al., 2019). A complex is a group of structures, often between 2 and 15 individual structures that are designed to work together. A complex may be composed of a single structure type (i.e., BDAs) or a mix of structure types. Like natural beaver dam complexes (Figure 16), complexes are more likely to be able to influence hydrologic and geomorphic processes when built in clusters. Individual PALS and BDAs that are part of a complex help to increase the stability of any given structure within the complex by altering flow timing, magnitude and pathway at the reach scale. Furthermore, individual structures can be located in such a way as to reduce the potential for scour and to maximize the ability to achieve restoration goals. Complexes are discussed in detail in Chapter 5 (Shahverdian et al., 2019b).

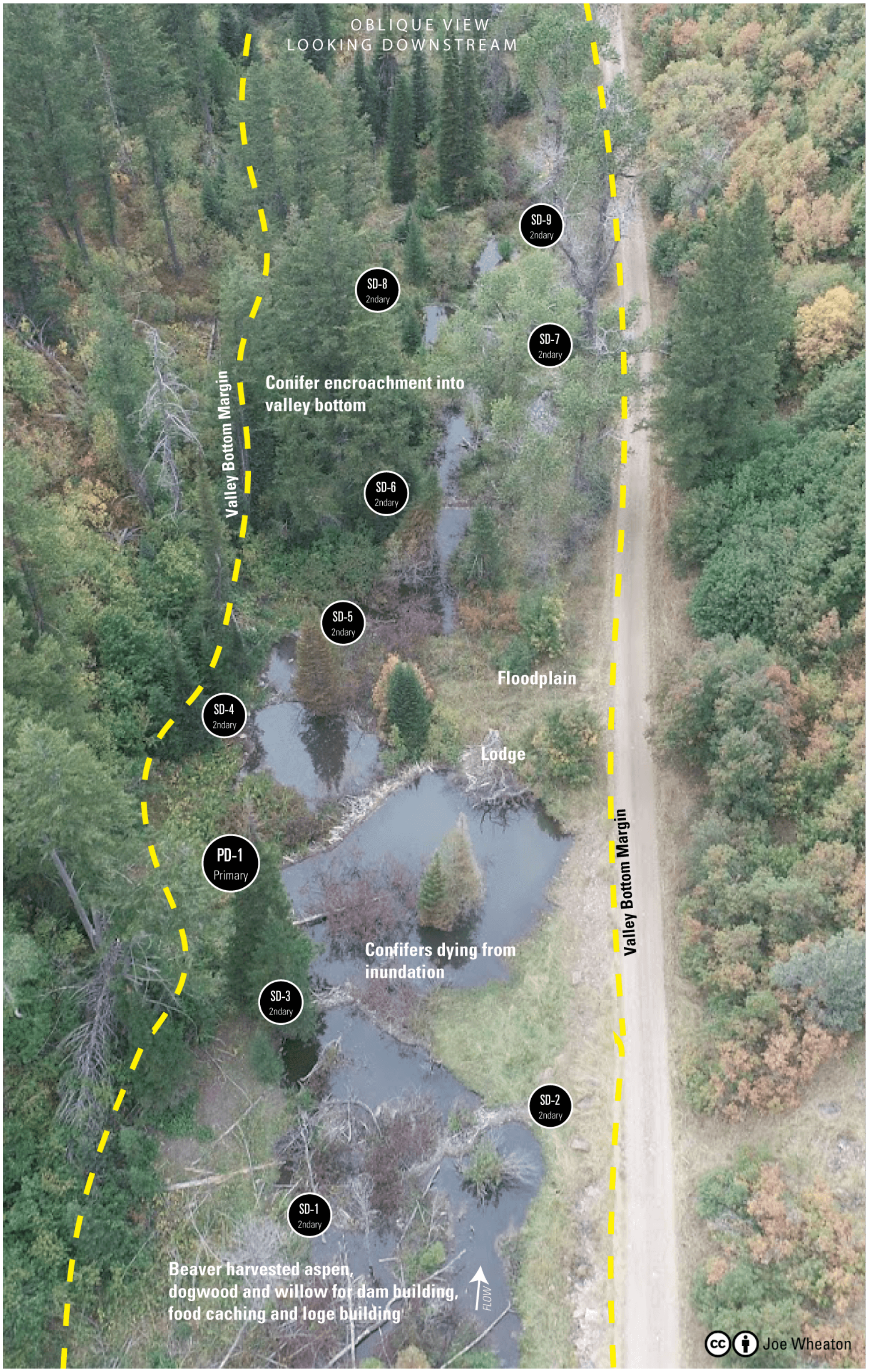


Figure 16 – The natural beaver dam complex should be the inspiration for designing a complex. Like natural beaver dams and accumulations of large woody debris, low-tech structures are more likely to achieve restoration goals when built to work together to influence hydraulic, hydrologic and geomorphic processes.

PALS AND BDAS CHANGE OVER TIME

In this chapter, we described the form and function of *intact* PALS and BDAs. However, PALS and BDAs are not intended to be permanent structures, and will change over time in response to flow conditions, wood accumulation, and sediment delivery. Deciding how to allocate limited restoration funds and developing realistic expectations for both PALS and BDAs is critical for designing effective low-tech restoration projects. In this section we describe common trajectories for both PALS and BDAs.

All PALS have a less than one-year design life (i.e., designed to withstand a typical mean annual flood), but their actual life-spans may extend in decades. This indicates that structures are not built to be permanent structures and are not guaranteed to withstand high flow events. However, like natural accumulations of large wood and natural beaver dams, many individual structures are likely to persist beyond one year.

PALS

PALS can be specifically intended to affect geomorphic change during high flows and are therefore likely to both force geomorphic changes and experience structural changes. Because PALS mimic and promote accumulation of large woody debris, it is common for structures to increase in size as large woody debris is trapped by existing structures (Figure 17). PALS may trap wood naturally delivered to the channel or lost by upstream PALS. PALS may also trap enough bedload to bury the main channel or cause an avulsion that reroutes the main flow around a PALS or complex, leaving structures high and dry. Mid-channel and bank-attached PALS can become channel-spanning debris jams if they capture enough woody material from upstream. None of the scenarios should be considered failures, unless they cause harm to the system or infrastructure, because the PALS still provide structure to the channel and floodplain, leaving it more resilient than it was prior to treatment. PALS can be maintained by adding more large woody debris and/or posts as they decay or otherwise lose material over time. Whether a PALS changes from mid-channel to channel-spanning, or channel-spanning to bank-attached is not of special importance. Instead, evaluating how the complex has changed (Chapter 5: Shahverdian et al., 2019b) is more important in determining future management actions.

Figure 17. Example of PALS evolution over the course of one year by promoting processes of wood accumulation. A and B show a mid-channel becoming a bank-attached, C and D show a bank-attached becoming a debris jam, and E and F show a bank-attached becoming a mid-channel. The geomorphic changes imposed by the presence of the PALS in each example shows clear alterations to the channel bed and hydraulics.

BDAs

The specific evolution of any particular BDA depends on flow conditions, sediment regime, beaver activity and maintenance done by restoration practitioners. Common outcomes for BDA include: blowouts (defined as a complete loss of the BDA), breach (an end section or middle section fails), sedimentation, remaining structurally intact but no longer ponding water, and intact and ponding water. If high flows occur, blowouts or breaches can occur where all or part of a BDA is washed downstream. While not the design intent, breached BDAs can still provide significant instream restoration benefit. In short, following a breach a BDA begins to function like a bank-attached or mid-channel PALS. In systems with high bedload transport, BDAs may force channel aggradation that reaches the BDA crest elevation. Depending on restoration objectives, this may represent a successful outcome, present new opportunities, or require new action. In cases where reconnection with the floodplain is the restoration goal it may be appropriate to build a new structure on top of the existing structure in order to continue the process of incision recovery. However, if the objective is the creation and maintenance of pool habitat (e.g., for fish), then filled-in BDAs will need to be rebuilt or replaced with another structure type to meet those objectives. In the absence of maintenance, whether by beaver or restoration practitioners, BDAs are unlikely to continue to force upstream ponding during typical flows, in which case they effectively evolve into channel-spanning PALS. Such a structure may or may not meet restoration objectives and require either rebuilding (to maintain pond habitat) or be sufficient (to promote channel aggradation and floodplain connectivity). For restoration practitioners, predicting and monitoring different structure responses can help improve restoration effectiveness and implementation efficiency.

USING PALS AND BDAS

In this chapter, we have presented a parallel discussion of PALS and BDAs. In practice, a low-tech restoration project can utilize any combination of PALS and BDAs to achieve restoration goals. In many cases local stream conditions, often at the sub-reach scale (10^1 -10^2 m) will lend themselves to a particular structure type. The decision to design a PALS or a BDA is based on both physical parameters of the site and restoration goals as well as pragmatic considerations on how to allocate limited project resources. Because PALS require fewer resources per structure than BDAs, more PALS than BDAs can be built for a given amount of funding. In accordance with low-tech restoration principles we suggest that the total number of structures and structure density is the single most important factor in any restoration project and as such often recommend strategies maximize the total number of structures. However, PALS and BDAs mimic and promote distinctive processes, regardless of logistic concerns. As will be elaborated in the design chapter, the structures that most appropriately invoke the process that matches the complex objective should be used. In areas with easily accessible floodplain or relic channels, BDAs can immediately increase floodplain connectivity, or activate another channel by forcing immediate overbank flows, even during baseflow conditions. Where restoration may incorporate other strategies such as riparian plantings, immediate increase in water resources may be desirable to increase the success of plantings. Where beaver translocation or the expansion of existing beaver populations is a goal, creating immediate pond habitat may encourage the successful colonization of a particular reach and reduce the likelihood of predation. In incised streams, characterized by narrow width and high banks (Stage 2-4 Cluer and Thorne (2013) or Stage 2, Pollock et al. (2014)), PALS are a more cost-effective way to promote channel widening and aggradation. If channel widening is the goal of restoration in order to promote incision recovery (Pollock et al., 2014), channel widening would necessarily result in the effective breaching of BDAs. In such a case, bank-attached or channel-spanning PALS can achieve the same restoration objectives with less resources per structure, enabling restoration practitioners to build more structures and expand their restoration treatment.

CONCLUSION

PALS and BDAs are low-tech restoration structures that mimic and promote the processes of wood accumulation and beaver dam activity. They are permeable, temporary structures that can be built by hand using natural materials. Both PALS and BDAs influence hydraulic, hydrologic and geomorphic processes in similar ways. The design process of PALS and BDAs requires considering flow conditions and local geomorphic context (e.g., gradient, planform, cross-section geometry). Both PALS and BDAs can be used to address common restoration objectives such as, increased instream complexity and increased channel floodplain connectivity. Therefore, the decision to use particular structure type is driven both by the restoration objective as well as logistic considerations, and the knowledge that greater numbers of individual structures are more likely to achieve restoration goals.

Chapter 4 – APPENDIX

APPENDIX A. FREQENTLY ASKED QUESTIONS ABOUT PALS AND BDAS

Since we began building beaver dam analogs (BDAs) and post-assisted log structures (PALS) in 2009, we have been asked many questions about their function, design, construction, effectiveness, and their potential negative impacts to the riverscape or aquatic species. Often the same questions come up over and over again. These questions suggest there are some misunderstandings about the general approach, about structural starvation of riverscapes in general, and assumptions of risk that need to be clarified. Therefore, we provide a list of the most common questions and our standard answers to these questions. We hope this will help practitioners become more comfortable with low-tech restoration.

Function

What happens if BDAs breach?

BDAs are not intended to be permanent structures. Like beaver dams, BDAs may be breached during high flow events. The outcome of a breach depends on how the BDA is breached, the type of BDA and the local geomorphic setting. BDAs may breach in the center of the structure by overtopping or along the bank by endcuts. The type of breach therefore controls the local geomorphic response; overtopping can result in a scour pool below the structure, while endcuts promote bank erosion, channel widening and an increase in sinuosity. While individual BDAs may breach and/or force erosion locally, sediment that is mobilized is likely to be captured at downstream structures.

Can a channel-spanning PALS (debris jam) mimic a beaver dam?

If enough wood accumulation, leaf-litter accumulation, and/or sediment deposition take place on the PALS, a channel-spanning PALS can act like a BDA. If this is the case, one strategy might be to build more PALS because they are quicker to build, more can be built.

What if PALS does not accomplish its primary objective?

For example, if the stream flow washes the part of the bank-attached PALS connected to the bank away (i.e., "end cuts") this does not need to be considered a failure. A bank-attached PALS primary objective is often to force flow to the opposite bank and either cause a hydraulic jet and scour a pool, erode a bank and build a bar downstream, or force overbank flow. However, if the stream end-cuts the bank-attached PALS it becomes a mid-channel structure and still contributes to channel complexity. The success or failure of low-tech treatments should be assessed at the complex or reach/project scale – not the individual structure.

Does it matter where BDAs are located?

Yes. The ability of a BDA to influence specific processes is determined by its location. A BDA in a highly incised channel is unlikely to promote floodplain connectivity. Conversely, a BDA located along a reach with an accessible floodplain can force overbank flow immediately. At broader spatial scales, BDAs are more likely to be able to address common restoration objectives within certain reach types. For example, BDAs located in steep, constricted headwater streams will have a limited ability to store water, promote riparian expansion, or increase channel and floodplain physical complexity.

Will BDAs work everywhere?

BDAs are designed to be implemented in areas that historically had beaver populations, and as such are generally located in partially confined or unconfined valley settings. These settings are characterized by medium to low hillslope connectivity and medium to high floodplain development. Similar to beaver (and this is a major consideration where beaver reintroduction is an objective), BDAs are designed to be implemented in areas that are conducive to their persistence. Therefore, highly confined, high gradient streams are not the intended setting for BDAs. Similarly, rivers with high annual peak flows, incapable of being dammed by beaver are not the intended setting for BDAs.

Do BDAs address the causes of degradation?

Much restoration literature emphasizes the importance of addressing the root causes of degradation. In a fluvial setting the causes of degradation can be local (e.g., channel straightening, levees, dams) or widespread (e.g., deforestation, urbanization, agriculture). Also, degradation can be caused by actions that have both systemic and local effects such as the removal of riparian vegetation. In many cases, the initial causes of degradation constrain the processes that are essential for functioning riverine ecosystems, or may have moved the stream into an alternative stable state incapable of supporting important stream functions and processes.

BDAs are intended to influence the processes initially affected by previous actions and create local and reach scale conditions that can restore processes that are critical to riverine health. Where the removal of beaver is one of the causes of degradation, then BDAs do facilitate and/or mimic reversing the precise cause of degradation. Where riparian vegetation has been removed, channel incision has taken place, or channel straightening has occurred (note that all three can be caused by multiple stressors), then BDAs can influence the hydraulic processes that were affected. Regarding riparian vegetation, BDAs can create the hydrological conditions (overbank flows, increased water table elevation) to recover the hydrology necessary to restoring riparian habitats. Regarding channel incision, BDAs promote channel aggradation and reconnection to the floodplain. Regarding channel straightening, BDAs can induce meanders and create and inset floodplain.

Can BDAs increase channel-floodplain connectivity?

Increasing channel-floodplain connectivity is often a goal of river restoration. We define connectivity as the ability of energy and materials to move between different areas on the landscape. In river restoration that often means water, sediment, nutrients and wood may move from the channel to the floodplain and vice-versa. Channel-floodplain connectivity therefore is controlled by the interaction of two factors: 1) channel geometry and 2) flow regime. Channel-floodplain connectivity can therefore by reduced by channel incision that prevents flows from being able to overtop banks, or by diminished flows from upstream flow regulations.

BDAs cause aggradation that increases the elevation of the channel bed, reducing the vertical distance to the floodplain that can enable flows to reach floodplain during higher flow events. The amount and rate of aggradation depends on local and watershed factors such as sediment supply. Also, depending on the magnitude of incision, channel-floodplain connectivity may take multiple years to re-establish. By ponding water and adding roughness to the channel, BDAs also increase the flow stage during low and high flow events which increases the likelihood of overbank flows. In areas with limited incision, BDAs can be built to cause immediate floodplain connectivity.

How long will BDAs and PALS last?

PALS and BDAs are designed to last < 1 year. However, they may persist for much longer depending on the flows and the density of structures built. The goal of these structures is to promote natural processes that will be self-sustaining.

Design and Construction

How many PALS/BDAs are required?

The number of PALS or BDAs ‘required’ depends on the project objectives (see Chapter 3: Bennett et al., 2019b) and is addressed in the design chapter (Chapter 5: Shahverdian et al., 2019b). When translocating beaver into areas with habitat already suitable to support beaver dam activity, it may be appropriate to build a smaller number of total structures (e.g., 6-20) to create deep water habitat for successful translocation. We suggest building a minimum of three beaver dam complexes in such a situation and releasing them into the middle complex and allowing the upstream and downstream complexes to provide them choices should they leave the release site. By contrast, where the goal is increasing channel-floodplain connectivity, spacing structures such that flows can be forced overbank regularly will help determine how many structures are needed. When in doubt however, more is better.

Are willows necessary for BDAs?

No. BDAs can be built using any woody vegetation, including willow, cottonwood, juniper or sagebrush. Woody riparian species are necessary for forage, if beaver are being translocated.

Does the orientation of a bank-attached PALS matter?

No. Some restoration practitioners orientate deflector structures upstream. Some downstream. What matters more is the number of structures and their influence on local hydraulics.

Are BDAs useful without beaver?

Yes. In areas where there are no beaver they can create immediate ponding for beaver translocation or floodplain connection. Where beaver translocation is not feasible, BDAs can provide many of the benefits associated with natural beaver dams, including sediment retention, elevated water tables, increased floodplain connectivity and riparian expansion which may be required for future beaver translocation.

How can the stability of PALS and BDAs be increased?

BDAs can be used across a diversity of settings, and as such will be subjected to different forces that affect the persistence of the structure. While breaching BDAs may still promote restoration goals, in other settings, BDAs may need to persist to achieve restoration objectives. Before choosing a method to increase the stability of BDAs, it is important to know the cause of failure. Where is the BDA located? Did the BDA experience breaching by being overtopped? Did scour undermine the base of the structure? If high flows have breached the structure by overtopping, then a lower dam crest height may allow flows over the dam rather than building up behind it resulting in a complete breach. Where scour has undermined the posts was it the result of headward erosion? Secondary dams used as grade control (where ponds reach the base of the primary dam) may increase primary dam stability. If the BDA is located in a confined setting where high flows cannot disperse, then perhaps the setting is inappropriate and/or the structure should be repurposed to initiate channel widening. In rivers with highly mobile substrate (sand-bedded rivers) using additional posts and more weave material may provide additional stability. Burlap sacks filled with sediment may also help prevent against scour at the base. Building wider PALs and building them up onto the floodplain can help increase their stability if necessary.

Can low-tech process-based restoration principles, PALS, and/or BDAs be incorporated into traditional restoration project designs?

Low-tech process-based restoration principles should absolutely be considered when designing any restoration project. For example, the Riverscape Principles outline the ideals of a healthy and fully functioning fluvial system that should be the end goal of restoration. Streams need space to adjust naturally, structural elements help force complex habitats, similar stream types provide insight into realistic expectations, and intact rivers are often hydraulically complex. These Riverscape Principles provide the framework for identifying realistic targets for designing a project that leads to a healthy and sustainable fluvial system. Likewise, the Restoration Principles outline overarching strategies for mimicking natural stream features that work with processes to develop and maintain sustainable habitat. We believe these core principles provide a natural and holistic lens to view restoration and rehabilitation practices and are readily applicable to traditional projects.

PALS and BDAs can easily be incorporated into traditional restoration project, either initially or as part of an adaptive management framework. As an example, imagine a project that contains 10 engineered log jams (ELJ) in a 1km plane-bed reach. These ELJs are likely stable and each one is expected to maintain a large scour pool and capture sediment creating a forced bar. Under that scenario, pockets of improved habitat were created, but the reach is now locked in an alternative stable state that is fully reliant on those ELJs remaining in place. PALS and BDAs can be incorporated into the design to increase the spatial coverage of habitat improvement. Similarly, mobile large woody debris can be added throughout the reach to give the stream additional opportunities to create effective structural elements without increased burden on the practitioner (defer decision making to the stream). For another example, consider the possibility that those 10 ELJs forced multiple avulsions to create side channels and increased the regularity of overbank flows. Because the legacy wood deficit applies to floodplains as well as contemporary channels, it is likely that these new side channels and the floodplain itself has few structural elements to force suitable habitat. Within an adaptive management framework, one could rapidly mobilize a second round of restoration (or maintenance) to place PALS and/or BDAs in the newly accessible areas in the valley bottom. We often build 'floodplain fences' (essentially PALS entirely on the floodplain) in areas where we expected instream structures to improve overbank access. Floodplain fences increase floodplain surface roughness and provide more 'meals' for the river as it adjusts to help create a more sustainable solution.

LT-PBR methods should not be viewed as mutually exclusive to traditional designs; however, the principles may be more difficult to fully integrate. We have seen several examples of engineered PALS and BDAs designs that met a project's objectives. However, for each example, the cost of engineered designs and heavy-handed implementation limited the amount of resources available to construct more structures that would cover a greater spatial extent. These projects are great examples where the structure types were considered without acknowledging the 10 principles outlined in Chapter 2. PALS and BDAs are examples of structure types that can be rapidly designed and built in order to follow the guiding principles. Increasing the design and implementation cost-per-structure, greatly reduces the potential for addressing the core principles (particularly, 2, 6, 8, 9, and 10).

Is it okay to use heavy equipment to build PALS or BDAs?

There are a number of examples of contractors and experienced practitioners using heavy equipment to build these structures. The biggest risk is over-building. We have used mini-excavators, backhoes and skid steers where convenient. If heavy equipment *actually* speeds up the process and, most importantly, if heavy equipment is not used to over-build the structure and the design principles are adhered to, then it is an option in some situations. Where access is easy, and you have a good and trusted operator it is an option. However, it does complicate permitting, can drive costs up unnecessarily, and in many situations is not any quicker.

Effectiveness and Maintenance

What maintenance is required?

The maintenance required for PALS and BDAs depends on flow events and whether or not beaver are present. If beaver are present and maintaining BDAs (or alternatively building new dams), then little or no maintenance may be required. If beaver are not present, seasonal maintenance will likely be required to maintain ponding and/or forcing overbank flows. Depending on the condition of the structure, maintenance can include adding additional posts, weaving woody vegetation and/or patching small gaps using cobbles and sediment.

Maintenance of PALS will depend on natural wood inputs and the output of wood from the project area. It is likely that structurally-starved systems will have a greater output than input of wood after one treatment. The need for more wood additions can be assessed annually and either unsecured wood added, or new PALS built in areas where wood densities have decreased.

What if a structure does not accomplish its primary objective?

For example, If the stream flow erodes the part of the bank-attached PALS connected to the bank away (i.e., "end cuts") this does not need to be considered a failure. A bank-attached PALS primary objective is often to force flow to the opposite bank and either cause a hydraulic jet and scour a pool, erode a bank and build a bar downstream, or force overbank flow. However, if the stream end-cuts the bank-attached PALS the PALS becomes a mid-channel structure and may still contribute to channel complexity. The success or failure of low-tech treatments should be assessed at the complex or reach/project scale – not the individual structure (see Chapter 5: Shahverdian et al., 2019b).

Potential Risks or Negative Impacts

What are the minor risks associated with PALS and BDAs?

Material could move and be caught on infrastructure downstream (i.e., bridge or culvert); however, because these are generally small materials this is a problem that can be mitigated in most cases. One easy mitigation is increasing density of mid-channel PALS at the downstream end of a project to act as Velcro or catcher's mitts for wood recruited from the project area. Flooding of infrastructure is possible if floodplain is connected; however, if the planning process in Chapter 3 is followed these risks are avoided or mitigated.

What are the biggest risks associated with PALS and BDAs?

Overbuilding, poor expectation-management and wanting them to last forever. Resist the temptation to over-build structures as it eats up time and materials, and the water will just find a way around it anyway. Be realistic about what one structure can do and be careful not to design projects to be overly dependent on any single structure or complex. There is resilience in redundancy. Finally, do not get to attached to any one structure and expect it to stay that way forever. If the processes of wood accumulation and beaver dam activity are active, they will bring plenty of new surprises and sustain complex habitat.

Do BDAs affect fish movement?

In general, BDAs are more leaky than beaver dams. Beavers are far more effective at plugging and maintaining dams than we are. In general, native fish and beavers have coevolved and fish can migrate upstream and downstream of beaver dams during certain times of the year or during certain flow conditions. Previous studies have shown salmonids can traverse BDAs and natural beaver dams (Bouwes et al., 2016a; Cutting et al., 2018; Lokteff et al., 2013). There is the potential that during very low flows beaver dams may slow fish passage – however, an easy solution to this is to build a secondary BDA below the dam providing a pool for fish to use to jump over the primary dam.

Do BDAs increase stream temperatures?

What is typically meant by this is "do beaver dams increase summer mean temperatures above lethal limits for certain biota (e.g., fish)?" The results from a number of studies on temperature impacts of beaver dams are inconclusive (Majerova et al., 2015) in terms of a consistent response (some mean temperatures increase, some decrease). What is remarkably consistent in terms of temperature response is an increase in the spatial variability of temperature, and diurnal buffering of temperature swings. The spatial variability of temperature can increase by 3° to 10° C creating pockets of both much warmer and much cooler temperatures (Weber et al., 2017). The warm areas are typically associated with shallow ponded water areas, whereas the cool areas tend to occur downstream of dams and appear to be associated with the displacement and upwelling of cooler ground water from the increased hydraulic head upstream of the dam. The diversity of hydraulic pathways and residence time of water may make systems more resilient to thermal extremes by providing choices for biota (i.e., thermal refugia).

What happens when BDAs or channel-spanning debris jams breach or blow out?

When BDAs or a channel spanning PALS breach, a portion of the dam height is lost, whereas if a BDA blows out, the entire height of the dam is lost. In both situations, a portion of the structure may still persist, but more fundamentally, there is a local change in base level. A channel spanning structure is a local and temporary base-level control. Streams grade their profiles to such base-levels. When the base-level is lowered, the profile lowers to adjust to this new local base-level and with that there is some evacuation of sediment. Natural beaver dams and wood accumulations 'fail' naturally all the time (Levine and Meyer, 2014). When they do, the riverscape adjusts and often leaves more complicated habitat. These dynamics are critical to maintaining turn-over and complex habitat. When a BDA blows-out or breaches, not all the sediment behind it evacuates. Much like what Walter and Merritts (2008) found in mill ponds, most of the sediment often remains and instead the stream slices and incises quickly through a fraction of the deposit like a butter knife through butter to the new base level. The rest of the wet sediment is quickly colonized by vegetation typically and stabilizes. In fact, Welsh (2012) documented with geomorphic change detection dam complexes after blowing out that were net aggradational as the 'blown out' state provided a more accessible floodplain for high flows to deposit sediment on to.

APPENDIX B: RECENT HISTORY OF POST-ASSISTED LOG STRUCTURES

In this Appendix we provide some background on the development of post-assisted log structures (PALS). Both PALS and BDAs have been tested in large-scale, long-term experiments, which have provided more insight into their effectiveness and to the use of wood in general as a restoration tool (Bennett et al., 2016). By reviewing the development of PALS, we highlight how the results from these experiments helped to inform the principles of low-tech restoration, improve our design process, and lead to more efficient and effective implementation of these actions.

Post-Assisted Log Structures (PALS) are built with woody material of various sizes held together with untreated wooden posts driven into the substrate to mimic natural wood accumulations. Post-assisted log structures (PALS) are designed to influence hydraulic, hydrologic and geomorphic processes. PALS are designed to influence hydraulics across a range of flows, and depending on the design, may force the creation of an upstream pond. While PALS influence hydraulics at all flows, they are most likely to force geomorphic change during high flows. PALS require the use of posts to provide temporary stability. PALS can be built in a range a shapes and sizes, best described by their location within the channel and desired objective, but in general consist of larger diameter and longer length material when available than used in the construction of BDAs. PALS can be used to achieve a range of restoration outcomes including: creating high flow refugia for aquatic species; increasing channel-floodplain connectivity at high flows; increasing physical complexity by altering patterns of erosion and deposition; and promoting channel incision recovery by forcing channel widening and aggradation.

PALS were developed in the Asotin Creek Intensively Monitored Watershed (IMW) study in southeast Washington (Bennett, 2018; Bennett and Bouwes, 2009; Wheaton et al., 2012), based on our experience of using post-assisted beaver dam analogues in the Bridge Creek IMW in central Oregon (see below). The primary goal of PALS was to simulate large trees and the processes of wood accumulation large trees often promote by using many small pieces of wood held together with posts. This expands the types and sources of woody debris that can be used because long, large diameter trees are not required to build PALS. PALS can be built on site with small trees that are often available at no cost during forest thinning fuels reduction, and/or range improvement operations (see Chapter 6: Bennett et al., 2019a). The smaller wood can be carried from staging areas to the installation location by the crew and avoid impacts to riparian areas with heavy equipment.

The Asotin IMW was implemented using an adaptive management framework (Bouwes et al., 2016a) where we identified conceptual models of the riverscape (Wheaton et al. 2012) and developed detailed hypotheses about how we thought the riverscape and Endangered Species Act (ESA) listed fish would respond to use PALS to create geomorphic complexity in a simplified planar stream channel (Figure 8). The restoration treatment consisted of installing approximately 700 PALS in over 14km. Restoration was implemented across several years in a staircase experimental design (Loughin, 2010). The project has been monitoring many the hypothesized responses for over 10 years, and has documented increases in geomorphic complexity (Camp, 2015b), improved fish carrying capacity (Wall et al., 2017; Wall et al., 2016), and potential increases juvenile steelhead abundance and production (Bennett, 2018). This experiment is ongoing and will continue to provide more information on the effectiveness of PALS at improving geomorphic and biological function in Asotin Creek that can be used to help improve restoration of many other wadeable streams using wood additions.

APPENDIX C: RECENT HISTORY OF BEAVER DAM ANALOGUES

Beaver dam analogues (BDAs) are man-made structures that mimic the form and function of natural beaver dams. They are a permeable, channel-spanning structure with a constant crest elevation, constructed with a mixture of woody debris and fill material to form a pond and mimic a natural beaver dam. They can be built with or without posts to secure them in place.

Like natural beaver dams they are designed and built in complexes, often between 2 and 15 individual structures. Also, similar to natural beaver dams, BDAs can be designed and built in a diverse range of settings, and a range of shapes and sizes that reflect restoration goals, local geomorphic, hydrologic setting, and available material. The design and implementation of BDAs is a simple, non-destructive and cost-effective method to restore the processes that are responsible for physically complex instream and floodplain habitat. They can be used to support existing populations of beaver by increasing the stability of existing dams; create immediate deep-water habitat for beaver translocation; or they can be used to simulate natural beaver dams (e.g., promoting healthy riparian areas).

The term 'beaver dam analogue' was coined by Pollock et al. (2014) though examples of mimicking and encouraging beaver dam building extends back to at least the 1930s (Collier, 1959). BDAs were the primary restoration technique used in a watershed-scale experiment completed in Bridge Creek, located in central Oregon, to test the benefits of a low-tech approach to restoring an incised stream to improve the habitat and the production of an ESA listed population of steelhead (*Oncorhynchus mykiss*) (Bouwes et al., 2016b).

Previous work indicated that beaver were present in the watershed; however their dams were short-lived, thereby not providing many of the ecological benefits commonly associated with beaver dams (Demmer and Beschta, 2008). Researchers believed the short live span of the beaver dams resulted from the large forces on dam in an incised channel not capable of dissipating high flows onto the floodplain, coupled with the lack of larger woody material available for dam building. Therefore, the design intent was to use posts to create a more stable dam to both mimic natural beaver dams and provide a more robust structure for beavers to build on that could withstand annual floods until floodplain connection was restored. Originally called Beaver Dam Support (BDS) structures, many of the initial restoration treatments consisted of reinforcing existing natural beaver dams using untreated wooden posts (Pollock et al., 2012) (Figure 18, top). Researchers also built new structures that relied on posts and locally available willow (Figure 18, bottom).

The study used an experimental design where a treatment (Bridge Creek) and a control watershed were compared pre- and post-restoration, where the treatment was the addition of approximately 120 BDAs to promote and support beaver dam building activity. Bouwes et al (2016b) hypothesized this treatment would initiate hydraulic, hydrologic and geomorphic responses that would improve steelhead habitat, riparian condition, and feedbacks that would improve beaver habitat allowing beaver to maintain the system (Figure 7). Over 10 years were spent monitoring most of these hypothesized responses (Bouwes et al., 2016b; Pollock et al., 2014). Ultimately, the restoration led to a 168%, 52%, 172% increase in abundance, survival, and production, respectively, of the juvenile steelhead population. This BDA-assisted restoration that successfully initiated self-sustaining beaver dam activity gave BDAs credibility as a viable restoration tool.

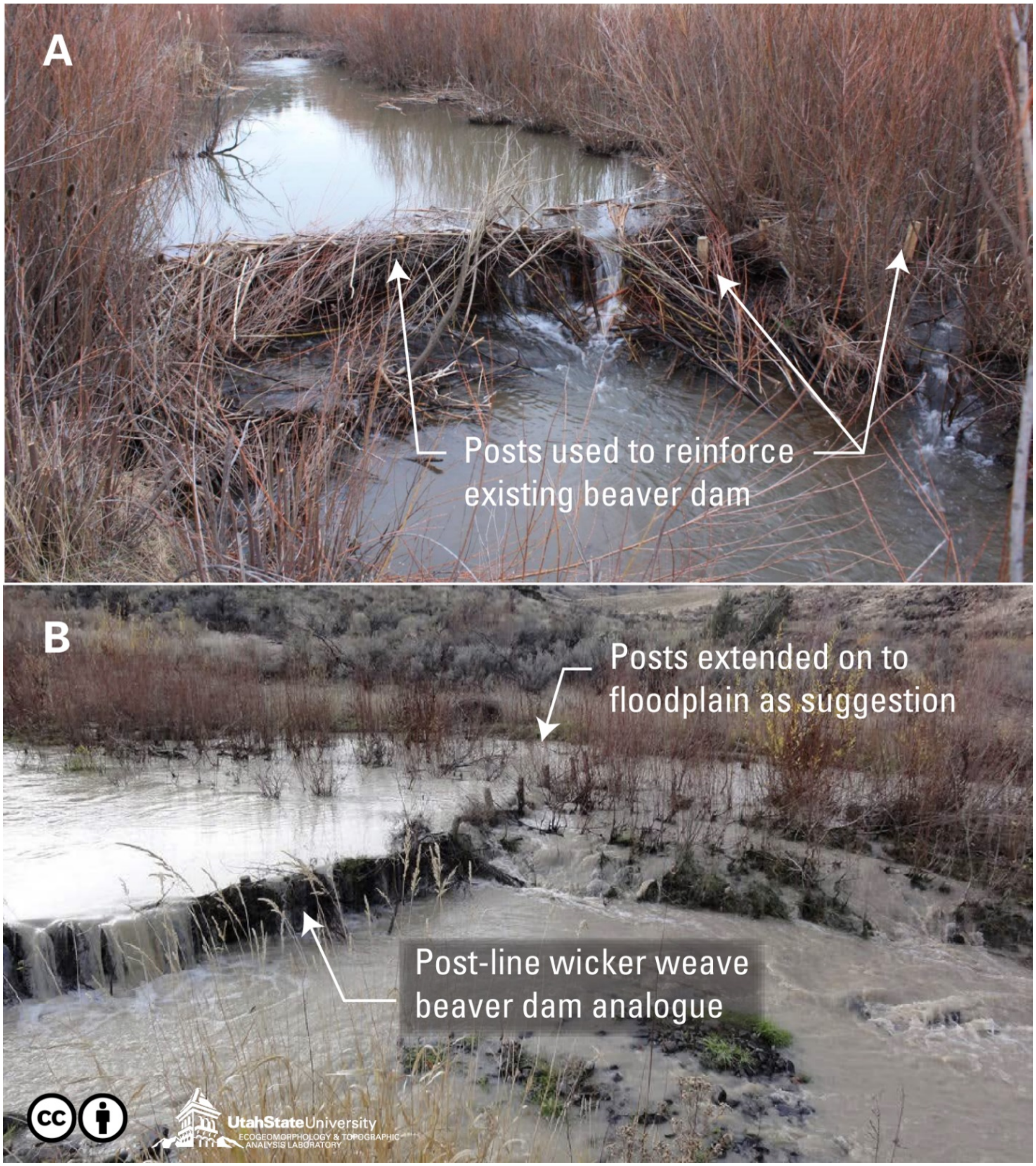


Figure 18 – Reinforced natural beaver dam (top) and post-line wicker weave BDA built in Bridge Creek (bottom).

Figure 19 - Early generation BDA. The structure is characterized by a tight willow weave and limited downstream mattress, leaving it more susceptible to scour that can undermine the posts. The downstream mattress shown here was built by beaver, and provided the original inspiration for incorporating mattresses into BDAs which diffuses flows coming over the dam.

Initially, the BDAs in Bridge Creek relied on a vertical wicker weave structure that was sometimes effective, especially if beavers built onto these structures (Figure 20). However, because these highly linear post-weave structures created uniform channel-wide hydraulics on the downstream side, scour undermined the post, resulting in the entire structure being pushed aside like a 'swinging door'. Continued work in Bridge Creek led to changes in construction, including the incorporation of a downstream 'mattress' of woody material oriented parallel to flow to reduce downstream scour, and modeled after natural beaver activity (Figure 19). Also, double post lines were used to increase the longitudinal width of individual structures and increase stability (Figure 21).

More recent restoration work has demonstrated that BDAs can be built with or without posts depending on the local setting (e.g., base and annual flood flows), using a range of woody materials including upland species such as sagebrush and juniper. In the following section, we detail the range of forms that BDAs may take as well as the materials that may be incorporated. We suggest that BDAs are not a one-size fits all, and that decisions regarding structure size, shape and materials are rooted in an understanding of the specific watershed and stream reach in which restoration is taking place.

Today BDAs and beaver are being used to address a large range of management goals including habitat improvement for amphibians, reptiles, birds, and mammals. Additionally, BDAs and beaver related restoration is used to promote ecosystems services such as resilience to drought and fire, flood control, water storage, water quality benefits, and increased livestock forage.

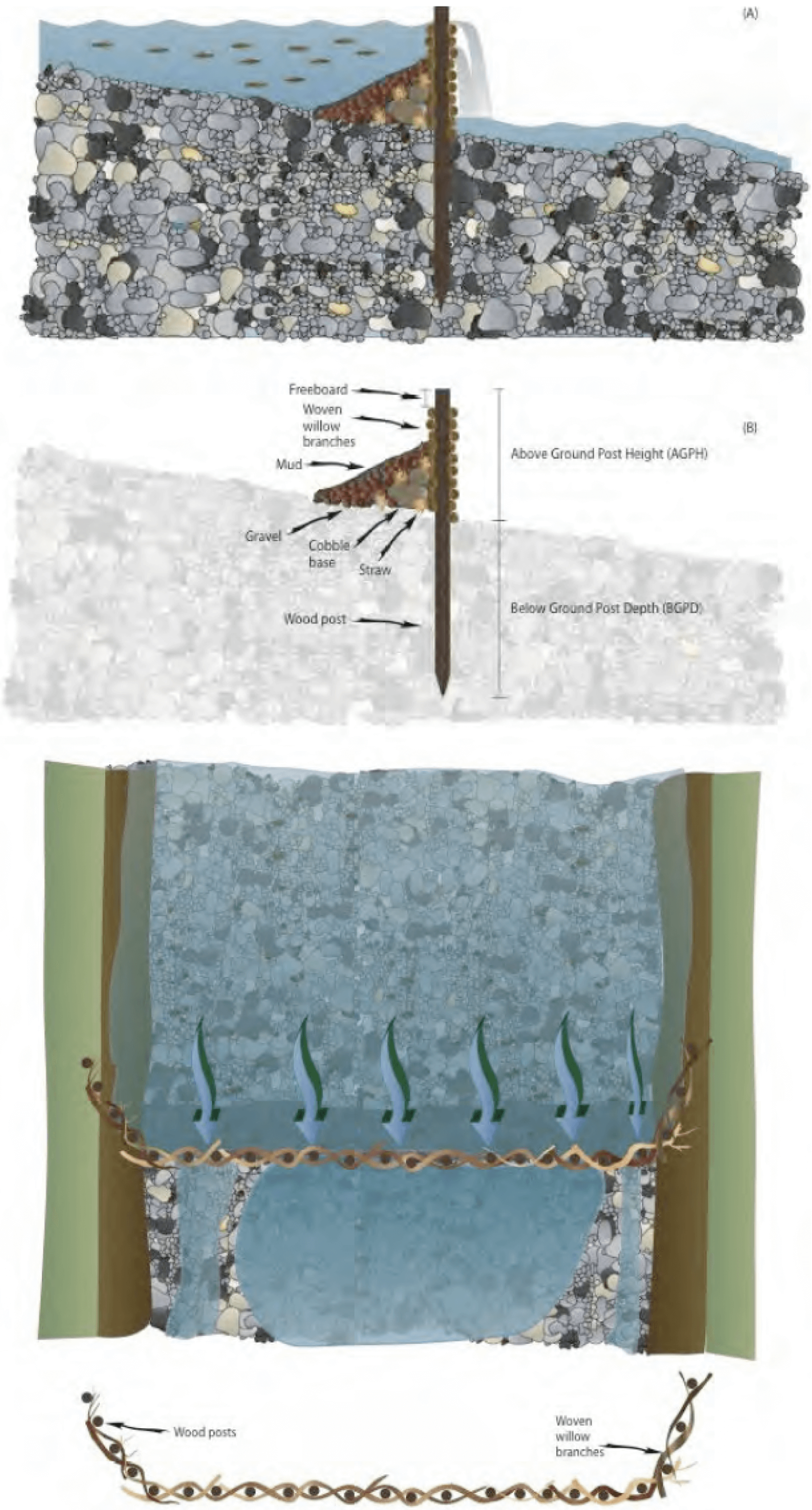


Figure 20 - Illustration of the one of the BDS structure types. Note the use of posts and a tight wicker weave between posts. Figure from Pollock et al. (2015). This is essentially a [post-line wicker weave](#).

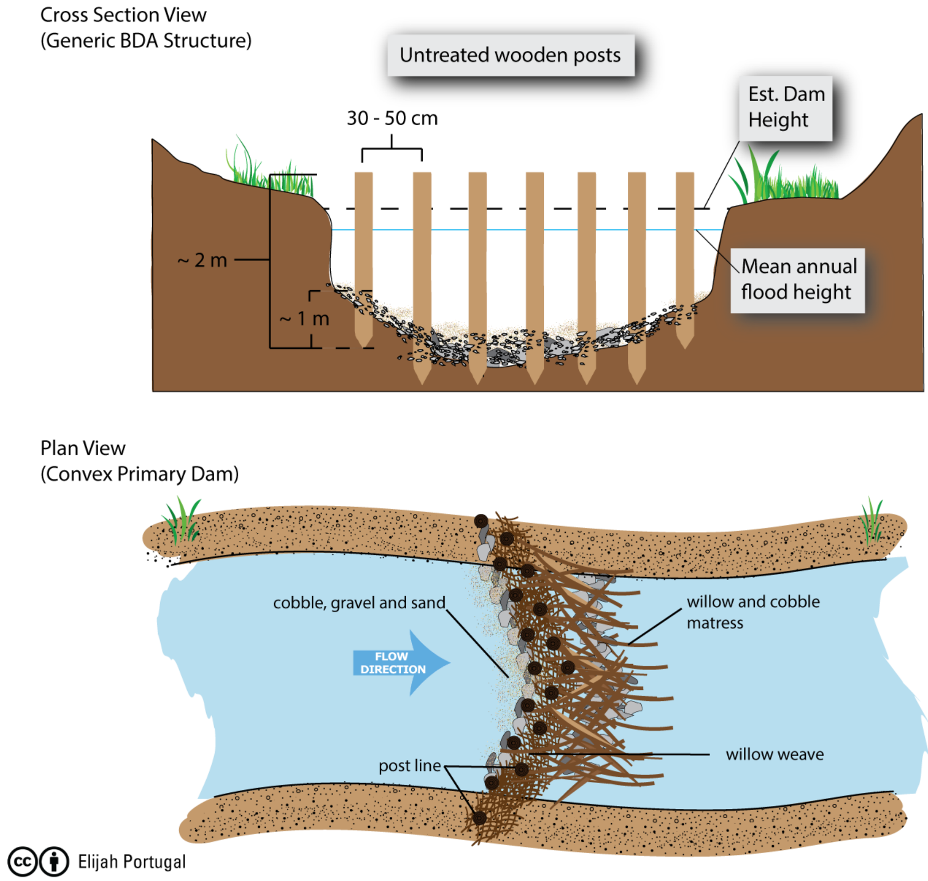


Figure 21 – Conceptual illustration of BDAs incorporating a downstream "mattress" and double post line. In practice BDAs can be built with or without posts and using a range of natural materials. Illustration credit: Elijah Portugal.

APPENDIX D: TYPICAL SCHEMATICS AND GENERAL SUGGESTIONS FOR PLACEMENT AND CONSTRUCTION OF PALS

We provide some basic building steps (i.e., recipes) and schematics of PALS and BDAs. We wish to stress that these recipes are not meant to describe the only way to build these structures, and the schematics are not meant as exact depictions of how these structures should be constructed. As noted in low-tech Restoration Principle 5 “it’s okay to be messy” (Chapter 2: Wheaton et al., 2019), each structure type should be built in a variety of shapes and sizes depending on the site conditions, materials available, and goals of the project. We provide the recipes and schematics as a rough guide for practitioners, an “entry point” into low-tech restoration, and for permitting agencies to understand the general building approach. All schematics are licensed with a Creative Commons attribution license so practitioners can use or modify them in their own designs, reports and permit applications with appropriate citation. See Chapter 6 for general permitting, construction logistics, and safety concerns (Bennett et al., 2019a).

General Post-Assisted Log Structure (PALS) Building Recipe

Ingredients:

- branches, limbs, small logs, brushy fill generally < 6-15’ long and 6-16” diameter (i.e., can be carried by 1-3 people and constructed by crew of 2-4) – (see Chapter 6: Bennett et al., 2019a)
- untreated wooden posts 6 - 8’ long 2-4” diameter; can sometimes be built on site with small diameter trees and/or branches, but may not be practical for building hundreds of structures (see Chapter 6: Bennett et al., 2019a)

Instructions:

- Decide location of PALS, configuration (e.g., orientation and type of PALS) as part of the design (see Chapter 5: Shahverdian et al., 2019b) of a complex of structures (multiple structures working together)
- Position larger logs on the base of the structure to make the general shape of structure
    - Limb branches from one side of the logs so that much of the log comes in contact with the bed to increase interaction between the flow and the structure, even at low flows
- Pin large pieces in place with posts; drive posts at angles and downstream to help hold wood in place at high flows
- Add more logs, and pack and wedge smaller material to fill spaces in the structure
- Build up the structure to desired crest elevation, but crest elevation need not be uniform

Options and Considerations:

- Build PALS with irregular shapes and branches and small debris sticking out in multiple directions (i.e., make a mess)
- For PALS where flow over the top is anticipated, consider constructing a mattress of woody material on downstream side to dissipate pour over flow energy over-top of structure. Alternatively, if the intention is to encourage formation of a plunge pool, maybe build mattress incompletely, or not at all
- When building bank-attached and channel-spanning PALS, extend the structures onto the floodplain by wedging structure material into existing vegetation, trunks, roots or boulders on the floodplain
- Build bank-attached PALS with a broader base (streamwise) where the structure attaches to the bank, to better shunt flows to the opposite bank
- Locate bank-attached PALS across from hard features like boulders or roots to force a scour pool
- Build a broad base (streamwise) for channel-spanning structures relative to channel width so that the structure is not narrow and “wall like”. Use multiple lines of offset posts to build it wide
- Build mid-channel PALS with large and wide logs perpendicular to the flow on the upstream end of the structure to act like a natural root wad
- In general, the larger the structure relative to the channel width (i.e., constriction width), the larger effect it will have on hydraulics, and subsequently geomorphic change during high flows

Typical Schematic or Design Details for PALS

In general construction, typical details and schematics are used in plans to indicate what and/or how to construct recurring design elements and features. For example, in a standard civil engineering plan of a parking lot, there may be standard details for curb and gutter, drop inlet structures, typical paving section, etc. These schematics differ from specific cross topographic cross sections at a particular location (Figure 22).

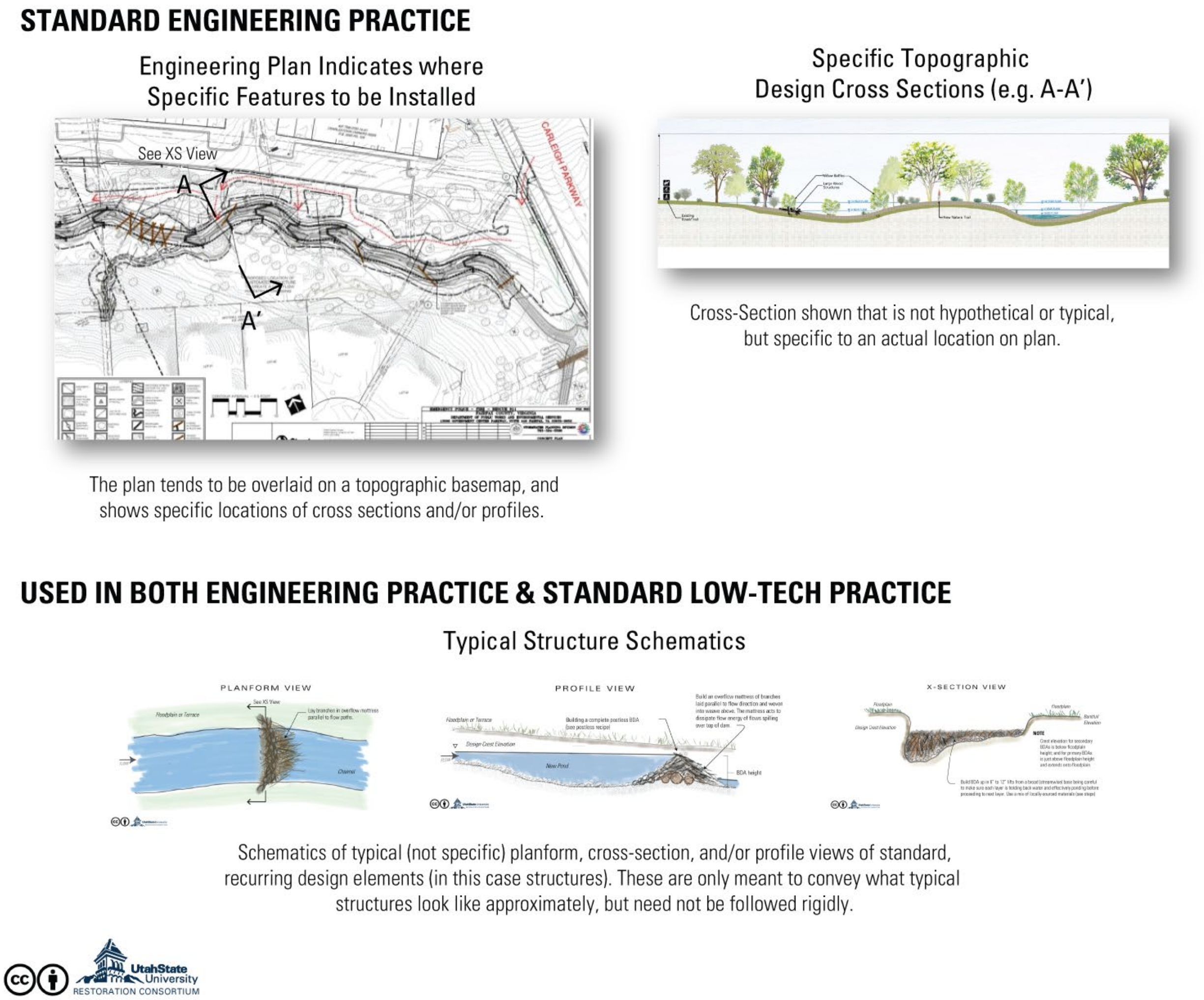


Figure 22 – In both standard engineering practice and low-tech practice, schematics as provided in this appendix are used. However, standard engineering practices tends to use plans on top of topographic basemap, from which specific topographic cross sections or elevation profiles are derived. In low-tech restoration, topography is explicitly read and interpreted in the field, but not used nor necessary as a basis for design. .

Bank-Attached PALS – to Force Constriction Jet

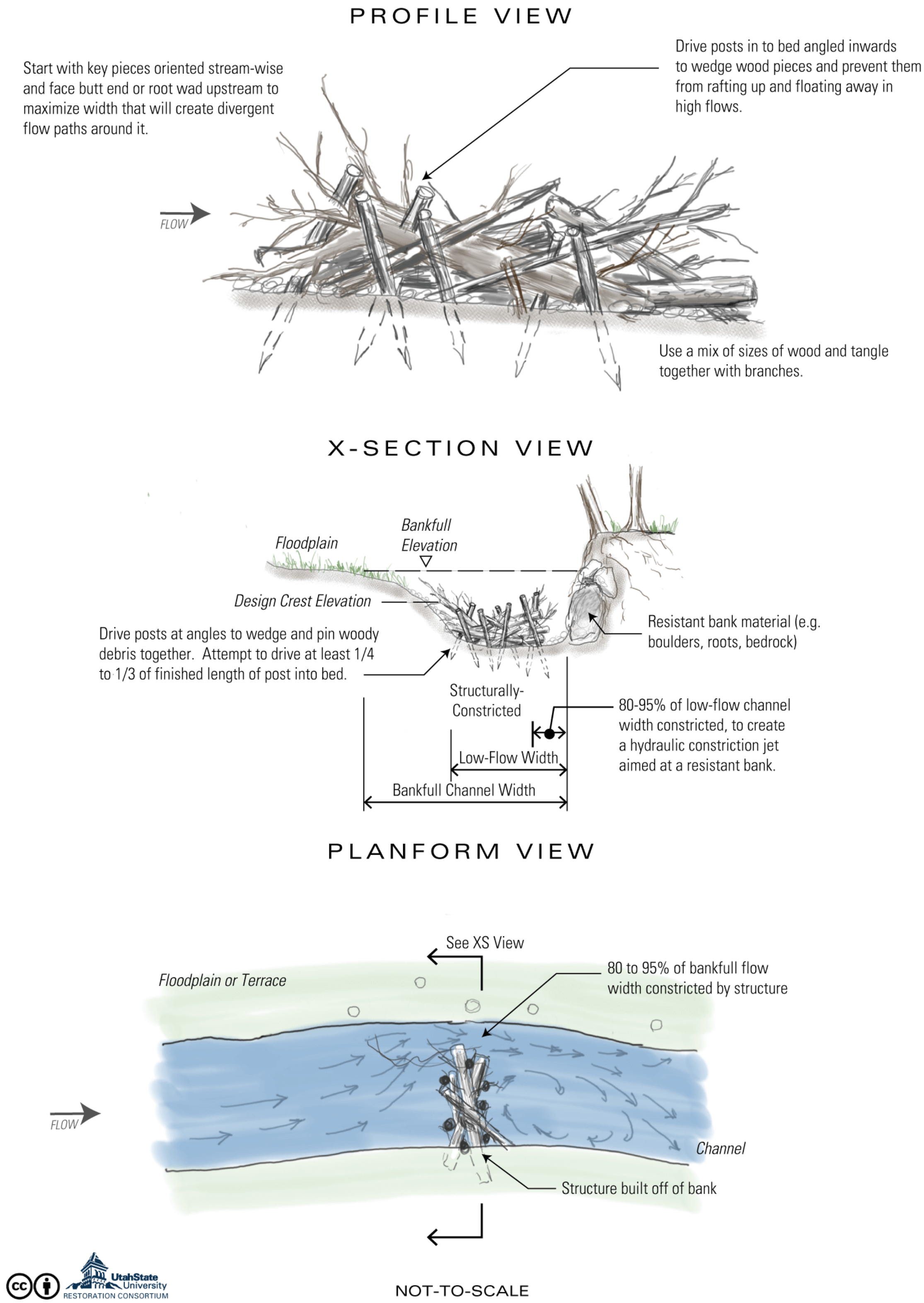


Figure 23 – Typical schematic of a bank-attached PALS directed at a resistant bank intended to force a constriction jet.

Bank-Attached PALS – Bank Blaster for Lateral Reworking and Recruitment

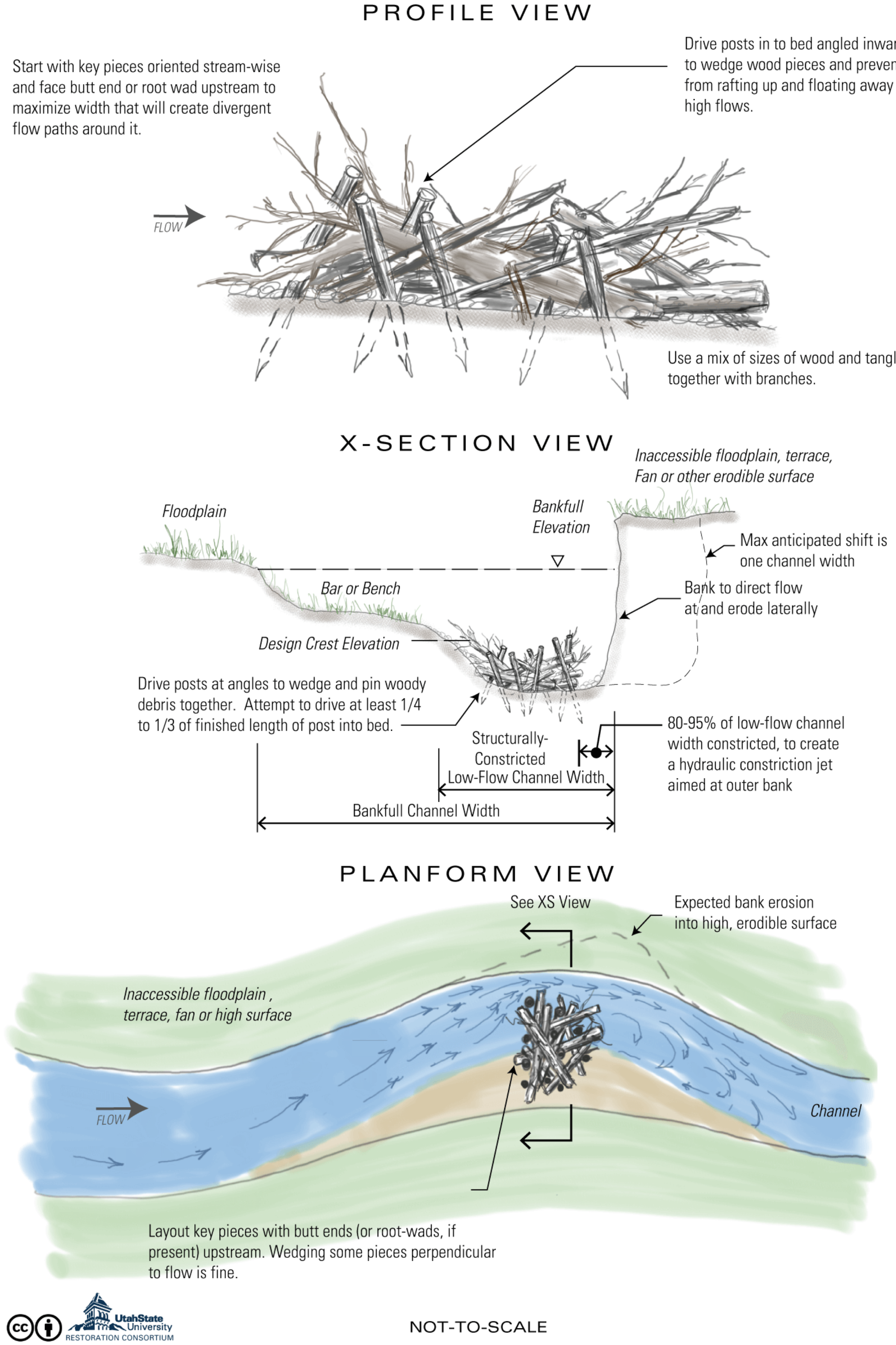


Figure 24 – Typical schematic sketches of a bank-attached PALS intended to blast and erode a bank to recruit sediment and/or wood.

Mid-Channel PALS

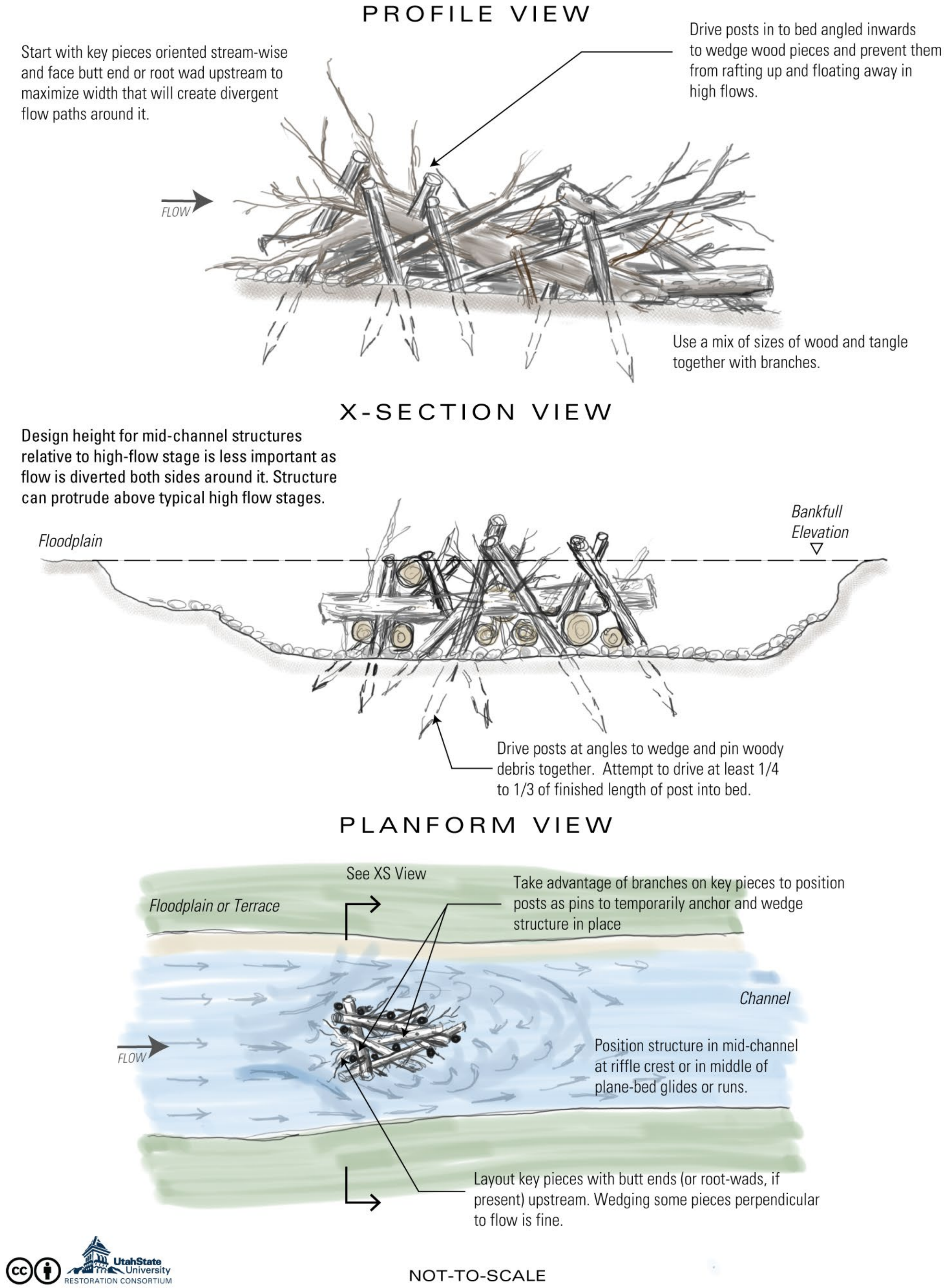


Figure 25 – Typical schematics of a mid-channel PALS.

Channel Spanning PALS

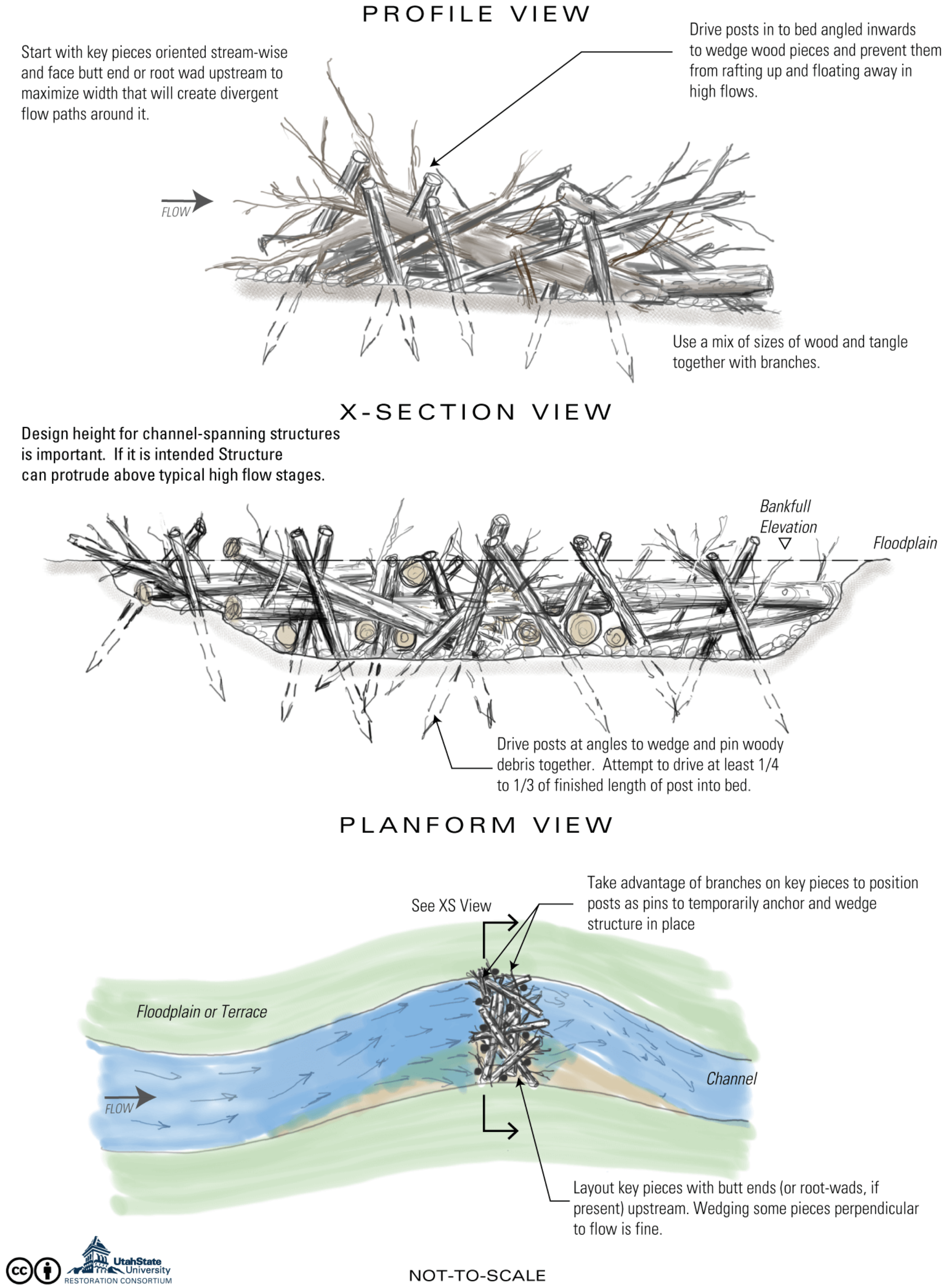


Figure 26 - Typical schematics of a channel-spanning PALS.

Variations and Constructions Tips for PALS

There are numerous ways to build PALS, and practitioners should experiment with different substitutions and techniques. In Figure 27 the idea of substituting different types of materials is illustrated. One can build smaller PALS to start, and then make them bigger once the key pieces are pinned in. We have found that installing posts at angles is far more effective at pinning material in place (Figure 28). Finally, posts don't always drive into the bed. Posts will drive surprisingly well into cobble and gravel, but bedrock, clay hardpan, and some beds will not always work. In such situations, it can be helpful to make larger and more complicated pieces by lashing material together, and securing it or wedging it against existing features. We DO NOT recommend cabling, but biodegradable rope is an option. We do not like cabling as it is both unnecessary and leaves artificial material in the system for too long. By contrast, biodegradable materials can provide temporary stability while the structure is mimicking a wood-accumulation, gives it a chance to act as Velcro for promoting more wood accumulation, but if it washes out, it will just be a source of recruited wood to accumulate in other natural jams and PALS. Figure 29 shows one technique for lashing material together using triangle frames. This can also be helpful for combining smaller pieces into something that mimics bigger key pieces.

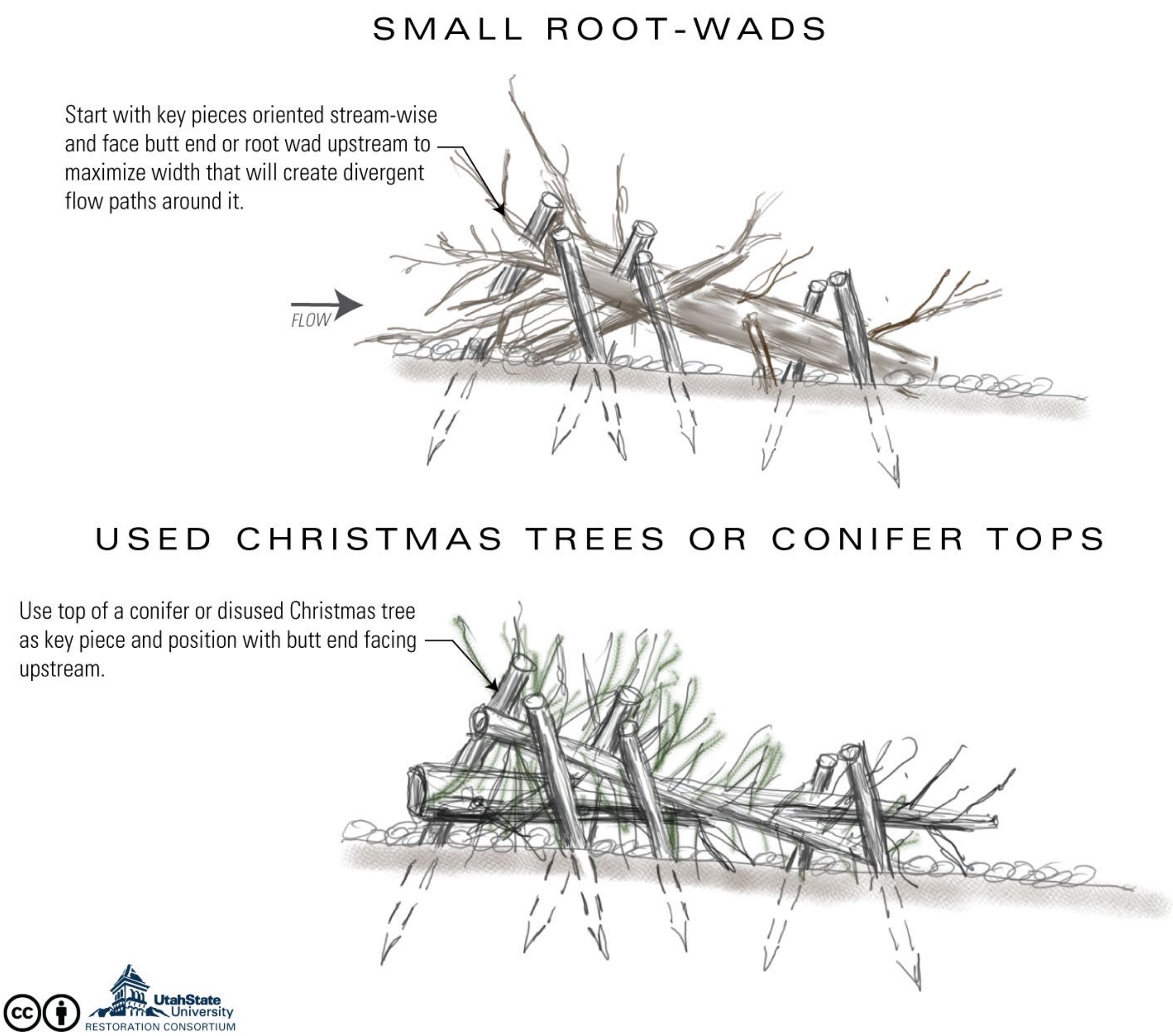


Figure 27 – Ideas for material substitutions with small root-wads and discarded/recycled Christmas trees or tops off of conifers. Smaller PALS like these can also be helpful to start with in streams and rivers with higher flow, to build something small and get it anchored, and then start piling on more material and pining it as necessary to produce something like found in the schematics.

Figure 28 – Installing posts at an angle (as opposed to plumb or vertical) is a helpful way to wedge woody material together and keep it from rafting up and floating away in high flows. It is also physically easier to install because the post-driver does not have to be lifted and held as high above the ground.

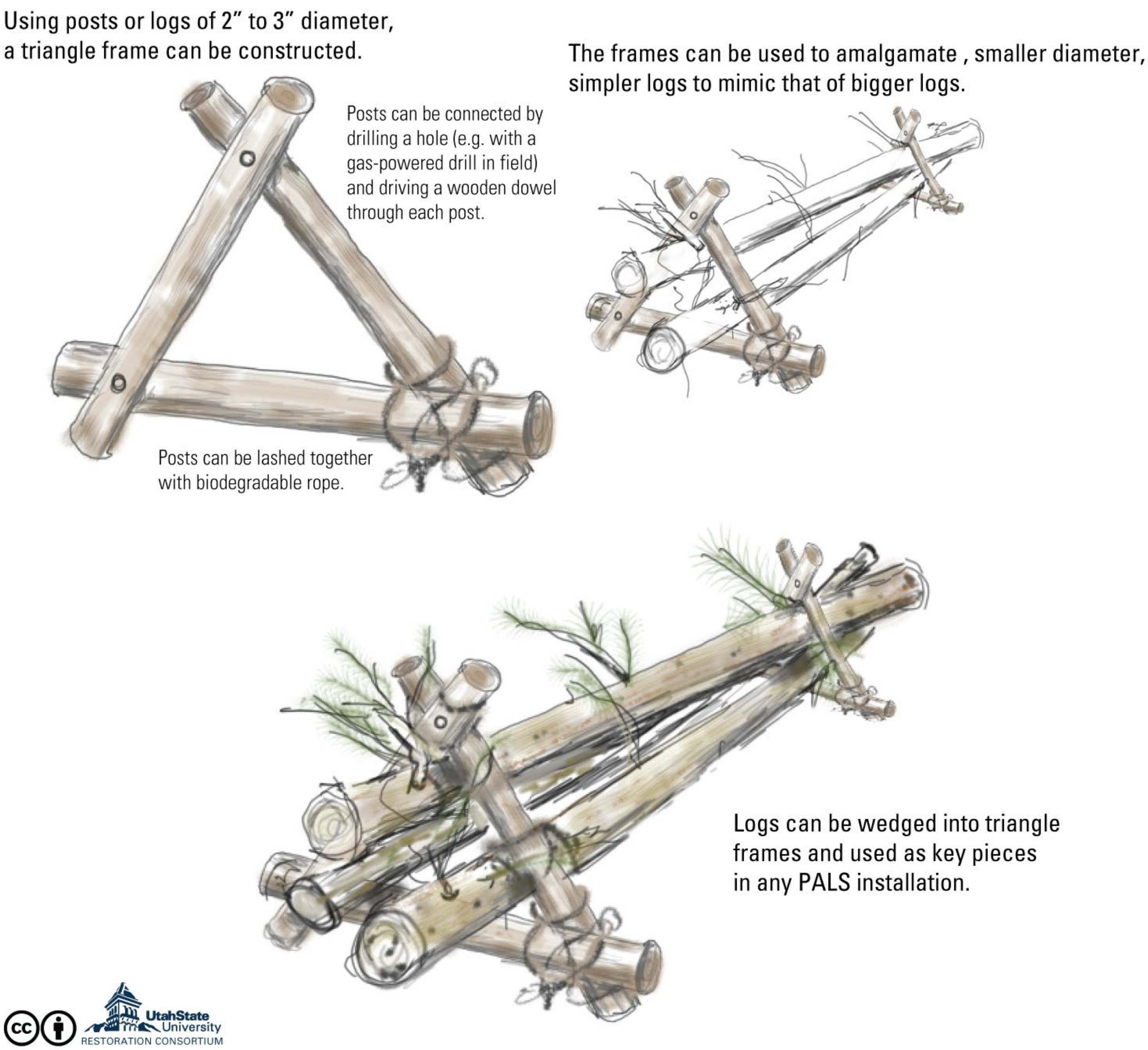


Figure 29 –Smaller logs can be effectively combined into bigger pieces with simple triangular frames. Frames can be sized to hold the smaller logs together, and connected with simple wooden dowels or, biodegradable rope lashing the frame and logs together. These structures can be especially useful where posts cannot be driven into the streambed due to bedrock or compaction.

APPENDIX E: TYPICAL SCHEMATICS AND GENERAL SUGGESTIONS FOR PLACEMENT AND CONSTRUCTION OF BDAS

Typical Schematic or Design Details for BDAs

In this section, we provide the sorts of schematics that can form part of a low-tech design package (see Chapter 5: Shahverdian et al., 2019b) and act as typical construction details. Many substitutions and creative adaptations to these typical details can be made to promote the processes defined in the design objectives. Do not be afraid to experiment, so long as you are following the guiding principles (see Chapter 2: Bennett et al., 2019a).

Postless BDA

Our preferred design for BDAs is very similar to how beaver build dams, without posts.

General Postless BDA Recipe

Ingredients:

- Woody fill material (preferably locally-sourced) branches, limbs, small logs, brushy fill
- Finer fill material: both organic (e.g., turf mats, roots, leaves, conifer needles, grass, etc.) and inorganic (e.g., fine bed sediment, silt, clay, soil, gravel)
- Optional if available on site: key pieces: logs, cobbles or small boulders

Tools Needed:

- Personal protective equipment (PPE) (see Chapter 6: Bennett et al., 2019a); Optionally: dry suit or waders
- Cutting tools: loppers minimally; Optionally: chainsaw, hand saw(s), and pruning shears – for sourcing, trimming and cutting to size woody fill material
- Digging tools: Shovel(s) minimally; Optionally: pick-axe and/or digging bars – for sourcing finer fill material
- 5 Gallon Buckets - for filling and moving finer fill material from source areas to BDA
- Optionally:
    - Cam straps are sometimes helpful to bundle together branches for easier hauling from source or staging areas to BDA.

Instructions:

1. Decide location of BDA dam crest orientation, configuration (e.g., straight or convex downstream), and crest elevation (use landscape flags if necessary). Position yourself with your eye-level at the proposed crest elevation of the dam (make sure it is < 5' in height). Look upstream to find where the pond will backwater to. Adjust crest elevation as necessary to achieve desired size of pond, inundation extent, and overflow patterns. If concerned about head drop (water surface elevation difference) over BDA, build a secondary BDA downstream with a crest elevation set to backwater into base of this BDA (and lessen head drop or elevation difference between water surface in pond and water surface downstream of BDA).
2. Build up first layer or course by widening base upstream and downstream of crest to flat height of 6 to 12" above existing water surface, and make sure it holds back water.
    a. If larger key pieces (i.e. larger logs, cobble or small boulders) are locally abundant, these can be used to lay out the crest position across the channel (as in Figure 32). Optionally, they can be 'keyed' in by excavating a small trench (no need to be deeper than ~1/3 of the height of key piece diameter) and place key pieces in and pack with excavated material.
    b. Lay out first layer of larger fill material, being careful not to go to higher than 6" to 12" above existing water surface. The first layer should be just high enough to backwater a flat water surface behind it.

c. Using mud, bed material & turf (typically sourced from backwater area of pond) as fine fill material to plug up leaks, combine with sticks and branches of various sizes to build a wide base. Make sure base is wide enough to accommodate anticipated dam height (most dams will have a 1.5:1 to 3:1 (horizontal : vertical) proportions.

d. Build up first layer only to top of key pieces from first layer. Make sure the crest is level across the channel and water is pooling to this temporary crest elevation.

3. Build up subsequent layer(s) in 6” to 12” lifts, packing well with fine fill material until ponding water to its next temporary crest elevation.
4. Repeat step 3 as many times as necessary to build up to design crest elevation.
5. Work a willow mattress (laying branches parallel to flow) into dam on downstream side and build to provide energy dissipation to overtopping flows.
6. If desired, and time permits, attempt to plug up BDA with mud and organic material (small sticks and turf) to flood pond to crest elevation. Optionally, you can leave this for maintenance by beaver or for infilling with leaves, woody debris and sediment.

Options, Considerations & Variations:

- For Step 2a, it is not necessary to build with larger key pieces (as in Figure 32) and plenty strong with a mix of smaller woody material and fine fill material (e.g., Figure 30). If woody key pieces are used, make sure to at least limb (cut off branches) on side in contact with bed.
- For Step 2b, if key pieces are limbed on the side that is in contact with bed, the branches removed from the other side can be used to help weave and wedge material in subsequent layers in. If this is done, make sure that limbs are trimmed at end to design crest elevation.
- Just like natural beaver dams, there are a huge number of variations in the woody fill material and fine fill material. In some riverscapes that lack woody riparian vegetation, or nearby woody material, beaver build very strong beaver dams out of nothing more than fine fill material.
- If building a ‘primary’ dam (larger dam that tends to be deep enough to support an underwater entrance to a beaver lodge, consider backwater inundation extents relative to good bank-lodging opportunities (e.g., overhanging banks, vegetation and cover from predation).
- If building multiple dams (typically secondary) in series, the dams within a complex tend to be positioned (spacing downstream) and built to heights that support flatwater from the crest of the downstream dam all the way upstream to the base of the next dam upstream.

Notes

- The temptation is always to build up (in height) quickly without making sure each layer is holding back water well and is stable. A better dam results in building up to the design crest elevation slowly.
- Overall dam height is best not to exceed the height of the people constructing it.
- It is easier to build in systems that already have a perennial water source and flowing water, as you can see instantly how well your structure backs up water. It is possible to build in intermittent channels or areas you expect to receive water in the future, but you will not immediately mimic a beaver pond in such situations.
- Much of the ‘strength’ of the dam comes from the messy carbon fiber matrix you are building with a mix of size and type of materials combined. Similar to concrete, the cement by itself is not strong, but the aggregate and/or reinforcing rebar is what gives the structure its strength.
- Resist the temptation to overbuild the BDA.
- A BDA that ‘breaches’ or ‘blows out’, just like natural beaver dams do, is not a ‘failure’ if designed to accommodate such a response. Often, BDAs that blow out or breach provide improved and more complex habitat.
- Design life: < 1 year (note actual life may last many years or even decades).

Postless BDA Details

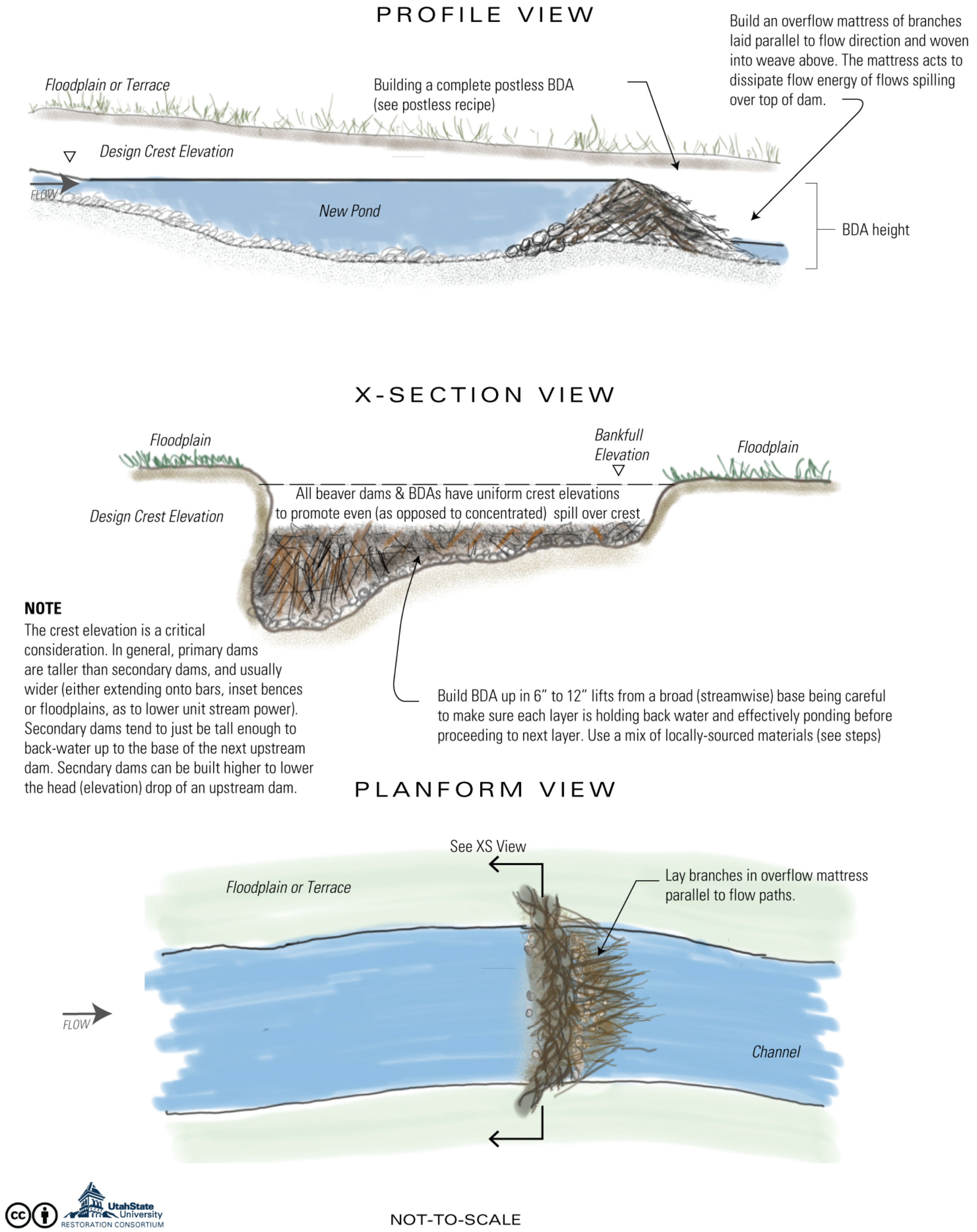


Figure 30 – Typical schematic sketches of a postless BDA.

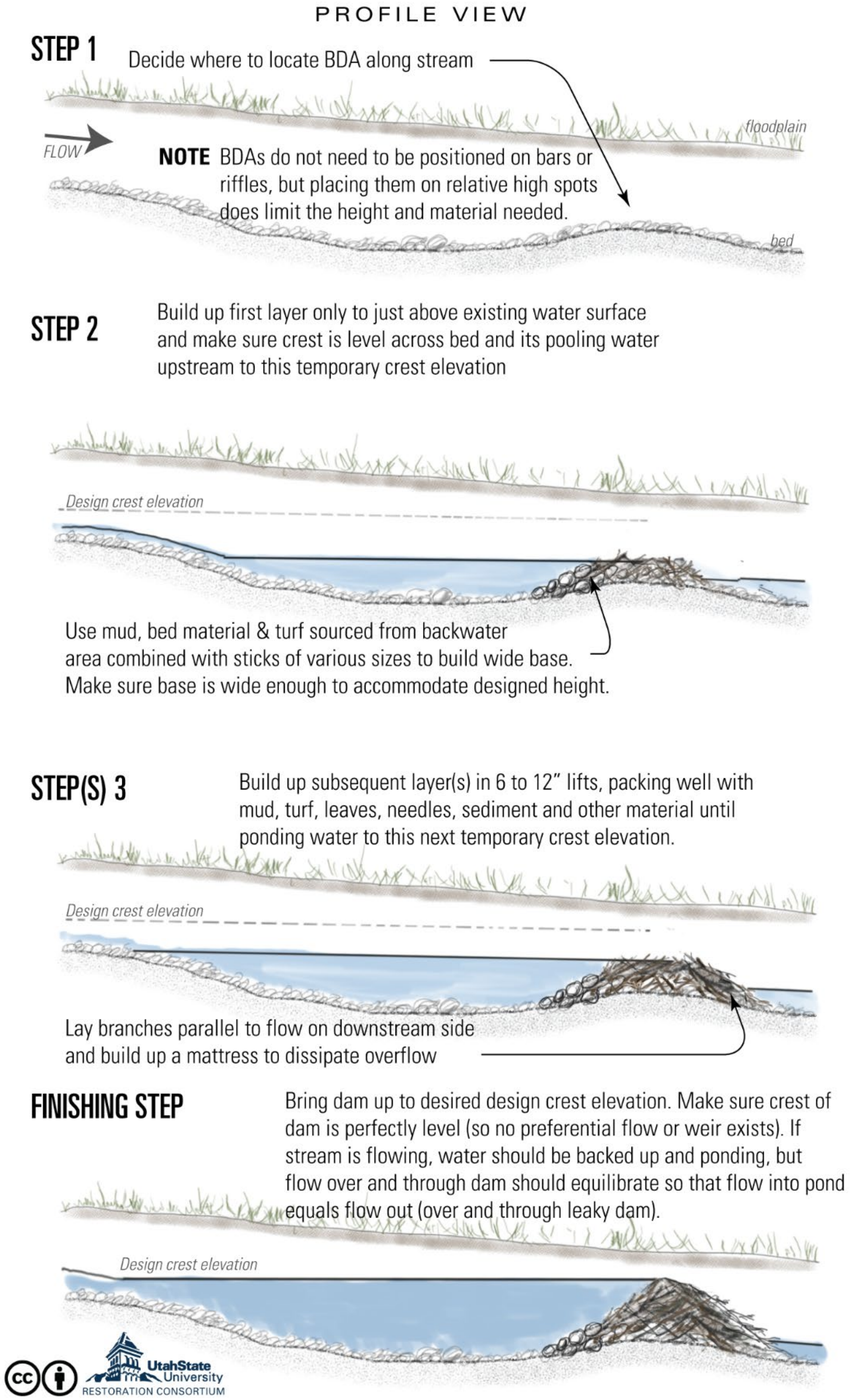


Figure 31 – Sequence for building postless BDAs, build up in 6" to 12" lifts, slowly, like beaver do. Make sure that your lifts are level, and water is backed up sufficiently that is flowing over the crest evenly (as opposed to through or under the dam), and the base is broad, before building up to your next layer.

Postless BDA with Key Pieces Details

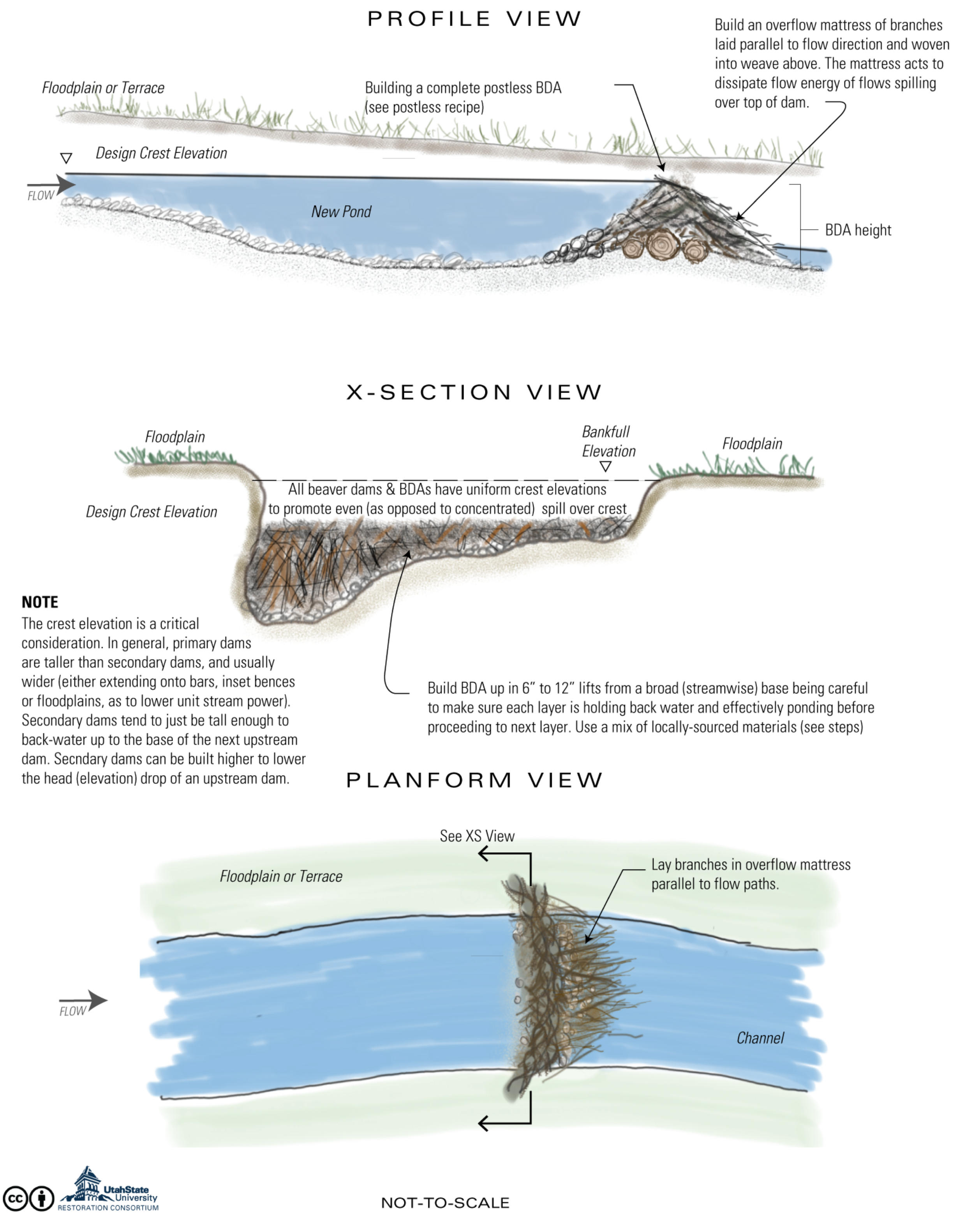


Figure 32 – Typical schematic sketches of a postless BDA with key pieces used in base.

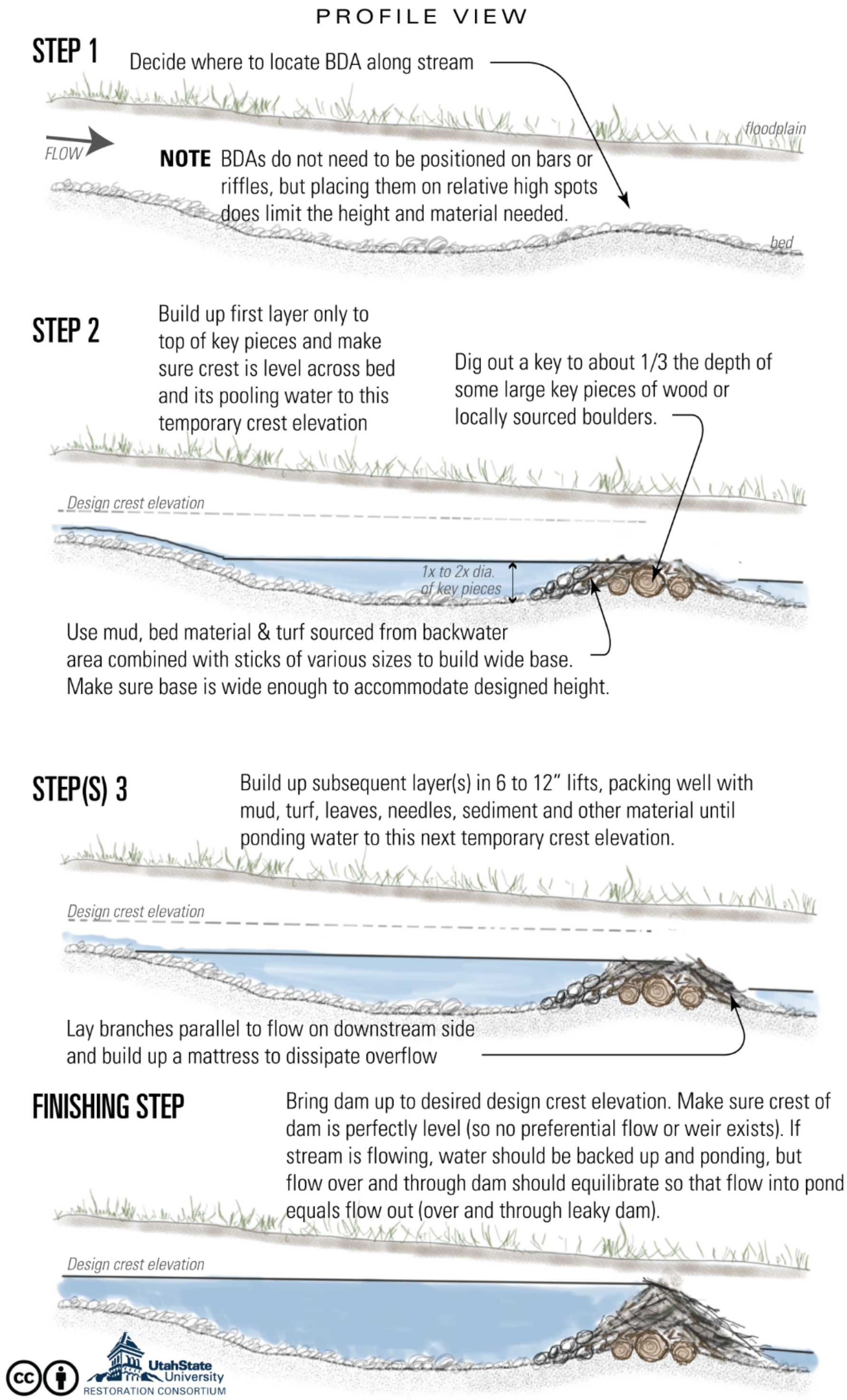


Figure 33 – Sequence for building postless BDAs with key pieces, build up in 6" to 12" lifts, slowly, like beaver do. Make sure that your lifts are level, and water is backed up sufficiently that is flowing over the crest evenly (as opposed to through or under the dam), and the base is broad, before building up to your next layer.

Post-Assisted BDA

Some practitioners who build BDAs have become very accustomed to using posts, because that's how the first details they saw of BDAs were built and they stuck to the post-line wicker-weave recipe (Figure 36 Appendix C and Figure 19). Posts can provide some temporary anchoring and stability to help with high flows in systems with flashier flow regimes or that produce larger magnitude floods. However, in many situations beaver can produce plenty strong dams without posts. For situations where additional support during high flows is deemed necessary, our suggested practice is to start out following the instructions to build a postless BDA, and then simply add posts (Figure 34 & Figure 35).

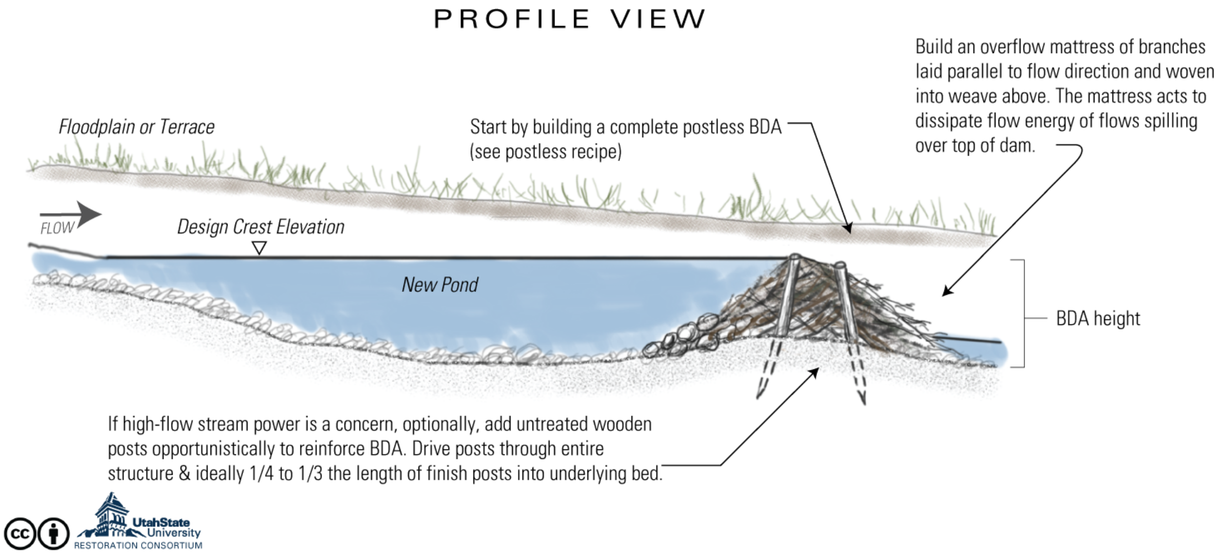


Figure 34 - Profile schematic of post-assisted BDA. If you think you need posts, our preferred approach is to build a postless BDA as per Figure 31, and then reinforce after the fact with some posts driven through the structure.

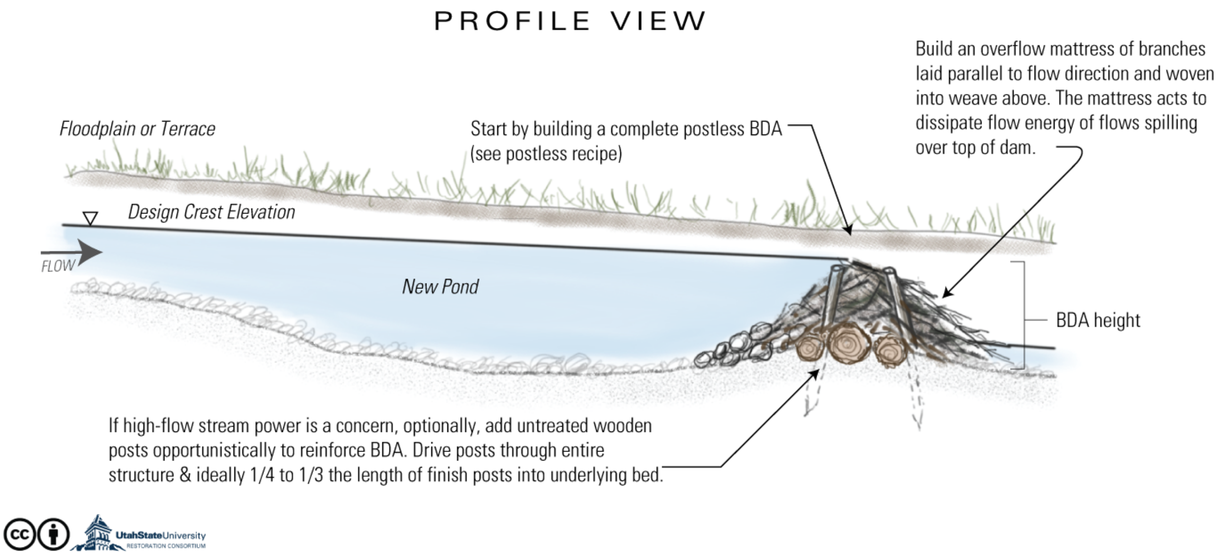


Figure 35 – Profile schematic of post-assisted BDA with key pieces. If you think you need posts, our preferred approach is to build a postless BDA as per Figure 33, and then reinforce after the fact with some posts driven through the structure.

Post-Line Wicker Weave as a BDA

As described in Appendix C, a simple post-line wicker weave was the first version of BDAs. Post-line wicker weaves have been used since at least the 1930s (Kraebel and Pillsbury, 1934) and in the 1800's in France (Chapter 1: Shahverdian et al., 2019a). Post-line wicker weaves as BDAs have the important characteristic that the crest elevation is built to be perfectly uniform in height. Post-line wicker weave BDAs can and have worked in many situations. Draw backs to this method are the emphasis often goes into building the weave and gaining elevation, and a postless BDA design emphasizes what a beaver dam is meant to: holding back water. We have also seen these wicker-weaves open in floods like a barn gate, which often produces good habitat, but those are situations a bank-attached PALS would have made more sense (e.g. Figure 24) and have been more economical to build.

General Post-Line Wicker Weave as BDA Recipe

Ingredients

- Untreated wooden fence posts (as many as needed to space 30 – 50 cm apart and staggered)
- Willow weave material (long (i.e., > 1 m), limbed branches of ¼" to 2" diameter willow branches
- Cobble, gravel, sand and mud

Tools needed

- Personal Protective Equipment (see Chapter 6)
- Cutting tools: loppers and chainsaw minimally; optionally hand saw(s), pruning shears
- Digging tools: Shovels & optionally pick-axe or digging bars
- 5 Gallon Buckets - for filling and moving finer fill material from source areas to BDA
- Optionally -cam straps are sometimes helpful to bundle together branches for easier hauling from source or staging areas to BDA.

Instructions

1. Decide location of BDA dam crest, configuration (e.g., straight or convex downstream), and crest elevation (use landscape flags if necessary). Position yourself with your eye-level at proposed crest elevation of dam (make sure it is < 1.5 meters in height) and look upstream to find where the pond will backwater to. Adjust crest elevation as necessary to achieve desired size of pond, inundation extent, and overflow patterns. If concerned about head drop over BDA, build a secondary BDA downstream with a crest elevation set to backwater into the base of this BDA (and lessen head drop or elevation difference between water surface in pond and water surface downstream of BDA).
2. Install posts with hydraulic post pounder into stream bed and banks in configuration as shown.
3. Trim (with chainsaw) posts to level, desired crest elevation (this can be done at end instead).
4. Weave willow branches in between posts across the channel. Pack stream substrate from area to be ponded against upstream face of dam to 'plug' up.
5. Work a willow mattress (laying branches parallel to flow) into dam on downstream side to provide energy dissipation for overtopping flows.
6. If desired, and time permits, attempt to plug up BDA with mud and organic material (small sticks and turf) in order to flood pond to crest elevation. Optionally, you can leave this for maintenance by beaver or for infilling with leaves, woody debris and sediment.

Notes

- Resist the temptation to overbuild the BDA.
- A BDA that 'breaches' or 'blows out', just like natural beaver dams do, is not a 'failure' if designed to accommodate such a response. Often, BDAs that blow out or breach provide improved and more complex habitat.
- Design life: < 1 year (note actual life may last many years or even decades).

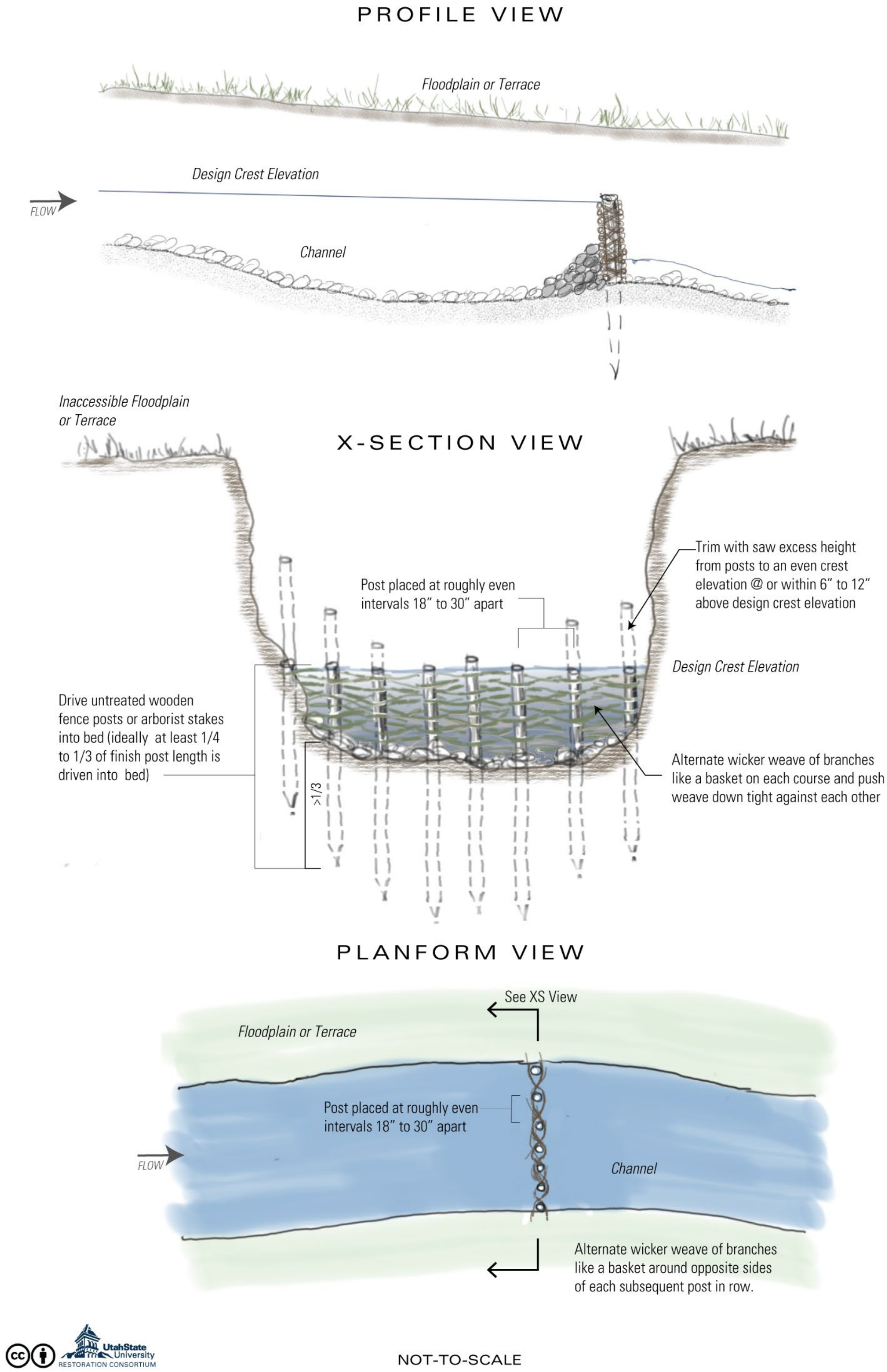


Figure 36 – Typical schematics of the first generation of wicker-weave post-assisted BDAs (similar to Figure 20) using a single row of posts and essentially building a vertical wall. We do not recommend this method, as the wall results in an overflow scour pool that can undermine the base, but in situations where the bed can aggrade quickly in the pond, the deposit can act to stabilize the dam.

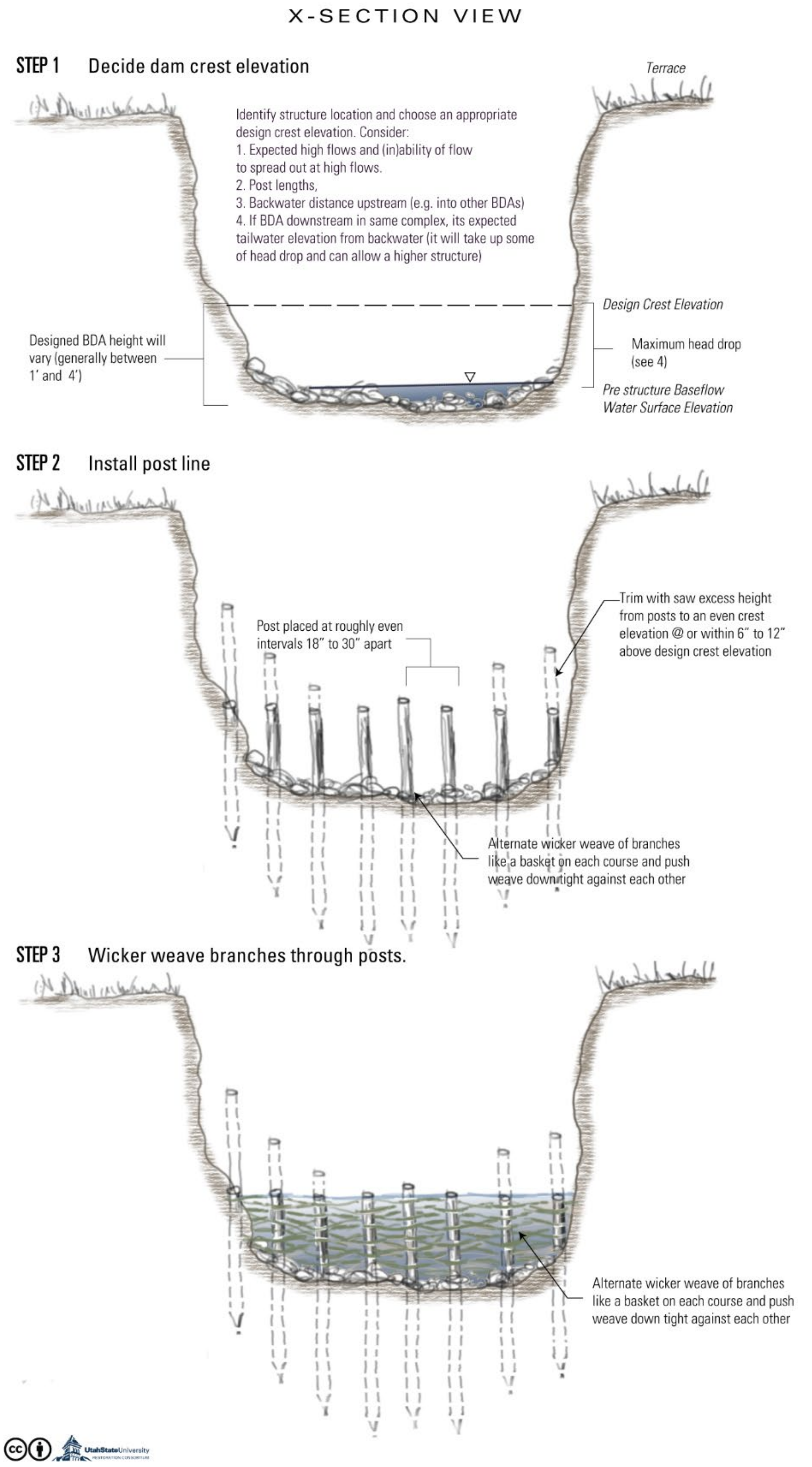


Figure 37 – Typical construction sequence for a post-line wicker weave BDA. First, a single row of posts is installed, and then the wicker weave is placed, and then an attempt is made to patch up the leaks.

Improvements to the Post-Line Wicker Weave BDA – Double Rows of Posts & Mattress

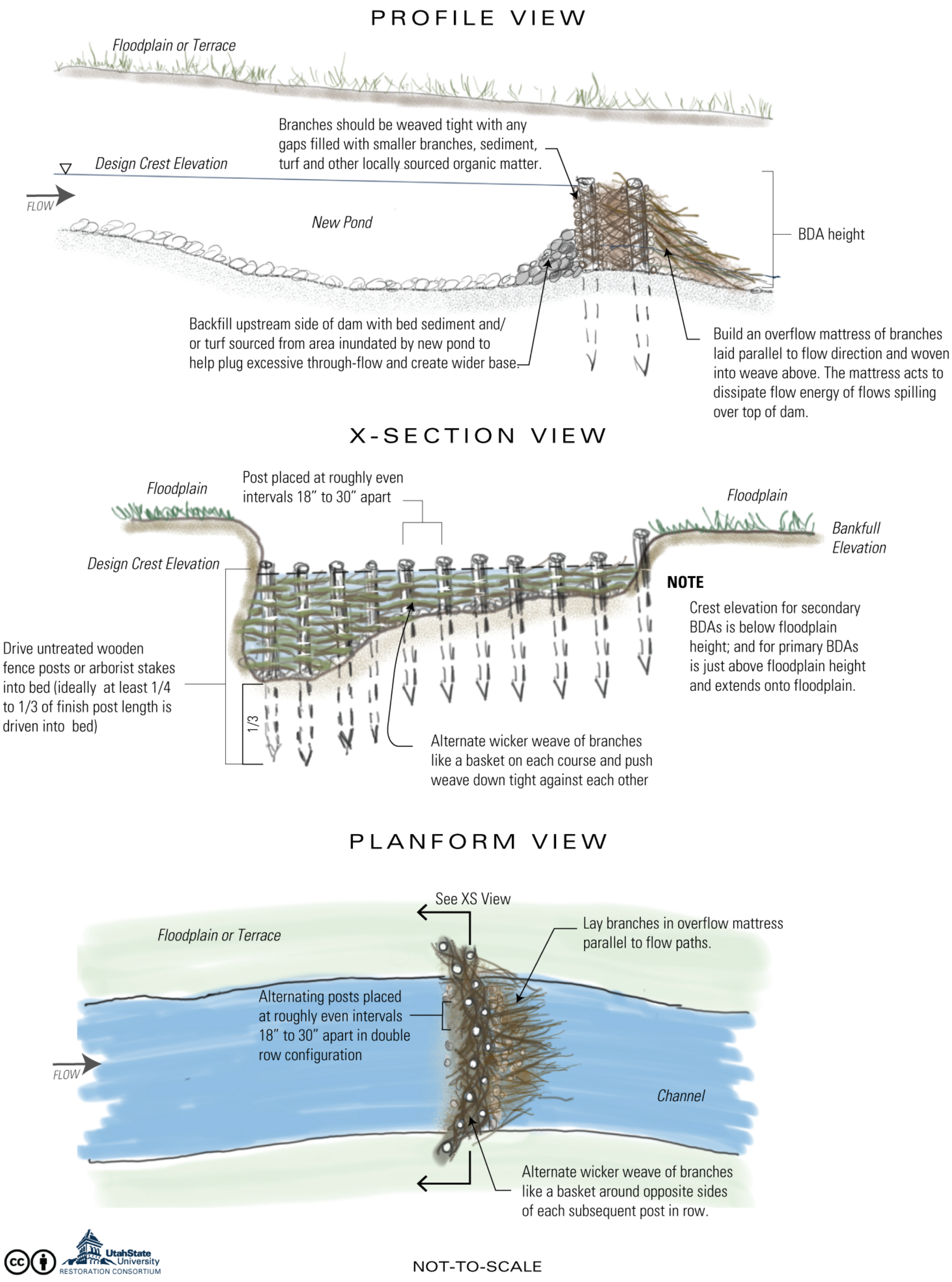


Figure 38 – Typical schematic sketches of a post-line wicker weave BDA, with simple improvements to include a double row of alternating posts, a convex downstream crest orientation, and most importantly an overflow mattress to dissipate flow over the top of the dam.

BDAs: General Considerations to Enhance Structure Efficiency

While the structure design generally describes the what (form), how (function), and where (location) of structures, several other attributes should help refine these designs (Table 4). Recognizing and working with these attributes will increase the ability of structures to promote the "system to do the work." Below we discuss some general attributes to become aware of while designing structures.

Table 4 –Flow, geomorphic and vegetation characteristics to consider when designing BDAs.

Characteristic	Importance
Flow	
Flow regime	Streams with high peak flows and or flashy hydrographs are more likely to cause structural failure of BDAs.
Unit stream power	Channels with higher gradient and discharge will exert more force on a BDA and make it more susceptible to breaching or blowing out.
Geomorphic	
Floodplain accessibility	In reaches with accessible floodplains, BDAs can promote lateral connectivity. Where high flows can disperse over the floodplain, the force exerted on BDAs decreases.
Channel bed substrate	Sand bedded streams and rivers have more highly mobile and erodible channel beds, making the BDAs more vulnerable to scour.
Channel gradient	Channel gradient influences the ponded extent a BDA can force. Steeper channels require higher dam crest elevations in order to create larger ponds. The crest elevation of BDAs does not have to be as high in low gradient systems to achieve the same pond length.
Channel width	Wider channels will require more material and time to create a BDA. More resources dedicated to a single structure often mean fewer resources available for additional structures.
Bank height	The depth of a pond that a BDA is capable of creating depends on the height of the adjacent banks. Taller banks allow for deeper dam pools, but BDAs may be more prone to structural failure. Shorter banks will create smaller pools but more easily promote overbank flows.
Vegetation	
Presence/absence and type	The presence of riparian vegetation and cover is a critical consideration if BDAs are for beaver translocation. Additionally, recruitment of riparian vegetation will also depend on the presences and location of desired and species.

Structure Design Specifications and Layout

In addition, practitioners have a number of structure-specific design considerations to address (Table 5). BDAs can be described by their type (primary or secondary), crest elevation, crest length, and whether they use posts. Each of these attributes is directly related to both the spatial extent that a BDA is capable of influencing as well as the time and resources required to construct it. In general, we differentiate between two 'types' of BDAs, primary BDAs and secondary BDAs. Primary BDAs tend to have a crest elevation equal to, or greater than bankfull elevation, and force the upstream ponding that would be suitable for beaver translocation. By contrast, secondary dams tend to have lower crest elevations and create smaller ponds. Crest elevation is an important design attribute because it determines the maximum pond depth, the extent of the backwater and whether a BDA can force floodplain connectivity during baseflow conditions. Crest elevation can be described in relative terms (e.g., below, equal to, or greater than bankfull) or using absolute measurements (e.g., 1.25 m). Whether the crest extends onto adjacent floodplain or is contained within the channel will determine the extent to which a BDA can force overbank flow during baseflow conditions. It also is a major factor in determining the areal extent of ponding. Not all BDAs require the use of posts. However, if site conditions (e.g., peak flows) are likely to limit BDA persistence, posts may provide additional stability.

The most important aspect of designing an individual BDA is to remember that restoration goals are most likely to be achieved at the scale of the complex or multiple complexes rather than any individual structure (Chapter 5: Shahverdian et al., 2019b). A common mistake practitioners make is to over-emphasize the importance of any particular structure, which leads to over-building and spending valuable resources on a single structure rather than extending their restoration footprint by building more structures (i.e., strength in numbers). However, in instances where a relic channel or floodplain inundation can be activated with one or two BDAs, then the extra time spent on building more robust structures might outweigh the loss a few other structures.

In practice, the extent to which BDA complexes, like individual BDAs, can achieve specific restoration objectives is constrained by their location. Therefore, matching BDA complex design/goals to the local setting is essential. However, if the switch can be made from mimicking beaver dam activity, to promoting it, to beaver dam activity becoming a self-sustaining process (Chapter 2: Wheaton et al., 2019), achieving broader restoration goals is likely.

Table 5- Design choices to be made when designing BDAs.

Design decisions	Description
Location/type	The location and type (primary or secondary) of BDA constrains its ability to influence flow.
Crest elevation	The crest elevation determines whether BDAs can force flows overbank during baseflow conditions, and determines the length of backwater forced and maximum pond depth.
Crest length	The crest length determines whether a BDA will extend onto the floodplain or be contained within the channel. It also determines the total ponded area forced by the BDA.
Crest orientation	The crest orientation of the dam relative to the channel should be considered if there is any desire to direct flow in a particular way. Orientations can be perpendicular or angled, and the crest path itself can be straight or convex, but concave should be avoided (Figure 39).
Posts	Posts may be required where the ability of BDAs to withstand annual peak flows is a concern.

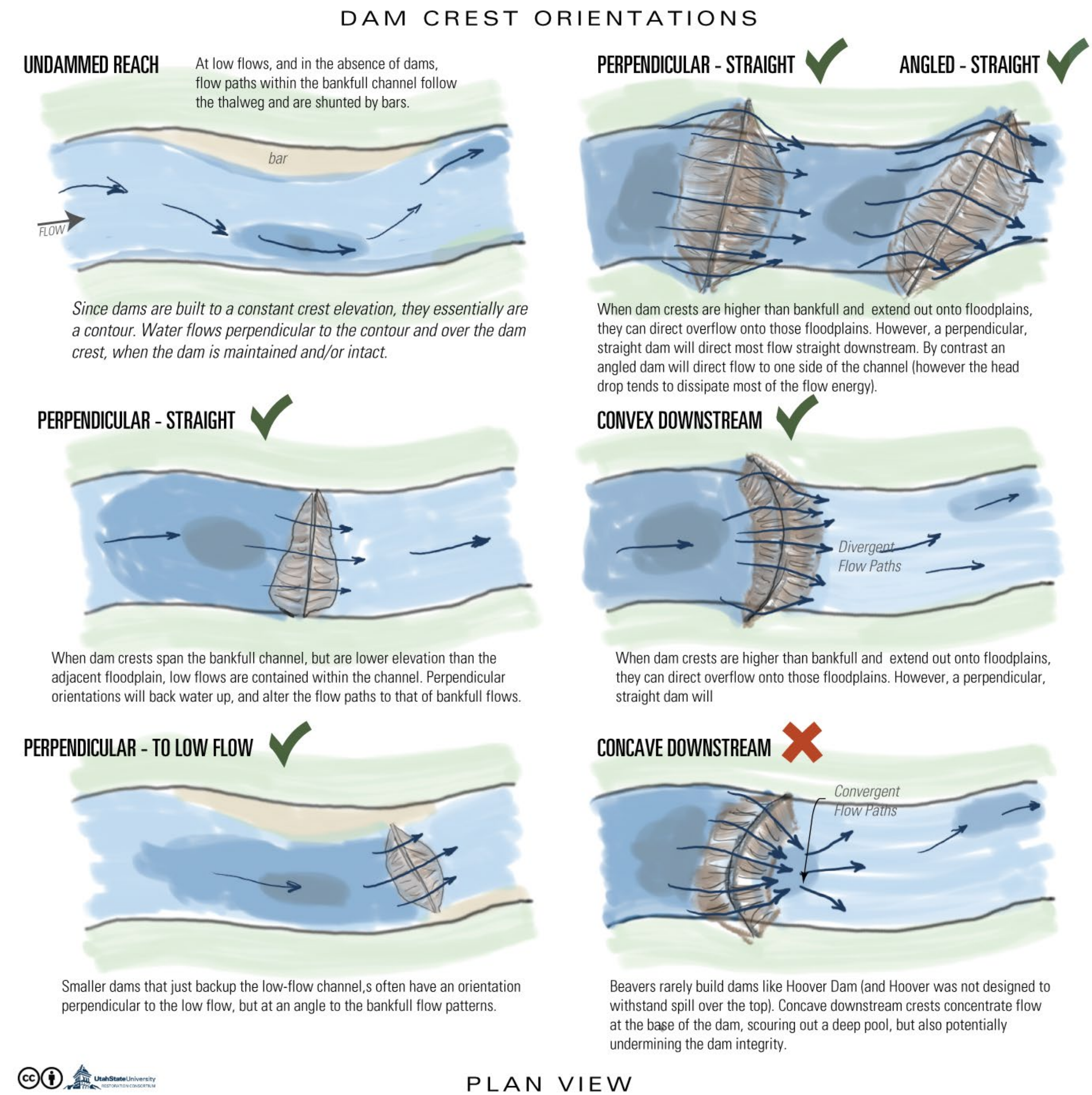


Figure 39 – BDAs can be built with various crest orientations (perpendicular, angled, convex downstream). Since a BDA crest is essentially a contour line (a line of equal elevation), flow paths will flow perpendicular over the crest. As such, if the intention is to direct flows in particular directions, think about your crest layout.

Guidelines for Post Placement

If a post-assisted BDA or post-line wicker weave is used, one of the critical construction considerations is how the posts are driven, and whether a staggered double-row placement is used (Figure 40). We prefer double rows of posts staggered because they encourage construction of a wider based (streamwise) dam, and avoid building a wall. Also, if posts are driven in at angle, make sure they tilt inward toward the crest of the dam.

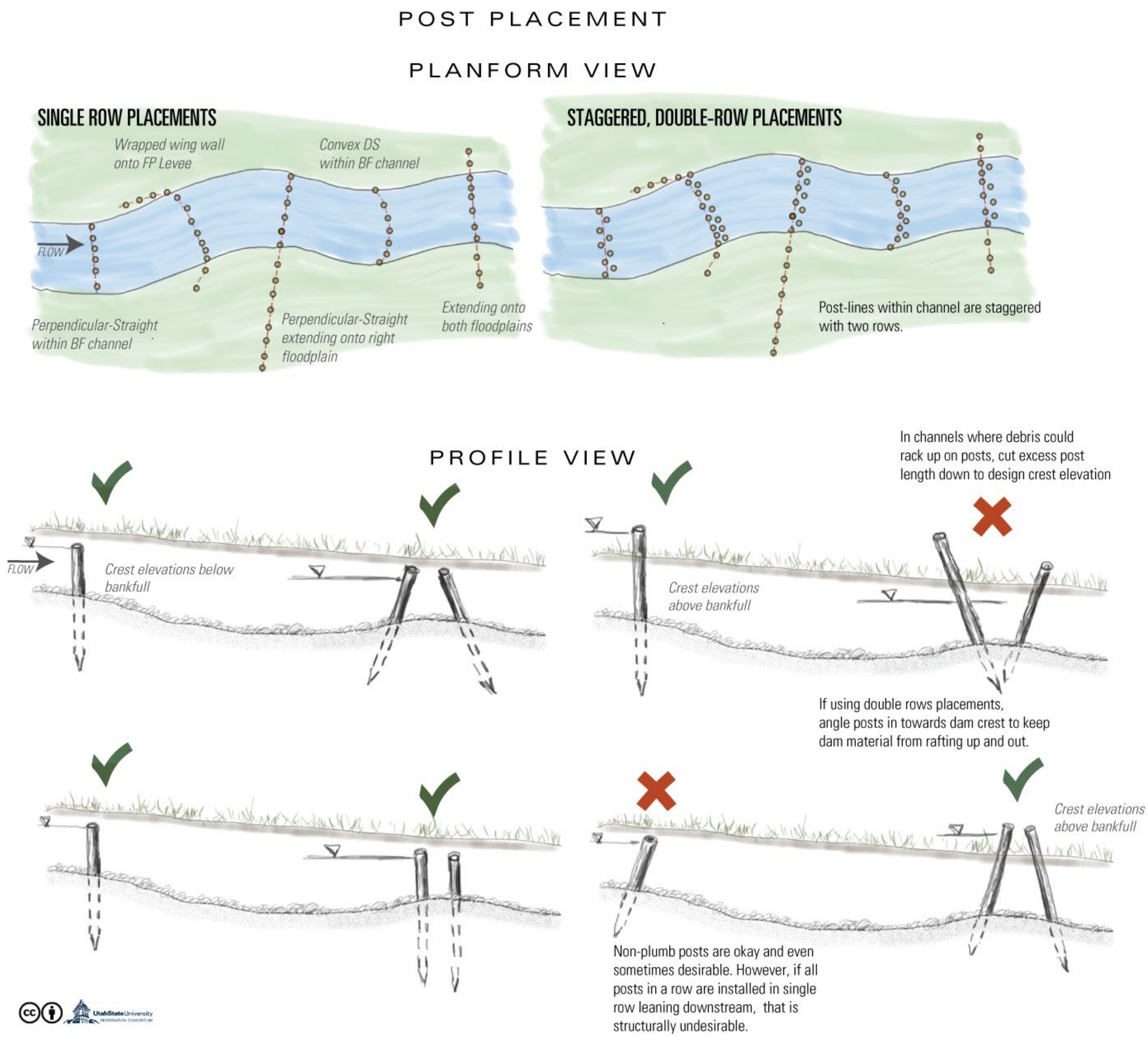


Figure 40 – Post placement considerations. When post are used in BDAs, consideration should be given to whether single-row or staggered double-row placements are used.

Chapter 4 - REFERENCES

Beechie, T.J. and Bolton, S., 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries, 24(4): 6-15

Bennett, S., 2018. Asotin Creek Intensively Monitored Watershed: 2018 Progress Memo, December 31, 2018. Prepared for the Washington State Recreation and Conservation Office, Olympia, WA.

Bennett, S. and Bouwes, N., 2009. Southeast Washington Intensively Monitored Watershed Project: Selection Process and Proposed Experimental and Monitoring Design for Asotin Creek. State of Washington, Recreation and Conservation Office, Olympia, Washington

Bennett, S., Pess, G., Bouwes, N., Roni, P., Bilby, R.E., Gallagher, S., Ruzycki, J., Buehrens, T., Krueger, K., Ehinger, W., Anderson, J., Jordan, C., Bowersox, B. and Greene, C., 2016. Progress and Challenges of Testing the Effectiveness of Stream Restoration in the Pacific Northwest Using Intensively Monitored Watersheds. Fisheries, 41(2): 92-103. DOI: 10.1080/03632415.2015.1127805

Bennett, S.N., Wheaton, J.M., Bouwes, N., Camp, R., Jordan, C.E., Macfarlane, W.W., Maestas, J.D., Shahverdian, S. and Weber, N., 2019a. Chapter 6 - Low-Tech Restoration Project Implementation. In: J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas and S.M. Shahverdian (Editors), Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Utah State University Restoration Consortium, Logan, Utah, pp. 36

Bennett, S.N., Wheaton, J.M., Bouwes, N., Jordan, C.E., Macfarlane, W.W., Maestas, J.D., Portugal, E. and Shahverdian, S.M., 2019b. Chapter 3 – Planning for Low-Tech Process-Based Restoration. In: J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas and S. Shahverdian (Editors), Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Utah State University Restoration Consortium, Logan, Utah, pp. 24

Bouwes, N., Bennett, S. and Wheaton, J., 2016a. Adapting Adaptive Management for Testing the Effectiveness of Stream Restoration: An Intensively Monitored Watershed Example. Fisheries, 41(2): 84-91. DOI: 10.1080/03632415.2015.1127806

Bouwes, N., Weber, N., Jordan, C.E., Saunders, W.C., Tattam, I.A., Volk, C., Wheaton, J.M. and Pollock, M.M., 2016b. Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (Oncorhynchus mykiss). Scientific reports, 6: 28581

Burchsted, D., Daniels, M., Thorson, R. and Vokoun, J., 2010. The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. Bioscience, 60(11): 908-922. DOI: 10.1525/bio.2010.60.11.7

Butler, D.R. and Malanson, G.P., 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology, 13(1-4): 255-269

Camp, R., 2015a. Short Term Effectiveness of High Density Large Woody Debris in Asotin Creek as a Cheap and Cheerful Restoration Restoration Action. MS Thesis, Utah State University, Logan, UT, 178 pp. Available at: http://digitalcommons.usu.edu/etd/4417/.

Camp, R.J., 2015b. Short-term effectiveness of high density large woody debris, a cheap and cheerful restoration action, in Asotin Creek. Master's thesis. Utah State University, Logan, Utah.

Cluer, B. and Thorne, C., 2013. A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. River Research and Applications, 30(2): 135-154. DOI: 10.1002/rra.2631

Cluer, B. and Thorne, C., 2014. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications, 30(2): 135-154

Collier, E., 1959. Three Against the Wilderness. . Surrey, BC: Touchwood

Cooke, H.A. and Zack, S., 2008. Influence of beaver dam density on riparian areas and riparian birds in shrubsteppe of Wyoming. Western North American Naturalist: 365-373

Cutting, K.A., Ferguson, J.M., Anderson, M.L., Cook, K., Davis, S.C. and Levine, R., 2018. Linking beaver dam affected flow dynamics to upstream passage of Arctic grayling. Ecology and Evolution. DOI: 10.1002/ece3.4728

Demmer, R. and Beschta, R.L., 2008. Recent history (1988–2004) of beaver dams along Bridge Creek in central Oregon. Northwest Science, 82(4): 309-318

Gurnell, A., Piegay, H., Swanson, F. and Gregory, S., 2002. Large wood and fluvial processes. Freshwater Biology, 47(4): 601-619

Kraebel, C.J. and Pillsbury, A.F., 1934. Handbook of Erosion Control in Mouuntain Meadows, U.S. Forest Service, California Forest and Range Experiment Station, Berkeley, CA.

Levine, R. and Meyer, G.A., 2014. Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. Geomorphology, 205(0): 51-64. DOI: 10.1016/j.geomorph.2013.04.035

Lokteff, R.L., Roper, B.B. and Wheaton, J.M., 2013. Do beaver dams impede the movement of trout? Transactions of the American Fisheries Society, 142(4): 1114-1125

Loughin, T., 2010. Comparison of the statistical power of BACI and hierarchical-staircase experimental designs to detect changes in fish abundance and habitat change within the framework of the Asotin Creek Intensively Monitored Watershed Project: Progress Report. September 30, 2010. Prepared by T. Loughin, Statistics and Actuarial Science, Simon Fraser University, Surrey, BC. Prepared for Eco Logical Research Inc. Providence, Utah.

Majerova, M., Neilson, B.T., Schmadel, N.M., Wheaton, J.M. and Snow, C.J., 2015. Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. Hydrol. Earth Syst. Sci., 19(8): 3541-3556. DOI: 10.5194/hess-19-3541-2015

McKinstry, M.C. and Anderson, S.H., 2002. Survival, fates, and success of transplanted beavers, Castor canadensis, in Wyoming. Canadian Field-Naturalist, 116(1): 60-68

Naiman, R.J., Johnston, C.A. and Kelley, J.C., 1988. Alteration of North American streams by beaver. BioScience, 38(11): 753-762

Nyssen, J., Pontzeele, J. and Billi, P., 2011. Effect of beaver dams on the hydrology of small mountain streams: example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. Journal of hydrology, 402(1): 92-102

Pollock, M., Lewallen, G., Woodruff, K., Jordan, C. and Castro, J., 2015. The beaver restoration guidebook: Working with beaver to restore streams, wetlands, and floodplains. United States Fish and Wildlife Service

Pollock, M.M., Beechie, T.J., Wheaton, J.M., Jordan, C.E., Bouwes, N., Weber, N. and Volk, C., 2014. Using beaver dams to restore incised stream ecosystems. BioScience, 64(4): 279-290

Pollock, M.M., Wheaton, J.M., Bouwes, N., Volk, C., Weber, N. and Jordan, C.E., 2012. Working with beaver to restore salmon habitat in the Bridge Creek intensively monitored watershed: design rationale and hypotheses. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-120, 47 p.

Roni, P., Beechie, T., Pess, G., Hanson, K. and Jonsson, B., 2015. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences, 72(3): 466-478. DOI: 10.1139/cjfas-2014-0344

Shahverdian, S. and Wheaton, J.M., 2017. Grouse Creek Restoration Adaptive Beaver Management Plan, Prepared for Utah Division of Wildlife Resources by Anabranch Solutions, LLC, Logan, UT. DOI: 10.13140/RG.2.2.31798.34885.

Shahverdian, S., Wheaton, J.M., Bennett, S.N., Bouwes, N. and Maestas, J.D., 2019a. Chapter 1 – Background & Purpose. In: J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas and S.M. Shahverdian (Editors), Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Utah State University Wheaton Restoration Consortium, Logan, Utah, pp. 28

Shahverdian, S.M., Bennett, S.N., Bouwes, N., Camp, R., Portugal, E. and Wheaton, J.M., 2019b. Chapter 5- Designing Low-Tech Restoration Projects. In: J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas and S. Shahverdian (Editors), Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Utah State University Restoration Consortium, Logan, Utah, pp. 26

Thompson, D. and Stull, G., 2002. The development and historic use of habitat structures in channel restoration in the United States: the grand experiment in fisheries management. Géographie physique et Quaternaire, 56(1): 45-60

Wall, C.E., Bouwes, N., Wheaton, J.M., Bennett, S.N., Saunders, W.C., McHugh, P.A. and Jordan, C.E., 2017. Design and monitoring of woody structures and their benefits to juvenile steelhead (Oncorhynchus mykiss) using a net rate of energy intake model. Canadian Journal of Fisheries and Aquatic Sciences, 74(5): 727-738. DOI: 10.1139/cjfas-2016-0131

Wall, C.E., Bouwes, N., Wheaton, J.M., Saunders, C. and Bennett, S., 2016. Net rate of energy intake predicts reach-level steelhead (Oncorhynchus mykiss) densities in diverse basins from a large monitoring program. Canadian Journal of Fisheries and Aquatic Sciences, 73: 1081–1091

Walter, R.C. and Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science, 319(5861): 299-304

Weber, N., Bouwes, N., Pollock, M.M., Volk, C., Wheaton, J.M., Wathen, G., Wirtz, J. and Jordan, C.E., 2017. Alteration of stream temperature by natural and artificial beaver dams. PLOS ONE, 12(5): e0176313. DOI: 10.1371/journal.pone.0176313

Welsh, S., 2012. Geomorphic Changes Following Beaver Dam Failure and Abandonment. MS Thesis, Utah State University, Logan, UT, 72 pp. Available at: http://digitalcommons.usu.edu/gradreports/217/`.

Westbrook, C.J., Cooper, D.J. and Baker, B.W., 2006. Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. Water Resources Research, 42(6)

Wheaton, J., Bennett, S., Bouwes, B. and Camp, R., 2012. Asotin Creek Intensively Monitored Watershed: Restoration plan for Charley Creek, North Fork Asotin, and South Fork Asotin Creeks. DRAFT: April 7, 2012. Prepared for the State of Washington Recreation and Conservation Office, Olympia, WA. Prepared by Eco Logical Research Ltd

Wheaton, J.M., Bennett, S.N., Bouwes, N., Camp, R., Maestas, J.D. and Shahverdian, S.M., 2019. Chapter 2 – Principles of Low-Tech Process-Based Restoration. In: J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas and S.M. Shahverdian (Editors), Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Utah State University Restoration Consortium, Logan, Utah, pp. 31

Wohl, E., 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society, 10(2)

Wohl, E., 2013. Floodplains and wood. Earth-Science Reviews, 123: 194-212

Wohl, E., 2014. A legacy of absence. Progress in Physical Geography, 38(5): 637-663. DOI: 10.1177/0309133314548091