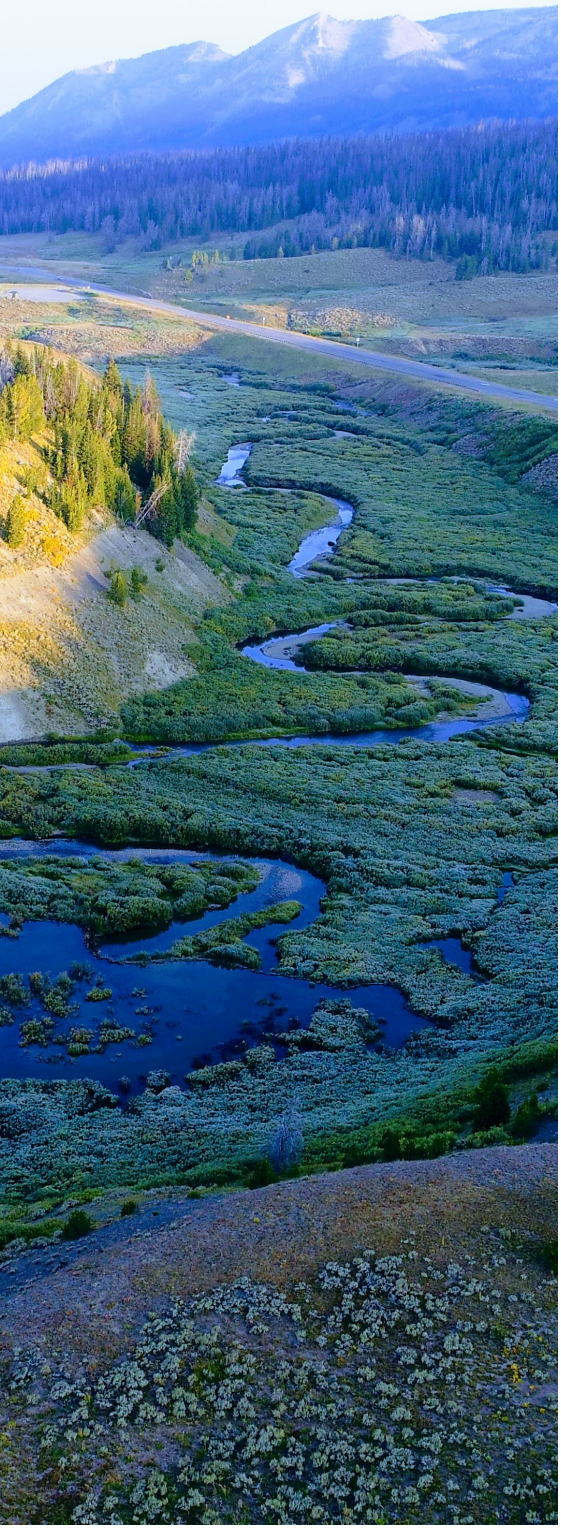

LOW-TECH PROCESS-BASED RESTORATION OF RIVERSCAPES

DESIGN MANUAL

Edited by: Joseph M. Wheaton, Stephen N. Bennett, Nicolaas Bouwes, Jeremy D. Maestas & Scott M. Shahverdian

Utah State University
RESTORATION CONSORTIUM

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March 2019 – Version 1.0

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EXECUTIVE SUMMARY

Stream and riverine landscapes or riverscapes are made up of a series of interconnected floodplain, groundwater, channel habitats, and their associated biotic communities that are maintained by physical and biological processes that vary across spatial and temporal scales (Ward, 1998). An over-arching goal of riverscape restoration and conservation is to improve the health of as many miles as possible, while ensuring those systems achieve and maintain their potential in self-sustaining ways. This design manual is intended to help the restoration community more efficiently maximize efforts to initiate self-sustaining recovery of degraded riverscapes at meaningful scales.

Structural-starvation of wood and beaver dams in riverscapes is one of the most common impairments affecting riverscape health. At a basic level, a riverscape starved of structure drains too quickly and efficiently, lacks connectivity with its floodplain and has simpler more homogenous habitat. By contrast, a riverscape system with an appropriate amount of structure provides obstructions to flow. What follows in the wake of structurally-forced hydraulic diversity are more complicated geomorphic processes that result in far more diverse habitat, resilience, and a rich suite of associated ecosystem services.

The purpose of this design manual is to provide restoration practitioners with guidelines for implementing a subset of low-tech tools—namely post-assisted log structures (PALS) and beaver dam analogues (BDAs)—for initiating process-based restoration in structurally-starved riverscapes. While the concept of process-based restoration in riverscapes has been advocated for at least two decades, details and specific examples on how to implement it remain sparse. Here, we describe 'low-tech process-based restoration' as a practice of using simple, low unit-cost, structural additions (e.g., wood and beaver dams) to riverscapes to mimic functions and initiate specific processes. Hallmarks of this approach include:

- An explicit focus on the processes that a low-tech restoration intervention is meant to promote
- A conscious effort to use cost-effective, low-tech treatments (e.g., hand-built, natural materials, non-engineered, short-term design life-spans)
- 'Letting the system do the work', which defers critical decision making to riverscapes and nature's ecosystem engineers

Importantly, the manual conveys underlying principles guiding use of low-tech tools in process-based restoration in systems impaired by insufficient structural complexity. Although intended to be simple, low-tech restoration still requires some basic understanding of watershed context, riverscape behavior and channel evolution, and careful planning. The manual provides interested practitioners with sufficient conceptual and applied information on planning, design, permitting, construction and adaptive management to get started, as well as references to additional information and resources. Detailed design and construction guidance is provided on two effective low-tech tools: 1) beaver dam analogues (BDAs) for mimicking beaver dam activity, and 2) post-assisted log structures (PALS) for mimicking wood accumulation in riverscapes. Throughout the manual, readers are reminded that the structures themselves are not the solution, but rather a means to initiate specific, desirable processes. Ultimately, embracing the design principles will help practitioners better understand the 'why' behind structural interventions and allow for more efficient and effective riverscape restoration.

> ***"What if restoration was about stream power doing the work, not diesel power?"***
>
> *— Jared McKee (USFWS)*


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ACKNOWLEDGEMENTS

The authors and editors are indebted to many scientists and practitioners before us (see Chapter 1: Shahverdian et al., 2019). There are too many individuals not mentioned here specifically whom we owe gratitude to for their support, inspiration and collaboration. This includes many colleagues at Utah State University and the entire mix of the Wheaton Ecogeomorphology Topographic Analysis Lab's past and present researchers, students and technicians. This design manual and the majority of the authorship team really grows out of two Intensively Monitored Watershed (IMW) efforts – Asotin Creek, Washington and Bridge Creek, Oregon. There are at least 17 IMWs established across the Pacific Northwest in response to the conservation and recovery of ESA-listed (Endangered Species Act) salmon and steelhead populations (Bennett et al., 2016). IMW projects are long-term (> 10 years), watershed-scale experiments with the purpose of i) testing if restoration is effective at increasing fish production (abundance, growth, and/or survival) and productivity (number of juveniles/female spawner), ii) determining the link(s) between physical or biological responses to restoration and changes in fish populations, and iii) extrapolating knowledge gained to other watersheds to help increase restoration effectiveness. This manual is, in part, a fulfillment of the third goal of IMWs – transferring the lessons learned about restoration of riverscapes from Asotin and Bridge IMWs into better, more effective restoration across a broad set of structurally-starved riverscapes.

Both the Bridge Creek and Asotin IMW projects focused on innovative, low-tech restoration methods of 'how' to restore habitat and understanding the processes that led to fish population responses. The Asotin IMW project in southeast Washington focused on restoring the processes of wood accumulation in a system starved of its natural wood loading rate, by using high-density large woody debris ($_{HD}$LWD) and was primarily led by Stephen Bennett with help from Reid Camp, Joe Wheaton, Andrew Hill, Nicolaas Bouwes and an army of hard-working and talented construction and monitoring crews. The Asotin Intensively Monitored Watershed (IMW) began in 2008 and is a collaborative multi-agency initiative sponsored by the Snake River Salmon Recovery Board (SRSRB). The majority of the IMW takes place on Washington Department of Fish and Wildlife (WDFW) and US Forest Service (USFS) land, and both agencies have supported the development and implementation of the project. We are particularly grateful for support from Steve Martin and John Foltz of the SRSRB, Bob Dice of the Blue Mountains Wildlife Management Area, Megan Stewart of the Asotin County Conservation District, the Koch and Thornton families, Ethan Crawford, Bruce Heiner and Mike Herr of WDFW, the Asotin County Public Utility Department, and Del Groat (now retired) and Billy Bowles of the USFS. Brad Johnson, of the Palouse Conservation District, deserves special mention for being an early adopter of PALS and instrumental in his efforts to promote low-tech restoration throughout southeast Washington. The Bridge Creek project in central Oregon focused on using beaver dam analogues (BDAs) to promote beaver dam activity, which would in turn accelerate recovery on an incised channel (Pollock et al., 2012; Pollock et al., 2014). The Bridge Creek IMW and was co-led by Chris Jordan, Nicolaas Bouwes and Michael Pollock with support from Nick Weber, Ian Tattam, Joe Wheaton, Carol Volk, Gus Wathan, Jake Wirtz, and many fantastic construction and monitoring crews, and many beaver. The broader motivation of the Bridge Creek project was to use those restoration treatments to produce a treatment effect large enough to produce a population level response in ESA-listed steelhead salmon, which Bouwes et al. (2016) were able to document (Goldfarb, 2018). Growing out of the Bridge Creek IMW, and in conjunction with the efforts by the Methow Beaver Project, Michael Pollock and Chris Jordan teamed up with a broader team to produce the Beaver Restoration Guidebooks (Pollock et al., 2015b; Pollock et al., 2018b), which have a more beaver-centric focus than this manual.

Our original attempt to develop this design manual emerged from concerted efforts to implement some low-tech process-based restoration demonstration projects (primarily focused on BDAs originally) in Utah beginning in 2014. These efforts were in partnership with Kent Sorenson at the Utah Division of Wildlife Resources and supported by the Utah Watershed Restoration Initiative (USU Awards: 130942, 150102, 200225, 200896). The idea Kent pushed for was to provide some basic guidance on 'how to' do low-tech process-based restoration in streams in Utah through a mix of demonstration projects and some guidelines. In terms of a demonstration project, it took a few attempts to actually get projects on the ground. An initial effort in baseline monitoring, evaluation and design in Rich County was abandoned prior to construction after objections from neighbors due to misconceptions about beaver. A second start was a good project, with land owners that were happy to use beaver dam analogues and beaver to improve stream health and range health through sub-irrigation of valley bottoms, but understandably did not want to be in the 'spotlight'

as the face of a demonstration project. Finally, in 2016 Utah State University began a partnership with the Tanner family and the Utah Division of Wildlife Resources (UDWR). Jay and Diane Tanner were already very involved in upland watershed restoration efforts to improve habitat for sage grouse and overall range health. They were willing and wonderful partners. Together, we developed and implemented a trial stream restoration project to inform a greater demonstration project to show how low-tech stream restoration techniques can be used on actively managed grazing lands to benefit cattle, downstream water users, and stream and riparian condition. Using lessons learned from the trial project, a full-scale restoration plan treating approximately 6+ miles (10+ km) of stream along three creeks in the Grouse Creek watershed was developed (Shahverdian et al., 2017b). In April 2017, Anabranch Solutions LLC was contracted to develop and implement a restoration design plan based on the restoration proposal developed by Shahverdian et al. (2017b). Development of a detailed design plan and implementation took place between April and July 2017 (Shahverdian and Wheaton, 2017c). The Shahverdian et al. (2017b) restoration proposal and the Shahverdian and Wheaton (2017c) design advocated and relied on the future translocation of beaver into the Grouse Creek Watershed. Restoration treatments were specifically designed to promote the successful translocation of beaver in areas with high quality beaver habitat (Shahverdian and Wheaton, 2017b). In 2018, beaver were finally reintroduced to the Grouse Creek watershed, in accordance with the updated Utah Beaver Management Plan, and appear to be successfully recolonizing. We are grateful to ranchers and land owners like Jay Tanner, Diane Tanner, Jay Wilde, Rebecca Patton and many others across the Western states who have had the foresight to try out some innovative approaches to conservation like those discussed here. Their willingness to try out low-tech restoration approaches helped pave the way for others to follow in their footsteps, and is actively giving practitioners the confidence to try these low-tech approaches.

Starting in 2015, Elijah Portugal (formerly Utah State University and Anabranch Solutions; currently California Department of Fish & Wildlife) and Joe Wheaton (Utah State University) began an effort, funded by the Utah Watershed Restoration Initiative (USU Awards: 130942, 150102, 200225, 200896), to put a design manual together. Much of the material from that effort is in this manual. Parallel to that, a separate process focused more narrowly on beaver restoration was led by Janine Castro, Michael Pollock, Chris Jordan, Kent Woodruff and Gregory Lewellan. Their effort culminated in a 'Beaver Restoration Guidebook', a version 1 that was published in 2015 (Pollock et al., 2015b) and a version 2 was published in 2018 (Pollock et al., 2018b). Some of the content of that guidebook came out of the abovementioned Bridge Creek collaboration (work with Pollock, Jordan, Bouwes, Weber and Wheaton), but it also provides critical background on beaver ecology (§1), and a range of beaver restoration and management considerations (§2) including beaver translocation (Woodruff and Pollock, 2015). A brief chapter on beaver dam analogues appears in Chapter 6 of both versions of the guidebook (Pollock et al., 2015a; Pollock et al., 2018a), which was co-authored by Nick Weber (a contributor to this manual). A 'place-holder' chapter on 'Comparison of BDAs with Other, Similar Structures' by Portugal and Pollock (2015) was in the first version of the guidebook. We are grateful to Kent Woodruff, Gregory Lewellan and Michael Pollock for many conversations and debates that have helped refine this manual. We are careful here not to duplicate that effort, but rather provide a complimentary resource that places beaver-assisted restoration and beaver-mimicry in a broader context.

One of the other visionaries behind this push for low-tech process-based restoration was Justin Jimenez at the Utah Bureau of Land Management. Justin was an early supporter and proponent of low-tech restoration and was the driving force behind getting demonstration projects going in Utah. For example, a desert river restoration led by Bureau of Land Management (BLM) and Utah Division of Wildlife Resources (UDWR) on the San Rafael River (Laub et al., 2015; Shahverdian et al., 2017a) was an excellent test of these techniques and the underlying principles in a new environment. These efforts extended to another joint demonstration project with BLM, the Utah Watershed Restoration Initiative and UDWR on Birch Creek (Shahverdian and Wheaton, 2017a) and the extension of the Grouse Creek project from private to public lands.

The timing of the release of this manual and the expansion from an effort just focused on providing guidance on BDAs was delayed by the recognition that these approaches were part of a broader suite of low-tech restoration approaches beyond just beaver. Bill Zeedyk's pioneering work on 'induced-meandering' and use of low-tech structures are excellent examples of low-tech process-based restoration (Maestas et al., 2018). The Zeedyk and Clothier (2009) book 'Let the

Water do the Work' was an inspiration for this manual. We are grateful to the hundreds of willing participants of over 40 workshops and short-courses we have now taught on the topics covered in this design manual who acted as guinea pigs for different ways to convey the messages and technical material found in this manual. Their patience with different metaphors, different ways of teaching and explaining these concepts, and waiting for this manual was much appreciated. While some of the specific restoration actions we had been taking were clear enough (e.g., building post-assisted log structures (PALS), beaver dam analogues (BDAs) and moving beaver around), it took us a while to find the threads and narrative that weave together these related activities into a broader, coherent framework.

We are also grateful to several peer reviewer for their thoughtful and constructive comments that greatly improved the manual. These include Timmie Mandish (USDA NRCS), Kent Sorenson (Utah Division of Wildlife Resources), Tyler Thompson (Utah Watershed Restoration Initiative), and Scott Nicolai (Yakama Nations Fisheries).

Finally, this first release of this design manual is in thanks to the generous support of the USDA - Natural Resources Conservation Service's Working Lands for Wildlife Initiative through Pheasants Forever (USU Award: 201426). As part of that effort through the Sage Grouse Initiative, we were able to deliver a series of workshops to NRCS conservationists and their partners throughout the west and produce this design manual. This series was envisioned by Jeremy Maestas (NRCS/SGI) and is possible thanks to partner matches by various local organizations and matching funds from Utah State University. This grew out of the successful 2016 Enhancing Mesic Habitat Resilience in Sagebrush Ecosystems Workshop at Utah State University (USU Award 200499). To everyone else who has helped along the way, we are grateful.

GLOSSARY OF RIVERSCAPE TERMS

The following is a list of technical terms, scientific jargon and phrases used in the manual and/or common synonyms for terms we use in this manual. We have attempted to be consistent in our use of terminology throughout the manual, and we provide this glossary of riverscape terms for the reader. Since the audience of this manual comes from very mixed disciplines and backgrounds, we have tried to minimize our unnecessary use of jargon. However, some technical terminology is unavoidable. If these terms have well established definitions and uses, we use those definitions (with source cited), if the terms have poorly defined definitions or have multiple definitions we define how we have used the terms for the purposes of the manual. Most of the definitions below are from a mix of Osterkamp (2008), Skidmore et al. (2011), dictionary definitions, and NRCS (2007). Where not citation is provided, we have defined the term.

A

Adaptive management

noun

1. An iterative process of decision making in the face of uncertainty, with the intent of reducing uncertainty through system monitoring, and continually moving toward a stated goal through ongoing actions informed by monitoring. From: Skidmore et al. (2011)

Adjustment (capacity)

noun

1. Adjustment, as applied to geomorphology in general and to fluvial systems in particular, is the tendency of non-rigid landforms, such as stream channels, to change in size and shape in response to the changing effects (mostly fluxes) of water, sediment, dissolved solids, and organic matter that alter them or pass through them. From: Osterkamp (2008)

Alluvial fan

noun

1. A wedge-shaped deposit of recent stream alluvium (erosion products) or poorly consolidated rock debris that radiates outward and downslope as, in plan view, an open fan from a site draining an area of high relief or topography, such as the mouth of a mountain valley, onto a gentler slope, typically a pediment or an alluvial plain; the deposit is thickest at the fan apex, near the valley mouth, and thins to a feather edge at the distal edge of the fan. Active alluvial fans are surfaces of net deposition whereas inactive alluvial fans generally exhibit erosion and stream incision at the apex, the depth of incision decreasing with distance downslope to the distal edges of the fan. From Osterkamp (2008)

Alluvium

noun

1. A general term for sediment deposited in a streambed, on a flood plain or other bottomland feature, delta, or at the base of a mountain during comparatively recent geologic time. From: Osterkamp (2008)

2. A deposit of clay, silt, sand, and gravel left by flowing streams in a river valley or delta, typically producing fertile soil. From: Dictionary

Anabranch (channel)

noun anabranch; *plural noun*: anabranches; *adjective*: anabranching

1. An anabranch is a secondary or alternative channel that branches off from a river or stream and later rejoins the mainstem channel (or primary anabranch) downstream. – From: Anabranch Solutions

2. A separate channel that has diverged from the main channel and rejoins the stream at some downstream site; an anabranch is a discrete, semi-permanent channel that may be of equal or smaller size as the main channel,

thereby distinguishing it from channel braids that are not discrete and may be highly ephemeral. From: Osterkamp (2008)

3. Jackson, an English geographer, introduced the term 'ana-branches' in 1834 as a contraction of 'anastomosing branches', referring to defined channels that leave the mainstem and then re-enter downstream, with non-flooding islands formed of floodplain material separating the individual branches (Jackson, 1834). – From (Carling et al., 2013), which provides an excellent review of multi-threaded river terminology and history.

synonym(s): anastomosing and braided channels

Anastomosing (channels)

noun

1. Channels which are multithreaded but split around vegetated islands (i.e., floodplain) and tend to be more stable than braided channels (split around active bars).

2. Composed of two or more interconnected channels that enclose floodplain.

3. A planform distinct from classic braiding systems was provided by Schumm (1968) to mean a multichannel suspended-load-dominated system with large, stable islands between channels that are excised within the neighbouring floodplain. – From (Carling et al., 2013), which provides an excellent review of multi-threaded river terminology and history.

synonym(s): braided channels and anabranching channels

Aquifer

noun

1. Any rock body or geologic deposit of alluvium or similar rock debris that is partially or fully saturated with ground water and has properties of permeability (transmissivity) and porosity that enable it to yield the ground water to a well or spring at a rate significantly high to fulfill a specified purpose; aquifers are grouped as unconfined, those controlled by near-surface gravitational and atmospheric-pressure conditions, and artesian, those that are poorly connected to the land surface due to an impermeable layer separating it from the land surface. From: Osterkamp (2008)

Avulsion

noun

1. An avulsion is a process by which a flowing channel (or anabranch) either switches its position and sends flow down a different channel or shuts off flow to one of two channels at a diffluence.

2. Anabranch avulsion within braided rivers involves three main mechanisms: choking avulsion caused by blockage of one channel by a sediment lobe, constriction avulsion produced by deflection, confinement and subsequent diversion of the flow by a barform and apex avulsion following erosion at the outside of sinuous thalwegs and confined meander bends. From: Leddy et al. (1993)

3. A rapid change in the course or position of a stream channel, especially by incision (erosion) of lowland alluvium, to bypass a meander and thereby shorten channel length and increase channel gradient; avulsion commonly occurs during floods but also can occur by normal processes of lateral migration of a stream channel during non-flood discharges. For legal purposes, bottomland areas, including channel islands, repositioned relative to the prior channel by avulsion belong to the previous owner and remain in the political jurisdiction (state or county) to which they had formerly belonged. From: Osterkamp (2008)

B

Backwater

noun

Refers generally to natural hydrologic systems, is any volume of water that is backed up or prevented from moving downslope or downstream by any barrier obstructing movement; in hydrology, backwater often is the slowing or reversal of flow in a stream or tributary upstream from its confluence with another stream that is at flood stage. From: Osterkamp (2008)

Bank-attached

adjective

1. A differentiating attribute of structural elements (natural or man-made) describing the relative position of the structural element with respect to the channel – namely, that it is connected or physically touching the margins of the bankfull channel. From: Wheaton et al. (2015a)

Bankfull discharge

noun

1. A hydrologic term, is the flow rate (m^3 s^{-1}) when the stage (height) of a stream is coincident with the uppermost level of the banks -- the water level at channel capacity, or bankfull stage. Thus, the concept of bankfull discharge, which often approximates the mean annual flood for perennial streams, includes the flood plain as a unique, identifiable geomorphic surface, all higher surfaces of alluvial bottomlands being terraces, and acknowledgement that bankfull discharge occurs only when stream stage is at flood-plain level. From Osterkamp (2008)

synonym: ordinary high water mark

Bankfull stage

noun

1. The stage at which flow starts to leave the channel, overtops its banks and spreads out onto an adjacent floodplain surface.

2. A fluvial-geomorphic term, is the water-surface level at the tops of alluvial- stream banks that corresponds to the level of adjacent flood-plain surfaces, if present. Thus, bankfull stage is the level at which bankfull discharge occurs, the upper limit of channel capacity. As such, the concept of bankfull stage requires an interpretation of site-specific landforms, especially bank. Although bankfull stage can refer to various channel-bank levels, it generally applies to alluvial-stream channels (1) having sizes and shapes adjusted to recent fluxes of water and sediment, (2) that are principal conduits for discharges moving through a length of alluvial bottomland, and (3) that are bounded by flood plains upon which water and sediment spill when the flow rate exceeds that of bankfull discharge. From: Osterkamp (2008)

Bar

noun

1. A geomorphic unit, defined topographically by its convex shape (curving outward), representing a deposit of alluvium in a channel. From: Wheaton et al. (2015a)

2. In-channel sediment of relatively coarse bed material, typically coarse sand through cobbles in size, that is generally deposited during the recession of a high flow and is mostly exposed during periods of low flow; the upper surface of bars of perennial streams is typically equivalent to a stage of about 40-percent flow duration. From: Osterkamp (2008)

antonym: pool, concavity

Baseflow

noun

1. Sustained, low, or fair-weather flow of a stream; baseflow ($m^3 s^{-1}$) generally is derived from ground-water inputs to the stream channel. From: Osterkamp (2008)

Bed

noun

1. The bottom surface of a water course, generally of a stream channel, upon which water and sediment move during periods of discharge. From: Osterkamp (2008)

synonym: streambed

Bedload

noun

1. The sediment that is moved by saltation, rolling, or sliding on or near the streambed, essentially in continuous contact with it. From: Osterkamp (2008)

Braided stream

noun

1. One with a wide, relatively horizontal channel bed over which water during low flows forms an interlacing pattern of splitting into numerous small conveyances that again coalesce a short distance downstream; the conveyances, or sub-channels, lack channel characteristics, are highly ephemeral, and thereby are distinguishable from anabranches. From: Osterkamp (2008)

2. A stream characterized by flow within several channels, which successively meet and divide. From: Skidmore et al. (2011)

see: anastomosing (channel) and anabranching (channel)

C

Catchment

noun

1. Is a synonym for drainage basin, or watershed, but the term often has the connotation of a smaller area than that of a drainage basin (a sub-basin). Catchment is more commonly used in British English and outside the United States. From: Osterkamp (2008)

Channel

noun

1. A natural or constructed passageway or depression of perceptible linear extent containing continuously or periodically flowing water and sediment, or a connecting link between two bodies of water; channel; physical feature consisting of a bed and banks that conveys water and sediment.

Channelization

noun: channelization; *verb:* channelized, channelizing

1. Process of changing (i.e., straightening) the course of a natural stream channel. From: Skidmore et al. (2011)

Channel head

noun

1. The location representing the transition from overland flow to concentrated channel flow. Channel heads form on floodplain surfaces where overbank flows find their way back to main channels upon re-entry into the lower channel. The waterfall, tends to erode headwards and, pull back upstream opposite to the direction of flow on the floodplain. Headcuts are an important mechanism for reworking floodplain topography and can lead to avulsions.

Colluvium

noun

1. A layer, generally less than 10 ft (3 m) in thickness, of unconsolidated and heterogeneous weathering products (soil material and sediment) and rock fragments deposited following sheet erosion by unconcentrated surface runoff and by gravitational processes, especially soil creep, other types of mass wasting, physical weathering, and bioturbation; colluvium generally occurs as a blanket of poorly sorted sediment and rock fragments on the lower parts of hillslopes underlain by bedrock. From: Osterkamp (2008)

Complex

noun

1. Cluster or group of restoration structures (e.g., wood structures or beaver dam analogues) designed to work together to mimic and/or promote specific processes to achieve specific restoration objective(s). The term comes from the concept of a beaver dam complex typically consisting of a primary dam with a lodge and secondary dams extending downstream and/or upstream to extend the foraging range. See Chapters 4 & 5.

Confinement

noun

1. A measure of the degree that a channel is confined or in contact with a confining margin along either bank ($C_{VB} = \left(\sum_{DS}^{US} CL_{EB} \, @C_M / CL_T\right) \cdot 100$). From: (Fryirs et al., 2015)

2. Channel(s) that is (are) physically limited by physiography, bedrock, or other geologic features. From: Skidmore et al. (2011)

Confined

adjective

1. The state (of a channel reach) of having greater than 90% of the length of the channel in contact with a confining valley bottom margin (e.g., hillslopes, terraces, fans), which limits its capacity to adjust its position laterally. From: (Fryirs et al., 2015)

2. Channel(s) that is (are) physically limited by physiography, bedrock, or other geologic features. From: Skidmore et al. (2011)

Confining margin

noun

1. Any section of channel bank (either bank) that abuts against a valley margin, valley bottom margin or anthropogenic margin. From: (Fryirs et al., 2015)

Confluence

noun

1. The junction of two channels flowing joining to form one channel downstream.

Constriction

noun

1. The proportion of the bankfull channel that is laterally covered by a structural element. For example, if a PALS is 8.5 feet wide in a 10 foot wide channel, the constriction of the PALS is 85%.

2. A special case of confinement where the channel's ability to adjust its position laterally is confined on both sides. From: (Fryirs et al., 2015)

Conveyance

noun

1. A measure of the amount of water that can pass through a stream-channel section without spilling onto higher surfaces as flood flow. From: Osterkamp (2008)

D

Diffluence

noun

1. Refers to the junction where a single channel splits or bifurcates into two or more channels.

Deposition

noun

1. The geomorphic process of a surface raising its elevation by way of sediment depositing.

2. The constructive process of accumulation into beds or irregular masses of loose sediment or other rock material by any natural agent; it is especially the mechanical settling of sediment from suspension or tractive movement in water. From: Osterkamp (2008)

Design

noun

1. In context of low-tech restoration, the form, location, type, and functional objectives of complexes or structures.

Design life

noun

1. The period of time during which the structure or feature is expected by its designers to work within specified parameters; in other words, the life expectancy of the structure. In traditional engineering design, design life is typically communicated with regards to the maximum flow that a structure or feature was meant to withstand (e.g., a 25-year recurrence interval flood event). In reality, many structures and features outlast their design life, but it communicates what it was designed to withstand. With low-tech restoration, we typically promote processes and don't design structures to withstand much more than the typical annual flood. Therefore, a structure with a design life of <1 year means that the structure should hold up to most typical floods, but it might mobilize, breach or blow out -none of which is necessarily interpreted as a 'failure' in low-tech restoration design. See Chapter 5.

Distributary

noun

1. A channel network system that splits or bifurcates at diffluences and is characterized by having more diffluences than confluences, such that flow is distributed laterally into different channels.

2. As a fluvial-geomorphic term, typically refers to the spitting of a stream channel into two or more segments that leave the main channel and do rejoin it, as generally occurs on deltas; less commonly the term is used to characterize the individual channels of an alluvial fan that split from a main, up-slope, channel and again coalesce downslope. From: Osterkamp (2008)

Drainage basin

noun

1. An area of land surface, upslope from a specified channel site to topographic divides separating the basin from adjacent drainage basins, over which water that results from precipitation moves and converges through a system of channels to (and past) the specified channel site.

synonyms: catchment, watershed

E

Ecosystem services

noun

1. Benefits that are generated and/or maintained by natural ecosystem processes and provide a free benefit to humans. A classic example is the free service to agriculture that bees and other insects provide by pollinating crops and natural vegetation. Another example is biofiltration provided by root mats and riparian vegetation near water courses.

2. The production of renewable natural resources through processes yielding clean water, soil, vegetation, and wildlife. From: Osterkamp (2008)

Ecoregions

noun

1. Ecoregions are areas where ecosystems (and the type, quality, and quantity of environmental resources) are generally similar. From: USEPA

2. A major ecosystem defined by distinctive geography and receiving uniform solar radiation and moisture. From: Dictionary

Ephemeral (streams)

adjective

1. Describes streamflow within a normally dry channel; the streamflow occurs inconsistently or infrequently and, except during periods when the ephemeral streamflows occur, the channel bed is directly underlain by unsaturated alluvium. From Osterkamp (2008)

Ephemeral-stream channel

noun

1. A channel in which streamflow occurs inconsistently or infrequently and, except during periods of streamflow, is directly underlain by unsaturated alluvium or rock; ephemeral-stream channels are most common in arid and semiarid regions and typically have a rectangular to steeply sided trapezoidal cross section, banks a meter or more in height formed of fine-grained, poorly consolidated over-bank sediment, and a nearly flat, sandy bed. From: Osterkamp (2008)

synonyms: dry wash, arroyo (northern Mexico and southwestern United States), and wadi (southwestern Asia, Arabian Peninsula, and northern Africa)

F

Floodplain

noun

1. Flat area adjoining a river channel constructed by the river in the present climate and that overbank flows inundate during bankfull discharge (ordinary high water) events;

2. A strip of relatively smooth land bordering a stream incision, built of sediment carried by the stream and dropped in slackwater beyond the influence of the swift current of the channel; the level of the flood plain is generally about the stage of the mean annual flood, and therefore one and only one flood-plain level can occur in a limited reach of bottomland. From: Osterkamp (2008)

Flow duration

noun

1. Refers to the percentage of time that a specified discharge is equaled or exceeded. From: Osterkamp (2008)

Fluvial

adjective

1. From the Latin word, *fluvius*, for river, refers to or pertains to streams; included are stream processes (fluvial processes), fluvial landforms, such as fluvial islands and bars, and biota living in and near stream channels. Common usage is often extended by geomorphologists to hydrologic processes on hillslopes. From: Osterkamp (2008)

G

Geomorphic processes

noun

1. Any processes that influence channel form, primarily including erosion and deposition. From: Skidmore et al. (2011)

Gully

noun

1. A small hollow or channel worn in earth or unconsolidated material, as on a hillside, by running water and through which water runs only after a rain or the melting of ice or snow; it is larger than a rill and smaller than a stream channel. From: Osterkamp (2008)

H

Headcut

noun, verb

1. Identifiable point of active incision where a break in grade occurs from a lower to a higher elevation. An active headcut point migrates in an upstream direction.;

2. A type of knickpoint, is a vertical or near-vertical face, or drop, on the bed of a stream channel that interrupts the channel gradient and, through processes of channel erosion, progressively moves up-channel. From: Osterkamp (2008)

Hydraulic

noun, adjective

1. In the study of open channel fluid dynamics, the hydraulics are characterized by depth (a scalar quantity) and velocity (a vector quantity with direction and magnitude). Thus, hydraulics characterize the nature of flow.

2. The forces of moving water. From: Skidmore et al. (2011)

Hydraulic geometry

noun

1. Describes, for a given cross section of a stream channel, the graphical relations among plots of hydraulic characteristics (width, depth, velocity, gradient, roughness coefficient, particle sizes) as simple power functions of river discharge. From: Osterkamp (2008)

2. Pertains to the water in a channel as opposed to the geometry of the channel. Hydraulic- geometry relations can be developed both for the at-a-station condition and the downstream-direction condition. From: Osterkamp (2008)

Hydraulic purchase

noun

1. Refers to the amount of contact (in terms of surface area normal to the flow field) a structural element has with flowing water; the more the structure obstructs flow, the greater influence the structural element has on velocity (direction and speed) of flow.

Hydrologic regime

noun

1. Spatial and temporal variation in stream flow in a river system, usually characterized by magnitude, frequency, duration, timing, and rate of change statistics. From: Skidmore et al. (2011)

I

Incision

noun: incision; *verb*: incise; *adjective*: incised

1. Stream channel in which the bed has dropped and as a result, the stream is disconnected from its floodplain. Incised channels are often referred to as degraded channels. Stage II, III, and IV in Schumm's Channel Evolution Model and Stage 1-3 in Cluer and Thorne's Stream Evolution Model.

synonym: degraded channel

Infrastructure

noun

1. Buildings, power, or transportation corridors (e.g., roads, trails, power lines, etc.) within a riverscape that could be negatively impacted by restoration actions.

Instream fish habitat

noun

1. Habitat features important to fish for concealment, feeding, and shelter from high water velocities and temperature; these features include large wood within the stream banks, boulders, undercut banks, and tree roots.

Intermittent (streams)

adjective

1. Streams that only flow during part of the year (such as in the spring and early summer after snowmelt) or in direct response to precipitation.

2. (Of streams, lakes, or springs) recurrent; showing water only part of the time. From Dictionary

J

K

Knickpoint

noun

1. Any interruption or break of a channel gradient, especially a headcut site of abrupt change or inflection in the longitudinal profile of a stream channel or its valley. From: Osterkamp (2008)

L

Landscape

noun

1. Area made of a variety of landforms (hills, valleys, plateaus, floodplains, etc.); less specific than riverscape but can include riverscapes and occurring at scales multiple spatial scales.

Large wood

noun

1. Relative expression of wood in a stream channel sufficient in size to be immobile at most flows and to interfere with channel hydraulics. From: Skidmore et al. (2011)

synonym: large woody debris (LWD)

Low-tech process-based restoration

noun

1. A practice of using simple, low unit-cost, structural additions (e.g., wood and beaver dams) to riverscapes to mimic functions and promote specific processes. Hallmarks of this approach include an explicit focus on the promoting geomorphic and fluvial processes, a conscious effort to use cost-effective, low-tech treatments (e.g., hand-built, natural materials, non-engineered, short-term design life-spans) because of the need to efficiently scale-up application, and '*Letting the system do the work',* which defers critical decision making to riverscapes and beaver.

M

Margin-attached bars

noun

1. Bars attached to channel banks.

Meander

noun: meander; *verb:* meande;r *adjective:* meandering

1. As in meander bend, following a series of winding, loops, turns along a sinuous course of a channel in an alluvial valley. A meandering reach type is a special case of a sinuous planform, in which the channel meanders and laterally migrates across its valley bottom via the process of point-bar growth on inside bends, and bank erosion on outer bends. This is contrast to sinuous planforms that result from deflecting off of confining margins (e.g., partly-confined valley setting).

Mid-channel

adjective

1. A differentiating attribute of structural elements (natural or man-made) describing the relative position of the structural element with respect to the channel – namely, that it is not connected or physically touching the margins of the bankfull channel and positioned in the middle of the channel. From: (Wheaton et al., 2015a)

Multi-threaded

adjective

1. The attribute of a riverscape that has two or more channels or anabranches. Multi-threaded channels are characterized by having a large number of diffluences that are equal to the number of anabranch plus channel head confluences.

synonyms: anabranching; *special cases of multi-threaded include* braided *and* anastamosing

N

O

P

Perennial streams

noun

1. Continuously flowing water in a natural stream channel; the surface of a perennial stream fluctuates at or near the upper level of the zone of saturation in the adjacent water-bearing alluvium or rocks. From: Osterkamp (2008)

2. Streams that flow throughout the year.

Pilot

noun

1. A small scale or trial restoration project initiated before implementing a large-scale restoration project; used when first using low-tech restoration in a new area or with a new group of partners.

synonym: trial project

Pinyon-juniper

noun

1. An open-woodland plant community, ecosystem, or habitat, of semiarid parts of North America (especially piedmont areas of New Mexico, Arizona, and Utah) that are dominated by pinyon pine (*Pinus edulis* and/or *P. cembroides*) and various species of juniper (especially oneseed juniper, *Juniperus monosperma*, and Rocky Mountain juniper, *J. scopulorum*); a pinyon-juniper community is comprised of one or more indicator species of pinyon and juniper genera, and generally occurs on well-drained sandy to gravelly soils of moderately to steeply sloping pediments and alluvial fans that have mean-annual precipitation range of 250 to 400 mm. From: Osterkamp (2008)

Planform

noun

1. Shape and geometric character of a channel's position on its valley bottom in map view.

2. The configuration of a river in plan view, provides a reach-scale summary of the channel and floodplain characteristics of an alluvial river. Channel planform is differentiated on the basis of three inter-related criteria, namely the number of channels, their sinuosity, and their lateral stability From: Brierley and Fryirs (2005)

Pool

noun

1. A geomorphic unit, defined topographically by its concave shape (curving inward), representing relatively deeper water in a channel. If the water in a channel stopped flowing and drained away, the puddles left over would be the residual pools. From: Wheaton et al. (2015a)

antonym: bar

Process-based restoration

noun

1. Aims to reestablish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems (e.g., rates of erosion and deposition, channel migration, growth and succession of riparian vegetation). From: Beechie et al. (2010)

Q

R

Rangelands

noun

1. Open country used for grazing or hunting animals.

Reach (type)

noun

1. The specific category or (type) of channel pattern or riverscape type, typically differentiated on the basis of valley setting, planform geometry, slope and/or flow regime.

synonyms: River Style, reach classification, channel pattern

Reach (segment)

noun

1. Section of stream having relatively uniform physical attributes, such as slope, sinuosity, bedforms, and dominant bed material.

synonyms: segment

Refuge

noun

1. Place of safety where organisms can hide from predators, flood flows, fires or other threats.

Resilience

noun

1. Ability of a river to buffer the effects of natural or anthropogenic disturbances through natural fluvial processes (e.g., ability to attenuate floods through energy dissipation on the floodplain).

2. The capacity of a system or community to resist or adapt to changes in environment (watershed controls) in order to maintain functionality/viability. From: Skidmore et al. (2011)

Riparian

adjective

1. Interface between land and a river or stream. Generally, the 'riparian' zone is the floodplain portion of the valley bottom, which supports vegetation with higher water tolerances and/or needs.

2. Pertains to the banks of a stream; within ecology the term has been broadened to refer to biota and other characteristics of alluvial bottomlands. From: Osterkamp (2008)

Riparian disturbance

noun

1. Measure of the evidence of human activities in and alongside streams and rivers, such as dams, roadways, construction, agriculture, pastureland and trash.

Riverscape

noun

1. Streams and riverine landscapes, or "riverscapes" are composed of connected floodplain and channel habitats that together make up the valley bottom. See Chapter 1

2. A term used to indicate a holistic perspective of the broad scale patterns and processes associated with fluvial systems. From: (Ward, 1998)

3. Defined spatially by the extents of a drainage network and laterally by the valley bottom margins. See Chapter 1

synonym: riverine landscape

S

Single-thread

adjective

1. Describes a stream or reach with one channel.

Stage

noun

1. Used in reference to particular stages that channels/streams evolve through in channel evolution models from highly intact stages with diverse geomorphic, hydraulic, riparian and ecological characteristics to more degraded and low diversity stages. Often, though not always, channel incision is a trigger that promotes channels to change stage.

2. The elevation of the water surface at a specified location above some arbitrary datum. From: Skidmore et al. (2011)

Stage 0

noun

1. A riverscape condition characterized by multiple channels around vegetated or forested islands (i.e., anastomosing) and high lateral connectivity that are resilient to disturbance and represent a stage of stream evolution. Adapted from Cluer and Thorne (2013)

Stage 8

noun

1. A riverscape condition characterized by recovery from highly incised stages to a stage on inset floodplains, recovering riparian vegetation, and relatively high densities of structural elements. Stage 8 may be the goal of restoration actions where Stage 0 is not possible due to constraints such as infrastructure or private property. Adapted from (Cluer and Thorne, 2013)

State

noun

1. The particular condition that someone or something is in at a specific time. From: Dictionary

Stream order

noun

1. Stream size, based on the confluence of one stream with another. First-order streams are the origin or headwaters. The confluence or joining of two first-order streams forms a second-order stream, the confluence of two second-order streams forms a third-order stream, and so on. From USEPA (2016)

2. A designation indicating the position that a stream-channel segment has within the hierarchy of channels of a drainage network; the uppermost, headwater channels of a drainage network are typically assigned a stream order of 1 and the most downstream channel segment has the highest stream-order designation, perhaps 6 or 8. Owing to subjectivity in how a channel hierarchy is interpreted (where, for example, a 1st-order headwater channel begins), and confusion caused by a variety of stream-ordering systems, the use of stream order, which was extensive in the 1950s and 1960s, is now limited. From: Osterkamp (2008)

Stream power

noun

1. A measure of energy of flowing water that represents the potential amount of geomorphic work that can done by the stream. Stream power is calculated as the product of the density of water, gravity, discharge and channel slope ($\Omega = \rho g Q S$).

2. The ability of flowing water to accomplish work (sediment transport, erosion), is the product of discharge and water-surface slope; stream power, per unit length of channel, is typically expressed in watts per meter ($W\ m^{-1}$). From: Osterkamp (2008)

Structural element

noun

1. Discrete objects that directly influence hydraulics (e.g., wood, boulders, beaver dams, bedrock, vegetation). From: Wheaton et al. (2015a)

synonyms: structure

Structurally-starved

adjective

1. Refers to any riverscape or system that has a deficiency of structural elements; due to direct removal and/or disruption of processes that maintain structural inputs into the riverscape. See Chapter 1.

Sustainability

noun

1. Capacity of a river to naturally maintain fluvial processes inherent in an intact system (e.g., wood recruitment rate roughly matches wood loss rate).

2. The ability to be maintained at a certain rate or level – e.g., "the sustainability of economic growth". From: Dictionary

3. Avoidance of the depletion of natural resources in order to maintain an ecological balance – e.g., "the pursuit of global environmental sustainability". From: Dictionary

System

noun

1. In this manual, the system is generally the riverscape, and/or its ecosystem. In Restoration Principle 8 (let the system do the work), the system is implicitly both the river (determined by flow regime) and potentially beaver. See Chapter 2.

T

Terrace

noun

1. A valley-contained surface that typically is expressed as a long, narrow, nearly level or gently inclined landform bounded along the lower edge by a steeper descending slope and along the higher edge by a steeper ascending slope; a terrace is always topographically higher than the flood plain, and is inundated by floods of greater magnitude than the mean annual flood. An alluvial terrace is an aggradational feature, is composed of unconsolidated to poorly consolidated alluvium and its weathering products, and generally reflects an abandoned floodplain surface; a strath (from the Gaelic word for wide river valley) terrace is an erosional feature formed by stream incision into a bedrock surface, and may have little or no relation to a former floodplain. From: Osterkamp (2008)

2. Inactive floodplain.

Trial Project

noun

1. A small-scale or pilot restoration project initiated before implementing a large-scale restoration project; used when first using low-tech restoration in a new area or with a new group of partners. See Chapter 6

synonym: pilot

U

Unit stream power

noun

1. Calculated as stream power divided by channel width ($\omega = \Omega/b = \rho g Q S/b$). Useful for comparing multiple streams or reaches, and identifying relationships to channel morphology.

synonym: specific stream power

V

Valley

noun

1. Relatively flat, low-lying area between hills or mountains typically containing watercourse. The geomorphic units that comprise valleys can include channel(s), floodplain(s), terrace(s), and fan(s). From: Wheaton et al. (2015b)

Valley bottom

noun

1. Low-lying area in a valley containing the stream channel and contemporary floodplain. The valley bottom represents the current maximum possible extent of channel movement and riparian areas.

2. Area comprised by the active channel and contemporary floodplain. From: Wheaton et al. (2015b)

W

Wandering (channel)

Noun

1. A transitional reach (type) between meandering and braided morphologies, characterized by a tendency to braid (or split flow) around mid-channel bars and/or islands wherever it has an opportunity to do so and with a braiding index typically between 1.5 and 2.

Wadeable streams

noun

1. Streams that are small and shallow enough to adequately sample by wading. From: USEPA (2016)

Watershed

noun

1. A drainage divide or a "water parting", but commonly usage of the term has been altered to signify a drainage-basin area contributing water to a network of stream channels, a lake, or other topographic lows where water can collect. From: Osterkamp (2008)

*synonym*s: drainage basin, catchment

Width constriction

noun

1. The proportion of the bankfull channel or flow width constricted by a structural element (e.g., structure width / bankfull width). See constriction. This ratio helps estimate the relative increase in flow strength when constricted against non or less deformable boundaries and banks (i.e., jet), or the relative magnitude of lateral migration or bank erosion if the boundary is erodible.

X

Y

Z

Zone of influence

noun

1. The area that a complex is capable of influencing hydraulically or geomorphically. See Chapter 5.

ACRONYMS

AOI	Area of Interest
ATV	All-Terrain Vehicle
BDA	Beaver Dam Analogue
BLM	Bureau of Land Management
BRAT	Beaver Restoration Assessment Tool
CWA	Clean Water Act
DEM	Digital Elevation Model
ELJ	Engineered Log Jam
ESA	Endangered Species Act
GCD	Geomorphic Change Detection
GUT	Geomorphic Unit Tool
IFPL	Industrial Fire Precaution Level
IMW	Intensely Monitored Watershed
$_{HD}$LWD	High-Density Large Woody Debris
LT-PBR	Low-Tech Process-Based Restoration
LWD	Large Woody Debris
NEPA	National Environmental Protection Act
NRCS	Natural Resources Conservation Service
NOAA	National Oceanic and Atmospheric Administration
OHV	Off-Highway Vehicles
ORV	Off-Road Vehicles
PALS	Post-Assisted Log Structures
PBR	Process-Based Restoration
PJ	Pinyon Juniper
PPE	Personal Protective Equipment
RCAT	Riparian Condition Assessment Tool
RVD	Riparian Vegetation Departure
SHPO	State Historic Preservation Office
SGI	Sage Grouse Initiative
SMART	Specific, Measurable, Achievable, Relevant, Time bound
SRSRB	Snake River Salmon Recovery Board
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USFS	United States Forest Service
UDWR	Utah Division of Wildlife Resources
UWRI	Utah Watershed Restoration Initiative
VBET	Valley Bottom Extraction Tool
WRI	Whitewater Rescue Institute
ZOI	Zone of Influence

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Chapter 1 – BACKGROUND & PURPOSE

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IMPLICATIONS FOR PRACTICE

- Riverscapes are composed of connected floodplain and channel habitats that together make up the valley bottom.
- The scope of degradation of riverscapes is massive. Tens of thousands of miles of riverscapes are in poor or fair condition.
- Structural-starvation is both a direct cause of degradation, as well as a consequence of land use changes and direct modification of stream and riparian areas.
- Engineering-based restoration tends to emphasize channel form and stability, rather than promoting the processes that create and maintain healthy riverscapes, which leads to increased costs and a limited ability to restore more miles of riverscapes.
- Process-based restoration focuses on restoring physical processes that lead to healthy riverscapes.
- Low-cost, simple, hand-built structures have been used for over a century. Restoration principles are needed to guide the use of low-tech structures in order to address the scope of degradation, which will require that practitioners "let the system do the work."
- The overarching goal of low-tech restoration is to improve the health of as many miles of riverscapes as possible and to promote and maintain the full range of self-sustaining riverscape processes.

INTRODUCTION

Riverscapes and Wadable Streams

Streams and riverine landscapes, or "riverscapes" are composed of connected floodplain and channel habitats that together make up the valley bottom. They are created and maintained by physical and biological processes that vary across spatial and temporal scales (Ward, 1998) and produce characteristic geomorphic features and biological communities based on local and regional climatic and physical setting. We adopt the term 'riverscape' throughout this manual in order to maintain a focus on both channel and floodplain habitats, which are often both targets of restoration. Riverscapes occur within valley bottoms, which are defined as the area comprised by the active channel and contemporary floodplain (Wheaton et al., 2015). A valley bottom is the relatively flat surface that is subject to reworking and influence by current fluvial processes. It therefore represents the maximum area that can be influenced by any riverscape restoration project.

The restoration approach (i.e., low-tech process-based restoration) described in this manual is intended to be implemented primarily in wadeable streams. Approximately 90% of the perennial streams and rivers in the United States are considered wadeable (EPA, 2006). Note that wadeable streams include perennial, intermittent (seasonal) and ephemerally flowing channels. The importance of wadeable streams, also often referred to as low-order or headwater streams, has been well-documented. Wadeable streams contribute to the biodiversity of river networks (Meyer et al., 2007), are important carbon-storage zones (Beckman and Wohl, 2014), contribute allochthonous inputs (nutrients, litter, etc.) to lower, larger depositional rivers (Bellmore and Baxter, 2014), and are important controls on water quality and quantity (Alexander et al., 2007). In this manual, we limit our discussion to the use of instream structures in wadeable streams. Wadeable streams present a unique opportunity to use low-tech restoration methods due to their location, often areas characterized by limited infrastructure, and lower flows relative to large rivers. As such, there is an opportunity to greatly increase our restoration footprint by focusing on wadeable streams. Although this manual focuses on low-tech process-based restoration in wadeable streams, the philosophy described in this manual may be applicable to large riverscapes.

Manual Purpose

The purpose of this manual is to provide guidelines for low-tech process-based restoration. The goals of this manual are to: i) define the principles that guide low-tech process-based restoration; ii) detail how low-tech restoration principles underlie and inform all steps of the restoration process from planning to design and implementation, to expectation management and long-term management and monitoring; and iii) describe the form, function and design of two low-tech restoration structures – post-assisted log structures (PALS) and beaver dam analogues (BDAs).

This manual is not a comprehensive guide to the restoration of all riverscapes, nor is it a primer on the multiple disciplines that together, guide restoration. An extensive literature exists on the practice of stream restoration (see Appendix A Table 4 for partial selection of existing resources). Instead, this manual provides guidance for a particular sub-set of restoration practices we refer to as low-tech and describes their application in a specific setting (i.e., wadeable streams).

The use of low-tech instream restoration structures, such as BDAs, has increased in recent years. While we are broadly supportive of the use of low-tech restoration approaches, we have also observed their inefficient use and misapplication in a range of settings, and unrealistic expectations for how such structures can achieve restoration goals. We believe that this is because there has not been a clear articulation of the underlying principles that guide low-tech restoration methods. Low-tech instream structures are not difficult to build. They can be built by a diverse set of people, including land managers, resources managers, conservation corps, private landowners and volunteers. Throughout this manual we refer to this diverse group as restoration practitioners. A significant difference between more highly engineered approaches to stream restoration and the low-tech approach presented here is the ability to engage and work with such a diverse group of practitioners. This manual is written with them in mind and we hope they can use the information

presented here to inform on-the-ground decisions. Land managers and resource managers can use this manual to help guide restoration over broad scales to help address the true scope of riverscape degradation.

Organization of the Manual

This manual is organized into seven chapters. This chapter (Chapter 1) covers the requisite background information and concepts that provide the context for low-tech process-based restoration. Chapter 2 (Wheaton et al., 2019b) defines the riverscapes and restoration principles that guide the planning, design and implementation of low-tech restoration projects. Chapter 3 (Bennett et al., 2019b) describes the planning process and how to identify where low-tech approaches are appropriate. Chapter 4 (Shahverdian et al., 2019a) describes the form, function, and design of PALS and BDAs. Chapter 5 (Shahverdian et al., 2019b) describes the design process for low-tech restoration and contrasts it against engineering-based design approaches. Chapter 6 (Bennett et al., 2019a) address logistic aspects of implementation, including permitting and project management. Chapter 7 (Wheaton et al., 2019a) reiterates the scope of degradation and is a call to action, and directs the reader to additional resources.

BACKGROUND

The on-the-ground implementation of low-tech restoration is simple. Due to their low technological and engineering requirements, they are often adopted without an understanding of their scientific basis, or the history of low-tech and engineering-based approaches to restoration. The current restoration paradigm is largely based on an engineering approach to stream management (see Restoration Review). We contend that such an approach, while often appropriate, has been applied in many locations where less deterministic and more flexible methods can achieve restoration goals over larger extents and for lower unit costs (i.e., per mile). Efficiently implementing effective, low-tech restoration projects depends on a broad conceptual understanding of the scientific concepts upon which it is based. Furthermore, understanding the historical context of stream restoration can help practitioners avoid previous pitfalls. In short, the background information in this chapter provides the basis for the guiding principles outlined in Chapter 2 (Wheaton et al., 2019b). Practitioners that can apply the principles in Chapter 2 to their restoration efforts are far more likely to successfully implement projects.

Scope of Degradation

Human alteration to riverscapes is pervasive. It is estimated that 79% of the 3.3 million miles (5.3 million km) of riverscapes in the contiguous United States have been altered by human activity with 19% flooded in reservoirs, leaving only 2% in a relatively pristine condition (Abell, 2000; Graf, 2001). Additionally, over one third of rivers are officially listed as impaired or polluted (EPA, 2000) and > 70% of riparian forests have been removed or degraded (Innis et al., 2000). Flood-storage capacity has been severely diminished by loss of floodplain connectivity and over-allocation in watersheds has led to major rivers that no longer flow continuously to the sea (Palmer, 2006). Aquatic habitat degradation and loss has led to the decline in abundance and diversity of aquatic and riparian organisms (Ricciardi and Rasmussen, 1999).

Among perennial wadeable streams in the contiguous United States, the EPA estimates that 42% are currently in poor condition, 25% are in fair condition and 28% are in good condition (USEPA, 2006). These percentages correspond to 281,170 miles (452,499 km) in poor condition, 167,092 miles (268,908 km) in fair condition, and 189,236 miles (304,545 km) in good condition. As outlined above, wadeable streams account for the vast majority of streams within a given watershed (Figure 1). The causes of degradation are varied and include both discrete and wide-spread drivers, including: flow regulation and diversion by dams, land use changes to agriculture and urbanization, channelization, construction of levees, increased sediment and nutrient inputs and many more. In the following section, we focus on one of the most widespread drivers of degradation in wadeable streams – the historic and ongoing removal of large wood and beaver dams.

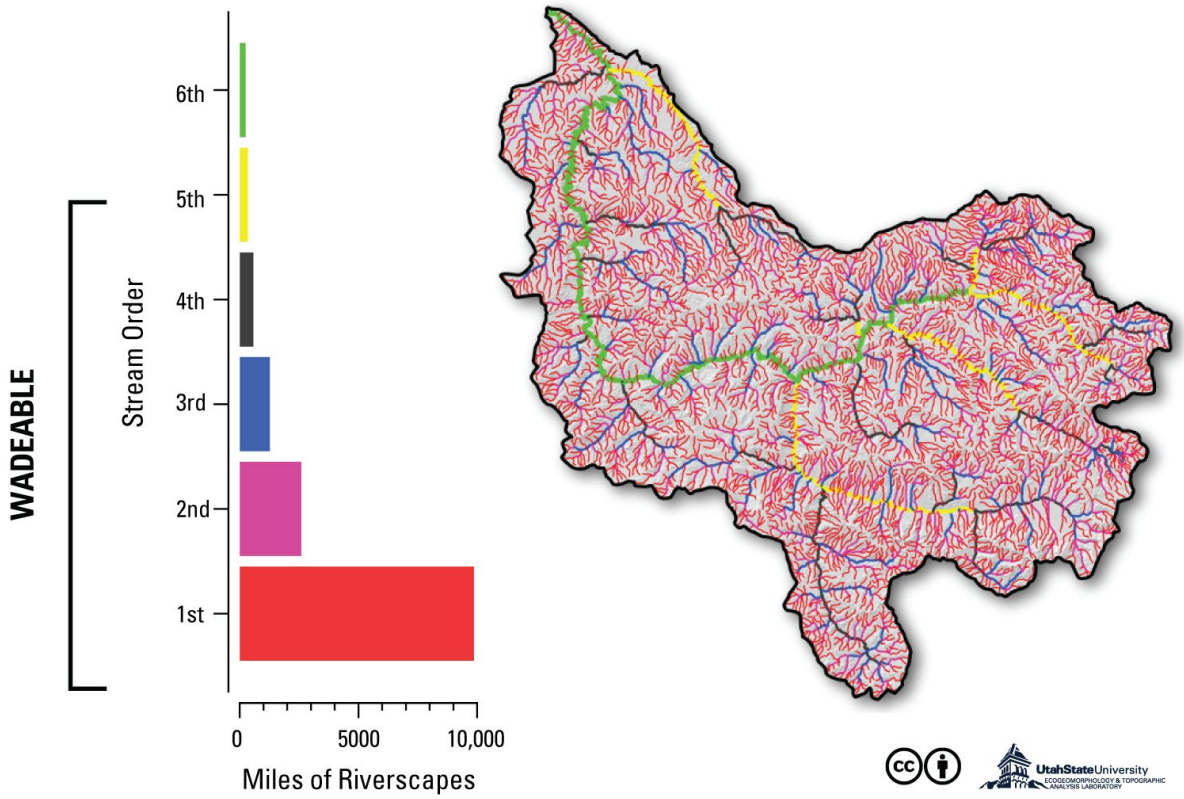


Figure 1 –The distribution of miles of riverscapes for a typical drainage network based on their stream-order and wadeability. The low-tech restoration techniques described in this manual are applicable in wadeable streams (e.g., less than 5th order streams). Wadeable streams typically account for roughly 90% of the perennial stream length within a drainage network.

Structurally-Starved Riverscapes

Structural elements are defined as "discrete objects that directly influence hydraulics" (Wheaton et al., 2015). In other words, a structural element is any obstruction to flow (e.g., boulder, beaver dam, large wood) that alters the depth and velocity of flow. We refer to riverscapes that lack the quantities of structural elements they historically (i.e., pre-European settlement) had as structurally-starved. Large wood and beaver dams are structural elements that influence physical, chemical, and biological processes that are essential for ecologically functional riverscapes. We refer to habitat features that are created by the interaction of flow and large wood or beaver dams as structurally-forced. In this section, we briefly review the ways in which large wood and beaver dams influence riverscape processes and ecological function, and the consequences of their systematic removal. We also provide historical context to better understand the magnitude of influence large wood and beaver had on pre-European settlement riverscapes.

Figure 2 shows a structurally-starved riverscape that has an incised channel and degraded riparian conditions. The channel is disconnected from its historic floodplain, which is now dominated by upland vegetation, and less productive with respect to forage for livestock and game species. Figure 3 shows a riverscape that appears to be in good condition due to the presence of abundant riparian vegetation, but is characterized by simplified, planar in-channel habitat, low channel-floodplain connectivity, and efficiently transports water and sediment from the system. This system has been artificially straightened, simplified and then allowed to recover from intensive land uses (e.g., logging and grazing), which has allowed the re-establishment of riparian vegetation. However, here the riparian vegetation is effectively protecting a degraded, simplified channel by armoring the banks, and it provides relatively little wood to the channel (recruitment) to obstruct flow and force more diverse habitat. Figure 2 and 3 are representative of conditions many

managers may not recognize as problematic (i.e., shifting baseline; Pauly, 1995). The scope of simplification and degradation by structural starvation is pervasive throughout the Western US.

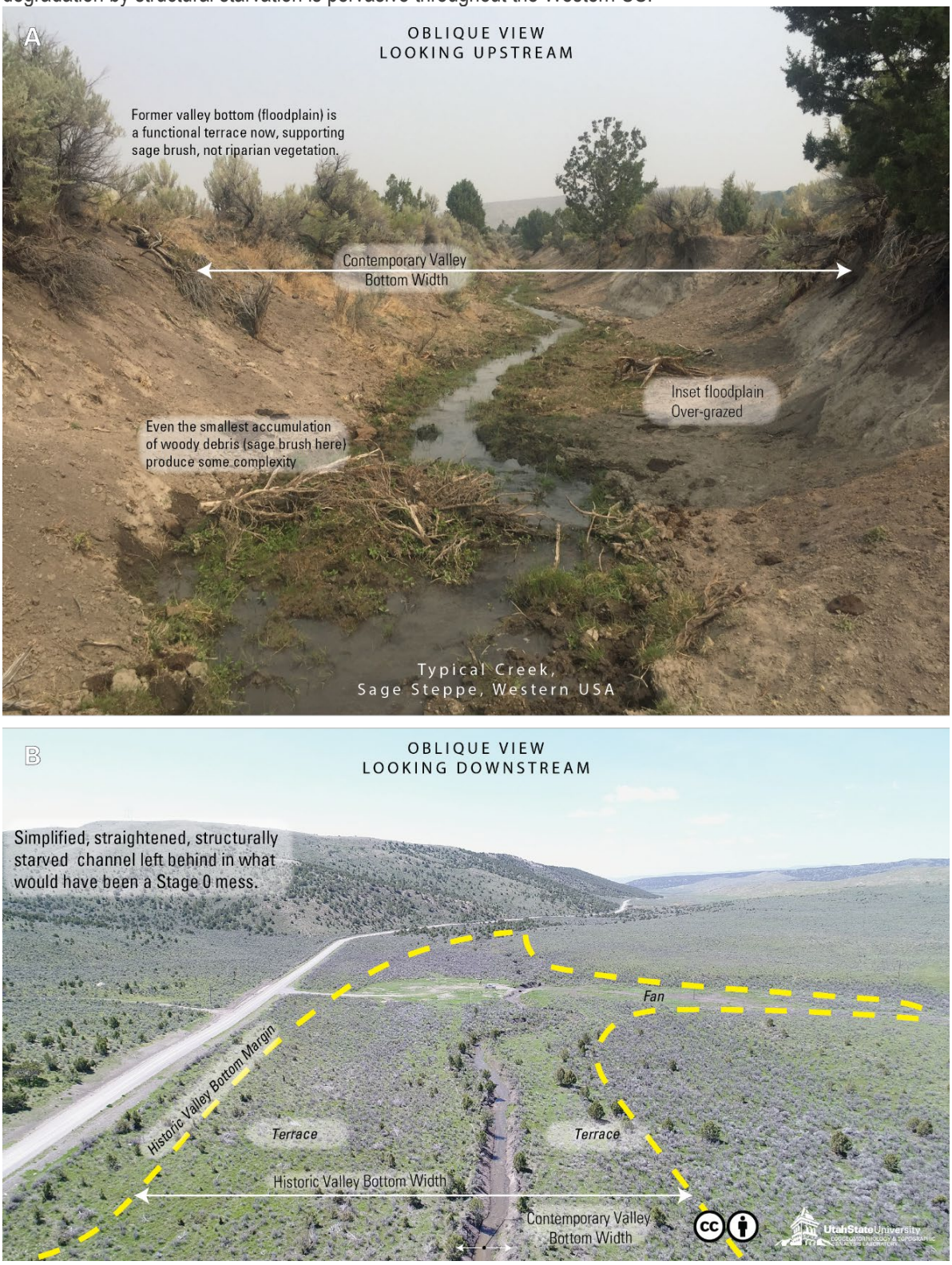


Figure 2 – Many riverscapes have been changed from dynamic, messy creeks with high water tables and multiple channels, to simplified ditches that drain too efficiently, leaving the valley bottoms less productive.

Figure 3- Structurally-starved stream that lacks large woody debris (LWD) or other structural elements capable of forcing physical complexity. Many streams that appear healthy due to riparian vegetation lack the processes of wood-recruitment and accumulation that force hydrological and geomorphic processes, such as overbank flow and channel migration, which create and maintain the diverse physical conditions necessary to ecologically functioning riverscapes.

Importance of Large Woody Debris and Beaver Dams

The influence of beaver on stream ecosystems has been well documented (Burchsted et al., 2010; Naiman et al., 1988). Beaver dams influence stream complexity by altering patterns of erosion and deposition, resulting in increased physical heterogeneity; increasing lateral connectivity by promoting overbank flows, which are critical for creating and maintaining floodplain habitats and promoting groundwater recharge (Westbrook et al., 2006); and increasing access for water resources for riparian vegetation. Prior to the arrival of Europeans in North America, estimates of beaver population range from 60-400 million, and their range extended from northern Mexico to the arctic tundra (Naiman et al., 1988). Historical accounts of trappers and explorers from the 19th century detail the ubiquity of beaver across much of North America (Dolin, 2011). The influence beaver had on riverscapes prior to European arrival is difficult to overstate.

Along both wadeable streams and large rivers, large woody debris (LWD) promotes healthy riverscapes by influencing hydraulic conditions, which leads to a structurally-forced pathway to more complex habitat (Abbe and Montgomery, 2003; Montgomery et al., 2003; Wheaton et al., 2019b). Hydraulic and geomorphic diversity creates niches for aquatic biota and conditions to meet the needs of individual organisms throughout a variety of life-stages (Lonzarich and Quinn, 1995; Zalewski et al., 2003). Large woody debris also increases channel-floodplain connectivity and channel planform and lateral mobility by increasing roughness and forcing multi-threaded channels (Gurnell et al., 2002). Similar to early observations of beaver dams, early accounts describe abundant large woody debris in nearly all forested regions of the continental United States (Kramer and Wohl, 2014; Wohl, 2014).

Consequences of Removal of Large Woody Debris and Beaver Dams

The systematic removal of large wood and beaver dams has had a significant impact on riverscape health (Goldfarb, 2018; Polvi and Wohl, 2013; Wohl, 2001). The loss of beaver dams is a result of historic near-extirpation driven by the fur trade (Dolin, 2010), and ongoing policies that favor lethal removal of nuisance beaver (Siemer et al., 2013). Specific consequences of the removal of large wood and beaver dams include: decreased physical complexity and simplification of instream habitat, decreased channel-floodplain connectivity; increased peak flows and reductions in baseflow,

channel incision, decreased groundwater tables and water storage, conversion of multi-threaded channels to single threaded channels (Wohl, 2013). Furthermore, the removal of large woody debris and beaver dams has disrupted hydrologic and geomorphic processes, such as overbank flows and channel migration that have resulted in a decreased ability for riverscapes to support riparian areas as well as decreased ability to recruit and retain these structural elements. The absence of beaver dams and large woody debris can therefore be important for two distinct reasons. First, their absence results in degraded stream conditions, as outlined above. Second, their absence negatively impacts a stream's ability to heal itself by impacting the processes that are required to maintain ecologically functional riverscapes.

Riverscapes States and Conditions

Riverscapes exhibit a wide range of characteristics depending on their regional and physiographic setting as well as their location within the drainage network. Given the natural diversity of riverscapes, it is critical to identify appropriate restoration reference conditions and targets to ensure that restoration actions are consistent with the local setting (see Chapter 3: Bennett et al., 2019b). Here we focus on a specific type of riverscape, specifically one that has floodplain (limited or extensive) capable of supporting riparian vegetation. We do not focus on riverscapes without floodplains due to their inability to adjust laterally and the low likelihood of their being prioritized for restoration efforts.

The Missing Reference Condition of Riverscapes - Stage 0

Recognition of the influence that large woody debris and beaver dams have on riverscapes has recently led to a rethinking of what many streams and rivers looked like prior to their removal and changes in land use (Goldfarb, 2018). Cluer and Thorne (2014) proposed an expansion of previous stream evolution models (Schumm et al., 1984; Simon and Hupp, 1987) that explicitly recognized that prior to alteration by European settlers, many riverscapes were characterized by multiple channels and high lateral connectivity that were resilient to disturbance. They refer to this state as "Stage 0", and detail its hydrologic, hydraulic and substrate, and geomorphic attributes as well as the ecological benefits. Because Stage 0 is increasingly being recognized and used as a target for restoration (Pope et al., 2018; Powers et al., 2018), we briefly summarize it in Table 1. In addition to providing a detailed description of the attributes of Stage 0, Cluer and Thorne (2014) present an updated stream evolution model that details the physical and ecological attributes associated with distinct stages along an evolutionary pathway. Unlike previous channel evolution models, they recognize that specific stages may move in more than one trajectory (Figure 4). For a complete description of each stage, its physical and vegetative attribute we refer the reader to Cluer and Thorne (2014).

Table 1 –Description of physical attributes that characterize Stage 0. Adapted from Cluer and Thorne (2014).

Stage 0	Hydrologic Regime	Hydraulics and Substrate	Morphology
Dynamically meta-stable network of anabranching channels with vegetated islands	Floods cover width of floodplain; Maximum flood attenuation; High water table	Maximum in-channel hydraulic diversity; Wide range of depth/velocity combinations; Wide range of substrate sizes in well-sorted patches	Multiple channels; Low bank height; Fully connected floodplain; High capacity to store sediment and wood

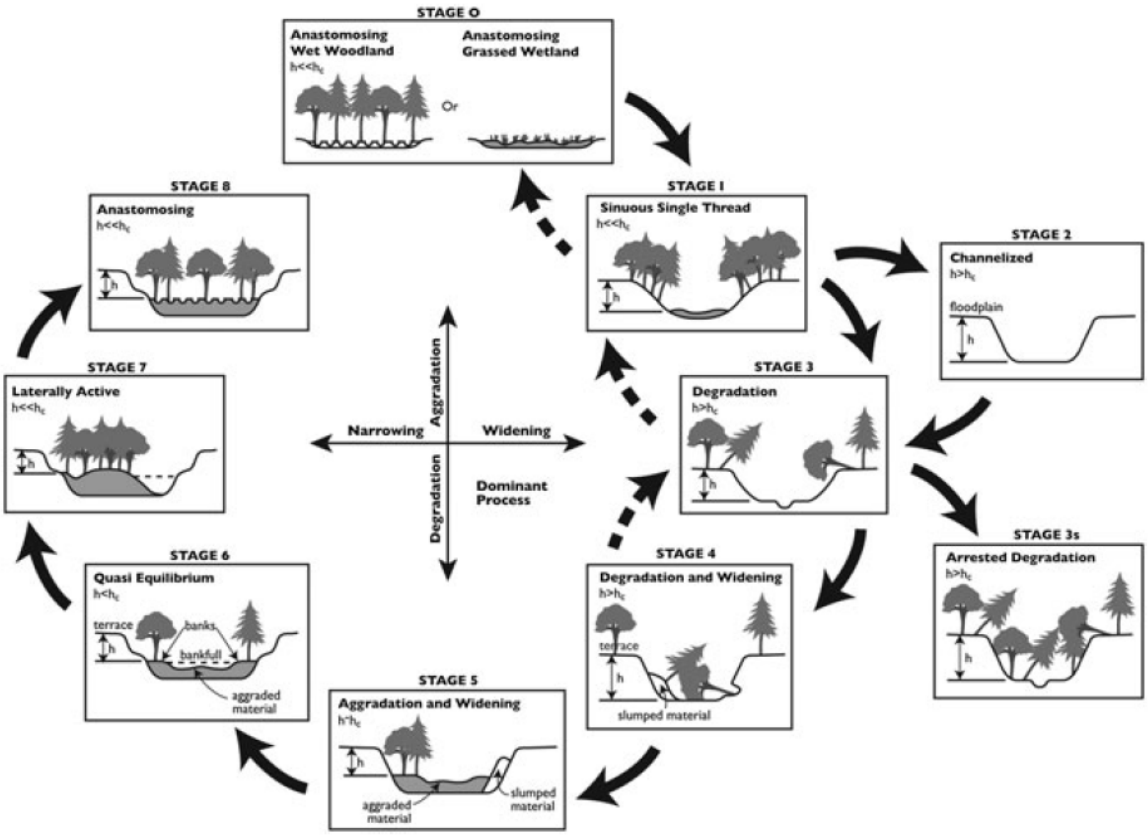
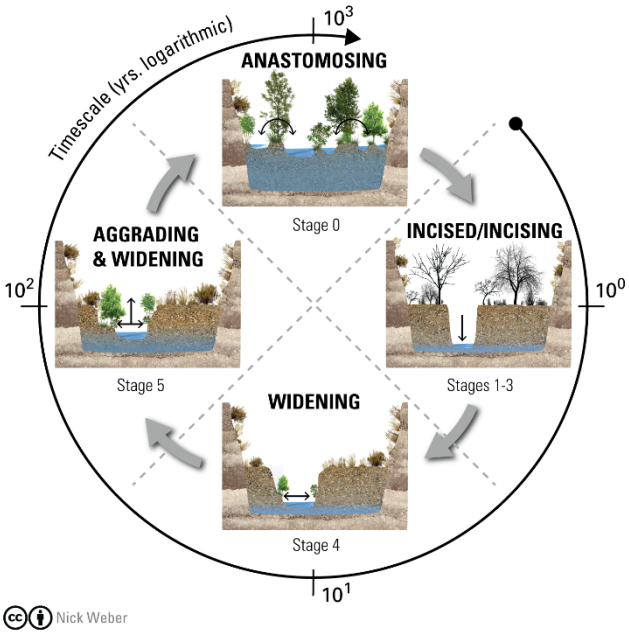


Figure 4 – Cluer and Thorne (2014) stream evolution model depicting pre-disturbance conditions (Stage 0). The vision of Stage 0 has pushed the restoration community to focus on a new target for restoration characterized by a physically complex valley bottom that has multiple channels and higher lateral connectivity.



Nick Weber

Figure 5 – A riverscapes evolution model simplification and adaptation of Cluer and Thorne (2014) stream evolution model.

In this manual, we embrace the Cluer and Thorne (2014) vision for Stage 0 and/or Stage 8 conditions, but just refer to this target simply as Anastomosing (Figure 5). The most important thing from a restoration perspective is the appreciation of these conditions as historically pervasive, advantageous to riverscape health, and an appropriate target for restoration. For the geomorphologist, the detail provided in Figure 4 is helpful for elaborating the various pathways, mechanisms and some of the special cases of how one gets from one stage to another. However, as memorable as Stage 0 is as a catch phrase and target, for most practitioners the extra detail in all the stages is confusing. In this manual we refer to a simplified set of 'stages' we used in (Pollock et al., 2014), but have revised to a riverscapes evolution model to show the entire valley bottom (Figure 5). Table 2 shows a comparison.

Despite being applicable to many streams, Stage 0 is not an appropriate target for all restoration projects. The presence of infrastructure or specific land uses, such as

agriculture, may preclude Stage 0 as an appropriate restoration target. In such cases, partial occupation of the valley bottom width with anastomosing channels and connected floodplain islands (e.g., Stage 8) may be more appropriate (see Chapter 3 on Planning: Bennett et al., 2019b). Stage 8 is not included in Figure 5 for simplicity, but in Figure 6 we illustrate the difference. We suggest that an understanding of the key stages (i.e., incised, widening, aggrading & widening, anastomosing) provides restoration practitioners with a useful way of assessing geomorphic condition in many systems. Moreover, where relevant, this provides a powerful framework to help guide restoration, articulate restoration goals, and describe pathways and methods capable of achieving goals in the short and long term. See Figure 7 for a view of anastomosing (Stage 0) conditions in a diverse array of riverscapes.

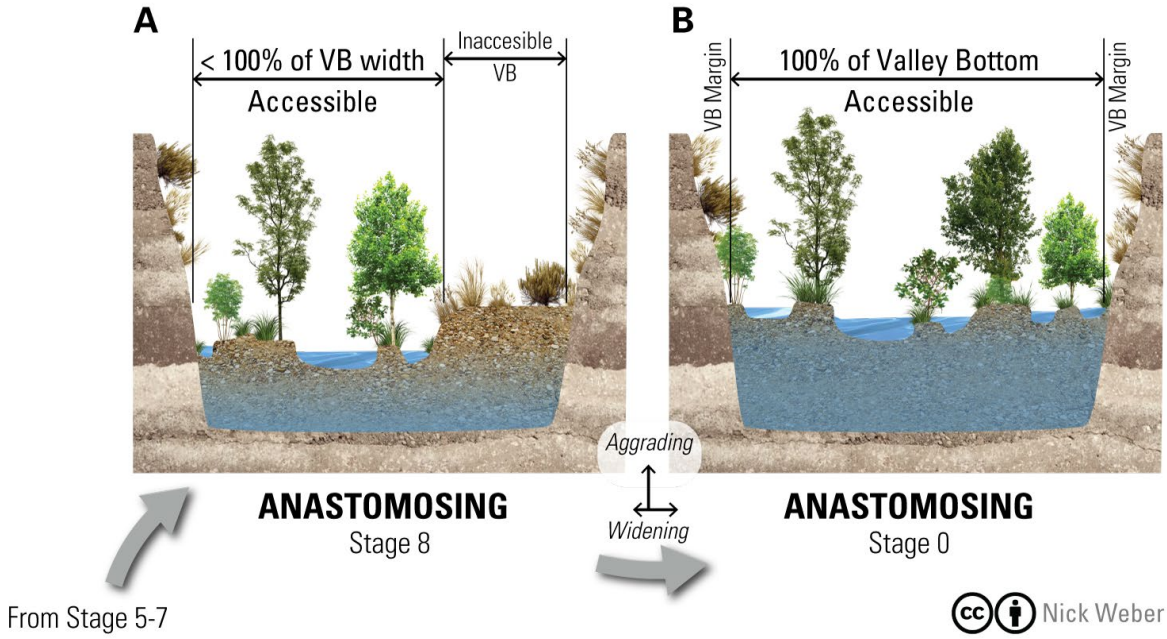


Figure 6 – An illustration of the difference between different 'anastomosing' of the Cluer and Thorne (2014) Stage 8 versus Stage 0. The difference is that in Stage 8, anastomosing behavior exists, but it does not span the entire width of the valley bottom. With continued lateral re-working of the 'high and dry' topography of the valley bottom (e.g. widening via bank erosion of the inaccessible valley bottom surface) and aggrading of the inset anastomosing channel network and islands, the entire valley bottom can become anastomosing. This not only helps understand the pathways by which the process occurs, but if infrastructure or incompatible land uses are in the inaccessible valley bottom, it helps identify limits on restoration targets.

Table 2 – Comparison of the simplified 'stage' terminology adopted in this manual to that of Cluer and Thorne (2014).

Description in this Manual	Proportion of Valley Bottom Width	Corresponding Cluer & Thorne Stage(s)	Cluer & Thorne Label
Anastomosing	100%	Stage 0	Anastomosing Set Woodland or Anastomosing Grassed Wetland
Incised	Far less < 100%	Stages 1 - 3	Sinuous Single Thread, Channelized, Degradation and Widening, or Arrested Degradation
Widening	< 100% & > Incised	Stage 4	Widening
Aggrading & Widening	<100% & > Widening	Stage 5	Aggradation & Widening
Not represented	Varies (< 100%)	Stages 6 and 7	Quasi-Equilibrium & Laterally Active
Anastomosing	< 100% and > Stages 1-7	Stage 8	Anastomosing

Figure 7 –Riverscapes where beaver dams force Stage 0 (anastomosing) conditions across a range of physiographic settings. Although these conditions were once pervasive across North America's riverscapes, they are rare today. Stage 0 maximizes physical heterogeneity across the valley bottom, creating habitat for aquatic and terrestrial biota. Note that C & D are courtesy of Mark Beardsley from EcoMetrics.

Restoration Review

Efforts to restore riverscapes have been underway for over a century (Thompson, 2005). In the Unites States alone, conservative estimates suggest that annual spending on stream and river restoration exceeds $1 billion (Bernhardt et al., 2005). However, despite this investment, thousands of miles of degraded riverscapes remain (EPA, 2006). There are many reasons to restore riverscapes. Commonly stated restoration goals generally fall under ecological, recreational and aesthetic categories and can include channel reconfiguration, dam removal, fish passage, floodplain reconnection, flow modification, and instream habitat improvement (Wohl et al., 2015). Recognition of the ecosystem services provided by healthy riverscapes has also helped promote restoration to improve forage production on rangeland and improve water quality. For a more in-depth review of stream restoration we refer the reader to Wohl et al. (2015). In this section we briefly review the practice of stream restoration. Our goal is not to provide a comprehensive history of restoration, but to highlight the disconnect between the dominant engineering-based approach to restoration and the scale of riverscape degradation. Additionally, we introduce critiques of riverscape restoration and the conceptual advances in restoration understanding. Finally, we introduce and describe the history of low-tech restoration practices and their recent re-emergence as an approach capable of addressing the scope or riverscape degradation.

Engineering-based Restoration

While there are a wide variety of approaches and techniques used in stream restoration we contend that engineering-based approaches have been, and continue to be, the most widely used. Rather than address specific techniques used in engineering-based restoration (e.g., channel reconfiguration, engineered log jams), here we highlight themes that we believe limit the ability of such an approach to effectively scale up to address the scope of degraded riverscapes. These include i) precisionism and the need for certainty, ii) an emphasis on stability, and iii) high cost and limited spatial extent.

Our intent in this section is not to suggest that engineering-based approaches to restoration should be replaced by the low-tech approach outlined in this manual. Engineering-based approaches to restoration are and will continue to be useful in many riverscapes, especially on larger rivers and in areas where uncertainty cannot be tolerated, as in areas with significant infrastructure. Rather, due to their location and size, many riverscapes could be more effectively restored using low-tech methods.

Precisionism

The belief that restoration practitioners can and should be able to accurately predict the specific and precise outcomes of restoration is common (Hiers et al., 2016). However, healthy riverscapes are dynamic, where specific attributes, such as the location of pools, bars, channel width and depth, and sinuosity change through time, in response to flow conditions, sediment delivery and the influence of structural elements. Many restoration funders and land managers are expected to evaluate the success of restoration projects by specific criteria, which creates a need for restoration practitioners to design projects that have a high certainty of meeting project objectives. As a result of these pressures, and in order to avoid uncertainty in outcomes, restoration often focuses on stability.

Stability

Stability is not a hallmark of healthy riverscapes. While healthy riverscapes can be generally characterized by a collection of attributes (e.g., Stage 0), the specific location of structural elements and habitat features changes through time while reach-scale metrics remain relatively constant. The desire to reduce uncertainty and precisely predict restoration outcomes has led to practices that tend to emphasize the stability of channels and instream structures (Kondolf et al., 2001). In the context of stream restoration, stability has often meant static. Constructed features and attributes such as planform, channel width, location of pools and riffles are designed in such a way that they do not change through time. An example of the emphasis on channel stability is the extensive use of rip-rap on meandering channels to prevent lateral migration. Importantly, lateral migration is the process responsible for the creation of meandering channels, limiting this process necessarily means the stream will not be able to function naturally. Another example of the emphasis on stability can be shown with the use of instream structures. Adding wood to degraded streams is generally considered to improve habitat conditions and is a common restoration practice (Bernhardt et al.,

2005). Wood is typically added to streams by constructing large woody debris structures that simulate log jams (e.g., engineered log jams (ELJs)) (Abbe and Montgomery, 2003); or by designing log structures to be static by cabling, burying, or using boulders to secure wood in place (Slaney and Zaldokas, 1997). The emphasis on stability requires detailed engineering designs, modeling, and heavy equipment, all of which contribute to the high cost of restoration. Studies have generally found that such structures do increase local geomorphic diversity (Roni et al., 2014). However, population level response of target species (e.g., salmon or steelhead) to these restoration actions is equivocal.

High Cost – Limited Footprint

Emphasizing stability and certainty leads to highly-engineered restoration projects that necessarily increase the cost of restoration. The results of the high cost, per unit length of stream, inevitably results in fewer stream miles being restored. This is important for at least two distinct reasons. First, we are unlikely to be able to address the scope of degraded riverscapes using a high-cost approach to restoration. Second, many ecological goals of restoration must be addressed at large spatial scales. For example, improving instream and floodplain habitats to affect a population level response in salmon necessarily requires restoring large spatial extents. In short, reach-scale projects are unlikely to achieve many ecological goals (Bernhardt and Palmer, 2011).

Process-Based Restoration

In many degraded streams and rivers, the processes that sustain healthy riverscapes have been altered by both watershed-scale changes (e.g., conversion of forest to agriculture) and reach-scale alterations (e.g., channelization, removal of wood and beaver). Generally, restoration has focused more on restoring riverscape form without addressing the underlying processes responsible for that form. In response, the scientific community proposed a process-based restoration philosophy (Beechie and Bolton, 1999; Kondolf et al., 2006; Kondolf et al., 2001). Process-based restoration is defined as protecting, enhancing, and/or restoring "normative rates and magnitudes of physical, chemical, and biological processes that sustain river and floodplain ecosystems" (Beechie et al., 2010). We adopt the principles outlined by Beechie et al. (2010) as a guide for informing the subset of process-based restoration we refer to as low-tech (Table 3). A central premise of process-based restoration is that restoration of natural systems (e.g., rivers, streams, their floodplains and watersheds) is best achieved by 'letting the system do the work'. Process-based restoration recognizes that to restore ecologically functional riverscapes, we need to restore the physical and ecological processes responsible for creating and maintaining those conditions.

Table 3 –Summary of process-based restoration principles. Adapted from Beechie et al. (2010).

Principle	Description
1. Target root causes of habitat and ecosystem change	Restoration actions are designed to address the human alterations to processes that are degrading habitat conditions
2. Tailor restoration actions to local potential	A given reach in a river network operates within specific constraints based on its location within the watershed and climatic and physiographic setting. Understanding the types and magnitudes of processes within a given reach helps design restoration actions.
3. Match the scale of restoration to the scale of the problem	When disrupted processes causing degradation occur at the reach scale, restoration actions at individual sites can effectively address root causes. When causes of degradation occur at the watershed scale, many individual site-scale actions are required.
4. Be explicit about expected outcomes	Process-based restoration is a long-term endeavor and there are often long lag times between implementation and recovery and biota may not improve dramatically with any single action. Articulating restoration goals and pathways is critical to setting appropriate expectations.

Low-Tech Process-Based Restoration

We define low-tech process-based restoration of riverscapes as, simple, cost-effective, hand-built solutions that help repair degraded streams. In the context of process-based restoration, low-tech approaches are designed to "kickstart

processes that allow the stream to repair itself" (Randall, 2018). Historic and current examples of low-tech restoration, as both a label and an approach, are abundant. 'Low-tech' restoration practices have been used in coral reef restoration (Bowden-Kerby, 2001), road crossings in streams (Johnson, 2002), in rangeland settings to increase soil moisture (Nichols et al., 2012), and as part of aquatic and riparian rehabilitation efforts (Basílico et al., 2016; Silverman et al., 2018). See Appendix B, for an elaboration of the semantics surrounding low-tech restoration and related terminology and approaches. These low-tech restoration approaches, such as simple rock and wood structures (Zeedyk and Clothier, 2014), management with beaver (Pollock et al., 2014), and time-controlled grazing management (Swanson et al., 2015) rely primarily on human labor, natural materials, and changes in management to restore hydrologic, ecologic, and geomorphic processes (see Appendix C). We review the historic and current use of low-tech approaches to restoration to demonstrate that we are not claiming to have invented or discovered an entirely new approach to restoration. Instead, we believe that by placing low-tech process-based restoration techniques within a broader well-defined framework, we may be able to encourage the increased application of these techniques.

While the recent increase in the use of low-tech restoration structures such as BDAs and PALS gives the impression that such techniques are new, similar structures have been used to restore channels for at least a century (see also Appendix D). Furthermore, erosion control techniques described by Kraebel and Pillsbury (1934) to reclaim gullies in mountain meadows (see Figure 8) are nearly identical to the techniques and principles outlined in this manual.

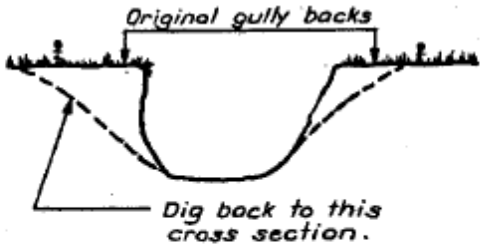


Figure 25
Sectional elevation of gully showing how banks should be sloped back.

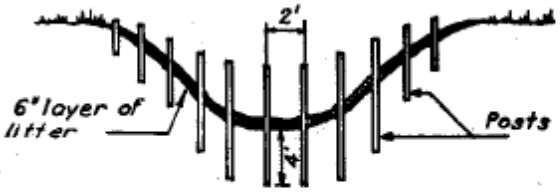


Figure 26
Sectional elevation of gully showing posts and litter in place for dam. Note that the posts are lower in the center.

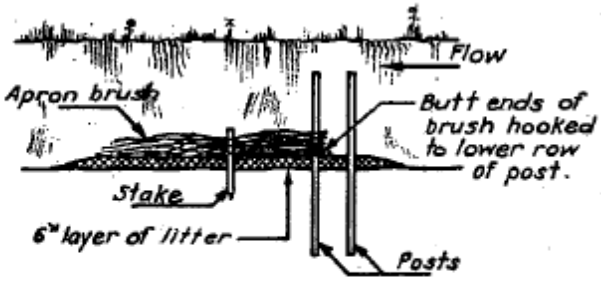


Figure 27
Side section of dam after apron brush has been placed.

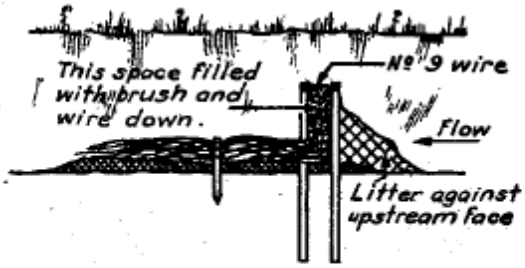


Figure 28
Side section of completed dam.

Figure 8 –Figures from Handbook of Erosion Control in Mountain Meadows (Kraebel and Pillsbury, 1934). The approach to restoration and many of the specific techniques are similar to the approaches outlined in this manual, though tending to focus on ephemeral channels.

Most importantly, the general approach to restoration outlined by Kraebel and Pillsbury (1934) foreshadows the principles we define in Chapter 2 (Wheaton et al., 2019b). They are worth quoting at length:

1. *Numerous low dams along a gully are preferred to a few high dams. A "low check dam is considered to not be over three or four feet in height. There is less danger of such structures washing out in time of flood, and if they should wash out less damage will result. Further, low dams are more economical than high dams.*

2. *It is more economical to reclaim a gully by stages, than to try to do it at one time or with one set of dams. The best method is to construct a series of low dams along the gully. When the catch-basins behind these dams have filled, another series of dams can be built on top of or just upstream from the original dams….*

3. *Temporary rather than permanent check dams are usually preferred….*

In addition to the systematic use of low-tech structures to reclaim gullies, human mimicking and/or maintenance of beaver dams is not new. *Three Against the Wilderness (Collier, 1959)* details the experience of a trapper in 1920s British Columbia who repairs abandoned beaver dams in order to restore habitats the attract the game he needs to survive.

Perhaps the best known current examples of low-tech restoration are described in *Let the Water Do the Work* (Zeedyk and Clothier, 2014), which details the application of a wide range of hand-built rock and wood structures to restore incised channels and increase stream complexity, using a technique they call "induced meandering." Additional low-tech restoration treatments are described in Appendix C.

Later in this manual we describe in detail the form, function and design of BDAs and PALS. While we encourage restoration practitioners to use the information presented in Chapter 4 (Shahverdian et al., 2019a) to guide their design and implementation, we caution against focusing too heavily on the structures themselves, and remind practitioners that low-tech process-based restoration is an approach to restoration, and understanding the context provided here and the principles defined in Chapter 2 (Wheaton et al., 2019b) are the foundation for effective restoration.

Restoration Practitioners and Ecosystem Engineers (Beaver)

While the low-tech restoration approach detailed in this manual has the potential to allow restoration practitioners to restore more stream miles than traditional engineering-based methods, it is unlikely to address the full scope of the problem without help from these riverscapes themselves. The use of beaver as restoration agents is an increasingly common practice (Lautz et al., 2019; Pilliod et al., 2018; Pollock et al., 2015). Our ability to mimic the dam building activities of beaver and maintain those dams is limited. Building and maintaining low-tech restoration structures such as PALS and BDAs may be cost-effective relative to engineered approaches to restoration. However, to realize continued benefits it is essential that the system itself is capable of maintaining the integrity of the processes that maintain ecosystem health. In many instances this means that beaver construct and maintain dams. Restoring and protecting beaver on the landscape, where feasible, is likely the most effective low-tech restoration strategy for restoring self-sustaining functioning riverscapes. This can be accomplished through a combination of protecting existing populations by using temporary or permanent trapping restrictions and translocating beaver to riverscapes that can support dam building but currently lack beaver (McKinstry and Anderson, 2003; Woodruff and Pollock, 2015).

Figure 9 – Passive low-tech restoration where the state wildlife management agency (in this case Utah Division of Wildlife Resources) has put a temporary trapping closure on beaver harvest on a creek to allow beaver populations to recover.

A HEALTH ANALOGY MOVING FORWARD

In river restoration practice and watershed management, the river health analogy has been used for over 20 years (e.g., Boulton, 1999; Fairweather, 1999; Karr, 1999; Norris and Thoms, 1999) and has been applied in the goals, design, application and communication of restoration practices (e.g., Bottrill et al., 2008; Hobbs and Kristjanson, 2003; Schaefer, 2003). Parallels to human health can help increase understanding of what creates and maintains healthy riverscapes, leading to more effective and scalable restoration actions. Specifically, the concepts of healthy diets and exercise for riverscapes are useful in promoting a greater awareness of the processes fundamental to riverscape health and how specific restoration actions promote or limit these processes. We argue that most restoration actions today are analogous to events like surgery (e.g., channel realignment), wherein drastic measures are taken to address immediate and major concerns. While sometimes necessary, such actions do not necessarily contribute to long-term health, whereas daily diet and exercise may preclude the need for drastic measures in the first place. Long-standing calls within the restoration science community for 'process-based' restoration advocate for a living (dynamic) river ethos, but it has been unclear what process-based restoration actions are required. We assert that feeding riverscapes structural elements and allowing the system to digest the structure is an analogy that helps more specifically focus our attention on what process-based actions restoration practitioners should consider. We assert that healthy rivers are fed meals by their watersheds, and are allowed regular exercise (i.e., channels actively adjust according to their natural capacities for adjustment). Using a healthy diet analogy, we show how focusing on a smaller, and continual meals (i.e., low-tech restoration structures) can help feed and nurse rivers back to recovery. Preparing and feeding these meals in the correct context can be tackled by less-skilled practitioners (i.e., cooks), whereas surgery is something that only skilled surgeons are licensed to perform (e.g., professional engineers). These simple analogies may help improve communication amongst stakeholders interested in the health of rivers, supporting efforts to more logically choose restoration actions that maintain or enhance sustainable health over those akin to life-support of a dying patient (see also Appendix E).

CONCLUSION

The poor health of many river systems has been the impetus for massive investment in river restoration. In this chapter, we have covered key concepts in understanding the scope and problem of structural starvation of riverscapes. We have reviewed and embraced the concept of process-based restoration and called for an increased emphasis on low-tech process-based restoration. The remainder of this manual describes the guiding principles of low-tech process-based restoration, planning, design, implementation and elaborates on two relatively new additions of methods for low-tech restoration – namely post-assisted log structures and beaver dam analogues. In the context of low-tech process-based restoration, we have structured this design manual around the over-arching goal of improving the health of as many miles of riverscapes as possible.

Chapter 1 - APPENDICES

APPENDIX A – PARTIAL SELECTION OF PAST LITERATURE RELEVANT TO LOW-TECH RESTORATION

Table 4 – A partial selection of other relevant manuals, books and technical guidance on process-based restoration of riverscapes and each reference's relationship to helping restore riverscapes

Reference	Relationship to Restoring Riverscapes
2005. Brierley, G. and Fryirs, K.: Geomorphology and River Management: Applications of the River Styles Framework, Blackwell Publishing, Victoria, Australia.	Both an introductory text to fluvial geomorphology for understanding riverscapes (via the River Styles framework), and an approach to managing and restoring riverscapes based on a respect and appreciation for the diversity of riverscapes.
1934. Kraebel, C. J. and Pillsbury, A. F.: Handbook of Erosion Control in Mountain Meadows, U.S. Forest Service, California Forest and Range Experiment Station, Berkeley, CA, 69 pp.	Provides extensive guidelines on low-tech structures and idea of using process to restore degraded meadows.
2018. Maestas, J. D., Conner, S., Zeedyk, B., Neely, B., Rondeau, R., N. Seward, Chapman, T., With, L., and Murph., R.: Hand-built structures for restoring degraded meadows in sagebrush rangelands: Examples and lessons learned from the Upper Gunnison River Basin, Colorado, USDA, Natural Resources Conservation Service, Denver, CO, 47 pp.,	Provides introduction to use of low-tech structures like Zuni Bowls and one-rock-dams in ephemeral and intermittent streams for meadow restoration.
2018. Pollock, M. M., Lewallen, G., Woodruff, K., Jordan, C. E., and Castro, J. M. (Eds.): The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains. Version 2.01, United States Fish and Wildlife Service, Portland, OR.	Provides guidance on using the ecosystem engineering of beaver to help restore riverscapes. Includes guidelines on translocation, and introduction of beaver dam analogues.
2013. Roni, P. and Beechie, T. (Eds.): Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats, Wiley, Chichester, U.K..	An edited volume on process-based restoration.
2011. Skidmore, P. B., Thorne, C. R., Cluer, B. L., Pess, G. R., Castro, J. M., Beechie, T. J., and Shea, C. C.: Science base and tools for evaluating stream engineering, management, and restoration proposals, U.S. Department of Commerce, Seattle, WA, 255 pp.	Useful screening and evaluation questions at planning and permitting stages. Includes the River RAT (Restoration Assessment Tool).
2016. Yochum, S. E.: Guidance for stream restoration and rehabilitation, US Department of Agriculture, Forest Service, National Stream and Aquatic Ecology Center. Technical Note no. TN-102.2, 2016.	Extensive review and annotated bibliography of various aspects of stream restoration and rehabilitation that includes many process-based restoration examples (e.g., beaver, large woody debris).
2009. Zeedyk, B. and Clothier, V.: Let the Water Do the Work: Induced Meandering, an Evolving Method for Restoring Incised Channels, Island Press, Washington D.C.,	Details the design and construction of structures that promote processes and letting 'the water do the work' (in this case for initiating widening and meandering in incised channels).

APPENDIX B – LOW-TECH PROCESS-BASED RESTORATION SEMANTICS

People are often imprecise or inconsistent in their naming and labels, or they use different phrases to resonate with different audiences. There are a variety of labels that have been used to describe what we refer to as low-tech process-based restoration (Box 1). Here we provide background on some of the different terms in use and their origins.

When we first started experimenting in the late 2000's with low-tech process-based restoration, it was a response to the mismatch of the extent of restoration efforts to the massive scope of degradation. In short, we were frustrated by the expensive price tags, unimpressively small foot-print of most projects, and minimal effectiveness of typical restoration efforts relative to how much need there was. We started out calling techniques like using beaver reintroduction, placing post-assisted log structures in high densities (high-density large woody debris), or mimicking beaver dam activity with beaver dam analogues – cheap and cheerful restoration. For reasons we elaborate below, we shifted to calling this collection of low-tech, cost-efficient and scalable restoration techniques low-tech process-based restoration. It is low-tech because the structures are built by hand, using natural (preferably on-site) materials.

ALIASES & EXAMPLES OF LOW-TECH PROCESS-BASED RESTORATION

Aliases

- Low-Tech Restoration
- Low-Tech Riparian Restoration
- Cheap & Cheerful Restoration
- Affordable Restoration
- Cost-Effective Restoration
- Non-Engineered Restoration

Examples

- Beaver-Assisted Restoration
- Beaver-Inspired Restoration
- Stage Zero Restoration
- High-Density Large Woody Debris

Box 1- A non-exhaustive list of aliases and examples low-tech process-based restoration.

Since 'cheap & cheerful' was an umbrella term we had applied to what in this manual we now call low-tech process-based restoration, it is worth elaborating on what we meant by that, and why we shifted away from it. The phrase 'cheap and cheerful' is a British slang phrase that means simple and inexpensive. We originally used the phrase 'cheap and cheerful' to refer to an approach to stream restoration practices that is distinct from an engineering-based approach. We did not mean to imply that 'cheap and cheerful' restoration was inherently *better* than conventional, engineering based approaches. Rather, the different approaches are each appropriate in different settings, and their ability to address restoration goals is directly related to the context in which they are implemented. To that end, deciding when and where 'cheap and cheerful' or low-tech methods are appropriate can be more challenging, and may be more important, than implementing the solutions themselves (see Chapter 3 on Planning: Bennett et al., 2019b). However, we do assert that we (as both a society and practitioners) will be incapable of addressing the current scope of riverscape degradation using traditional engineering-based restoration methods. We simply lack the financial resources to 'fix' these systems. We used the word 'cheap' to indicate that the low-tech restoration methods outlined in this manual are less expensive on a per stream mile basis, however we advocate that we use any cost savings to expand the spatial extent of restoration, in order to address the true scope of the problem. As the 'cheap and cheerful' phrase and rhetoric began to spread from 2011 to 2017, we have realized two important and unintended consequences of its use.

- It may be unintentionally offensive to some practitioners who already try their hardest to maximize the investment of every restoration dollar
- It may confuse funders of restoration projects or create unrealistic expectations about total project costs

We now try to be more careful in our use of the phrase to avoid these misconceptions. However, to the extent that it focuses attention on both effectiveness and efficiency in restoration, we continue to promote the details behind the rhetoric. However, we are instead using the phrase 'low-tech process-based restoration' to avoid the above confusion.

APPENDIX C- TABLE OF EXISTING LOW-TECH PRACTICES

There are many different low-tech structures and techniques available on any given restoration project. The specific tools practitioners can use depend on site-specific watershed context, including hydrologic and geomorphic setting, condition, recovery potential, the causes of degradation, financial resources and other variables (see Chapter 3: Bennett et al., 2019b). One of the foundational premises of low-tech restoration is the efficient use of resources. It is tempting to jump in the riverscape and begin construction immediately, however if there are alternatives we recommend exploring them first. Can the riverscape recover simply by reintroducing beaver alone? Will a different approach to grazing promote riparian expansion? Does the riverscape need an increase in structural elements to increase physical complexity? There are many different approaches available to the restoration practitioner and we catalog some of them for the practitioner to reference in Table 5. Most, if not all, of these tools can and should be used to complement one another to have the best chance at achieving restoration goals.

Table 5 – A list of typical low-tech approaches to promoting specific process-based restoration outcomes.

Name	Helpful Reference(s)
Promoting and/or Mimicking Wood Accumulation	
Seeding of Wood – Direct Recruitment of Unanchored Wood	
Direct Felling	Carah et al. (2014)
Grip-Hoisting	Micelston (2014)
Structural Placement of Wood Accumulations	
Post-Assisted Log Structures	Chapter 4 (Shahverdian et al., 2019a)
Improving Supply of Woody Material	
Riparian Plantings	Hall et al. (2011)
Grazing Management	Swanson et al. (2015)
Promoting and/or Mimicking Beaver Dam Activity	
Beaver Translocation	Woodruff and Pollock (2015)
Beaver Dam Analogues	Chapter 4 (Shahverdian et al., 2019a)
Trapping Closures	Figure 9; (Valachovic)
Erosion Control (often for intermittent & ephemeral channels)	
Baffles	Zeedyk and Clothier (2009)
One Rock Dams	Maestas et al. (2018); Zeedyk and Clothier (2009)
Post and Brush Plugs	Kraebel and Pillsbury (1934)
Tree Dam	Kraebel and Pillsbury (1934)
Tree Plug	Kraebel and Pillsbury (1934)
Vanes	Zeedyk and Clothier (2009)
Wicker Weirs	Kraebel and Pillsbury (1934)
Zuni Bowls	Maestas et al. (2018); Zeedyk and Clothier (2009)

APPENDIX D – NOTHING IS REALLY NEW

Despite packaging and appearances, nothing we are doing is really new. Some of it might be innovative, but the ideas predate us all. It is important that we learn from history and those before us. We fully acknowledge and appreciate that many practitioners already adopt a low-tech and/or process-based philosophy in what they do and try to maximize the impact of their actions. The important thing is that we attempt to learn from the experience of others and take the ideas we like and incorporate them into our own experiences. We should always be careful to not assume we are the 'first'. Ideas evolve through time as they are passed on and 'stolen' and adapted to become our own. As scientists, we have an obligation to make sure we appropriately cite past work. However, as practitioners, the most gratifying thing is to see ideas in others that spawned from seeds you planted, turn into someone else's idea. It is when the ideas grow beyond us to capture the imagination of broader communities that we might stand a chance of addressing the true scope of degradation of our riverscapes.

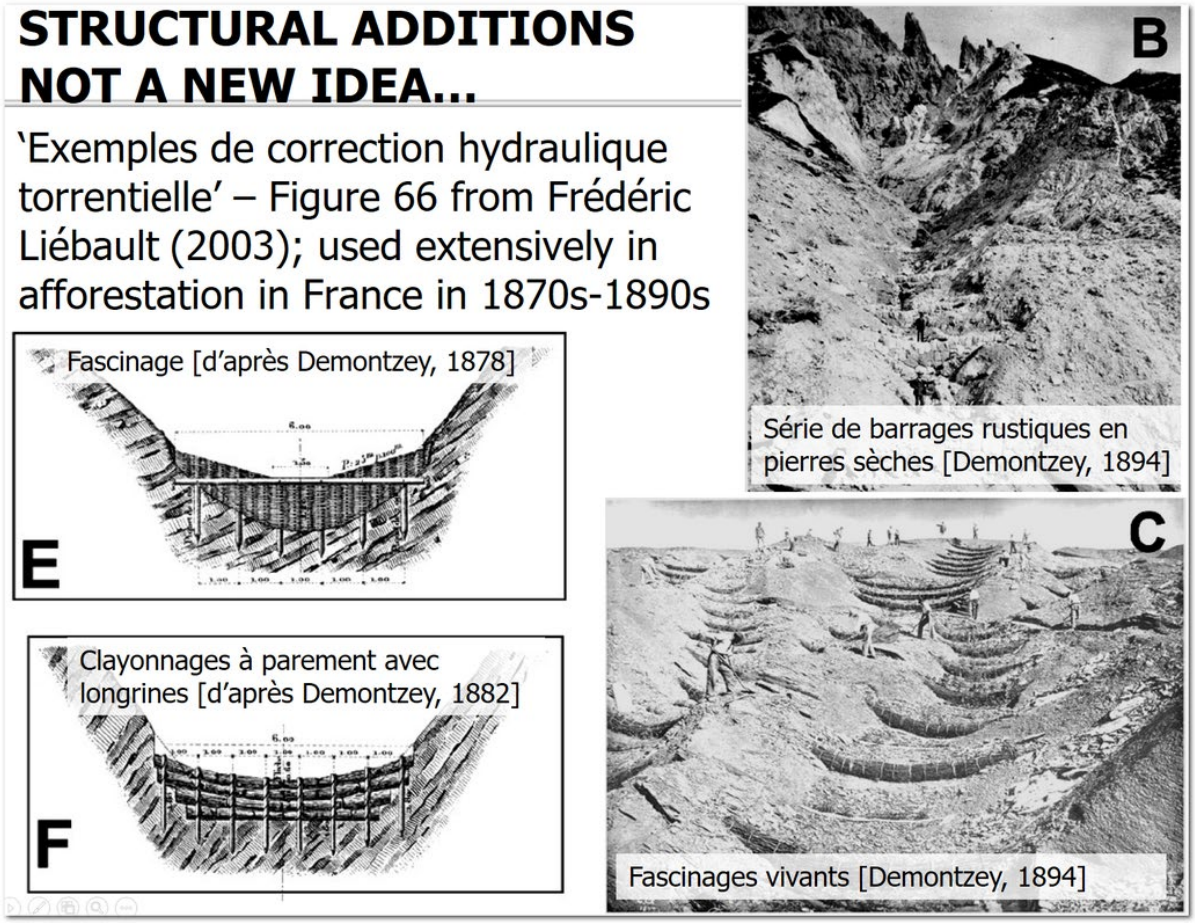


Figure 10 – An example from the Drome Catchment in France in the 1800s where large numbers of simple hand-built structures were added to degraded streams ('hydraulique torrentielle') to restore (correct) the problem. This figure highlights just how long some of these concepts have been around (even if forgotten). The pen and ink drawings of Demontzey in E & F show the use of posts, wicker weaves, and log cribs in what later became known as 'check dams' and are similar to techniques we use with post-assisted log structures. Adaptation of figure from figure 66 of Liébault (2003) PhD thesis. Slide from Wheaton (2018).

The Now Famous Parachuting Beaver Examples

As beaver restoration became popular over the past decade, there was a sense in the restoration community that this was a new technique. Biologists at Idaho Fish & Game in the 1940s wanted to use beaver to make better trout habitat and reduce flood damage by sourcing nuisance beaver that were flooding vacation homes in McCall, Idaho, and releasing them in the Frank Church Wilderness where their numbers had dwindled. The problem was that moving them in by horse-back was too expensive. With presumably new found skills as returning paratroopers and a post-war surplus of pilots, planes and parachutes, they found a more cost-effective method by parachuting beaver into the Frank Church Wilderness. Heter (1950) reported his findings in the Journal of Wildlife Management. Sound familiar? Similar efforts by California Department of Fish and Game in the 1950s also exist (Figure 11).

California transplants beaver into El Dorado National Forest via parachute in 1950 (Source: CA Dept. of Fish and Wildlife).[16]

Figure 11 - A poster from California Department of Fish and Game promoting the benefits of using beaver as a conservation tool to the benefit of water resources for fish, wildlife and agriculture. Source: Poster appears in Lundquist and Dolman (2018) based on work by Lundquist et al. (2013).

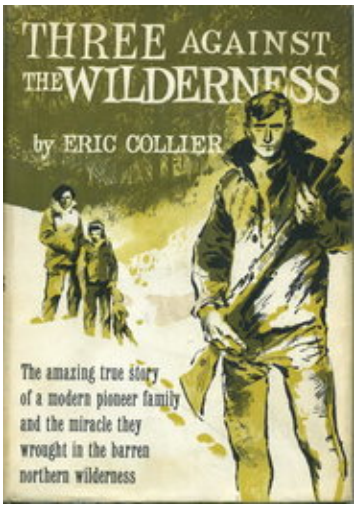


Figure 12- Potentially first known example of BDAs from Eric Collier (1959)?

The 'First' BDAs?

If you really want to convince yourself no one is on to anything new when it comes to partnering with beaver as a restoration tool, read Eric Collier's Three Against the Wilderness (Collier, 1959). Although published in 1959 (Figure 12), Eric describes his family's efforts in the 1920s and 1930s to mimic the work of beaver in British Columbia by repairing the abandon dams left behind from their extirpation in his watershed in the 1830s and 1840s. It is one of the earliest examples we know of, of what you might call beaver dam analogues. Eventually, he is able to stop doing the maintenance when a game warden brings him a few translocated, live beaver to introduce to the area.

Erosion Control Principles

'Erosion control principles' sounds contemporary does it not (Figure 13)? This idea is from a USFS publication from the 1930s by Kraebel and Pillsbury (1934), that was so useful that the USFS reproduced it in 1980 (still long enough ago for us to have forgotten it again)!

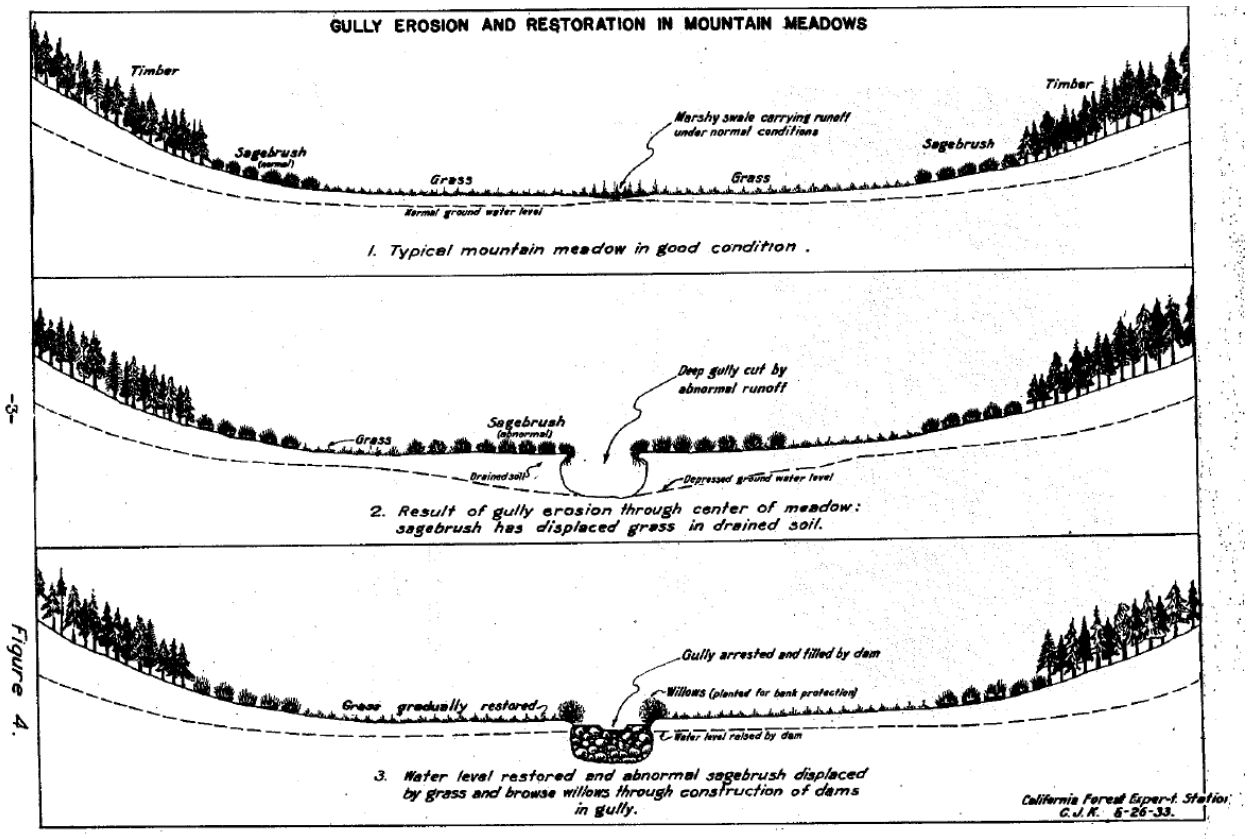


Figure 13 – Example from Kraebel and Pillsbury (1934) of principles of restoring meadows (i.e., valley bottoms of riverscapes) with check dams (i.e., structure), by addressing gully erosion (i.e., incision) and promoting aggradation and floodplain reconnection.

APPENDIX E – HEALTH ANALOGY TABLE DEFINED

Table 6 and Table 7 below were created by Gary Brierley and Joseph Wheaton to help elaborate the concepts of riverscape health (Wheaton, 2018).

Table 6 - Definitions of metaphors related to river health used in this paper. The first column presents the term (in bold) and its dictionary definition (in italics). That definition is expanded in the second column as it applies analogously to river health.

	Term (metaphor) – and its definition	Definition in relation to river health
Processes	**Metabolism** – n. *the chemical and physical processes by which a living thing uses food for energy and growth*	The physical processes (hydrologic, hydraulic, geomorphic and biogeochemical) that collectively determine the rate at which water, sediment, wood, and nutrients are consumed by a river. This describes the ways in which a river uses its energy to maintain its geoecological functionality (i.e., uses food to provide nutrition for the system).
	Exercise - n. *the physical action performed to make or keep the body healthy*	Rivers adjust their size, shape and form during competent flow events (i.e., they maintain their dynamic regime (health) through exercise). In this sense, exercise refers to how a river works – its forms and rates of adjustment, and associated evolutionary traits. Healthy rivers are never static. Neither are they necessarily equilibrium systems. Rather, they have their own 'capacity for adjustment' and ranges of variability, responding to disturbance events in differing ways as they use available energy (metabolism) at any given time. Available ingredients and food (water, sediment, riparian vegetation, wood, nutrients, etc.) are supplied, reworked and exported at variable rates. For a living river, these are mutual adjustments, as the channel adjusts to set its own patterns of resistance elements, thereby impacting upon the geomorphic effectiveness of disturbance events.
Food / Diet	**Diet** – n. – *the food and drink usually taken by a person or group*	Food that supports the biogeochemical functionality and metabolism of a river, providing the nutrition (energy) that maintains health. Most rivers can survive on a broad range of diets.
	Food – n. – *something that can be taken in by an animal and used to keep it alive and allow it to grow or develop*	Protein, carbs etc. – what is available in any given region (cf., globalization has made everything available everywhere, but this doesn't mean everything is appropriate). Empty carbs may taste good and provide instant gratification, but they cause other problems with a suite of secondary health problems that are often very expensive to address (recovery is not always possible).
	Ingredients – n. – *one of the parts of a mixture*	Raw ingredients such as water, sediment, wood, vegetation and can be considered as analogous to flour, water, salt, etc. While some ingredients constitute food, by themselves, in general, the raw ingredients are combined to produce the food that a river consumes.
	Meal – n. – *an occasion when food is served or eaten, or the food itself on such an occasion*	A meal is a regular event in which food is eaten. Typically, we put things together to prepare a dish, which can be thought of as the food makes up one course of a meal. This represents the formative processes that shape a river system. After a given event, the system adjusts to prevailing fluxes. Unlike humans, rivers don't need consume meals every day, but rather are fed meals by the imposed boundary conditions of climate, geology, flow regime, sediment supply periodically or even episodically. Rivers can run dry, but perennial rivers need a regular water supply (drink). The river consumes a meal, and processes waste products in due course. In some dinners left overs are left (some rivers have excess 'food', which they store for another day). Eating small amounts regularly may be important, rather than over-indulging. Also, the serving size (what we make available) may be important.

Table 7 – Table of treatment metaphors for river restoration and management.

	Term (metaphor) – and its definition	Definition in relation to river management
Diet Treatments	**Treatment** – n. - *The techniques or actions customarily applied in a specified situation*	Treatments to improve river health can be broken into those that focus on improving diets, versus medical treatments targeted at specific ailments, injuries or illnesses.
	Recipe – n. – *A set of instructions telling you how to prepare and cook a particular food, including a list of what foods are needed for this*	Recipes lay out specifics for how ingredients (e.g., water, sediment, wood, nutrients, vegetation) are prepared and combined to create a specific food (e.g., a type of geomorphic unit, or structural element). The recipe details the ingredients, the order they are added, the degree to which the cook mixes and creates them versus the degree to which the river processes and prepares the food.
	Serving Size – n. – *The amount of one type of food given to one person*	How much food is added (e.g., in a gravel augmentation or a high flow release) in one meal.
	Cookbook – n. - *A book containing detailed information on how to prepare and cook different foods*	A collection of recipes, best practices for preparation of specific foods or food dishes (e.g., a restoration design manual). Most cook books stop short of spelling out all steps in meal planning and preparation and leave this to the judgement of the cook.
	Prepared Meal – n. – *A meal prepared by someone other than the individual(s) consuming it*	In the same way that soup is something you might serve to a patient with a cold, to help nourish them towards recovery, we can prepare meals for rivers (i.e., some mixture of water, sediment, wood, nutrients, etc.), which are fed to the channel at discrete points in time.
	Cook – n. – *A person who cooks (or prepares a meal)*	The cook need not always be a licensed professional. Simple dishes and meals can be prepared by amateur cooks in the right context, whereas more complicated meals may be more appropriately prepared by a more experienced amateur cook or professional chef.
Medical Treatments	**Diagnosis** - *The making of a judgment about the exact character of a disease or other problem, esp. after an examination, or such a judgment*	A trained river professional (e.g., geomorphologists, hydrologists, ecologists) diagnoses the condition of a riverscape through a condition assessment (often in response to a perceived problem).
	Prognosis – n. - *A doctor's judgment of the likely or expected development of a disease, or a statement of what the likely future situation is*	After a diagnosis, a professional judgement is often made about the likely recovery potential of a river and its likelihood to respond positively to various types of treatments.
	Injury – n. – *physical harm or damage to a living thing (often occurs by accident or unintentionally)*	Riverscapes diagnosed with poor condition often exhibit specific injuries locally (e.g., a levee or road disconnecting a channel and floodplain), which might be treated locally with surgery or medicine.
	Disease/Illness – n. - *A condition of a person, animal, or plant in which its body or structure is harmed because an organ or part is unable to work as it usually does; an illness (often develops gradually)*	A disease is a poor condition of a riverscape that is often brought about by broader-scale, upstream impacts to the river system (e.g., chronic over-extraction of water, changes in flow regime, land use changes, etc.), and the treatments might require a broader, system-wide approach.
	Health Monitoring – n. – *The process of watching and checking the health of an individual or group of individuals over a period of time*	Monitoring programs are often used to track the status (i.e., condition) and trends through time, as well as the effectiveness of various treatments (i.e., restoration actions).
	Prescription Medicine – n. – *A substance taken into the body in treating an illness that is prescribed by a doctor*	Most medicine can be thought of non-native, anthropogenic inputs of structural elements (e.g., engineered large woody debris with anchoring) intended to address specific symptoms.
	Dosage – n. – *A measured amount of medicine*	The amount & frequency of structural elements prescribed.
	Surgery – n. - *The treatment of injuries or diseases by cutting open the body and removing or repairing the damaged part, or an operation of this type*	Discrete actions that involve earthwork, realignment, and major invasive rearrangement of the channel or floodplain topography with heavy equipment by skilled operators.
	Doctor - n. – *A person with a medical degree whose job is to treat people who are ill or injured*	In restoration practice, as in medical practice, many medical treatments are administered by restoration professionals (e.g., licensed engineers, design geomorphologists).

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Chapter 2 – PRINCIPLES OF LOW-TECH PROCESS-BASED RESTORATION

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IMPLICATIONS FOR PRACTICE

- Low-tech process-based restoration principles are critical to understand as both the basis for effectively applying low-tech restoration treatments and managing expectations about timing and magnitude of outcomes.
- We propose and synthesize principles that help practitioners tackle low-tech process-based restoration of structurally-starved riverscapes. Many of these principles likely apply to a greater range of riverscapes, but we do not cover those applications here.
- We break our guiding principles into
    - Riverscapes Principles - those that represent an understanding of what constitutes healthy riverscapes to help define what restoration should be aiming for; and
    - Restoration Principles – those that influence the choices and approach we take in planning, designing and implementing low-tech restoration.
- Since we focus on structurally-starved riverscapes, low-tech restoration that mimics and promotes the processes of wood accumulation and beaver dam activity specifically emerge out of these principles.

- These principles collectively provide practitioners with the rationale and strategies to attempt to tackle the true scope of degradation with simple, smart, agile and scalable low-tech solutions that rely on the system itself to do most of the work of recovery and find self-sustaining and resilient futures.

PURPOSE

The purpose of this chapter is to define some key principles that guide low-tech process-based restoration. We first introduce core principles for working in structurally-starved systems. We then elaborate their theoretical, conceptual and empirical bases with reference to some the supporting scientific literature on which they are based. Some of these principles are a reiteration of broader process-based restoration principles (e.g., Beechie et al., 2010; Brierley and Fryirs, 2005) previously articulated (see Chapter 1: Shahverdian et al., 2019b). The rest are part of a broader body of science that highlights fluvial dynamics creating and sustaining complex and heterogeneous habitats, which promote higher biodiversity.

Principles should act as the guiding rules, premises and central tenets around which practitioners approach design. We choose here to anchor these principles directly in a chain of reasoning that comes out of riverscape science from the disciplines of hydraulics, geomorphology, hydrology, ecology and engineering (e.g., Brierley and Fryirs, 2005; Naiman et al., 2005; Roni and Beechie, 2013). Of critical importance, these principles are not only grounded in scientific reasoning, but have been refined from and build off of nearly a century of restoration practice. Most these principles are not new and have held up to the stress, strain and scrutiny of working with a broad range of practitioners and stakeholders over the past decade, with competing ideas and interests in diverse riverscapes. These principles have been applied in riverscapes with real anthropogenic constraints that intersect and serve working rangelands, public and commercial forests, public parks and even the heart of urban areas. In other words, the application of these principles to the management, conservation and restoration of riverscapes helps not only to create healthier riverscapes, but also sets realistic expectation management for how we can coexist with dynamic riverscapes and reap the larger benefits of ecosystem services a healthier riverscape can provide.

LOW-TECH PROCESS-BASED RESTORATION PRINCIPLES FOR STRUCTURALLY-STARVED RIVERSCAPES

Riverscapes Principles

1. Streams need space
2. Structure forces complexity and builds resilience
3. The importance of structure varies
4. Inefficient conveyance of water is healthy

Restoration Principles

5. It's okay to be messy
6. There is strength in numbers
7. Use natural building materials
8. Let the system do the work
9. Defer decision making to the system
10. Self-sustaining systems are the solution

Box 1 – Low-Tech Process-Based Restoration Principles

GUIDING PRINCIPLES

We have distilled the core basis for low-tech process-based restoration for structurally-starved systems into ten guiding principles. First, we briefly define the principles, then elaborate their basis later in this chapter. Principles are broken into two categories: 1) Riverscapes, and 2) Restoration. The 'Riverscapes Principles' inform planning and design through an understanding of what constitutes healthy, functioning riverscapes and therefore what are appropriate targets and analogues to aim for. By contrast, the 'Restoration Principles' relate to our specific

restoration actions and give us clues as to how to develop designs to promote processes that lead to recovery and resilience.

Riverscapes Principles

1. **Streams need space**. Healthy streams are dynamic, regularly shifting position within their valley bottom, re-working and interacting with their floodplain. Allowing streams to adjust within their valley bottom is essential for maintaining functioning riverscapes.
2. **Structure forces complexity and builds resilience.** Structural elements, such as beaver dams and large woody debris, force changes in flow patterns that produce physically diverse habitats. Physically diverse habitats are more resilient to disturbances than simplified, homogeneous habitats**.**
3. **The importance of structure varies.** The relative importance and abundance of structural elements varies based on reach type, valley setting, flow regime and watershed context. Recognizing what type of stream you are dealing with (i.e., what other streams it is similar to) helps develop realistic expectations about what that stream should or could look (form) and behave (process) like.
4. **Inefficient conveyance of water is often healthy.** Hydrologic inefficiency is the hallmark of a healthy system. More diverse residence times for water can attenuate potentially damaging floods, fill up valley bottom sponges, and slowly release that water later elevating baseflow and producing critical ecosystem services.

Restoration Principles

5. **It's okay to be messy**. When structure is added back to streams, it is meant to mimic and promote the processes of wood accumulation and beaver dam activity. Structures are fed to the system like a meal and should resemble natural structures (log jams, beaver dams, fallen trees) in naturally 'messy' systems. Structures do not have to be perfectly built to yield desirable outcomes. Focus less on the form and more on the processes the structures will promote.
6. **There is strength in numbers.** A large number of smaller structures working in concert with each other can achieve much more than a few isolated, over-built, highly-secured structures. Using a lot of smaller structures provides redundancy and reduces the importance of any one structure. It generally takes many structures, designed in a complex (see Chapter 5: Shahverdian et al., 2019c), to promote the processes of wood accumulation and beaver dam activity that lead to the desired outcomes.
7. **Use natural building materials**. Natural materials should be used because structures are simply intended to initiate process recovery and go away over time. Locally sourced materials are preferable because they simplify logistics and keep costs down.
8. **Let the system do the work.** Giving the riverscape and/or beaver the tools (structure) to promote natural processes to heal itself with stream power and ecosystem engineering, as opposed to diesel power, promotes efficiency that allows restoration to scale to the scope of degradation.
9. **Defer decision making to the system**. Wherever possible, let the system make critical design decisions by simply providing the tools and space it needs to adjust. Deferring decision making to the system downplays the significance of uncertainty due to limited knowledge. For example, choosing a floodplain elevation to grade to based on limited hydrology information can be a complex and uncertain endeavor, but deferring to the hydrology of that system to build its own floodplain grade reduces the importance of uncertainty due to limited knowledge.
10. **Self-sustaining systems are the solution.** Low-tech restoration actions in and of themselves are not the solution. Rather they are just intended to initiate processes and nudge the system towards the ultimate goal of building a resilient, self-sustaining riverscape.

GUIDING PRINCIPLES - ELABORATED:

For each principle, we elaborate its definition, ground it in some of the underlying science, and where appropriate provide some visuals that attempt to capture their essence. For the interested reader seeking a deeper understanding of the science behind each principle, we highly recommend engaging with the cited literature. However, because these principles place more confidence and trust in riverscapes and the natural processes that shape them, they implicitly reduce the burden on restoration practitioners to have all the 'right' answers or highly-specialized expertise to apply them.

Riverscapes Principles

Four principles help articulate key aspects of healthy riverscapes that inform the low-tech process-based restoration approach. For those riverscapes with valley bottoms, much of this is embodied in the Stage 0 condition defined by Cluer and Thorne (2013) and elaborated in Chapter 1 (Shahverdian et al., 2019b). Figure 1, below, illustrates these four principles with one anecdotal example.

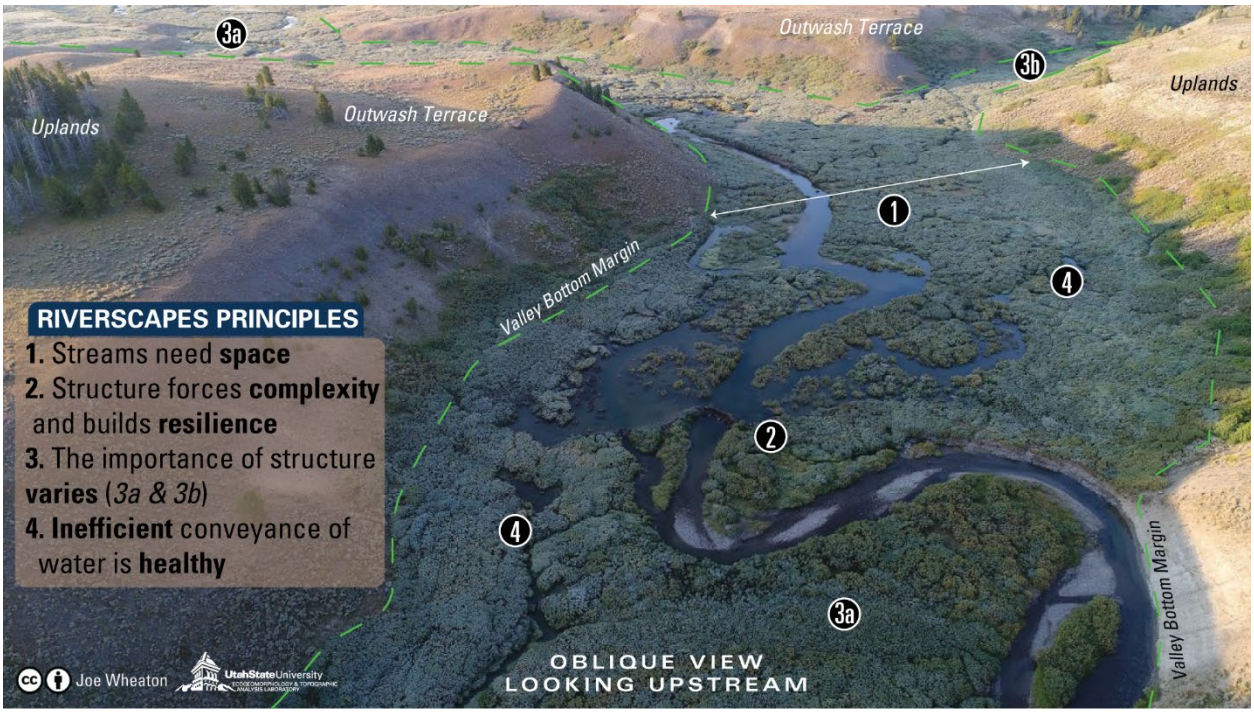


Figure 1 – Illustration of the four Riverscapes Principles of low-tech process-based restoration in a healthy riverscape. How much space (1) a riverscape 'needs' is finite, and well-defined laterally by its own valley bottom (margins shown in dashed green). This is the space in which we can expect the channel(s) to adjust (or exercise) and flood. Structure from wood accumulation and beaver dam activity (2) forces hydraulic complexity (in this example backwater ponding and overbank flooding even at low flow), from which predictable geomorphic processes build more complex channel and floodplain habitats, which are subsequently much more resilient to disturbances like major floods, droughts and fire. The flow regimes, valley setting and what to expect differs for different types of streams (e.g., the 3a mainstem vs. the 3b tributary), yet recognizing what riverscapes are similar (e.g., upstream and downstream portions of 3a and 3a) helps build expectations for what is possible in similar riverscapes. Finally, in systems that have lots of structurally-forced flooding and clogging from wood accumulation and beaver dam activity, overall pathways for water to move are more complex, residence time is more variable, and the valley bottom groundwater sponge temporarily stores water (4). This more inefficient conveyance of water downstream provides elevated late-season baseflows and much more productive valley bottoms.

STREAMS NEED SPACE
RIVERSCAPES PRINCIPLE 1.

Healthy streams are dynamic, regularly shifting position within their valley bottom, re-working and interacting with their floodplain. Allowing streams to adjust within their valley bottom is essential for maintaining functioning riverscapes.

The concept of a riverscape explicitly considers that 'scape' to be both the active floodplain(s) and active channel(s) comprising the valley bottom (Stanford, 2007). If streams have space to move within their valley bottom, then healthy stream ecosystems, functioning riverscapes and 'shifting habitat mosaics' can be maintained (Brierley and Fryirs, 2005; Stanford et al., 2005; Ward et al., 1999). Even gorges and bedrock canyons that naturally have little or no floodplain will develop margin-attached bars or occasional floodplain pockets in the tiniest opportunities for accommodation space. Freedom space is not limited to the floodplain, as streams also need room to adjust vertically through erosion and deposition and redistribute elevation within the valley bottom. Healthy, intact systems have 'wiggle room' to adjust laterally and vertically in response to floods and other disturbances and are more resilient as a result. If we want to '*let the system do the work*' (Restoration Principle 8), we also need to allow it 'freedom space' (Biron et al., 2014; Buffin-Bélanger et al., 2015) to do its work (i.e., room to exercise through flooding, erosion and deposition). Streams that cannot regularly interact with their floodplain will be unable to provide the ecological benefits they would in a Stage 0 or Stage 8 (see Chapter 1: Shahverdian et al., 2019b) condition (Cluer and Thorne, 2013). In many riverscapes, there is a lack of appreciation for how important large wood accumulations and beaver dam activity were for forcing this floodplain interaction (Wohl, 2013b). In some riverscapes, the floodplains are 'stepped' and their formation is difficult to explain without beaver dam activity that forces flooding more regularly and extensively (Polvi and Wohl, 2012; Westbrook et al., 2011).

Giving streams space does not mean we ignore anthropogenic constraints (e.g., infrastructure and land uses in the valley bottom) or what Lewin (2013) refers to as 'genetically-modified' floodplains. Careful consideration of recovery potential in the context of existing constraints, as opposed to just historical, pre-disturbance conditions (Fryirs, 2015), sets realistic expectations for what is possible. Precise prediction is typically not necessary (e.g., flood mapping), and instead plausible bounds like 'channel migration zones' from historical channel positions (Rapp and Abbe, 2003), 'flood spaces' (Figure 2) and even just valley bottom boundaries (Chapter 3: Bennett et al., 2019b; Gilbert et al., 2016 and RCAT: http://rcat.riverscapes.xyz) can all be used to inform what is available and what might be 'needed' in terms of space. This allows for informed discussions with landowners and managers about appropriateness of this approach for their property and expectation management of potential outcomes.

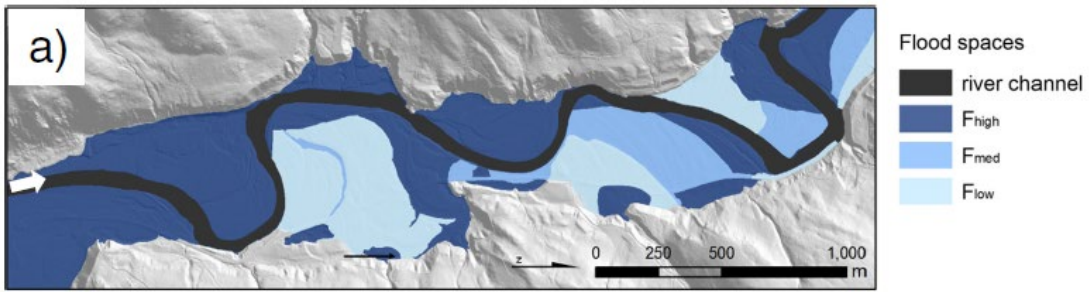


Figure 2 – Example of different ways of estimating 'freedom space', or how much space a river needs to exercise from Buffin-Bélanger et al. (2015). The map shows 'flood spaces' in terms of how likely areas are to flood. A rudimetnry, even simpler approximation of this space can be achieved by simply mapping valley bottom extents. Figure 4 from Buffin-Bélanger et al. (2015).

STRUCTURE FORCES COMPLEXITY & BUILDS RESILIENCE
RIVERSCAPES PRINCIPLE 2.

Structural elements such as beaver dams and large woody debris force changes in flow patterns that produce physically diverse habitats. Physically diverse habitats are more resilient to disturbances than simplified, homogeneous habitats.

Figure 3 – Structurally-forced complexity in a beaver dam complex resulting from both beaver dam activity and wood accumulation is the embodiment of Riverscapes Principle 2.

This principle is perhaps the most fundamental to understanding the structurally-forced processes that are critical to maintaining Stage 0 riverscapes (see Chapter 1: Shahverdian et al., 2019b), as well recognizing how and why structural elements can build riverscape resilience. As such, we devote more space to explaining this principle than the other nine. To do this, we review i) the structurally-forced cascade, ii) the two key mechanisms that maintain that cascade – wood accumulation and beaver dam activity, and iii) the idea and evidence for resilience that arises out of this complexity.

Structurally-Forced Pathway to Complexity

For systems that can or could interact with their valley bottoms (Riverscapes Principle 1), structural elements can amplify and force this interaction beyond what the flow regime alone can do during high flow events. We tend to conceptualize 'flooding' of floodplains as something that only occurs during high-flow events, but with structure, it can occur even at low flow. Wheaton et al. (2015) defined structural elements as "discrete objects that directly influence hydraulics", or in other words: obstructions to flow (see also Chapter 1: Shahverdian et al., 2019b). Hydraulics are characterized by flow depth and velocity vectors (both direction and magnitude; see NRCS (2007) for overview of stream hydraulics). The presence of a structural element in a flow causes velocity vectors to converge and diverge as they shunt around, flow over, back-up behind, split around, flow through, and separate into shear zones as flow moves past the obstruction(s). In terms of connectivity, riverscapes with adequate structure in their channel(s) and floodplain obstruct flow and disrupt longitudinal connectivity, but increase vertical and lateral connectivity (Covino, 2016), by forcing flooding at lower flows (Figure 3). Moreover, these vertical increases in connectivity are not just

upward in terms of forcing flows up and over, but the increased hydraulic head also increases both hyporehic exchange in the benthos (Zhou and Endreny, 2013).

The structurally-forced pathway to complexity (Figure 4) can be conceptualized as structural elements (obstructions as defined in Chapter 1 (Shahverdian et al., 2019b) → forcing more diverse hydraulics → creating gradients in flow energy that amplify geomorphic processes of erosion, deposition, transport and storage of sediment → that shape and build more diverse geomorphic units (e.g., bars, pools) → that serves to provide more heterogeneous and complex in-channel and floodplain habitats →, which provides more niches and serves more biodiverse riverscape ecosystems. One can easily look at Figure 3 and see the habitat heterogeneity but be unsure how it is formed or maintained. However, working backwards from that complexity through the structurally-forced pathways to complexity, the patterns are utterly systematic, and the processes shaping those habitats are conceptually explained (quantifying and precisely predicting is more challenging, though not always necessary). Everything stems from structurally-forced hydraulic diversity. Hydraulically uniform flow patterns produce homogeneous, low diversity plane bed habitats. Hydraulically diverse flow patterns (i.e., flow separations, shear zones, convergent flow, divergent flow), lead to varied and predictable geomorphic responses that systematically produce more diverse habitats (Brierley and Fryirs, 2005). These habitats, in turn, provide more niches, to serve different functions for diverse biota, and generally increase the resilience of these systems to disturbance.

Hydraulic refers to 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 that result from the changes in patterns of erosion and deposition that structural elements cause.

If we accept the concept of a structurally-forced pathway to complexity (Figure 4), the next logical question is, what drives the occurrence and residence time of those structural elements in a riverscape? Many factors are important, but for many riverscapes, the most important processes leading to structural forcing are wood accumulation and beaver dam activity:

- **Wood accumulation** – In riverscapes that intersect forested areas or support their own riparian forests, natural accumulations of wood occur as woody material recruited into the channel (via processes like lateral migration of channels into forested areas, trees falling directly into or across the channel, or mass-wasting from hillslopes), which can act as a direct obstruction to flow on which other woody material in transport accumulates and/or can itself be mobilized and transported to accumulate elsewhere. Similarly, if the rate of wood transport is significantly higher than the rate of wood accumulation, then structurally-forced morphologies may be short-lived or transient.
- **Beaver dam activity** – In riverscapes that don't naturally provide deep enough water to maintain underwater entrances to lodges and cover from predation, beaver undertake a variety of activities to modify, manipulate and maintain water levels to avoid predation. The most obvious amongst these is the construction and maintenance of dams and beaver ponds to provide deep water habitats.

There are a plethora of scientific papers covering both the processes of wood accumulation and beaver dam activity as well as their forms in the form of woody debris jams and beaver dams. For a concise reviews of the role of wood in riverscapes we refer the reader to Gurnell et al. (2002) and Wohl (2013b). Similarly, for overviews of the role of beavers as dam-building ecosystem engineers see Naiman (1988), Gurnell (1998) and Pollock et al. (2003).

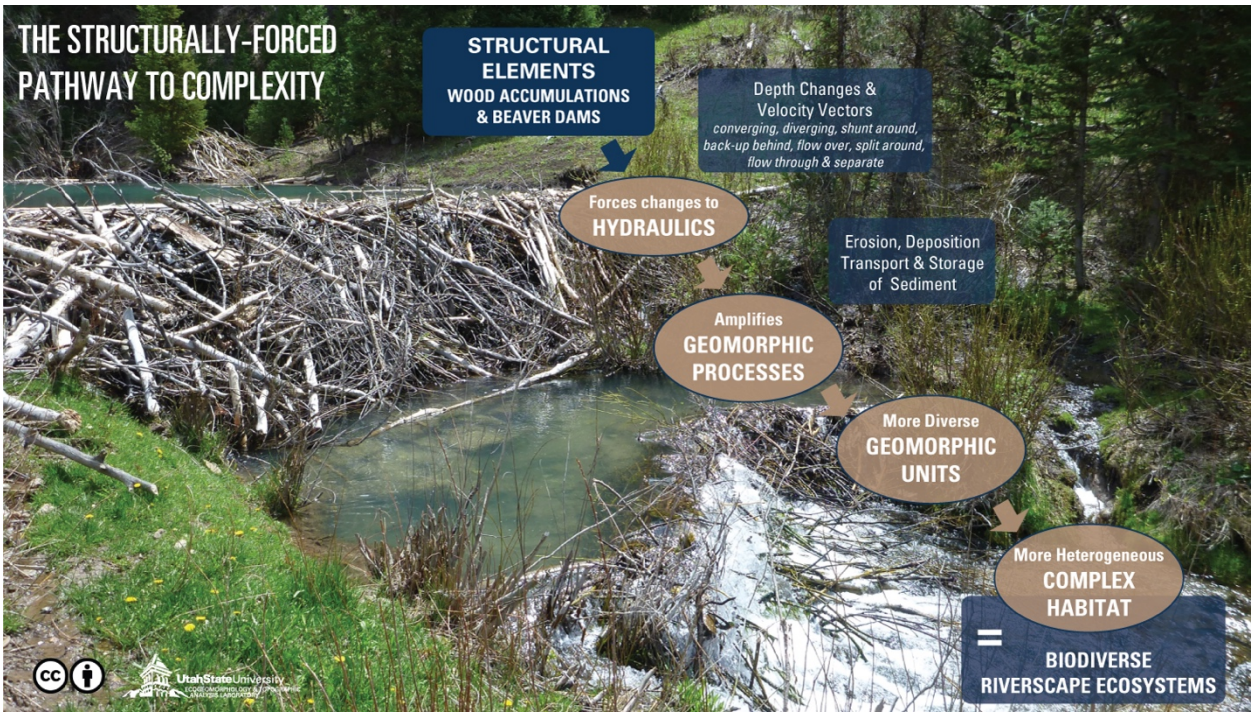


Figure 4 – The concept of the structurally-forced pathway (boxes, arrows and circles) to complexity underlying Riverscapes Principle 2. Illustrated with example of the structural forcing from beaver dams, but the same pathways are followed when wood accumulations provide the obstructions to flow.

Building Resilience?

Resilient riverscapes are capable of maintaining their state or key attributes when subjected to disturbances like large floods, fires and droughts. Quantifying resilience has proven challenging in ecosystem management, but we highlight a couple examples here that suggest resilience being derived from improved structural complexity in western riverscapes. Silverman et al. (2018) documented a decrease in sensitivity of riparian vegetation productivity to precipitation over time, regardless of drought and wet years, in a restored riverscape situated in an arid shrubland of northeast Nevada (Figure 5). Here, improvements in grazing management facilitated woody and herbaceous riparian expansion that fueled beaver dam building activity, which subsequently further expanded riparian vegetation productivity and maintained water in the valley-bottom sponge even through drought. Importantly, the signal of vegetation productivity (greenness) was so strong it could be measured from space with freely-available satellite data a relatively coarse (30-m) resolution over broad riverscape scales. In an adjacent project area, Fesenmyer et al. (2018) showed similar findings of increased vegetation productivity and tied them directly to beaver dam activity. The increase and maintenance of riparian vegetation productivity over time, even though dry times, in these studies provides evidence of drought resilience possible with low-tech restoration and increased structural complexity.

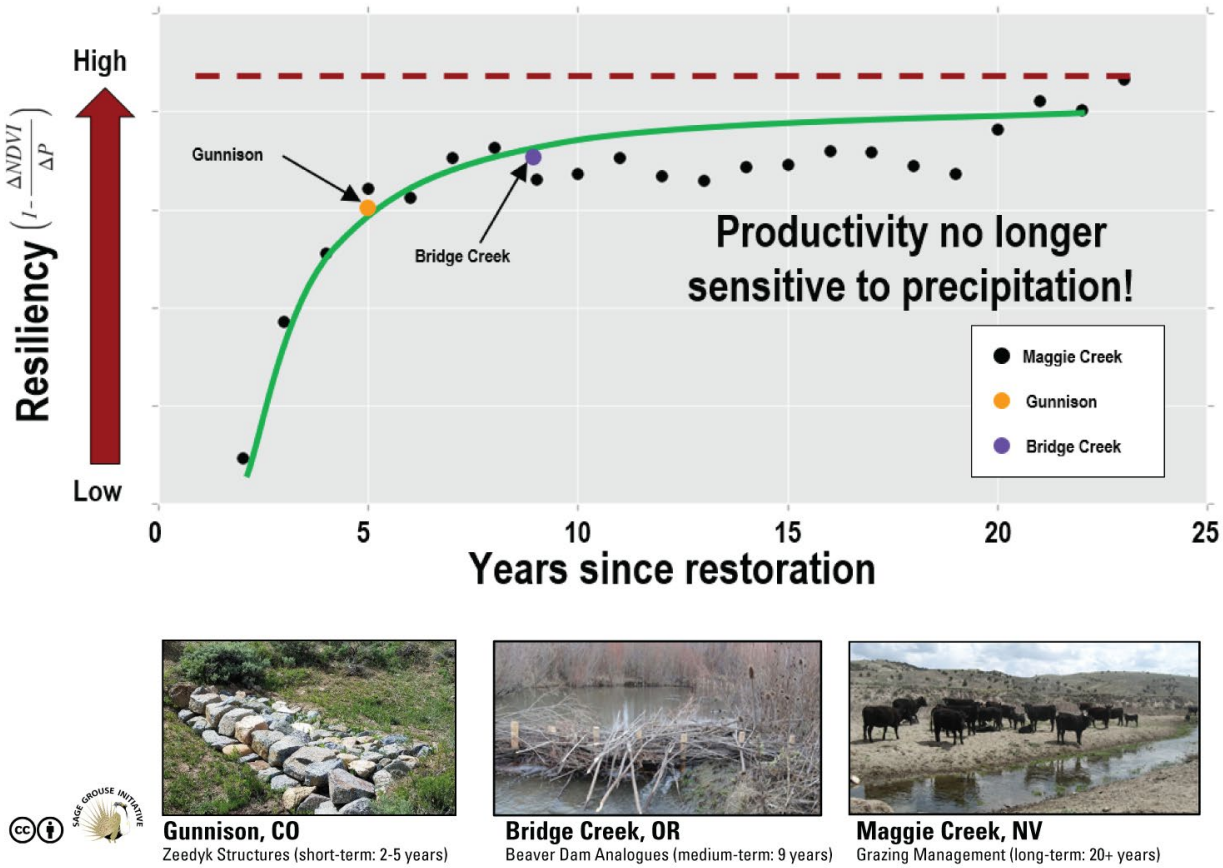


Figure 5 – Evidence of resilience from structurally-forced changes to valley bottoms using a variety of low-tech process-based restoration methods caused vegetation productivity (greenness as measured from satellite imagery) to no longer be a function of precipitation. Figure adapted from SGI Science to Solutions and data published in Silverman et al. (2018).

Figure 6 – Example of structurally-forced resilience to fire where beaver dam activity kept parts of the riverscape from burning, providing critical wildlife and livestock refugia during the fire, and assisting in post-fire recovery. Example from Baugh Creek, Idaho.

While less well-documented, structurally-forced complexity may also yield greater resilience to wildfire. In one anecdote from central Idaho, beaver dam activity helped preserve riverscape structure and function in the heart of a 65,000-acre wildfire (Randall, 2018). The majority of riparian areas within the fire perimeter burned right up to the banks, leaving the floodplains black with ash. However, reaches that supported beaver dam complexes remained largely green and unburned. In larger valley bottoms, beaver dam complexes can act as actual fire breaks during the fire. In narrower valley bottoms like that shown in Figure 6, these complexes were not enough to stop to fire but still provided critical refugia during and after the fire for both wildlife and livestock. Moreover, in the post-fire recovery these are critically important habitats and seed banks for recovery as well as helping keep the riverscape resilient to elevated runoff and or debris-flows post-fire.

THE IMPORTANCE OF STRUCTURE VARIES
RIVERSCAPES PRINCIPLE 3.

The relative importance and abundance of structural elements varies based on reach type, valley setting, flow regime and watershed context. Recognizing what type of stream you are dealing with (i.e., what other streams it is similar to) helps develop realistic expectations about what that stream should or could look (form) and behave (process) like.

In this low-tech restoration manual, we focus on riverscapes where the processes of wood accumulation and beaver dam activity are important drivers. However, there are many systems that naturally have no beaver – and therefore no beaver dams, and some systems that naturally do not support woody vegetation – and therefore no woody debris jams or accumulations. For those riverscapes that can support either or both, the key to building appropriate expectations for how much (typically expressed in linear density terms like woody debris jams per mile, large woody debris pieces per mile, or beaver dams per mile) is understanding the hydro-geomorphic setting of your riverscape. Riverscapes occur across a diverse range of climatic, physiographic, geologic settings, and each has its own landscape and development history. While every riverscape accumulates, sorts, degrades, and cycles through structural elements at different rates (i.e., system metabolism), some of this is constrained by the reach type and flow regime (Poff et al., 1997).

There are a number of different stream classification techniques for differentiating reach types (Kasprak et al., 2016), which can be helpful for considering the relative importance of structural elements. This idea is embodied in the Beechie et al. (2010) second principle of process-based restoration: "Tailor restoration actions to local potential." It is another way of saying that choosing appropriate restoration goals (see Chapter 3: Bennett et al., 2019b) and actions should be placed in the context of the type of riverscape you are working in and local constraints. This could be interpreted as 'know your watershed'. In Brierley and Fryirs (2005) River Styles Framework, they highlight four principles all of which are built around this idea of knowing the geomorphic setting you are working in:

1. "Respect stream diversity" – i.e., the diversity of reach types matters
2. "Work with stream dynamics and change" – i.e., processes are continually shaping rivers
3. "Work with linkages to biophysical processes" – e.g., the processes of wood accumulation and beaver dam activity are explicitly tied to biophysical processes
4. "Use geomorphology as an integrative physical template for river management" – i.e., geomorphology matters

An example of how the importance of structure varies according to reach type and flow regime is illustrated in Figure 7 from Hill et al. (2019). Specifically, the role that wood accumulation plays and the specific processes of wood accumulation and types of woody debris jams varies predictably based on reach type. Many authors have drawn contrasts between the importance of wood accumulation in different channel types, each of which has different wood availability, flow regimes and therefore flood disturbance regimes to recruit and accumulate wood (e.g., Collins et al., 2012; Nakamura, 2000; Viles et al., 2008; Ward, 1998). Similarly, when the capacity to support building dam activity is modeled across entire drainage networks (e.g., Macfarlane et al., 2015), and overlaid with reach types, the relative importance, and type of beaver dam building varies systematically (Bush and Wissinger, 2016).

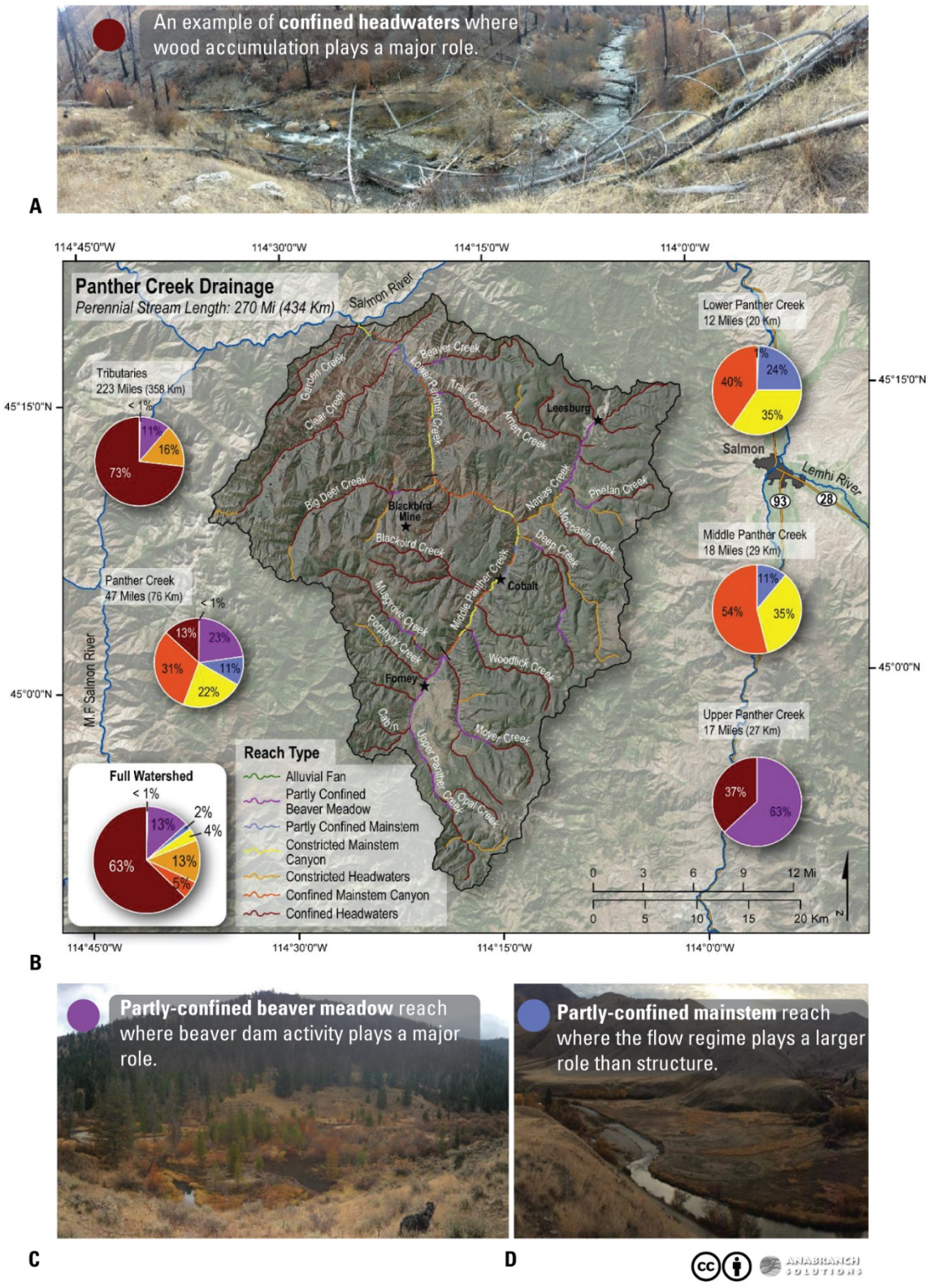


Figure 7 – The key to understanding the relative importance of structure is recognizing the reach type such that the flow regime and geomorphic setting are clear. Above is an example from a riverscapes assessment by Hill et al. (2019) where all the reach types for the drainage network are mapped out in B, and three examples of the varying importance of structure are shown in confined headwaters (A), partly-confined beaver meadows (C) and partly-confined mainstem (D).

INEFFICIENT CONVEYANCE OF WATER IS HEALTHY
RIVERSCAPES PRINCIPLE 4.

Hydrologic inefficiency is the hallmark of a healthy system. More diverse residence times for water can attenuate potentially damaging floods, fill up valley bottom sponges, and slowly release that water later elevating baseflow and producing critical ecosystem services.

Simplified channels rapidly transport water and sediment through the system. Diverse flow paths and greater interaction between the channel and floodplain increase the variability in the time it takes for water and sediment to move through the system (i.e., residence time). Hydrologic inefficiency is natural and healthy for most riverscapes (e.g., Figure 9). Simplified, canal-like channels rapidly transport water, sediment and nutrients through, and out of, a watershed. Healthy riverscapes tend to temporarily store water, sediment and nutrients through more diverse flow paths often forced by structural elements that maintain critical physical, chemical and biological processes that promote healthy riverscape ecosystems. To be clear, this principle does not imply that *stopping* water and sediment transport is beneficial, rather, that intact streams often have complex flow paths that result in a natural modulation of transport rates.

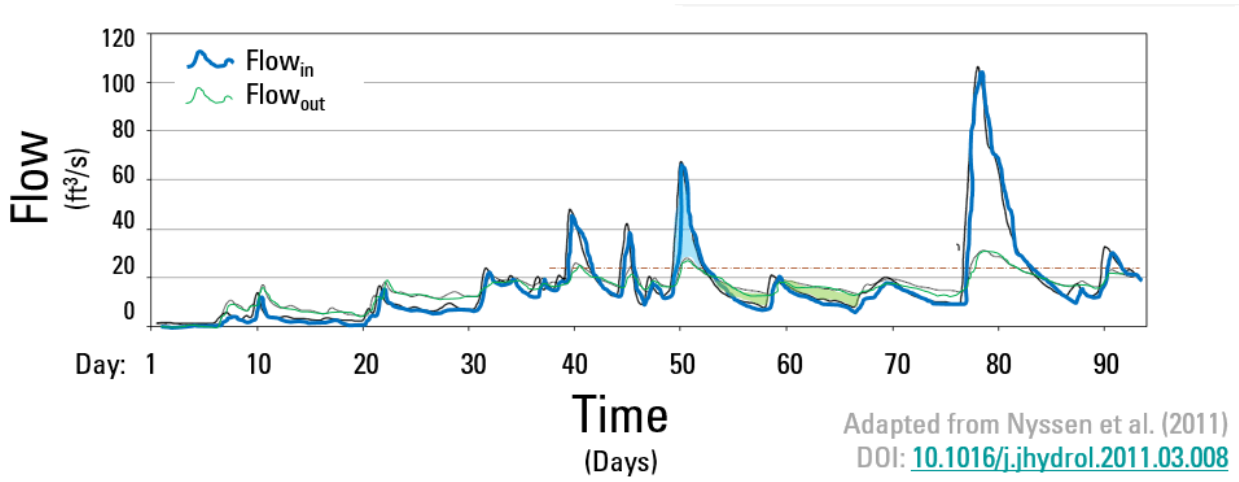


Figure 8 – An attenuated hydrograph showing 'inefficient conveyance' through a beaver dam complex where the peak flows coming in (blue) are higher than the flows leaving (green), whereas post-flood, baseflows are elevated at the bottom out of the reach as the water temporarily stored on floodplain surfaces and in the valley bottom sponge. Figure adapted from (Nyssen et al., 2011)

Streams and rivers are characterized by different types of connectivity (Covino, 2016). Longitudinal connectivity refers to the downstream conveyance of mass (primarily water, but also can include sediment, nutrients and woody debris). Most traditional, and now antiquated, approaches to flood control focused on conveyance to speed a flood wave through the riverscape and 'away' to avoid flooding. In natural systems, riverscapes flood their floodplains and that decreases longitudinal connectivity (e.g., Figure 8). This decreased longitudinal connectivity attenuates peak flood flows by dampening the peak magnitude, slowing the flood wave down with temporary storage on the floodplain, and more slowly receding, all the while increasing infiltration and temporary storage of water in floodplain sponges

(groundwater in the alluvial, unconfined aquifers that make up valley bottom fills). Lateral connectivity refers to the ability of water, nutrients and sediment to move between channel(s) and the floodplain components of the riverscape (Wegener et al., 2017). Lateral connectivity i) promotes the exchange of nutrients between channels and their floodplains, ii) provides groundwater recharge and access to water resources for riparian areas, iii) creates physical heterogeneity on the floodplain, iv) creates areas of flow refuge during high flow events, and v) creates important habitats for fish to meet life history requirements (Pollock et al., 2003). In many areas, the removal of structural elements has resulted in increased longitudinal connectivity and reduced lateral connectivity. 'Longitudinal disconnectivity', or inefficient conveyance of water, is critical in creating complex, physically heterogeneous stream ecosystems (Burchsted et al., 2014; Grant et al., 2016). In low order streams, decreased longitudinal connectivity (and increased lateral connectivity) is often the result of beaver dams and log jams that obstruct flow (Burchsted et al., 2010; Wohl, 2013a). A host of researchers have shown beaver dams to attenuate flood flows, and elevate (magnitude) and extend (temporally) post-flood baseflows for days to weeks or even months in some systems (Majerova et al., 2015; Nyssen et al., 2011; Puttock et al., 2018; Puttock et al., 2017). The total amount of increased surface and groundwater storage can be used to estimate the magnitude of impact on downstream water resources (Hafen, 2017; Nash et al., 2018). The 'attenuated' water goes in part to elevating baseflows, but also to increasing vegetative productivity (i.e., evapotranspiration) on the valley bottom.

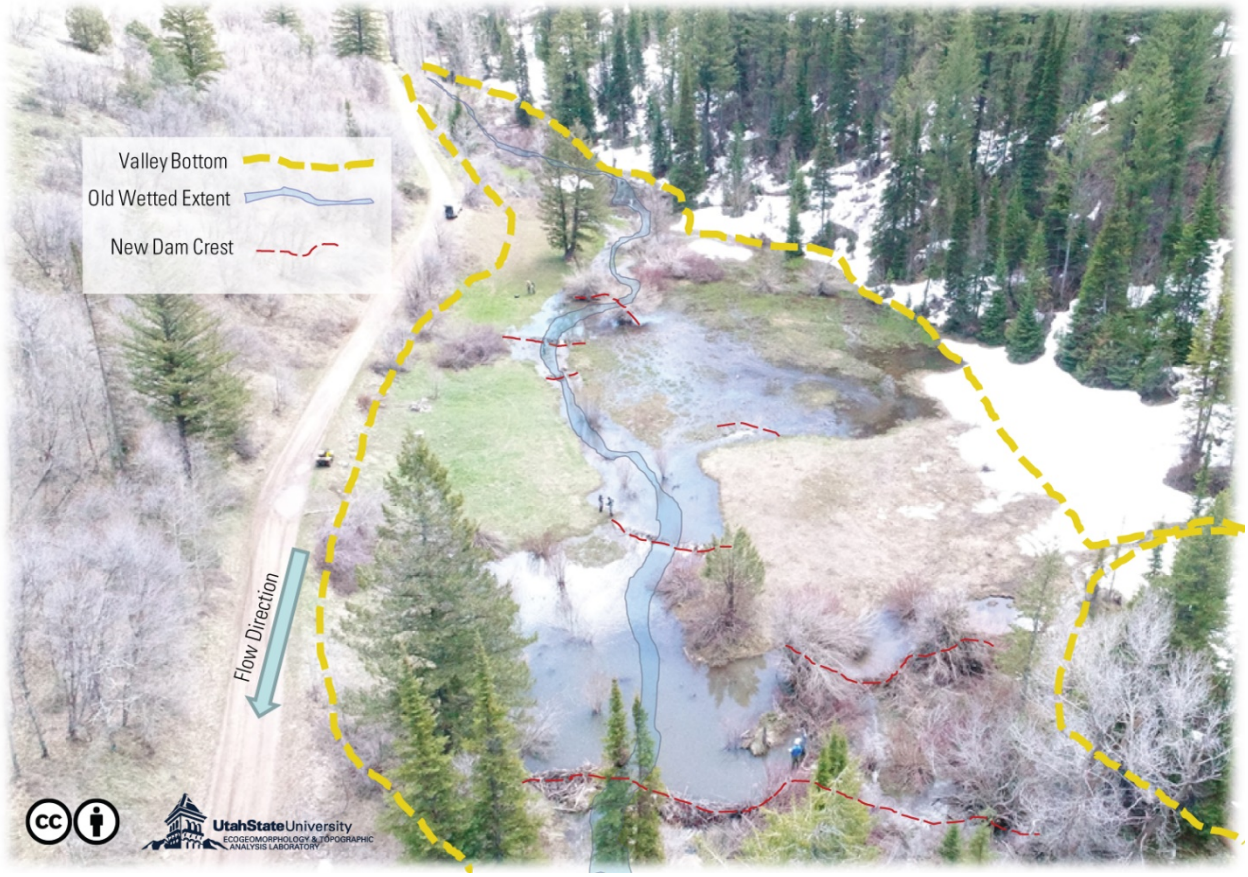


Figure 9 - The 'old wetted extent' was a much more efficient way to move water through this meadow. However, the far less efficient movement of water through this system as manipulated and maintained by beaver makes this a much more effective sponge capturing excess flow during peak runoff and slowly releasing it out over the summer months. Photo taken one year after beaver reintroduced. Read about this project in Goldfarb (2018b). Beaver initially over-wintered in beaver dam analogue (BDA) complexes built for them, and then expanded the following spring into this meadow.

Restoration Principles

Six key principles inform low-tech process-based restoration. These principles are rooted in the notion that we are not designing and building the solution, but rather we are simply initiating and promoting natural processes with structural additions as efficiently as possible to maximize the miles of riverscape we can improve. Since the basic action we take with low-tech restoration is to add structures that promote and mimic wood accumulation and beaver dam activity, there is a natural tendency to focus on individual structures (see Chapter 5: Shahverdian et al., 2019c). While much can be learned at this structure scale, focusing on single structures leads to some major short-comings:

- Over-designing every structure and losing sight of broader-scale riverscapes goals and objectives
- Unnecessarily complicating the design process, making it more expensive, and less scalable
- Following individual recipes too literally and rigidly; while missing opportunities for material substitutions, creative adaptations to local situations, and possibilities to scale up more efficiently (i.e., build more structures)
- Over-building structures primarily for stability, instead of recognizing that like a meal, it will be eaten, digested and processed by the system giving it the energy to exercise, build, maintain, create, and rearrange habitat

The low-tech Restoration Principles elaborated below and illustrated in Figure 10, help place our restoration actions in the right context to maximize our effectiveness in promoting better riverscape health.

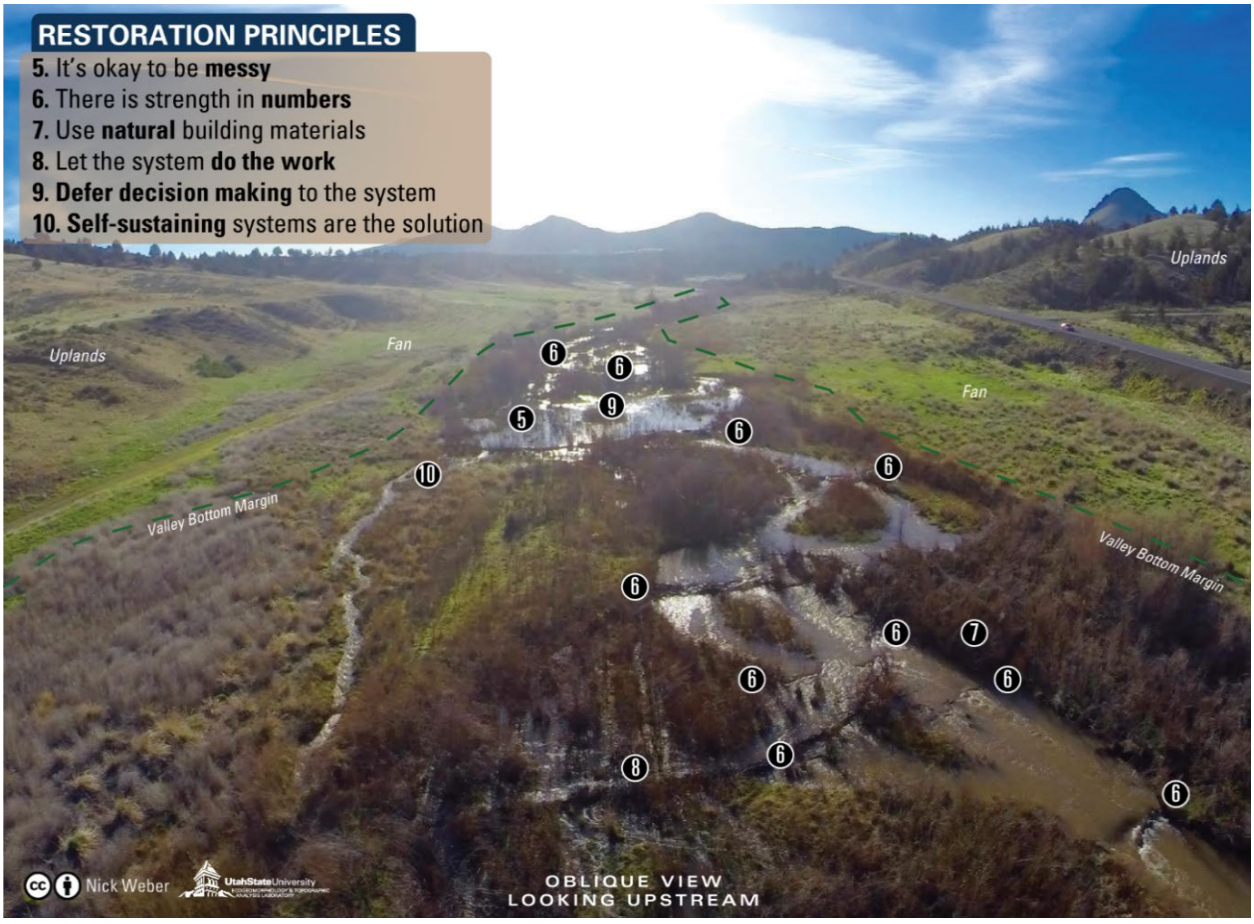


Figure 10 – Illustration of six restoration principles in play, eight years after a restoration treatment. In this reach, roughly 35 beaver dam analogues (BDAs; 9 labeled in photo with "6"), were originally installed in a single-thread channel. Within a year of installation, such a mess was made (5) that the floodplain was experiencing some flooding even at low flow. Other than natural, untreated wooden fence posts, all the building materials were sourced on-site (7). Within months, beaver that were in low numbers in the system opportunistically colonized the BDAs and took over maintenance (8). Within a few years, the beaver extended many of the dams across the valley bottom, effectively converting the valley bottom back to a Stage 0, multi-threaded mess with a highly connected floodplain. Riparian vegetation recruitment has taken off, and beaver now rotate through different complexes in the area (self-sustaining – 9). Now the combination of the flow regime and beaver are making decisions about what parts of the floodplain to flood and when (10).

IT'S OKAY TO BE MESSY
RESTORATION PRINCIPLE 5.

When structure is added back to streams, it is meant to mimic and promote the processes of wood accumulation and beaver dam activity. Structures are fed to the system like a meal and should resemble natural structures (log jams, beaver dams, fallen trees) in naturally 'messy' systems. Structures do not have to be perfectly built to yield desirable outcomes. Focus less on the form and more on the processes the structures will promote.

Messy is just a proxy for complexity or habitat heterogeneity. In this context, most of that is structurally-forced (see Riverscapes Principle 2). The primary action taken in low-tech restoration is adding structural elements back into streams (Figure 11 and Figure 12). As reviewed in Chapter 1 (Shahverdian et al., 2019b), wood accumulation and beaver dam activity (the primary processes we are promoting) are messy processes. As stated in Riverscapes Principle 2, structurally-forced messiness is what makes resilient systems. There is safety in variability! Structures are meals and they don't need to be neat and tidy, rather they should resemble natural structures (log jams, beaver dams, fallen trees) that are inherently messy and create naturally messy systems. There is no single 'right' structure for any particular situation. The important thing is to prepare something nutritious and strive for variety. Although individual structure longevity is not a primary goal in low-tech process-based restoration, messy structures are also likely to be more stable than simple structures. Having many logs and slash splaying out in multiple directions can dissipate flow energy by disrupting homogeneous flow paths and provides multiple angles of support during larger floods. Additionally, a messy structure is easier and quicker to build. Building a messy pile rather than trying to replicate a design drawing or place materials in a particular configuration can save several minutes per structure, potentially shaving days off of the implementation process.

Figure 11 – Proud 'meal preparers' from a NRCS/SGI workshop who just got done feeding the creek a series of messy, but highly effective, post-assisted beaver dam analogues. This is what we can do as practitioners. We can organize dinner parties, and get a bunch of people together to prepare from meals for the riverscape.

Figure 12 - Example of a 'messy' mid-channel post-assisted log structure (PALS) (A) versus a 'simple' mid-channel PALS (B). Natural wood accumulations are messier.

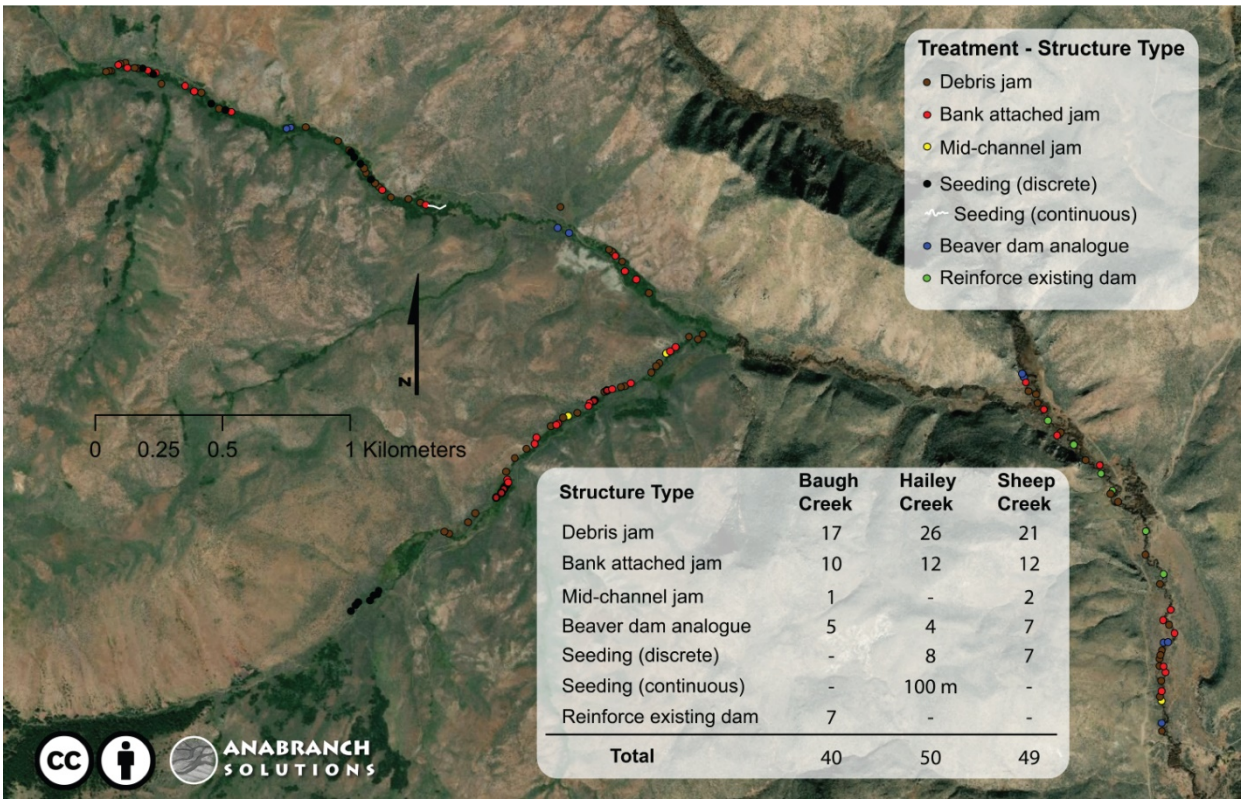
THERE IS STRENGTH IN NUMBERS
RESTORATION PRINCIPLE 6.

A large number of smaller structures working in concert with each other can achieve much more than a few isolated, over-built, highly-secured structures. Using a lot of smaller structures provides redundancy and reduces the importance of any one structure. It generally takes many structures, designed in a complex (see Chapter 5: Shahverdian et al., 2019c), to promote the processes of wood accumulation and beaver dam activity that lead to the desired outcomes.

The strength in numbers principle is based on the idea that by using simple, low-tech treatments, we can afford to expand our restoration footprint so we can address the widespread scope of degradation. This riverscapes principle is embodied in third Beechie et al. (2010) principle of process-based restoration: "Match the scale of the restoration to the scale of the problem." A large number of smaller structures is more effective than a few highly-secured structures, a principle Kraebel and Pillsbury (1934) articulated in the 1930s with respect to using low-tech structures to restore meadows; (see Chapter 1: Shahverdian et al., 2019b). A greater number of structures also reduces the importance of any single structure and increases the chances of retaining any structures that may breach or blow out during high flow event. It also drives design costs down by not spending too long (e.g., < 5 minutes of design per structure) on any single structure and focusing on broader scale targets (e.g., Stage 0).

Strength in numbers as a principle also drives design decisions where you might favor quicker, easy-to-build structures that can promote the same processes with less effort by you. For example, many practitioners get into low-tech restoration because of beaver dam analogues (BDAs). However, while BDAs are relatively quick to build compared with traditional structures (maybe 45 minutes to 3 hours), they are far more laborious to build than a post-assisted log structure (PALS); which may take 10 to 60 minutes each). BDAs have been used to accelerate Stage 0 recovery in incised channels (Pollock et al., 2014), by promoting channel widening where dams fail by end cutting and promote bank erosion. While a bank-attached PALS directed at the same bank could achieve the same result quicker and with only 15 minutes of construction. Plus, it then may create conditions that are easier to build a more effective BDA in a subsequent meal. The take-home is not to use one structure over another, but to think first about what process you are attempting to promote, and then ask what choice of structure will allow me to prepare the best meal that feeds the most riverscape (see Chapter 4: Shahverdian et al., 2019a)?

By strength in numbers, we mean both a high density of structures (number/mile) and the size of the treatment (number of miles restored). To make a dent in the scale of degradation (see Chapter 1: Shahverdian et al., 2019b), this translates to projects on the order of 10's to 100's of miles with high densities of structures throughout the treatment area. We think of this as high-density large woody debris ($_{HD}$LWD) meals. Quantities of woody debris accumulation and beaver dams can be expressed in quantities like large woody debris pieces / mile, wood accumulations per mile and beaver dams per mile (i.e., densities: count per length of riverscape). Natural background densities in systems where Stage 0 is possible, tend to be on the order of 250 – 1000 large woody debris pieces /mile, 10-50 wood accumulations per mile, and 10-70 beaver dams per mile (Al-Chokhachy et al., 2010; Fox and Bolton, 2007; Macfarlane et al., 2015). Restoration treatments need to think about making up for structural starvation deficits, by targeting similarly high densities in treatments (e.g., see Figure 13 and Figure 14).



Structure Type	Baugh Creek	Hailey Creek	Sheep Creek
Debris jam	17	26	21
Bank attached jam	10	12	12
Mid-channel jam	1	-	2
Beaver dam analogue	5	4	7
Seeding (discrete)	-	8	7
Seeding (continuous)	-	100 m	-
Reinforce existing dam	7	-	-
Total	40	50	49

Figure 13 – An example of a post-fire emergency treatment (meal) of a large mix of structures to a relatively short extent of three creeks (i.e., 2.5 miles) in which 139 structures of different types were strategically designed and placed to promote wood accumulation and beaver dam activity to make the degraded sections of the creek more resillient to anticipated, post-fire elevated runoff and/or debris flows. Under traditional restoration, this might be considered a relatively large footprint project. In low-tech process-based restoration, and under the 'strength in numbers principle', this is a simple trial project where we placed a large number of different types of structures to learn what types of structures might be most effective in post-fire recovery work. Figure from Shahverdian et al. (2018). See Steubner (2018) Conservation the Idaho Way for more information on project. See http://lowtechpbr.restoration.usu.edu/resources/casestudies.html for more examples.

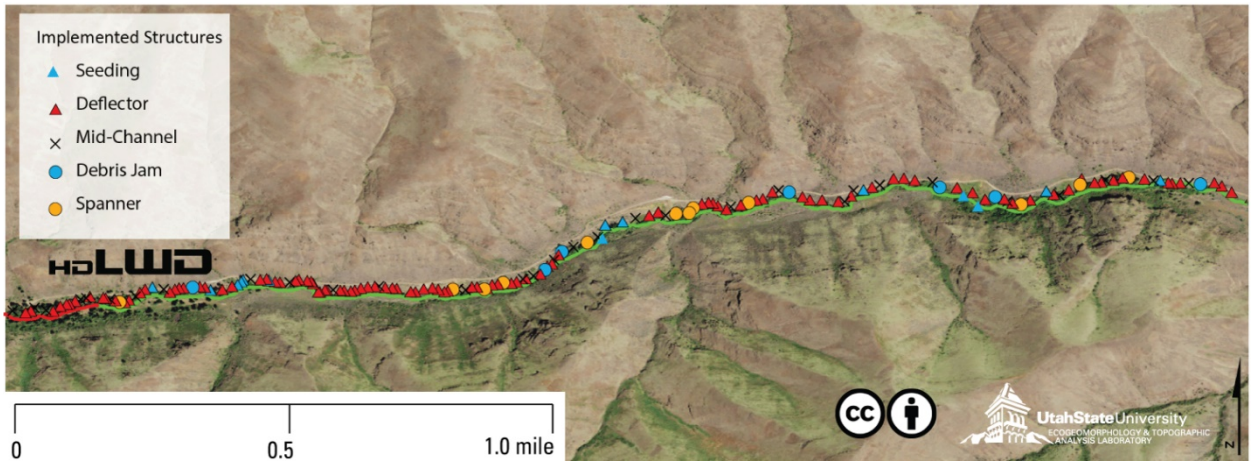


Figure 14 – Another example of what strength in numbers looks like in a high-density large woody debris restoration project at just the scale of two miles. Every dot is a post-assisted log structure (note, this project was twelve miles).

USE NATURAL BUILDING MATERIALS
RESTORATION PRINCIPLE 7.

Natural materials should be used as structures are simply intended to initiate process recovery and go away over time. Locally sourced materials are preferable because they simplify logistics and keep costs down.

Structures should always be built with natural materials, and preferably locally-sourced materials, to keep costs low and simplify logistics (e.g., Figure 15). Remember that natural wood accumulations are made with wood the riverscape was either able to grow itself (on its valley bottom) and recruit, or that it might receive from upland forests via debris-flows, landslides, wind-throw or simply eating away at the toe of slopes growing that vegetation. Beaver will drag material from both the floodplain and uplands down to the water within 100 – 150 yards from the edge of channel. Different species of wood persist in situ in riverscapes for varying degrees of time. A downed alder (*Alnus sp.*) may decompose within a few years, whereas a juniper (*Juniperus sp.*) may persist for decades.

Figure 15 – A low-tech restoration crew cutting Juniper from an upland juniper removal treatment and fuels reduction, cutting into smaller pieces.

In general, it is better to use materials that would plausibly be found in the riverscape, via wood accumulation and/or beaver dam activity to reduce costs for transporting materials and because it is assumed that local materials were the structural elements found historically. However, there are two considerations (elaborated in Chapter 6: Bennett et al., 2019a) with respect to sourcing woody material where it might make sense to relax this tendency to mimic the type and species of wood brought into the system.

1. Make practical substitutions for building materials to use what is excessive based on local availability.
2. In vegetation-limited or recovering riverscapes, it may be desirable to avoid using species that beaver prefer to use as both a building material and food source (e.g., cottonwood, aspen, willow) and use the species beaver only use as building materials if they need to (e.g., sagebrush, conifers, etc.).

Where posts are used (see Chapter 6: Bennett et al., 2019a), use untreated wooden posts, and never use posts that are pressure-treated or coated in chemicals that could leach into the stream. Posts are used to provide temporary stability (through low flows and small or typical floods), by pinning structure material in place. They are not meant to last forever. While functionally a metal T-post may serve a similar purpose, that foreign, metal object may persist in the

system well beyond the life of the structure and should be avoided. This is similar to eating food fortified in heavy preservatives. Yes, it has a longer-shelf life, but do you want those preservatives in your system forever? Fresh ingredients are desirable. Many traditional instream woody structure placements rely on metal cable to anchor wood into place or to bind smaller pieces together in bundles. We avoid such material at all costs. If you want to mimic larger accumulations of wood with smaller pieces, you can use wooden dowels (expensive) or biodegradable rope (e.g., hemp).

Let the System Do the Work

LET THE SYSTEM DO THE WORK
RESTORATION PRINICPLE 8.

Giving the riverscape and/or beaver the tools (structure) to promote natural processes to heal itself with stream power and ecosystem engineering, as opposed to diesel power, promotes efficiency that allows restoration to scale to the scope of degradation.

Always remembering that structures are designed to promote processes and are not themselves the solution, is easier when you remember to let the system do the work. This phrase is borrowed from the sentiment in the title to Zeedyk and Clothier (2009) 'Let the Water do the Work: Induced Meandering, An Evolving Method for Restoring Incised Channels'. Although the Zeedyk and Clothier (2009) book spends a lot of time explaining how to install simple, low-tech structures, the title is a reminder that the 'real work' is done by stream power when high flows interact with those structures (e.g., Figure 16). The idea really goes back to the hydraulic and geomorphic processes, which come out of Riverscapes Principle 2, that bigger floods provide the stream power (simply a product of discharge, slope, water density and gravity) that can do the work via that structurally-forced cascade. Due to the importance of beavers as ecosystem engineers, we extended this sentiment to another axiom: "Let the rodent do the work" (also the title to the last chapter in Goldfarb (2018b)'s 'Eager'). The combination of these two axioms is Restoration Principle 8 and the paradox of process-based restoration: let the system do the work.

We follow this principle by giving the riverscape and/or rodents the tools (structure) to harness *natural* processes to heal itself with stream power and ecosystem engineering as opposed to diesel power. Part of 'letting the system do the work' on shorter and medium term time frames (instead of just in long-term from really big floods) has to do with deliberately placing structures with a purpose and hydraulic purchase (i.e., actually obstructing flow at low flows or small flood flows).

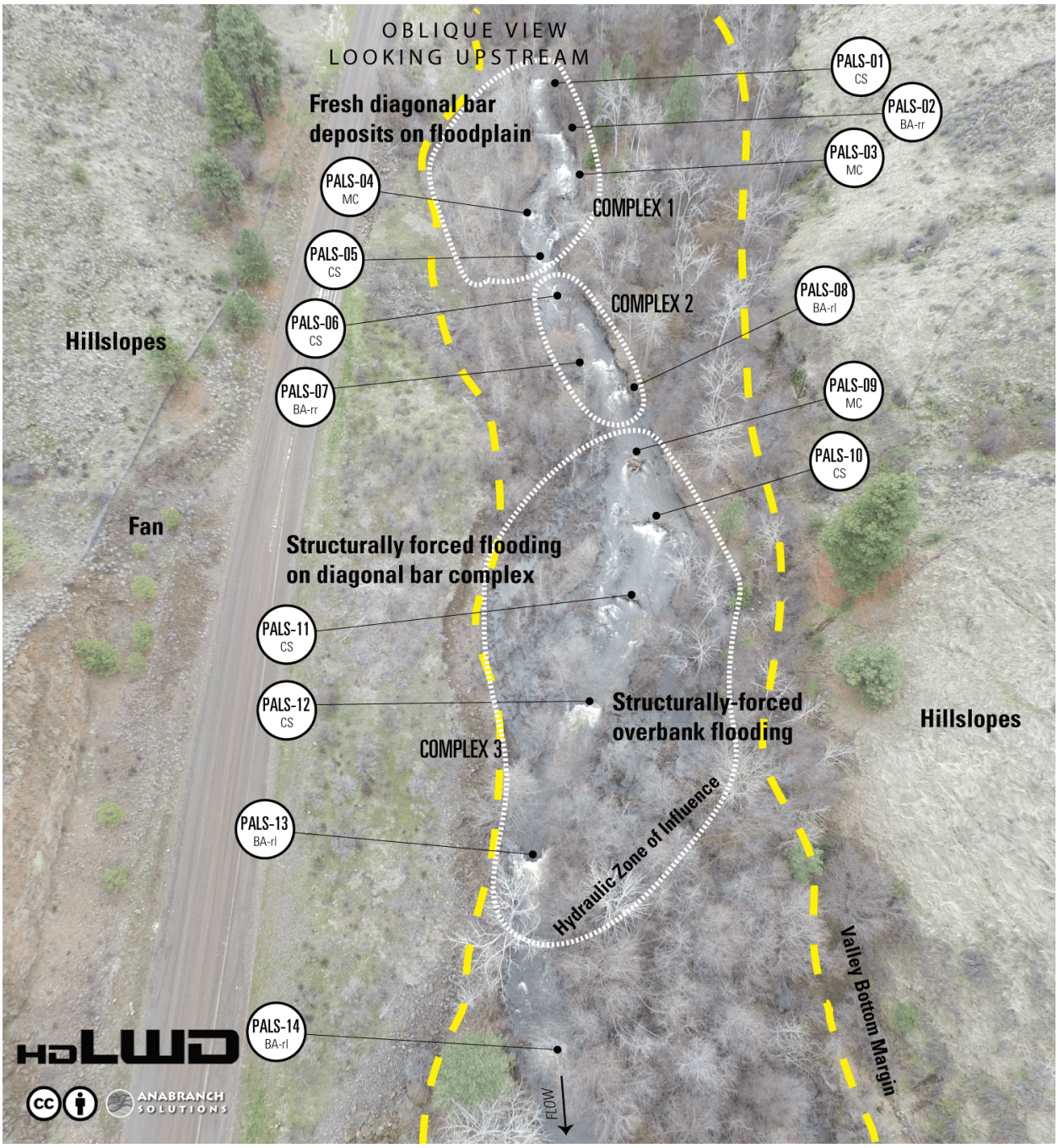


Figure 16 – An example of where the structural additions of PALS (14 of ~800) are letting the system do the work during flooding. That work includes the processes of overbank flooding, diagnol bar formation, wood recruitment, pool creation, and additional wood accumulation – all of which are structurally-forced (see Riverscapes Principle 2). There is no critical infrstructure in the valley bottom or immediately threatened by 'letting the system do the work'. The road is elevated and built across fan surfaces.

DEFER DECISION MAKING TO THE SYSTEM
RESTORATION PRINCIPLE 9.

Wherever possible, let the system make critical design decisions for us by simply providing the tools and space it needs to adjust. Deferring decision making to the system downplays the significance of uncertainty due to limited knowledge. For example, choosing a floodplain elevation to grade to based on limited hydrology information can be a complex and uncertain endeavor, but deferring to the hydrology of that system to build its own floodplain grade reduces the importance of uncertainty due to limited knowledge.

We do not have to exert control and make every decision for the riverscape to achieve benefits we care about. The elegance of low-tech process-based restoration, is that the riverscape can make some of the most critical design decisions for us. In places where we have the ability to give the stream space (Riverscapes Principle 1), we do not have to be too prescriptive. Oftentimes, we just need to get enough structure back into the system to let the structurally-forced pathway to complexity unfold (Riverscapes Principle 2). As we will cover in Chapter 3 (Bennett et al., 2019b), low-tech restoration is best focused in structurally-starved systems where threats to infrastructure are low and or easily avoidable. Putting trust in the system relies on the system's own natural processes to make decisions that would otherwise require designers to know a lot more about the hydrology, hydraulics, geomorphology and ecology of the system.

A classic design example of traditional river restoration that requires a significant amount of expertise is floodplain reconnection. Traditional practice has tended to invoke three basic methods – all involving lots of grading and diesel power: 1. Regrade floodplain to lower it down to degraded channel, 2. Realign and undersize new channel to promote more regular flooding and plug old channel, or 3. If relic channel alignment exists, attempt to reconnect to that relic channel, and abandon and plug in place current channel. Putting aside the large cost of construction of floodplain reconnection via these approaches, all three require a great deal of expertise, data and analysis to support a defensible design approach. The designer really needs have a solid grasp on the hydrology of that system (easier if lucky enough to have a flow gage in system, though not always the case). Assuming the hydrology is well-understood, then the designer needs to design how regularly they want the system to flood and would need to undertake hydraulic modeling or analysis to ensure their design achieves that inundation at the chosen return interval flows. To do this and produce the grading plan, a high-resolution topographic survey is necessary as a basis for design. This entire process is something only a highly trained geomorphologist, hydrologist or civil engineer are qualified to undertake. Despite the complexities of this design approach, there are numerous problematic assumptions embedded in each step, each of which can have serious consequences in terms of both project effectiveness and liability.

Alternatively, in many settings, it is possible to tackle the problem of floodplain reconnection using a low-tech process-based restoration approach focused on deferred decision making. If a Stage 0 (see Chapter 1: Shahverdian et al., 2019b) target is the goal, but you are currently in a Stage 3 degraded condition (Cluer and Thorne, 2013), the decision to make in feeding a meal is where to put structures and what processes to promote. The easiest way to reconnect a floodplain for an incised channel is ironically by erosion. Direct flows at the banks of the incision trench, and let the water erode those banks and widen the trench. The river will decide how far to erode it (generally not more than the width of the channel in one treatment), and in the accommodation space left behind, a wider trench will have more room for the sediment eroded to deposit. The most difficult design choice in floodplain reconnection has to do with

choosing the elevation of the floodplain surface(s) to build. With this approach, the flow regime and floods will make that decision.

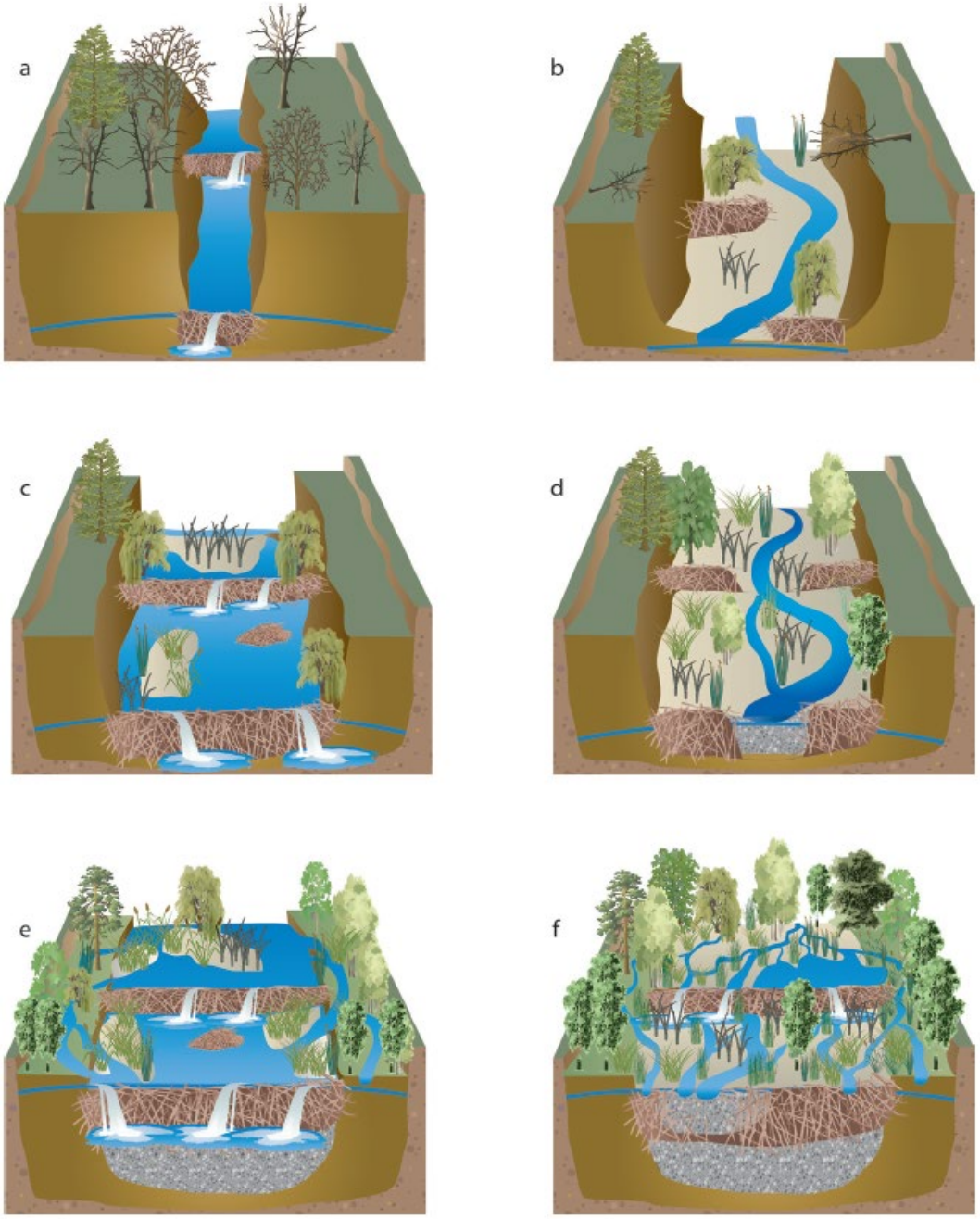


Figure 17 - An example of 'deferred decision making' where beaver decide where and when to build dams in an incised channel, which helps accelerate the process of channel evolution (see Chapter 1 (Stage 0), and: Cluer and Thorne, 2013), and floodplain reconnection. Note that the floodplain reconnection is not necessarily reconnecting to a former surface, but rather rebuilding a new inset floodplain, only when trench widening (i.e., bank erosion) occurs (decision of when and how much to widen determined by flow regime) and in accommodation space created the eroded material can redeposit. Figure 4 from (Pollock et al., 2014).

The variability in the elevation of those surfaces it builds will be a direct reflection of the variability in the flood hydrographs that lay down those deposits. Importantly, those surfaces are laid at an elevation that is in tune with the hydrology of that system and will provide good access to the water table to recruit and grow new riparian vegetation.

This may take multiple stages to 're-work' and let the system redistribute the elevation of the valley bottom, but the resulting floodplains will be well-connected, complicated messes built on a foundation of highly resilient carbon-fiber matrix of sediment, roots and vegetation. This idea is reflected in Figure 17 from Pollock et al. (2014) for an incised channel where the decisions of a) when to flood and b) how much to widen the incision trench at beaver dam failures are made by the flow/flood regime. However, the decisions of c) where to build dams, d) when to build, maintain and repair are all made by beaver. Thus, beaver translocation may be a necessary part of your low-tech restoration if beaver are not present or in very small numbers.

Some will argue that you cannot just let a system 'do whatever it wants'. There are places where that is true, but for the vast majority of riverscapes, a command-and-control approach (Holling and Meffe, 1996) to restoration is unwarranted and counterproductive. Perhaps more fundamental than the philosophical argument for the principle of deferred decision making, is that there are simply too many miles riverscapes in poor condition for us to micromanage. Growing challenges with species imperilment, climate change, water availability, and more make the need to enlist nature's help in riverscape restoration even more urgent if we are to have any hope of matching the scope of degradation.

Self-Sustaining Systems are the Solution

SELF-SUSTAINING SYSTEMS ARE THE SOLUTION
RESTORATION PRINCIPLE 10.

Low-tech restoration actions in and of themselves are not the solution. Rather they are just intended to initiate processes and nudge the system towards the ultimate goal of building a resilient, self-sustaining riverscape.

The principle of self-sustaining processes being the solution is a critically important low-tech restoration goal as it focuses on the processes critical to riverscape health. Specifically, the processes of exercise (geomorphic adjustment) and diet (water, wood, sediment, nutrients in transport and temporary storage through riverscape) instead of only what a healthy river looks like. As articulated in Riverscapes Principle 2, the processes of wood accumulation and beaver dam activity are the target. Thus, self-sustaining low-tech restoration is intended to initially mimic and promote those processes with targeted meal preparation (meals of structures), but the exit strategy from continued meal preparation in the form of restoration is identifying when the river is healthy enough to grow its own food and prepare its own meals without assistance. Thus 'structure failure' may be a better indicator that the processes of wood accumulation and/or beaver dam activity are at play and working, than the presence of a static, unoccupied structure neither experiencing wood accumulation or beaver dam activity.

How can we help create self-sustaining healthy streams and floodplains? The goal of restoration is not to restore a characteristic form to a stream or river, but rather to restore the processes that create and maintain characteristic forms. The goal of low-tech restoration is to initiate the processes that allow streams to take care of themselves through the strategic and widespread introduction of structural elements. We use the examples of post-assisted log structures (PALS) and beaver dam analogues (BDAs) below for how to think about the wood accumulation and beaver dam activity they mimic in the short-term (low flow), but also what they promote in response to typical floods. We do this to identify the 'exit strategy' and to identify when a self-sustaining condition appears to have taken hold.

In the short-term at low flows, PALS mimic the form of a wood accumulation and directly force the processes associated with woody debris accumulations. However, in response to typical floods, PALS can:

i. grow by acting as platforms/obstructions for more wood to accumulate on,
ii. promote direct recruitment of woody debris by the hydraulics they force from other surfaces,

iii. force creation of surfaces (bars and floodplains) that recruit more woody vegetation establishment, and
iv. the material in PALS can be mobilized and accumulate into their own natural woody accumulations downstream.

The process of wood accumulation is sustainable, when the above processes are no longer dependent on us building more PALS or adding more wood to the system, but take place on their own accord and with their own materials.

In the short-term, BDAs mimic the form of a beaver dam and can produce ponds similar to beaver ponds. In the medium to long-term, BDAs and our maintenance of them can:

i. diversify hydraulics, build ponds, raise water levels and adjacent water tables,
ii. promote overbank flooding (even at low flows),
iii. promote aggradation, diversify residence time of water, sediment, wood (i.e., wood accumulation) and nutrients and act as sinks for all mass moving through the riverscape, and
iv. increase riparian and wetland vegetation and habitats in valley bottoms.

The above processes are typically associated with 'beaver dam activity', which is ideally done by beaver. When beaver occupy BDAs, maintain them, build them up, expand them or expand the footprint of natural beaver dams in an area, maintenance has been adopted by beaver (see Figure 18). We have used BDAs to take advantage of the opportunistic nature of beaver and offer suggestions to where they might work. Where they take up maintenance, they rarely leave it just how it was built, and often have more grandiose plans. Such beaver dam activity is sustainable, when multiple colonies are cycling through and building, maintaining, abandoning, returning, rebuilding, fixing up, expanding within a riverscape, such that they do not need our BDAs. While PALS seem clearly linked to wood accumulation, and BDAs clearly linked to beaver dam activity, BDAs also promote natural woody accumulation, and beaver will sometimes convert PALS into beaver dams. None of these processes result in permanent structures that remain static through time. When these processes are healthily playing out on their own, the structure (a woody debris accumulation/jam) or a beaver dam changes over time. As long as enough of this structure is present and that structures are out of phase (in time), both the processes and overall presence of a complex habitat mosaic persists. Thus, when building PALS and BDAs, do not get too attached to any one structure and focus more on the promotion, maintenance and sustaining of processes of wood accumulation and beaver dam activity.

Figure 18 – An example from Goldfarb (2018a) of achieving a self-sustaining condition where meals of beaver dam analogues (BDAs) mimic beaver dam activity, and then the maintenance and expansion of beaver dam activity is taken over by actual beaver, and then they maintain a complex system state. Figure © Science by V. Altounian.

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Chapter 3 - PLANNING FOR LOW-TECH PROCESS-BASED RESTORATION

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IMPLICATIONS FOR PRACTICE

- Planning for low-tech process-based restoration is similar to planning for other forms of restoration.
- We adapt the Conservation Planning Process to show what aspects of the process are distinctive to low-tech process-based restoration. The Conservation Planning Process follows an adaptive management framework and has three phases: i) a Collection and Analysis (focused on planning), ii) a Decision Support (focused on design), and iii) an Application and Evaluation (focused on implementation).
- For low-tech restoration, we pose four screening questions to identify where and if low-tech process-based restoration is appropriate.
- In the Collection and Analysis Phase, current conditions of the riverscape (valley bottom), constraints and recovery potential are identified to help frame appropriate and realistic treatments and objectives in the design.
- Low-tech restoration to reverse structural starvation of riverscapes frequently takes more than one treatment (and design). Therefore, in the design phase we set expectations for how many treatments might be necessary to achieve the long-term restoration goal of a self-sustaining riverscape.
- The implementation of a design involves an iteration between carrying out an individual treatment of structural additions and evaluation. Ultimately, it is assumed project goals will be met if the processes of wood accumulation and/or beaver dam activity make the transition from being mimicked and promoted by treatments to occurring on their own in a self-sustaining fashion. As such, the need for additional treatments versus recognizing the project has achieved its goals is evaluated with respect to the sustainability of these processes.

INTRODUCTION

In this chapter, we provide guidance for planning low-tech process-based restoration projects that address structurally-starved riverscapes. There are numerous technical resources that describe planning frameworks and steps for developing and implementing restoration projects (e.g., Beechie et al., 2008; Brierley and Fryirs, 2005; Roni and Beechie, 2013; Skidmore et al., 2011). All of these planning frameworks have parallels in how they proceed through a project from the inception and scoping through to design, implementation and evaluation (Appendix 3 A). Any of these planning frameworks are reasonable to apply to low-tech restoration. This chapter is organized around the three phases of the USDA's Natural Resources Conservation Service's Conservation Planning Process (modified from NRCS (2007a), Figure 1):

1. **Phase 1**: Collection & Analysis – Understanding Problems & Opportunities (i.e., Planning)
2. **Phase 2:** Decision Support – Understanding the Solution (i.e., Design)
3. **Phase 3:** Application & Evaluation – Understanding the Results (i.e., Implementation)

We recognize that the details and scope of project planning will vary greatly depending on whether the project is developed within a large–scale strategic planning process or as a stand-alone project. However, if practitioners engage with the intent behind these basic planning steps, it will increase the likelihood of achieving project goals regardless of the spatial footprint of the project. We do not provide details on how to complete each planning step, as plenty of details already exist. Instead we use the Conservation Planning Process in Figure 1 to highlight aspects of each step that are either distinctive or especially relevant to low-tech process-based restoration. More detail is provided in this chapter on Phase 1, as this is a planning chapter. By contrast, in Phase 2 (design) and Phase 3 (implementation), a succinct overview is provided and the focus is placed on key questions that practitioners need to answer during these phases. The reader is referred to Chapters 5 for design and 6 for implementation details.

For many practitioners, low-tech process-based restoration is a departure from engineering-based restoration approaches. Low-tech and engineering-based approaches can be complementary in many settings, but engineering-based approaches have plenty of standards and manuals already defining those standards of practice. We seek here to define the standards of practice for planning low-tech restoration. It is not uncommon to encounter skepticism or resistance to what are perceived as new or unfamiliar approaches. However, low-tech treatments have existed for centuries and have been forgotten (see Chapter 1, Appendix D: Shahverdian et al., 2019a). It may also be difficult for practitioners and permitting agencies to assess the risk of low-tech restoration because they have no direct experience with its implementation. We use this chapter to place low-tech restoration planning in the context of the well-established Conservation Planning Process. Starting from this place of familiarity for most restoration practitioners and conservation planners, we then proceed into what specific considerations are important for low-tech restoration. We define the key planning considerations essential to developing appropriate expectation management, and we also define clear exit points from the process to help practitioners and planners avoid using low-tech restoration in inappropriate settings.

Most contemporary planning frameworks, including the NRCS's Conservation Planning Process, advocate the use of adaptive management. Adaptive management is a method to implement uncertain, relatively novel, management strategies while managing risk and increasing our understanding of how these actions perform. Adaptive management is often referred to as 'learning by doing' (Walters and Holling, 1990). Adaptive management is particularly well suited for low-tech process-based restoration because the approach defers critical decision making to the system, the scope of degradation is very large, and enhancement/maintenance is an explicit part of low-tech implementation. Implementing low-tech restoration in trials can be an effective way to find efficiencies, test new ideas and make adjustments to improve the effectiveness of later and/or larger scaler treatments (i.e., Evaluate, Learn, and Adjust, Figure 1). We provide details on managing uncertainty and risk in Step 3 and Appendix 3D. Low-tech restoration is likely to be implemented in many new riverscape settings because the scope of structural-starvation is so large. Using adaptive management can help structure and speed up learning. To address the scope of structural starvation and achieve self-sustaining riverscapes may take several treatments. Using an adaptive management framework, plausible

bounds and expectations can be developed about how many treatments may be necessary, whether to continue and when they can be ended.

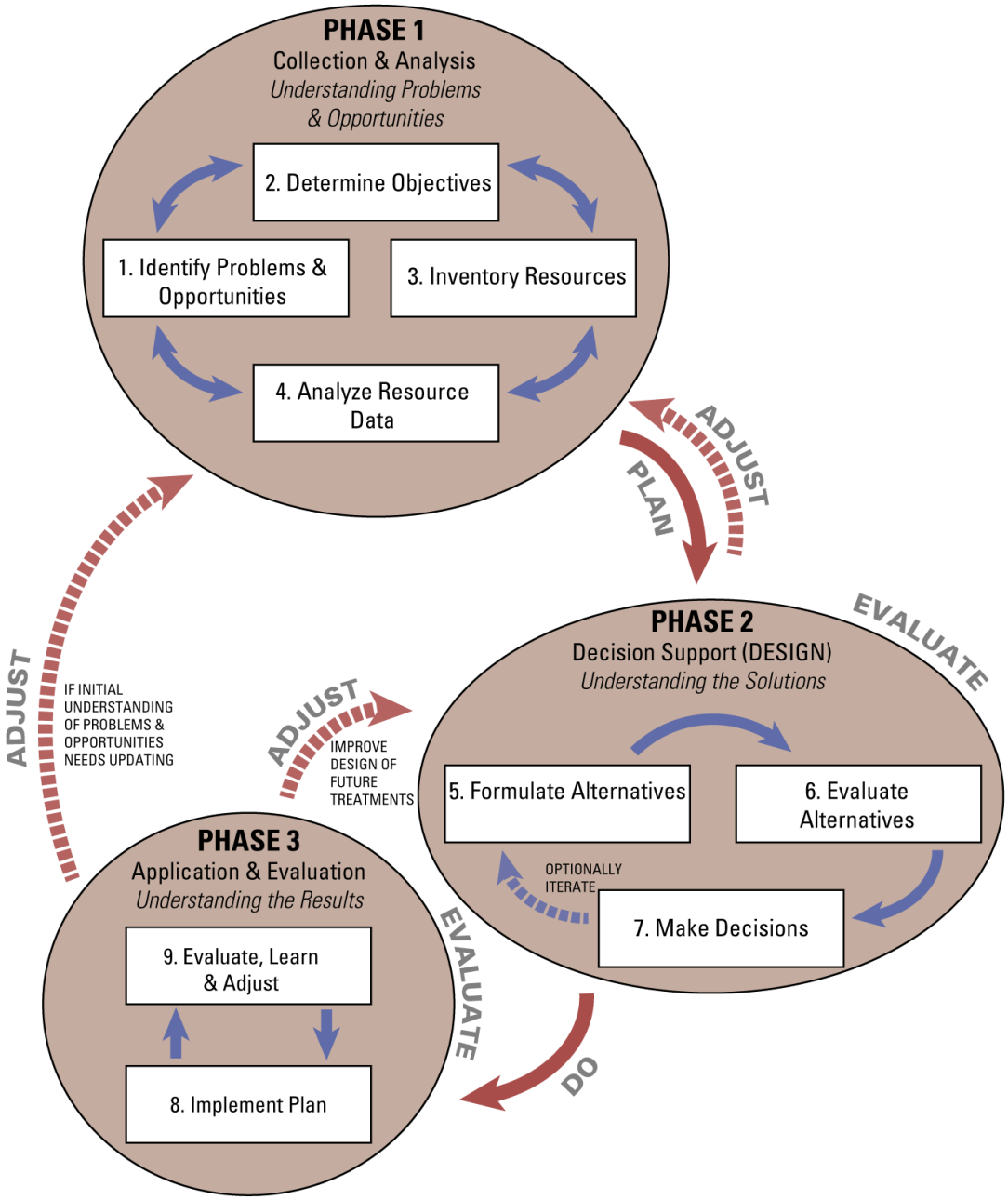


Figure 1 – The USDA Natural Resources Conservation Service's Conservation Planning Process is broken into three phases and iterative steps. This process is similar to many other restoration planning processes, and we expand on it in this chapter to show what specific additional consideration are necessary for low-tech restoration. Adapted from Figure 2-2 in NRCS (2007a). Blue arrows represent potentially iterative steps within phases. Solid red arrows represent the traditional linear order of singe-phase projects. Dashed red arrows represent the optional adjustments made under adaptive management in response to critical evaluation.

SPATIAL SCALE OF PLANNING

As highlighted in Chapter 1 (Shahverdian et al., 2019a), the spatial extent and scope of degradation is difficult to overstate. Phase 1 of the Planning Process may take place over very broad spatial extents (e.g., entire watershed, entire region, entire state, etc.), but minimally is defined for a particular project area (Figure 2). As the blue arrows indicate in Phase 1 of Figure 1, the collection and analysis phase may be iterated through multiple times at different spatial scales, potentially starting at broader extents and coarser resolution and then focusing in on finer scales. Where this is done to identify project opportunities for potential specific project areas or as part of a prioritization process (e.g., Bennett et al., 2018; Hill et al., 2019a), we highly recommend doing this process over network scales (see Appendix B for examples). Watershed-scale assessments can also lead to cost savings due to economies of scale in the assessment and implementation phases, and a higher likelihood of implementing restoration over a scale that matches the scope of degradation (BenDor et al., 2015; Bernhardt et al., 2005).

Individual projects tend to take place over riverscapes that cover some subset of an entire drainage network. Ideally, these are at locations selected at the intersection of priorities (e.g., Appendix B) and practical opportunities (e.g., willing land managers or owners). Projects tend to be organized around these discrete locations, a collaboration of project organizers and stakeholders, and tied to a specific set of conservation and/or restoration actions often tied to a finite amount of funding over a relatively short time (i.e., 1-2 years). Regardless of the total extent of an individual project, we recommend iterating through the three planning phases at least once for each reach. We define the spatial extent of reaches laterally by the valley-bottom extents (i.e., floodplain and/or channel(s)) and longitudinally by upstream and downstream breaks in reach boundaries. There are many ways to define reach breaks or boundaries. For the purposes of planning, reach breaks are necessary where the answers to any of the planning questions differ. For example, if a planning question focuses on what risks are present, and not all reaches in a project area have the same answer, reaches should be broken on the basis of those with different answers. The remainder of this chapter is organized around the

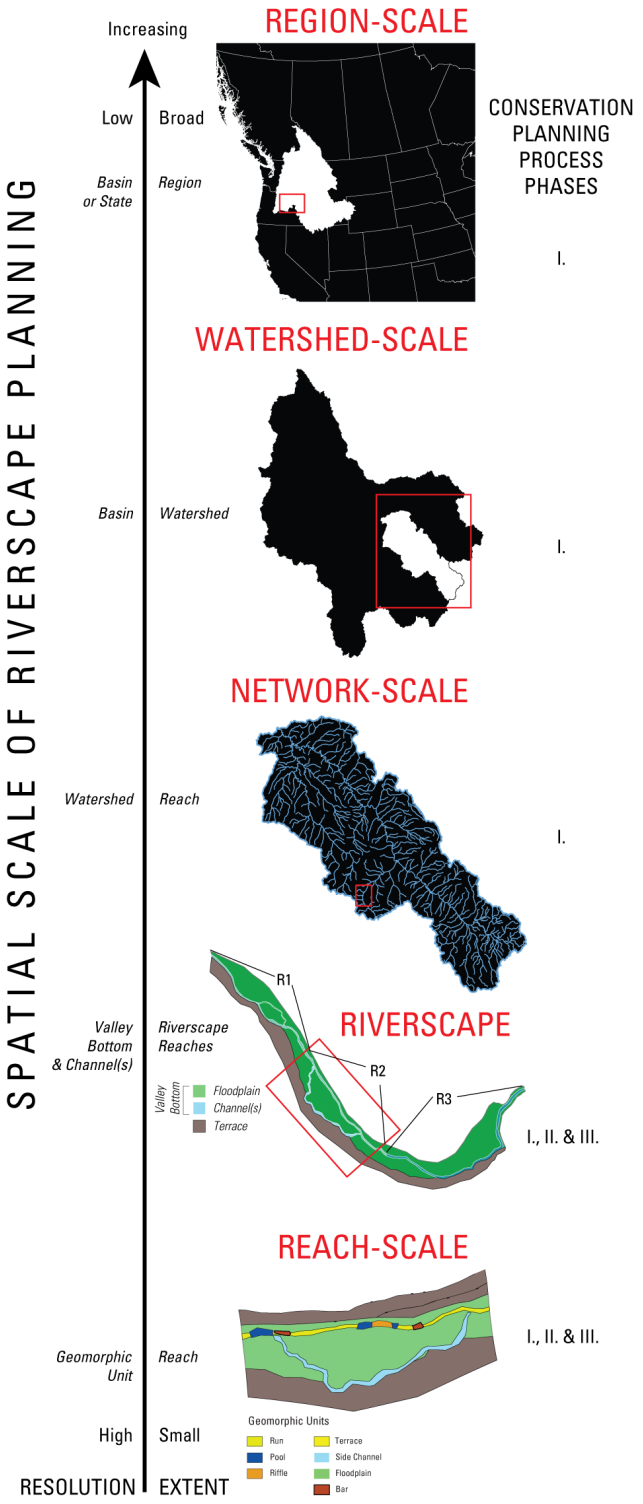


Figure 2 – Definition of nested-hierarchical spatial scales defined in terms of their extent and resolution (left). The typical spatial scales at which the different phases of the conservation planning processes are shown on right. Adapted from Wheaton et al. (2017).

assumption that the planning process will be implemented on a reach-by-reach basis.

PHASE 1: COLLECTION & ANALYSIS

Within this initial collection and analysis phase, the emphasis is on understanding problems and opportunities (Figure 3, NRCS, 2007a). Outside the Conservation Planning Process, many consider this phase to simply be planning.

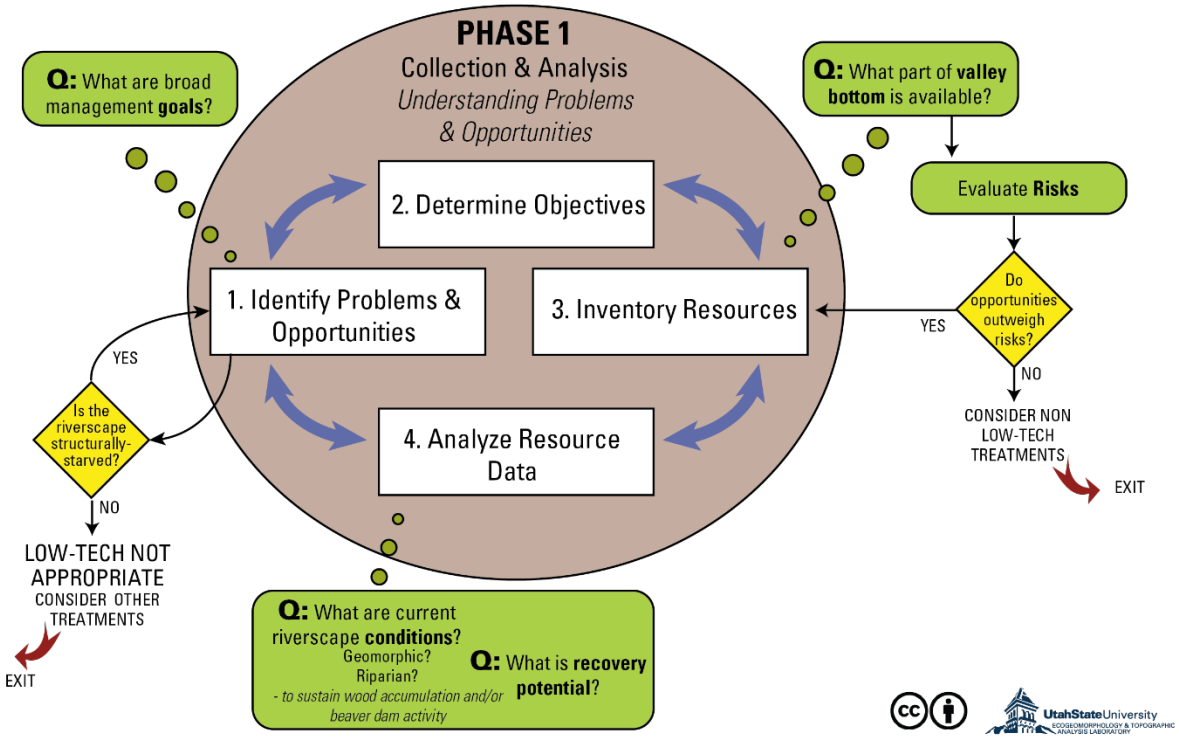


Figure 3 – The Phase 1 of the Conservation Planning Process (see Figure 1) adapted for low-tech restoration. Critical questions and processes to consider specifically for low-tech restoration are shown in green, and two key decisions (yellow diamonds), with potential exit points from continuing with low-tech restoration are shown.

Step 1. Identify Problems and Opportunities

Intent and Rationale

Before making structural additions to riverscapes, articulate, confirm or clarify the management setting, stakeholders, problems, and opportunities. This would include identifying if there are broad management drivers or mandates (e.g., Endangered Species Act (ESA), Clean Water Act, etc.) that will have over-arching goals you may need to be aware of. At this stage, try to determine what the general problems are in the riverscape, their potential causes, and where and when there may be opportunities to identify areas where low-tech process-based restoration is suitable and where stakeholder interest and support already exists. Low-tech process-based restoration may not be suited to address every resource concern that a landowner or manager may have in their riverscape. For example, stabilizing an eroding bank to protect infrastructure may require a different treatment philosophy and approach. Low-tech restoration is best aligned with management goals seeking ecological outcomes, cost-effectiveness, and self-sustaining solutions in areas with minimal risk to infrastructure.

Key Low-Tech Questions and Considerations

What is/are the Broad Management Goal(s)?

Although the local or regional management setting may have specific species or habitat goals (e.g., increasing habitat for juvenile fish or protecting rare plant species), in general the ultimate goal of process-based riverscape restoration is to restore and sustain ecological function and resilience. As asserted by the Riverscapes Principles (see Chapter 2: Wheaton et al., 2019), for many riverscapes, if an anastomosing (Stage 0 or Stage 8) goal were achieved (see Chapter 1: Shahverdian et al., 2019a, Figures 5 & 6), ecosystem function and resilience would be maximized. With this in mind, a provisional goal of most projects would be to have an anastomosing, Stage 0 or Stage 8 goal. Then, it becomes a matter of connecting that provisional goal to the management drivers. Regardless of what the specific management drivers are, attempt to make the connection in articulating the project goal(s) between broader management goals and that anastomosing vision. If that connection can be articulated, it will become simpler to show progress towards the more specific management goals and objectives and the project outcomes later. These overarching goals will drive the planning and focus of the restoration project.

Is the Riverscape Structurally-Starved (Potential Exit Consideration)?

This is a screening question, intended to flag whether low-tech restoration should be considered. As highlighted in Riverscapes Principle 3 (see Figure 7, Chapter 2: Wheaton et al., 2019), the importance of structure varies by geomorphic reach type. Wood accumulations are really important and common naturally in some reach types, and not present naturally in others. There are many riverscapes (e.g., Figure 2 of Chapter 1: Shahverdian et al., 2019a), which are obviously structurally-starved because they lack any wood accumulations or beaver dams in areas that historically they would have been ubiquitous. As such, it is helpful to consider the question of structural starvation (see Chapter 1 for explanation: Shahverdian et al., 2019a) independently from the perspective of wood accumulation starvation, versus beaver dam starvation. Some riverscapes may be starved of any beaver dams, which may have historically had them, but are not starved of wood accumulations. Others may be starved of beaver dams, not have any wood accumulations, nor would they have historically. In some situations the role structure would have played historically, is playing and could play is obvious. In situations where it is not, a geomorphic assessment of reach types can help clarify the importance of structure (Brierley and Fryirs, 2005; Kasprak, 2015).

If the riverscape is not structurally-starved, reintroducing and/or increasing structure back into the system may not be appropriate. However, practitioners will encounter riverscapes where the question of structural starvation is not a yes or no, but a degree. Figure 4 shows one of the potentially misleading situations where the stream channel is intersecting a riverscape floodplain with a reasonable amount of wood in it. However, just because a lot of wood might be available in the riparian, does not mean the processes of wood recruitment to the channel are present, or for wood accumulations to form. However, we caution against assuming the riverscape is not structurally-starved based purely on an aesthetic evaluation Figure 4. The shifting baseline phenomenon (Pauly, 1995) is particularly applicable to the structural-starvation of North American riverscapes. When successive generations grow up with degraded riverscapes, the collective expectation of what is possible is lowered, and degraded conditions are accepted as the norm. It is generally true that riverscapes are more frequently protected from development; however, there is a legacy deficit of structure that will take decades or longer to address (see Chapter 1: Shahverdian et al., 2019a). Therefore, if working in an area where the riverscape intersects a woody riparian area, and/or is directly adjacent to upland forests (or formerly forested uplands), but there are no wood accumulations present in the channel, it is a good bet that the riverscape is structurally-starved (Shahverdian et al., 2019a). Also, even in non-forested settings, such as, rangelands, it is also highly likely that system is structurally-starved if beaver were historically present but are no longer present, or are present at low densities (i.e. rare: 0 to 2 dams per mile). To help discern whether a riverscape is structurally-starved, look for evidence that:

- Woody vegetation and wood accumulations should be present in greater quantities in the riverscape based on historic photos, written accounts, landscape setting (i.e., climate and geology) or recent evidence (i.e., stumps, downed wood, old beaver activity);

- Current conditions may be limiting woody vegetation, such as invasive plants displacing native woody vegetation (Figure 5), overgrazing, or channel incision leading to upland vegetation encroaching into previous valley bottom habitat.

Figure 4 - Structurally-starved riverscape that lacks large woody debris (LWD) or other structural elements capable of forcing physical complexity. Many riverscapes that appear 'healthy' because of the presence of riparian vegetation lack the processes of wood-recruitment and wood accumulation. High densities of wood lead to diverse hydraulic and geomorphic conditions, such as overbank flow and channel migration, which create and maintain the diverse physical conditions necessary for ecologically functioning riverscapes.

Figure 5 - A deeply incised riverscape where the inset valley bottom has been over-taken with invasive reed canary grass. Reed canary grass is now effectively preventing colonization of native woody plants including willow species, limiting both processes of wood accumulation and beaver dam activity.

Step 2. Determine Objectives

Intent and Rationale

Project goals outline generally what the restoration project hopes to accomplish. For example, to increase habitat diversity and fish populations by increasing habitat capacity and survival through recovering an anastomosing riverscape. A well-articulated goal provides a vision for the post-project condition and outcomes. An example of a clearly defined goal is to … *restore and protect dynamic channel processes that lead to resilient and sustainable riparian function.* Objectives are more specific and measurable, and they define actions necessary to achieve a stated goal (Barber and Taylor, 1990; Doran, 1981). An objective related to moving a riverscape more towards full recovery could be to … *promote overbank flow during low flow conditions instead of only every 1-2 years* (see Chapter 1: Shahverdian et al., 2019a).

The acronym SMART is widely used in business planning to describe well-defined objectives, and has been adapted by Skidmore et al. (2011) for riverscape restoration planning as:

1. **Specific**: objectives are clear, concise statements that specify what you want to achieve.
2. **Measurable**: objectives use parameters that can be measured before and after project implementation.
3. **Achievable**: objectives are geomorphically and ecologically possible.
4. **Relevant**: objectives are clearly related to and support the project goal.
5. **Time bound**: objectives are bound by a specified time frame.

For low-tech restoration, time bound objectives should be clearly articulated in an adaptive management context that estimates roughly how many treatments (meals) are anticipated to reach the desired self-sustaining state (e.g., anastamosing; see Restoration Principle 10, Chapter 2: Wheaton et al., 2019). It may be possible to achieve project goals with one treatment and many projects will require multiple treatments to mimic and promote the processes of wood accumulation and/or beaver dam activity. Thus, if based on the likely hydraulic zone of influence (defined in Chapter 5: Shahverdian et al., 2019b) of a treatment relative to the valley bottom width, one might estimate that it might take three or four high flow events to shift the channel laterally and rework the valley bottom topography. After each shift, it might be imagined than an additional treatment of wood additions was necessary to keep accelerating that lateral reworking. In this example, we would not phrase the time-bound objective as laterally rework valley bottom in four years. While it is certainly specific and measurable, and even achievable, it unnecessarily sets an arbitrarily precise objective that does not account for natural variability (yes typical floods occur most years, but there may be a few drought years). Instead, a time-bound objective could be cast as laterally rework valley bottom in three to six typical spring runoff events. This ties the objective in a time-bound way to the real driving force (i.e., flow events of a minimum magnitude), but allows flexibility for whether or not those events occur as well as communicating uncertainty in the response by setting a specific range of number of events, instead of specifying the exact number. At each step, adaptive management can be used to develop conceptual models of riverscape function which can help highlight uncertainties. Phrase the project objectives as testable hypotheses and develop events that will trigger actions to implement maintenance or risk management (See step 9).

As Figure 1, suggests for phase 1, steps 1 – 4 are iterative. Initial project objectives may be refined and informed by the inventory and analysis of resources. We suggest that objectives that specify a single and arbitrarily precisely defined target be avoided as low-tech process-based approaches recognize the dynamic and highly variable nature of natural riverscapes. As an example, an objective of increasing wood accumulations can be made more specific by tying it to a specific, measurable indicator of 800 pieces of large woody debris (LWD)/mile. This might be logically chosen on the basis of estimates of background historic wood loading rates (in the context of a resource inventory of current wood loading rates of 2-5 pieces of LWD/mile). However, counting LWD is slow and laborious, and ultimately wood accumulations or debris jams are more important from a functional perspective. Perhaps a better, easier to measure indicator would be the density (or count per mile) of wood accumulations. So this can be modified to something like an indicator of 200 ± 50/mi wood accumulations per mile, which is both more easily measurable and realistic in expressing a range. These objectives should not be made arbitrarily specific without some theoretical (e.g., geomorphic

understanding) and empirical evidence to constrain them. Table 1 shows an example of some typical indicators for low-tech restoration, which can be tied to SMART objectives.

Table 1 – An example of measurable indicators, which can be tied to project objectives for a hypothetical project. In this example, objectives are set in terms of imprecise percentages (e.g., +/-5% at best) or approximate counts turned into densities (e.g., number per length or number per area). Also, the indicators chosen tie directly to broader project goals (e.g., a Stage 0 or 8 anastomosing riverscape) and objectives in terms of the key processes of wood accumulation or beaver dam activity. Also, of key importance, these are all easily measurable in the field or with remote sensing. BD = beaver dams, BDA = beaver dam analogue, LWD = large woody debris, PALS = post-assisted log structure, S = Stream Evolution Stage based on Cluer and Thorne (2013), VB = valley bottom.

INDICATOR	**EXISTING**	**AS-BUILT**	**AFTER 1-2 TYPICAL FLOODS** (1-4 years + Phase 2 Treatment)	**AFTER 2-4 TYPICAL FLOODS & 1 OR MORE LARGE FLOODS** (5- 10 years)
Proportion active channel(s) & floodplain (by VB area)	~20%	~ 25%	~ 40%	~ 90% ± 10
Number of active channels (i.e. braiding index)	1	1.5	2 – 3	2 - 5
Cluer and Thorne (2013) – Stream Evolution Model Stage proportions (by VB length)	0% (S0) 25% (S8) 35% (S7) 10% (S5) 20% (S2)	0% (S0) 25% (S8) 35% (S7) 10% (S5) 20% (S2)	0% (S0) 75% ± 10 (S8) 15% ± 10 (S7) <5% (S5) <5% (S2)	80% ± 20 (S0) 15% ± 10 (S8) 5% ± 5 (S7) 0% (S5) 0% (S2)
LWD accumulations (structures per mile)	~ 2-5 /mi	~100 ± 10 /mi (PALS)	~200 ± 10/mi (PALS) (Add 100 more PALS & some natural)	~ 200 ± 50/mi (natural wood accumulations & wood accumulations on PALS indistinguishable)
Beaver dam density (dams per mile)	0 /mi	50 ± 10 /mi (BDAs)	75 ± 20 / mi (mix of new BD, occupied BDAs, and new BDAs)	30–60 /mi (expect 10 – 50% occupied BDs; BDs and BDAs indistinguishable)

In instances where there are more reaches that could use restoration than available resources (funding and time), it may be necessary to prioritize restoration objectives as well as reaches. Project planers and stakeholders may rank the priorities of competing objectives, and after existing and potential natural resources are inventoried (Step 3) and analyzed (Step 4), these priorities can be mapped on to the available reaches (see Appendix B for example).

Step 3. Inventory Resources

Intent and Rationale

In Step 3, natural resource, economic and social information are collected. When this inventory and analysis of resources extends across the entire riverscape drainage network at a watershed extent, they are referred to as watershed assessments (e.g., Beechie et al., 2012; Bennett et al., 2018; Hill et al., 2019a; O'Brien et al., 2017). When done just over the riverscape at a project extent, they are referred to as project assessments. The planning team can further refine the problems and opportunities identified in Step 1 by gathering and analyzing information on the riverscape setting, past and current development activities, stream form and function, and riparian and geomorphic condition. The scale of assessments range widely from a single landowner with a few miles of stream to a large watershed involving multiple stakeholders. We focus on the riverscape in this manual but recognize that any assessment should establish if causes of riverscape degradation originate outside the riverscape (e.g., excess sediment from poor land use, modified flow regime due to water withdrawals). If the cause of degradation cannot be attributed to riverscape specific conditions, the assessment will require expansion to the watershed-scale.

Identify the Lateral Extents of Your Riverscape (i.e., Valley Bottom)

Before conducting an assessment of a riverscape it is critical to first define its extent. Longitudinally, this is defined simply enough by the drainage network. Laterally, this is defined by the valley bottom boundaries (Fryirs et al., 2015; Gilbert et al., 2016; Wheaton et al., 2015, Figure 2). Identification of the riverscape will allow the development of realistic expectations both for setting goals of restoration, as well as what risks may be present (e.g., incompatibility of processes to sustain that riverscape and land use or infrastructural constraints). The valley is defined as the area between the adjacent hillslopes (Wheaton et al., 2015). The valley bottom describes the area within the valley that contains the active channel and active floodplain (Chapter 2: Wheaton et al., 2019). Think of the valley bottom as the area that could plausibly be flooded in the contemporary flow regime. Do not confuse this deliberately less precise definition of a valley bottom with related definitions of floodplains based on hydraulic analysis of inundation extents for various return-interval flows (e.g., 100-year or 500-year return interval floods), which may have legal ramifications (e.g., FEMA mapping). Geomorphic units (landforms) are the building blocks of any landscape. In the Wheaton et al. (2015) fluvial taxonomy, the primary tier 1 geomorphic units that comprise the riverscape or valley bottom are the floodplain and/or channel(s). Collectively the valley bottom, and other valley features include alluvial fans, terraces, and moraines (Figure 6). The valley bottom margin can abut alluvial fans entering the valley from tributaries, and terraces which are floodplains features within the valley that are no longer inundated by modern day flow events. The valley bottom is the area where riparian vegetation is sustained and is the source of much of the woody structure for riverscapes and the lateral extent of flooding.

One of the most critical resources to identify for riverscapes is the location and amount (i.e., width and area) of valley bottom present (see Riverscapes Principle 1; Chapter 1: Wheaton et al., 2019). Identification can be done approximately with simple locations (e.g., along a network), and the length (e.g., along valley bottom center-line or channel) and average valley bottom width. It can also be mapped more explicitly on the basis of field estimates or even using freely available coarse-resolution digital elevation models (e.g., USGS 10 m NED). If mapping, it is important not to become overly obsessed with the precision of valley bottom mapping. While a better job can be done with high resolution data (e.g., ≥ 2m resolution LiDAR), it is not essential for broad inventorying of resources, assessment of risk, and developing realistic expectations of areas that could be plausibly influenced by flooding (Gilbert et al., 2016). Be aware that in degraded conditions with incised channels, the valley bottom extents can be confusing to delineate as it may be difficult to discern whether or not the surfaces outside the channel can still be plausibly flooded or are functionally terraces. In such situations, if a surface is in question as to whether or not it could be 'in play' as floodplain or a terrace, it often makes sense to conservatively include it as valley bottom. Whereas Figure 6 shows some example schematic sketches of valley bottom mapping in different riverscape settings, Appendix 3C highlights some techniques for doing this across broader spatial extents from digital elevation models.

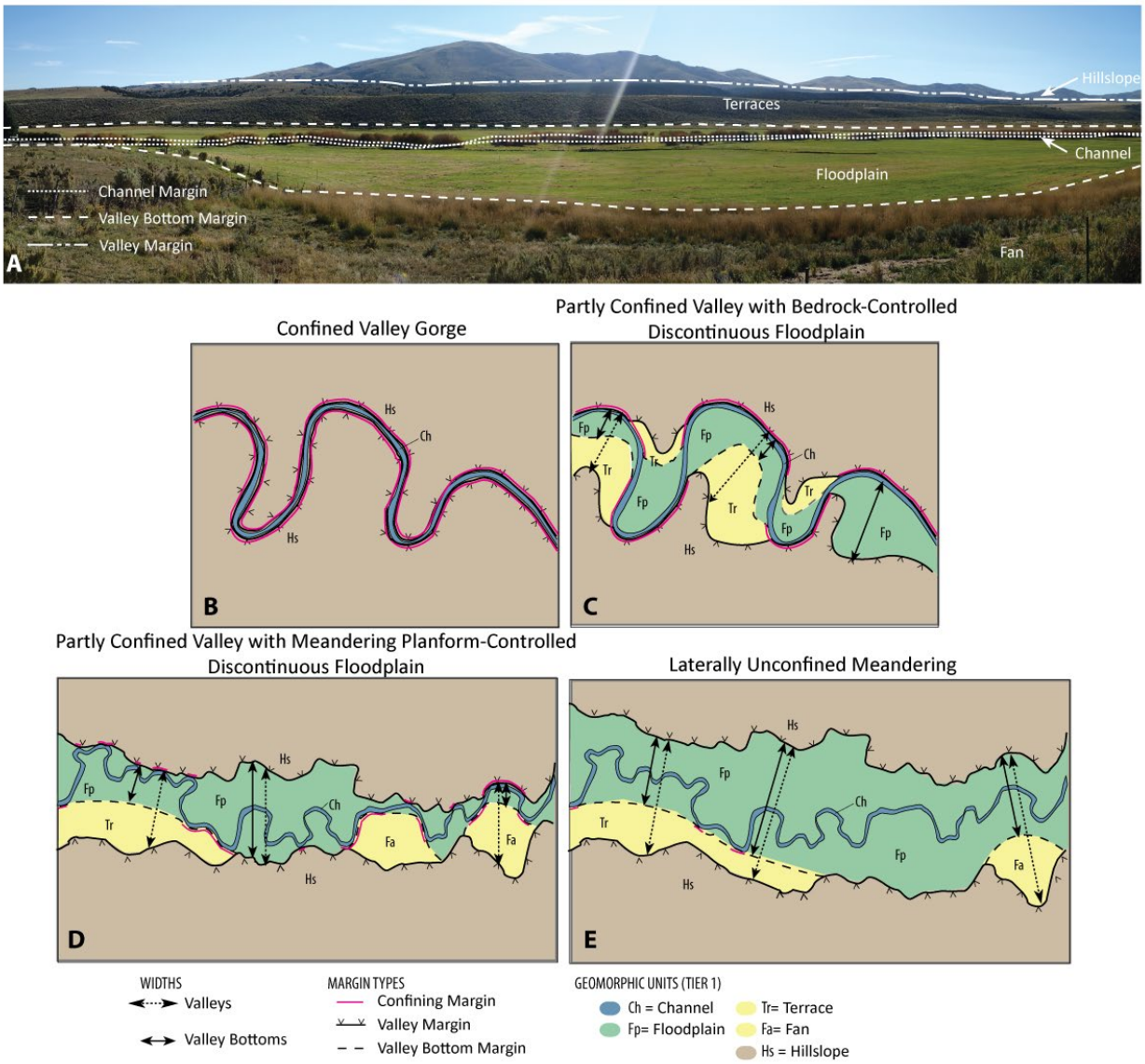


Figure 6 - In different valley settings (differentiated here by confinement or channel contact with valley bottom margin), expectations can be built about what space might be available for low-tech process-based restoration. In short, the 'riverscape' is the combination of green (floodplain) and blue (channel) areas. A critical planning step is to read the riverscape to identify these boundaries, and then ask whether it could all be in play, or if specific land uses, or infrastructure in the valley bottom or along the valley bottom margins would be threatened by such activity. Delineation of key valley bottom margins and geomorphic forms across some contrasting riverscapes: A) Oblique view of channel, valley bottom, and valley margins. Planform schematic of valley bottom margins and geomorphic forms in laterally confined (B), partly confined (C-D), and unconfined valley bottom settings (E). Figure from Wheaton et al. (2015).

Evaluate Risks Within and Adjacent to the Riverscape

Once the valley bottom is mapped, the appropriateness of a low-tech restoration approach that needs space to flood and adjust geomorphically (i.e., exercise) needs to be considered. In many riverscapes, there may be no land-use or infrastructural constraints. It is important to identify what risks might be present and inventory them. Appendix D provides an explicit process developed by the NRCS to facilitate both the evaluation of risk and the conversation with riverscape landowners or land managers about their willingness to accept some risk. There are some tools for inventorying and approximating answers to those questions from freely-available nation-wide GIS data in Figure 24 of Appendix D. In many riverscapes, (e.g., Figure 24) risks are negligible for a majority of the drainage network.

Do Opportunities Outweigh Risks?

As shown in Figure 3, once the risks are inventoried, it is then a choice amongst project stakeholders, land owner(s) and or manager(s) about what level of risk is acceptable. Even where risks are present, it does not mean low-tech cannot be effective. Many risks are easily mitigated against if the problem is actually realized with adaptive management (see Step 9 and Appendix G). Moreover, just like with investment, the level of reward (e.g., maximizing riverscape uplift) is often tied to risk. This does not mean reckless and unnecessary risks should be taken. However, avoiding risk entirely is an equally reckless strategy when managing imperiled and endangered species populations and resiliency of riverscapes and the communities and economies that depend on them is threatened (Clark, 2002). Thus, as a planner and practitioner, it is important to discuss with stakeholders, land owner(s) and/or manager(s) the potential risks of a project, but also the risks of not taking action and the potential benefits of the actions for increasing long-term ecosystem resilience and productivity.

What part of the valley bottom is available for low-tech restoration?

An important part of inventorying resources and assessing risk is coming up with a map of what part of the valley bottom is available or in play for low-tech restoration. To help conceptualize this, we return to the vision for low-tech process-based restoration laid out in Chapter 1: Shahverdian et al. (2019a). Specifically, an anastomosing riverscape. This does not have to be a binary inventory of either a healthy riverscape is possible, or is not (i.e., Stage 0 and entire valley bottom is anastomosing). A partial achievement of the anastomosing vision is likely in many riverscapes due to anthropogenic constraints (i.e., < 100% of the valley bottom is accessible due to roads or infrastructure). This concept is illustrated in Figure 7, where a 'Stage 8' goal represents a stage moving towards a fully anastomosing condition, but a portion of the valley bottom is inaccessible. Multiple treatments may be necessary to get to a Stage 0 goal, and different Stage 8 conditions may be experienced with progressively more, and more of the valley bottom becoming accessible. Cluer and Thorne (2013) point out the quality and quantity of ecosystem services, habitat and biodiversity associated with progressively more Stage 8 and ultimately Stage 0 far exceed that of Stage 1 through Stage 7.

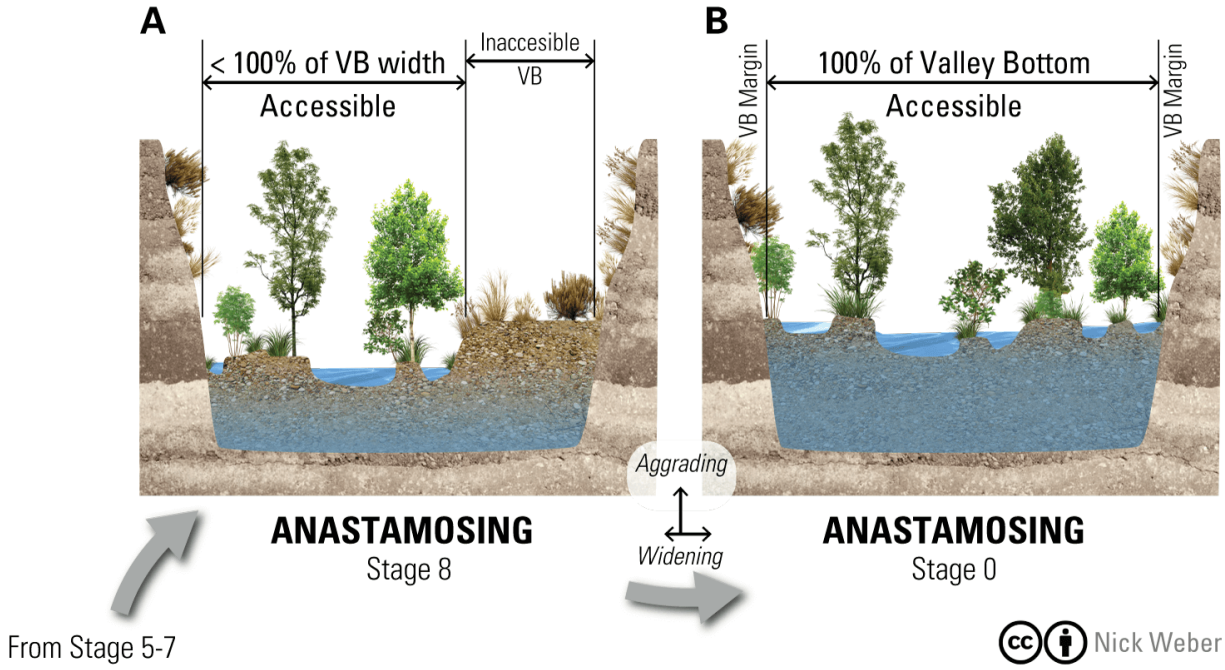


Figure 7- Typical 'vision' for a low-tech restoration project is a well-connected channel and floodplain network – or anastomosing (Chapter 1: Shahverdian et al., 2019a). Once the valley bottom extents are identified and mapped it will be possible to determine if an anastomosing condition is achievable. If most the valley bottom is accessible, a Stage 8 goal is achievable (A). By contrast, if the entire valley bottom could be accessed then Stage 0 is achievable (B). Adapted from Cluer and Thorne (2013).

Applying the concept of an accessible valley bottom to a real project reach is straightforward. Figure 8 shows one such illustration, contrasting a situation where a longer-term Stage 0 Anastomosing goal is possible (after multiple treatments), versus a situation where some Stage 8 Anastomosing is achievable, but it is constrained by valley bottom land uses.

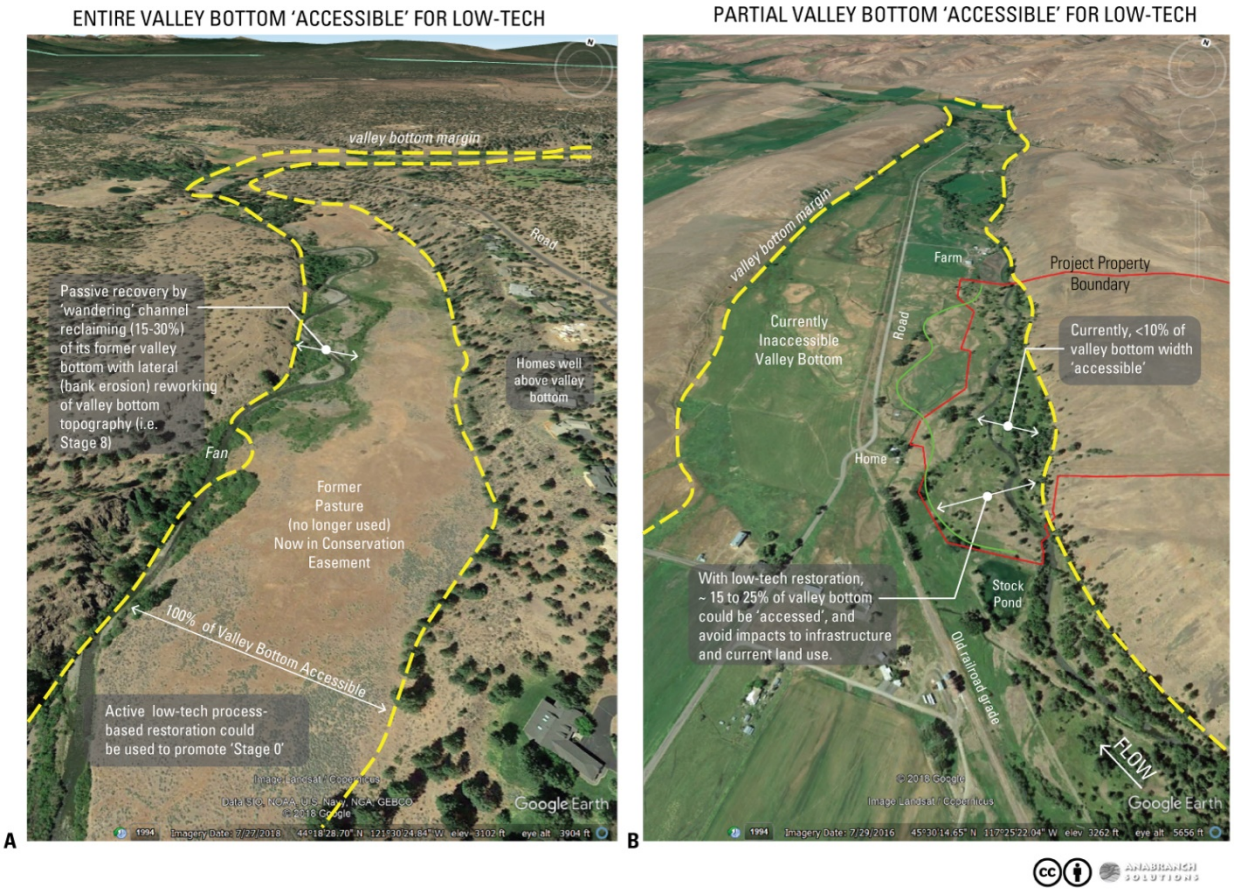


Figure 8 – A practical example of two simlar types of riverscapes (in terms of flow regime and reach type), but with very different answers to the question of what part of the valley bottom (mapped in yellow) is available for low-tech process-based restoration (i.e., could be flooded and allowed to adjust). For (A), Stage 0 anastamosing (see Figure 7B) is possible because there are no incompatible land uses within the valley bottom. By contrast, for (B), Stage 8 anastomosing (see Figure 7A) is possible, but Stage 0 is not realistic because it is outside the property/project area, homes and farms are in the valley bottom, and a railroad grade and road are making a large portion of the river left valley bottom inaccessible.

Low-Tech Adaptive Management

With the collection and analysis of assessment data and a re-examination of the original problem identification, the elements of the adaptive management framework (e.g., goals and objectives, conceptual models, monitoring programs, restoration actions, evaluation and adjustment decisions) can be updated to reflect further understanding of the riverscape behavior and conditions (Bouwes et al., 2016). The synthesis of this understanding is critical for formulating hypotheses or predictions about how the system will respond to potential alternative actions considered in Phase 2.

Step 4. Analyze Resources

Intent and Rationale

Analyzing resources may take the form of collating existing information and analyses, conducting entirely new analyses, or some combination of the two. Depending on the spatial scale of planning, a project-scale or watershed-scale

assessment may be appropriate. When reviewing an existing assessment, confirm that the conclusions were or still are appropriate before accepting it as the analysis to guide the implementation. For structurally-starved riverscapes, we can distill this down to questions about geomorphic and riparian conditions. The geomorphic conditions screen out whether you are working in a riverscape with a floodplain in which Stage 0 or Stage 8 may be appropriate targets (Chapter 1: Shahverdian et al., 2019a). The riparian conditions screen out whether woody vegetation was historically present and likely played a role in river form and function.

Key Low-Tech Questions and Considerations

There are two key questions, with regards to analysis of resources, for low-tech restoration we consider from two perspectives (Figure 3). Those key questions are:

- What are the current riverscape conditions?
- What is the recovery potential of the riverscape?

Since the primary strategy with low-tech process-based restoration of riverscapes is mimicking, promoting and eventually sustaining processes of wood accumulation and/or beaver dam activity, we must consider the above questions about current and potential conditions from the perspective of geomorphic conditions and riparian conditions. Therefore, we can cast these key questions from both a geomorphic and riparian perspective as:

1. Are my channel(s) and floodplain well-connected (geomorphology/hydrology)?
2. Is it likely that a self-sustaining source of woody structure can be restored (riparian and beaver ecology)?

Current & Potential Geomorphic Condition

The question of channel(s) – floodplain connectivity requires consideration of both the flow regime (hydrology) and geomorphic conditions. We recommend minimally answering the question of "are my channel(s) and floodplain well-connected" by first considering the hydrologic regime that drives geomorphic processes. Then geomorphic condition can be considered more easily based on the recognition that geomorphic conditions limit what is achievable with process-based restoration, and that the flow regime is what produces the stream power that can potentially do the work of driving geomorphic processes to restore and sustain a system.

Is Flow Regime Present to "Do the Work" of Restoration?

With the idea of "letting the system do the work" (Restoration Principle 7; Chapter 2: Wheaton et al., 2019), low-tech process-based restoration explicitly relies on high-flow stream power to do the work of restoration and recovery. Specifically, the high-flow stream power is what promotes and allows the geomorphic processes of erosion and deposition to reshape valley bottom topography into better conditions (Riverscapes Principle 2; Chapter 2: Wheaton et al., 2019). Thus, an understanding of the flow regime, including the size and frequency of peak flows, is critical. Where possible, use stream-flow gauge to perform flow frequency analysis (NRCS, 2007b). However, the vast majority of riverscapes and project areas are, and will remain ungauged. While it is possible to perform a hydrologic modeling analysis, this is typically overkill and will unnecessarily drive up planning costs. Much can be learned about the flow regime from reading the riverscape on-site and looking for clues of typical high-stage indicators and larger floods (Fryirs et al., 2012; Fryirs and Brierley, 2013).

Another reasonable way to assess the flow regime is to do a simple stream-flow estimate using regional curve data to assess the relationship between drainage area and flow statistics from flow frequency analyses at gaged sites (Ries et al., 2005). It is now possible to do this analysis for almost everywhere in the United States in a matter of minutes on the US Geological Surveys StreamStats web app (Ries et al., 2005). With StreamStats, the user simply selects the location on the drainage network (i.e. top of your reach) representing the outlet of the watershed, and can produce a variety of statistics including peak flow statistics. These peak flow statistics can provide a very reasonable crude approximation of the relative order of magnitude of 'geomorphic' work to be done. With some straight forward GIS work, the regional curves can be applied with local reach slope, and drainage area to estimate base flow, and various peak flow statistics (Figure 9).

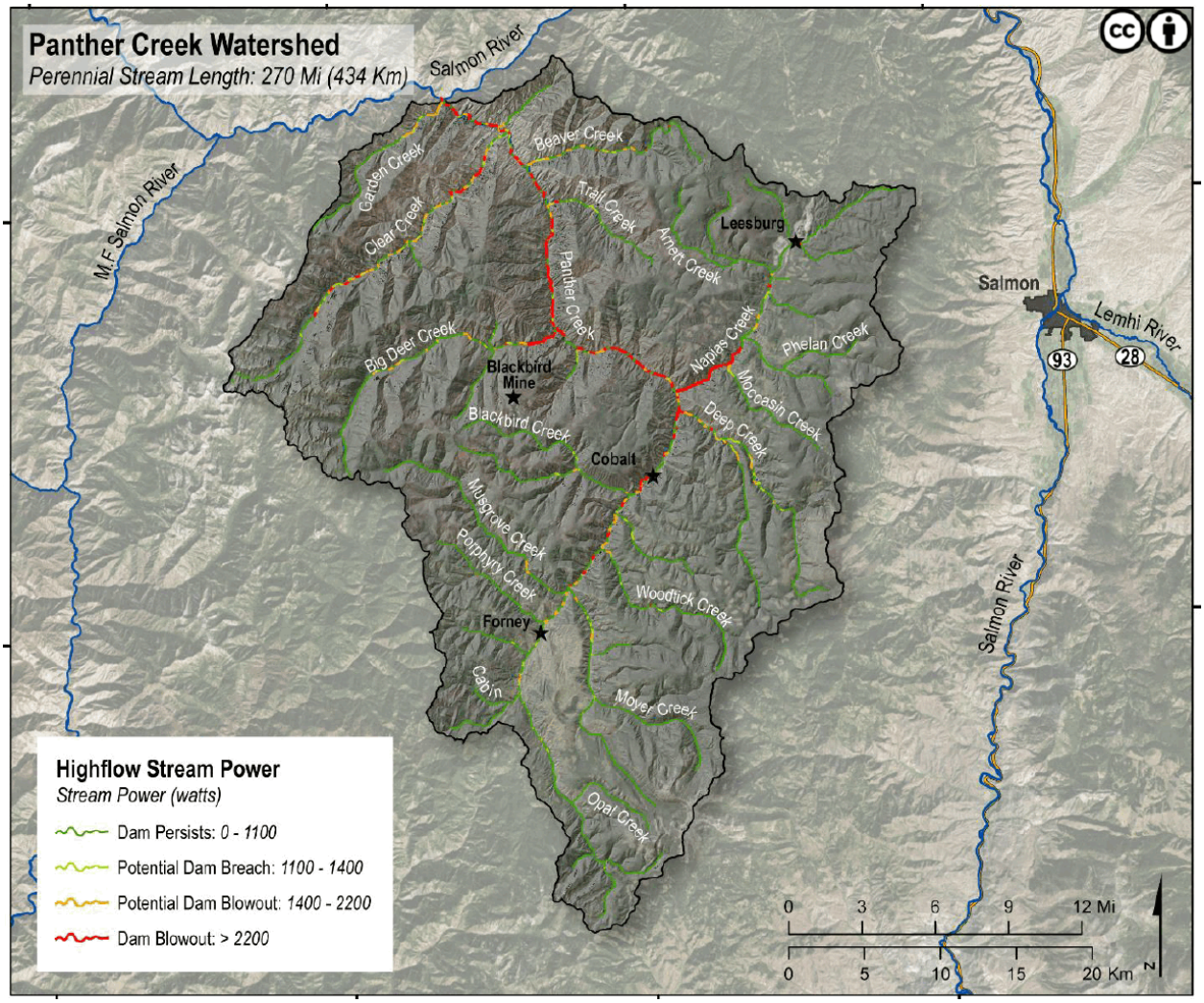


Figure 9 – Example of network scale estimate of flow regime (using here 2 year recurrence interval peak discharge to estimate stream power) to determine to what degree the flow regime is present or potentially excessive to "do the work". This example is a standard intermediate output of the BRAT (http://brat.riverscapes.xyz). Here the flow is multiplied by local reach slope, gravity and the density of water to estimate stream power, which is symbolized above in terms of likely impact on beaver dams (e.g. persisting, breaching or blowing out). Note that, breaches and blow outs accelerate the riverscapes evolution model (Figure 11) as outlined in (Pollock et al., 2014). Specific example here from Macfarlane (2019).

What is the Current and Potential Geomorphic Condition?

There are many methods for assessing current geomorphic conditions and forecasting recovery potential to estimate what conditions could be improved to with restoration. Regardless of the complexity of the assessment or analytical methods, a simple summary synthesis (e.g., into categories of good, moderate and poor as shown in Figure 10) is recommended. We refer readers to Brierley and Fryirs (2005) and the River Styles Framework for a rather thorough and well-established treatment of the subject. Both Beechie et al. (2012) and Skidmore et al. (2011) layout helpful principles for geomorphic assessment and review various methods. Ultimately, current and potential (i.e., historic) geomorphic conditions are mapped by reach, which can be done at individual reaches, or for all reaches in a network as in Figure 10.

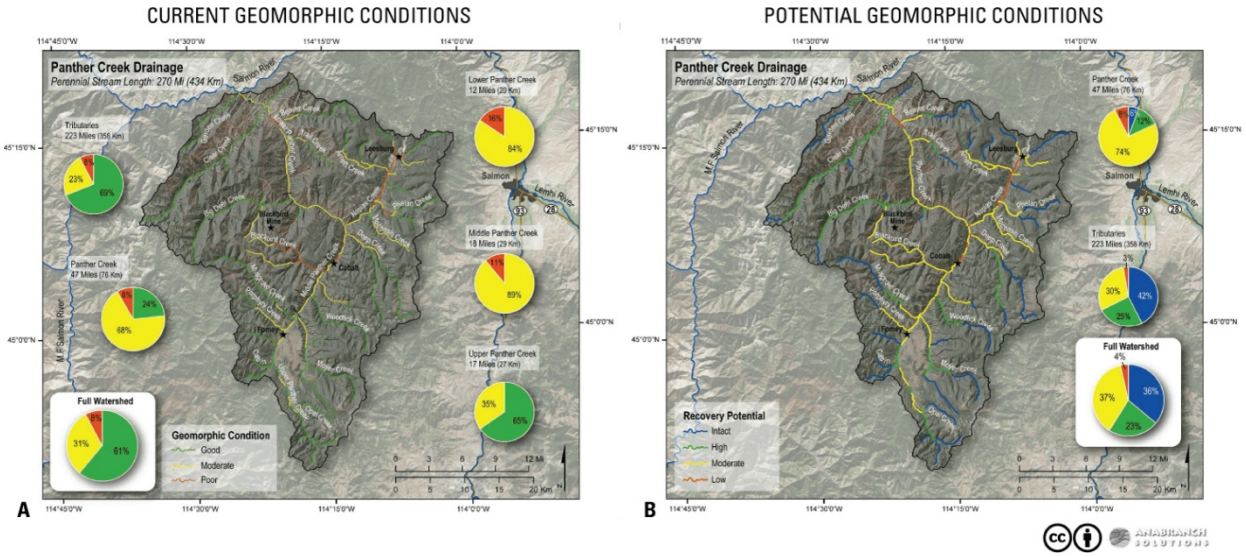
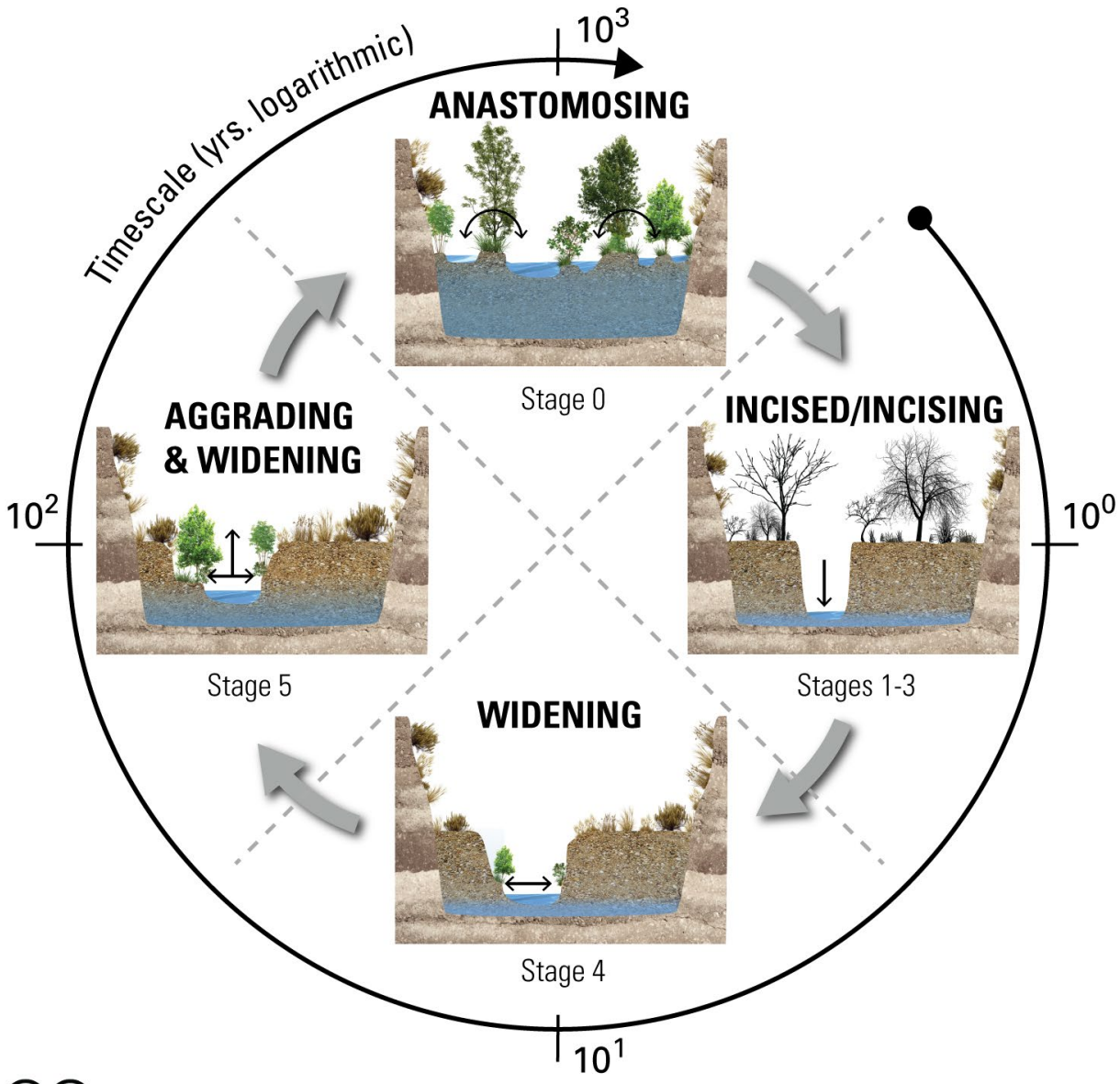


Figure 10 – Network-scale example maps contrasting current geomorphic conditions (A) with potential geomorphic conditions (B) given existing and anticipated anthropogenic and climatic constraints in the same watershed. Note, historic (pre-settlement) geomorphic conditions are assumed to have been good everywhere. Note that recovery potential does not equal historic conditions as they are not always an appropriate restoration goal. Example from (Hill et al., 2019b).

What Stage is the Stream in? - Stream Evolution & Stage Zero

One of the simpler ways to address the question of whether or not the channel(s) and floodplain are well-connected is to think about the stage the riverscape is in rather than specific condition of different riverscape components (Cluer and Thorne, 2013; Phillips and Van Dyke, 2017). For example, if your riverscape is not in anastomosing Stage 0 condition (i.e., fully connected valley bottom; see Figure 11 and Figure 7), it is likely that the channel and original floodplain are not well connected (Figure 2, Chapter 1: Shahverdian et al., 2019a). However, there are stages where inset floodplains develop (after erosion, channel widening, and building of inset floodplains via deposition) and riparian vegetation can re-establish (i.e., aggradation and widening Stage 5-8) and the current channel and newly-built inset floodplains are connected. These stages may be as far as restoration can move the riverscape towards Stage 0 because of constraints (social or physical; see Figure 7).



Nick Weber

Figure 11 – A simplified riverscapes evolution model based on Cluer and Thorne (2013), which identifies four broad categories of stages or states the riverscape can exist in (Chapter 1: Shahverdian et al., 2019a). These stages can be used as a geo-indicator for many riverscapes in a River Styles assessment of geomorphic condition Brierley and Fryirs (2005). They can also be treated as a proxy themselves to the overall question of geomorphic condition for many of the riverscapes prone to structural starvation. The incised stage, would correspond to a poor condition. The widening and aggrading/widening stages would correspond to a moderate condition. The anastomosing stage would correspond to a good condition.

Applying the simplified riverscapes evolution model of Figure 11 as a proxy for geomorphic condition at the reach-scale is a straight-forward way to communicate geomorphic conditions. Figure 12 shows an example of riverscape evolution model stage being applied at a small project scale over multiple reaches. In the maps (Figure 12A & C), the more nuanced Cluer and Thorne (2013) stages are shown to identify current conditions and potential conditions. However, Figure 12B shows the cross walk into a simpler assessment of geomorphic condition.

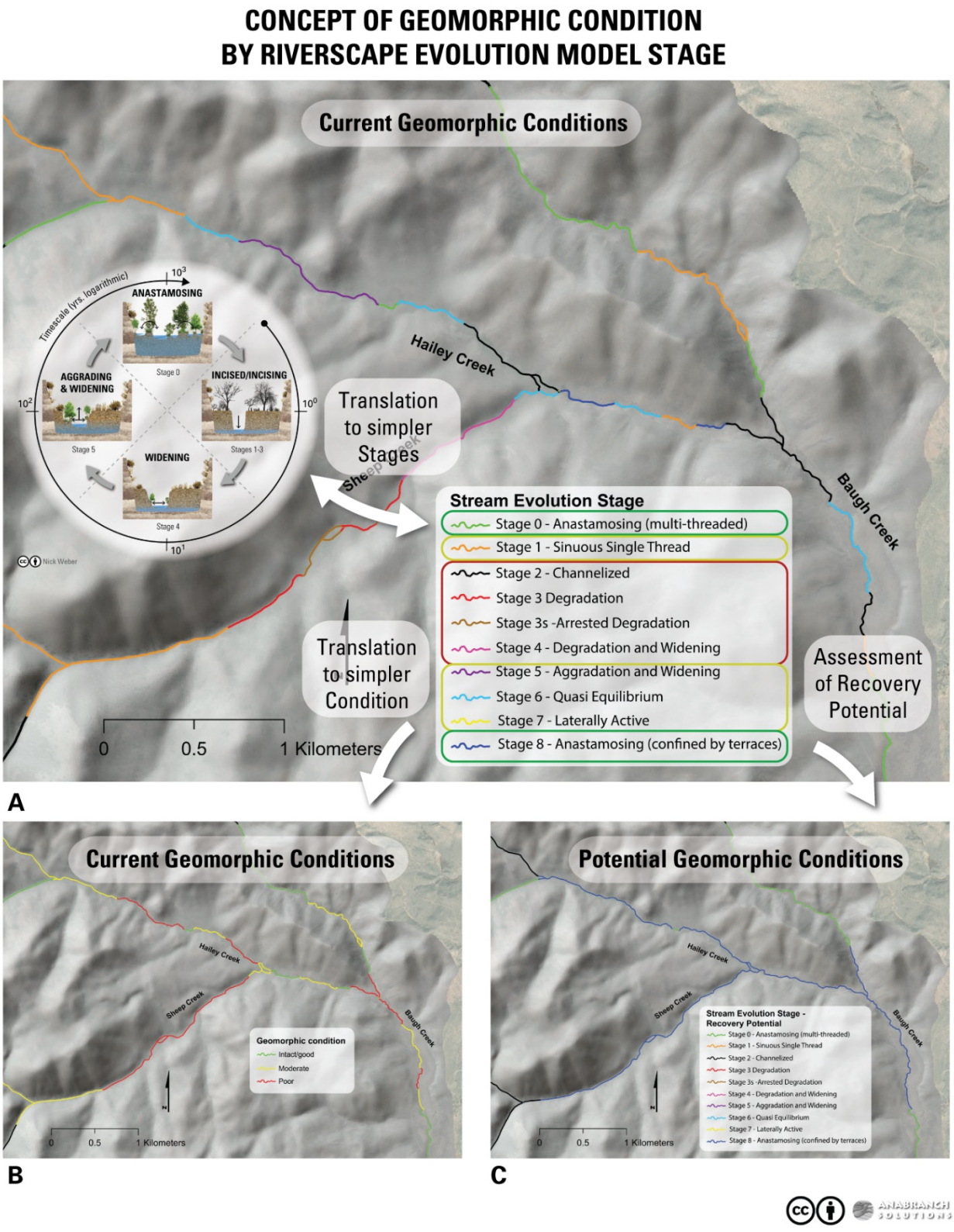


Figure 12 – Project-scale example of identifying geomorphic condition by using the Cluer and Thorne (2013) Stream Evolution Stage in A, and recovery potential in C (i.e., maximum obtainable stage with restoration and given anthropogenic constraints). The Stream Evolution Model stage can be simplified to the Riverscapes Evolution model stages (i.e. Figure 11), and both can be cast in terms of a simplified, stoplight categorization of conditions (i.e. good, moderate or poor as shown in B). This example is from a low-tech post-fire emergency project (Shahverdian et al., 2018).

Current & Potential Riparian Condition (Structure & Trees)

We look at riparian conditions to address the key question of "is it likely that a self-sustaining source of woody structure can be restored?" Generally, when a riverscape is not in Stage 0 then some loss of riparian habitat has taken place. This is sometimes due to either channel incision, which lowers the water table, and/or a loss of beaver dams/woody debris, which also lowers the water table and reduces the frequency of overbank flows leading to degraded riparian habitat. Other factors that could degrade riparian areas and limit the input of woody material include excess browse pressure (whether from livestock grazing or wildlife), agriculture, land use, infrastructure (e.g., levees, roads railways, etc.), or invasive vegetation.

Important considerations about riparian vegetation (note - upland vegetation that contributes to wood accumulation in riverscapes should be evaluated too):

- What is existing riparian vegetation in the valley bottom relative to historic conditions? – See Appendix 3E
- Can the riverscape and adjacent uplands support beaver dam activity? – See Appendix 3F
- How accessible is the floodplain for flooding and riparian vegetation recruitment (infrastructure / like levees)? – See Appendix 3E
- What land uses are taking place in the valley bottom and are they compatible with maintaining a self-sustaining source of structure? – See Appendix 3E

As with geomorphic condition, these questions can often be answered simply by walking a site and assessing wood resources and recruitment potential. Depending on the extent of the project, a field assessment could be done in anything from a few hours to several days and may cost as little as several hundred to a few thousand dollars per mile. The cost of walking a project area is largely determined by how long it takes for a professional to get to the site (i.e., travel time). However, when planning and developing conceptual restoration plans for large riverscapes or entire watersheds, walking the entire project area is not always practical or feasible. For broader-scale assessments, some type of network models using readily available (and preferably continuous) geographic information system (GIS) data are necessary. Using GIS, such assessments can be run over very large areas, which can substantially reduce the cost per mile of conducting the assessment. If freely available data is available (e.g., digital elevation models, vegetation cover mapping, aerial imagery – all of which exist for the entire US), the costs of desktop assessments can be as little as $0.50 to $20.00 per mile when applied to large regions (e.g., > 1000 miles of riverscapes). Costs for GIS assessments are driven by the need for trained staff, acquisition and management of GIS data. These costs can easily go up to $100 to $500 /mile if manual digitization, input refinement and/or field visits to calibrate and improve model results. In some cases this may be important, in other cases, these refinements can be made by returning to the same questions when specific locations and sites are visited for more detailed project planning and/or design (Chapter 5: Shahverdian et al., 2019b). We provide links to some GIS tools specifically developed to assess extent of the valley bottom, riparian vegetation conditions, and capacity of the riverscape to support beaver dam activity in Appendices 3D, 3E and 3F respectively.

PHASE 2: DECISION SUPPORT & DESIGN

The decision support phase of the Conservation Planning Process is about taking the information developed in Phase 1, and using that to inform and constrain the development of specific design alternatives and treatments, evaluating those different alternatives, and then deciding what specific treatment to pursue in Phase 3. Outside the Conservation Planning Process, many simply refer to this phase as the design phase. Since low-tech restoration is often iterative, it is important to determine how many treatments might be necessary to achieve overall project goals (Chapter 5: Shahverdian et al., 2019b). For example, if the project goals are set in terms of a proportion of the valley bottom to push towards anastomosing (Figure 7), there are some situations where one treatment might push the system all the way to that end goal. There are many others, where it might take multiple treatments, with significant gains and improvements being realized along the way.

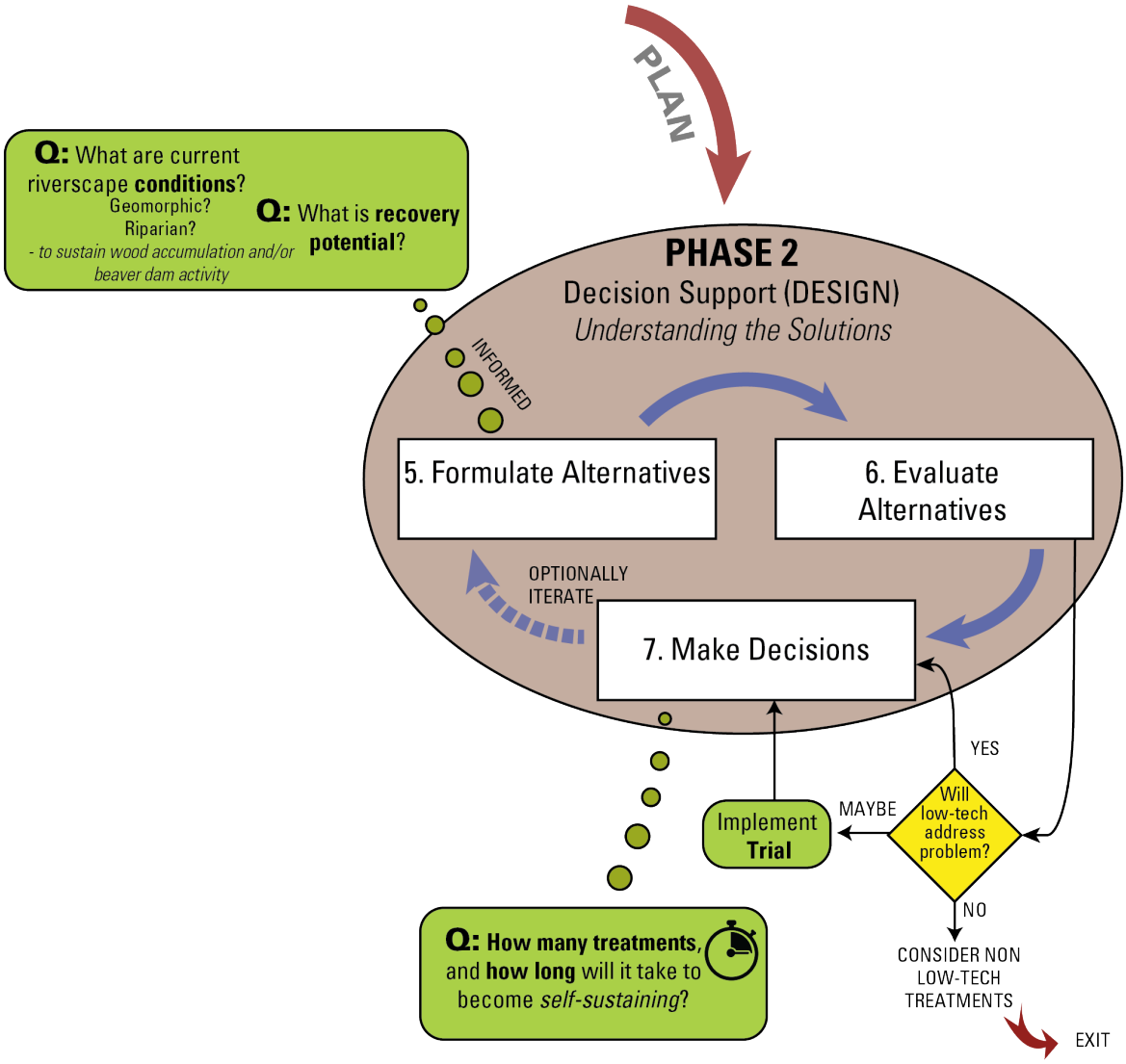


Figure 13 - Phase 2 of the Conservation Planning Process adapted for low-tech. Critical questions and processes to consider specifically for low-tech restoration are shown in green, and two key decisions (yellow diamonds), with potential exit points from continuing with low-tech restoration are shown.

Steps 5 & 6. Formulate & Evaluate Alternatives (Design)

In Chapter 5 (Shahverdian et al., 2019b), we more exhaustively cover the topic of low-tech restoration design. Therein, we specifically define what constitutes a minimum viable product for a low-tech restoration design and describe the key components and considerations in the design process. We define designs as the set of specifications of what structure to place where and how it is intended to contribute to achieving the desired project goals via a specific set of design objectives for one treatment (e.g., meal to a structurally-starved system). There are some instances where one treatment is enough to achieve overarching project goals through mimicking and promoting the desired processes of wood accumulation and/or beaver dam activity and those processes are initiated so quickly and extensively that they become self-sustaining. However, in most instances, multiple treatments, and therefore designs (or phases of design) are required to achieve the ultimate self-sustaining goal (Restoration Principle 10; Chapter 2: Wheaton et al., 2019).

Key Low-Tech Questions and Considerations

What kind of low-tech appropriate? If the assessment (Steps 3 & 4) confirmed that structural-starvation is the main impairment, then it is important to determine if beaver dam analogues and post-assisted log structures are an appropriate restoration action. There is a general progression from management strategies to direct intervention and installation of structure. Current riverscape management should be evaluated before considering installing structures. Riverscapes may be structurally-starved because riparian management does not support growth of woody vegetation. Implementing riparian buffers, restricting or improving use (e.g. actively managed grazing, harvesting, development), or planting woody vegetation could be used to promote wood accumulation in riverscapes. Changes in riparian management may also allow beavers to recolonize areas and build dams where currently there is insufficient woody vegetation (Kozlowski et al., 2016).

Changing beaver management could also be highly effective at restoring structure to riverscapes. Beaver management may be another alternative to address structural starvation. Beaver may be unable to recolonize an area or may be being trapped at levels that do not permit consistent and expansive dam building. Changes in trapping practices or utilizing "living with beaver" methods could allow cost-effective expansion of beaver and dam building activity (Pollock et al., 2017; UDWR, 2017). Another cost-effective management action is the relocation of beaver. Beaver relocation programs have been implemented for decades in almost every state and some started not long after intensive trapping ended in the late 1800's (Goldfarb, 2018; McKinstry and Anderson, 2002). Relocation programs have the added advantage that they often use nuisance beaver that would otherwise be lethal trapped. Relocated beavers are highly susceptible to predation and there is some evidence that releasing beavers into existing ponds or ponds created using beaver-dam analogues to create ponds may help decrease predation and increase the chances of successful relocation.

The addition of structure should be considered if management alternatives are deemed not feasible, or both management alternatives and addition of structure are required (i.e., relocating beaver into ponds created by BDAs). Structure can be efficiently added to riverscapes by directly falling and/or hoisting wood and trees. This can be done without using posts to secure the wood but requires special conditions where abundant trees are available and/or the risk to infrastructure is low (Carah et al., 2014). If these alternatives are not appropriate, installation of BDAs or PALS may be cost-effective option for adding structure. See Chapter 4 for individual BDA and PALS designs (Shahverdian et al., 2019c), Chapter 5 (Shahverdian et al., 2019b) for details on complex design (groups of structures), and Chapter 6 (Bennett et al., 2019) for general construction and implementation details.

Step 7. Make Decisions

Intent and Rationale

In this step, stakeholders (i.e., landowners, agencies, public) review the proposed design and decide whether to proceed. Sometimes, if multiple design alternatives are provided, this involves a choice between those design alternatives. In some projects, there may be a recognition that multiple phases will be required to reach the restoration goals. In other instances, it may be a matter of setting priorities to apply limited resources and choosing which treatments to tackle first. Restoration planning can often include using frameworks to decide how to prioritize where to implement restoration and what restoration actions to use (Roni et al., 2002). It is beyond the scope of this manual to review prioritization frameworks; however, there are some simple considerations for choosing specific locations for low-tech projects. When possible select project areas: where there are few constraints (low risk settings), with more of the valley bottom readily accessible, and upstream or downstream of existing good condition reaches to expand refugia/propagate benefits downstream (i.e., expand ecological effectiveness). It may be possible to eliminate the source of impairment or change management strategies in conjunction with (or as an alternative to) low-tech restoration (e.g., alter timing of grazing, treat invasive plants, or restore flows). If structural-starvation is determined to be the primary limiting factor, then beaver dam analogues (BDAs) and post-assisted log structures (PALS) may be appropriate restoration actions to implement. There are many other types of low-tech restoration actions that can also be used

including beaver management, beaver relocation, felling trees, erosion control, intensive grazing management, mechanically assisted wood additions (see Chapter 6 for brief overview: Bennett et al., 2019).

Key Low-Tech Questions and Considerations

Will Proposed Low-Tech Restoration Address Problem?

It is always useful to revisit the basic question and re-evaluate whether or not the proposed alternatives and treatments with low-tech restoration are actually likely to address the problem. This critical re-evaluation can provide an important exit point (Figure 13), but may also reassure the project team about the course of action. If there is disagreement about the next steps, a smaller-scale trial implementation is an easy, affordable and typically reversible adaptive management strategy to learn from.

Is there enough uncertainty to justify implementing a trial

There may be uncertainty in the historic role of wood or beavers in the project area, it may be unclear from the assessment what the precise cause of impairment is, and/or stakeholders may not be sure what restoration actions are appropriate. These uncertainties can often be partially or fully addressed by implementing a trial project to test the effectiveness and feasibility of low-tech restoration. For example, the assessment results (Step 3 & 4) may have determined that riverscape is structurally-starved but there is uncertainty about whether PALS can sustain flashy high flows common to the project area. A trial project can be used to test this uncertainty (Bouwes et al., 2016). A trial project consists of a small number of structures (10s to 100s) used learn about your restoration site to make a full-scale implementation more efficient and effective. Trials can also be used to answer a number of questions before full implementation such as: “Are channel-spanning structures, such as beaver dam analogues likely to breach?”, “Does the stream need to widen before aggrading?”, as well as logistic questions such as, “Is there sufficient on-site woody material to complete the project?” or “Does site access limit the use of particular equipment such as a hydraulic post pounder?”

Low-tech restoration can minimize chance of damage by avoiding high risk areas in the selection of project sites, by using trials before full implementation, by the nature of the actions themselves (i.e., hand-built structures, low site impacts), and by using adaptive management to implement projects (Bouwes et al., 2016). Low-tech structures can also be removed or dismantled if they cause damage more easily than large highly engineered structures. See more detail below in the Low-tech Adaptive Management and a NRCS risk matrix in (Appendix 3D).

PHASE 3 – APPLICATION & EVALUATION

The application and evaluation phase is about doing the restoration project and evaluating it (Figure 14). The implementation part consists both of consultation and potentially acquiring permits from regulatory agencies and construction. Implementation is detailed in Chapter 6 (Bennett et al., 2019).

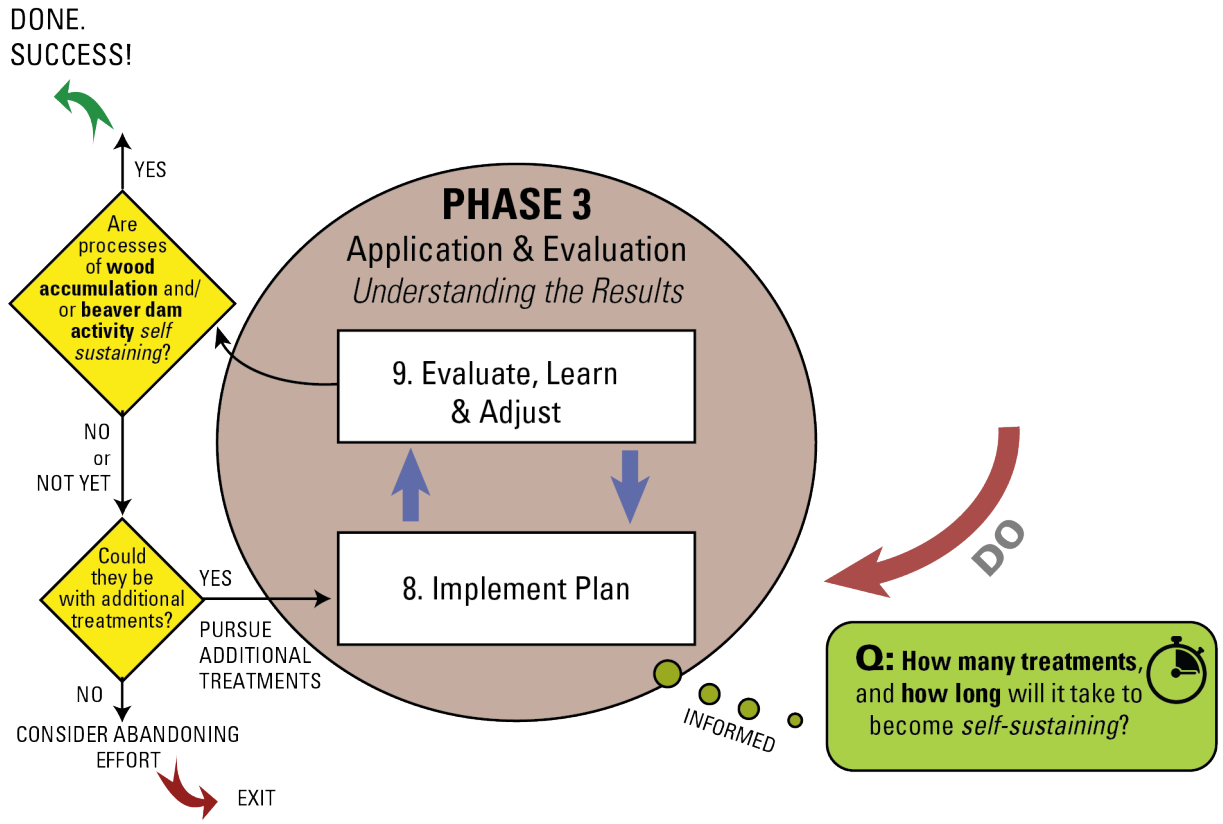


Figure 14 - The Phase 3 of the Conservation Planning Process adapted for low-tech. Critical questions and processes to consider specifically for low-tech restoration are shown in green, and two key decisions (yellow diamonds), with potential exit points from continuing with low-tech restoration are shown.

Step 8. Implement the Plan

In this step, the treatment(s) are installed. We detail the logistics of low-tech restoration implementation in Chapter 6 (Bennett et al., 2019). An underlying goal of most low-tech restoration implementation is to build a high density of structures over a large area as efficiently as possible. This requires focusing on the logistics of material acquisition, transportation, and installation.

Step 9. Evaluate, Learn and Adjust

Intent and Rationale

In this step, the project is evaluated in either an informal (site visit) or more formal (adaptive management) approach. The goal of the evaluation is to determine if progress towards project goals have been made, if adjustments are required in the restoration or monitoring designs, if maintenance of the existing treatment(s) are required, and/or if additional treatments are necessary. The evaluation phase is an opportunity to learn about the effectiveness of the restoration treatment and how the riverscape reacted to the addition of structure. The specific things to be evaluated and the frequency of evaluations will depend on each project's goals and objectives, but commonly include:

- Was the right problem identified?
- Is restoration achieving the predicted responses (e.g., hydraulic, geomorphic, riparian)?
- Is the restoration producing unexpected responses (i.e., learning)?
- Is restoration causing harm (damage to infrastructure, or harm to riverscape function)?
- Was the monitoring intensity appropriate?
- Were the appropriate attributes monitored?
- Has the riverscape reached a self-sustaining condition?

Most critical amongst these is whether or not the riverscape has reached a self-sustaining stage, while the overall project goals have also been met (Figure 14).

Key Questions and Considerations

Are the processes of wood accumulation and/or beaver dam activity self-sustaining?

In the context of low-tech process-based restoration of structurally riverscapes, the ultimate goal is for the processes of wood accumulation and/or beaver dam activity to be self-sustaining (see Restoration Principle 10, Chapter 2: Wheaton et al., 2019). As such, the most fundamental question is what constitutes these processes being self-sustaining. Conceptually, if treatments reflect actions that mimic these desired processes immediately and maybe promote them in the short to medium term, then it is when we see evidence that these processes are occurring naturally and at rates that will naturally vary, but seem sustainable through time. This is, admittedly, not a precise target. However, this question does not have to be treated with absolute finality, but instead an assessment based on the best available information at that time. For example, just because a doctor gives a patient a diagnosis that they are healthy, does not imply that they will be health forever. If anything changes in the future, the question can be revisited, and if an area is actively managed through time for conservation purposes, this is one of the questions that can be periodically revisited.

In practical terms, the question of self-sustaining processes really translates to whether or not more treatments are deemed necessary to help it towards this goal. For most projects, practitioners should expect to conduct additional treatments on their low-tech projects, but consider themselves lucky if only one treatment proves necessary. Most often, these subsequent treatments are much smaller than the initial treatment, and do not require adjustments to Phase 1 or Phase 2 of the Conservation Planning Process. However, if evaluation reveals that there were shortcomings in the assessments of Phase 1 or design of Phase 2, adaptive management adjustments can easily be made. The question of whether or not additional treatments could push the system towards a self-sustaining state, is a critical evaluation point. Structural elements have been systematically and thoroughly removed from virtually every watershed through either direct means and/or via degradation and disruption of the transport (i.e., residence time has decreased) and delivery (i.e., delivery rate has decreased) of woody debris to riverscapes. Therefore, many riverscapes have a deficit of woody debris that will not be restored with one restoration treatment.

Once the project has been evaluated, and determined that more treatments may help push it towards a self-sustaining state, it is necessary to decide how much, where, and by what methods. This can involve an explicit return to Phase 2 and a new design. It can also often be achieved with a simple field design. More structures can be built and expanded as needed, but in the case of a large footprint treatment, simply adding more structure as unsecured

wood in subsequent treatment may be feasible. In other words, once the system has enough roughness present, those roughness elements can act like Velcro to promote more natural wood accumulations and so the focus can shift to mimicking the process of wood recruitment. Common maintenance activities for PALS include (Figure 15 and Figure 16):

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

Common maintenance activities for BDAs are things mimicking maintenance that active beaver would otherwise do, and may include (Figure 17 and Figure 18):

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

Figure 15 - Maintenance in a high-density large woody debris treatment section where alder trees were directly felled into the riverscape amongst existing post-assisted log structures.

Figure 16 - Example of using a grip hoist to pull in wood into the riverscape (i.e. mimicking process of wood recruitment) to enhance or create a new wood accumulation (structure) in treatment sections as part of ongoing treatments until the processes of wood recruitment and wood accumulation are self-sustaining..

Figure 17 –Example of a beaver dam analogue (BDA) that needs maintenance if the goal is to build a large pond upstream of the structure. The BDA has been partially breached in the center and would need more posts and wood material to function fully. Note this BDA could also use a better mattress on the downstream side of the BDA to reduce the potential for water undercutting the structure.

Figure 18 –Example of a beaver dam analogue (BDA) that could have some maintenance to plug it back up. Most of the original ponded area from the BDA has been buried by sediment and there are only the top of the posts left visible. As shown in Figure 19, this would be the point at which the functional lifespan of the structure is over, the process of beaver dam activity is not yet self-sustaining, but it is deemed it could be with additional treatments. This is a good demonstration of how restoration can be staged – by adding more woody material to this structure the system would continue to aggrade and may force more floodplain connection, which may attract and make it easier for beaver to take over the process.

Follow-up or subsequent treatments on low-tech restoration projects does not need to be a costly or require a huge time and labor commitment. Maintenance of low-tech projects is relatively simple once a large treatment has been installed with significant opportunities to reduce costs and achieve multiple objectives for the riverscapes restoration community, other natural resource management communities, and local economies and community groups. First, a smaller crew can be used to strategically add more wood to only structures and locations that require more structure. This can be extremely easy to accomplish if there are trees in the riparian zone that can be harvested (Carah et al., 2014). Harvesting trees from some riparian sites may be an appropriate action if i) there are abundant trees in the riparian (i.e., shading and other riparian objectives are already realized) and ii) if riparian vegetation is restricting lateral migration of the channel (i.e., highly degraded riverscapes can become locked in place when dense riparian vegetation stabilizes the banks to the point where the stream cannot create natural meanders via bank erosion). Second, as noted in Chapter 6 (Bennett et al., 2019), riverscape restoration can be combined with rangeland and forest restoration by coordinating forest thinning and juniper removal (or other activities focused on removing upland vegetation that is encroaching on rangelands) and using the material for adding structure to riverscapes.

Low-Tech Adaptive Management

We provide an example of questions to ask to evaluate the performance of a complexes in Figure 19 and individual restoration structures in Appendix G (see also Chapter 5: Shahverdian et al., 2019c). By going through a systematic evaluation of specific aspects of the project and predefining triggers that will lead to adjustments – managers avoid ad-hoc changes to projects.

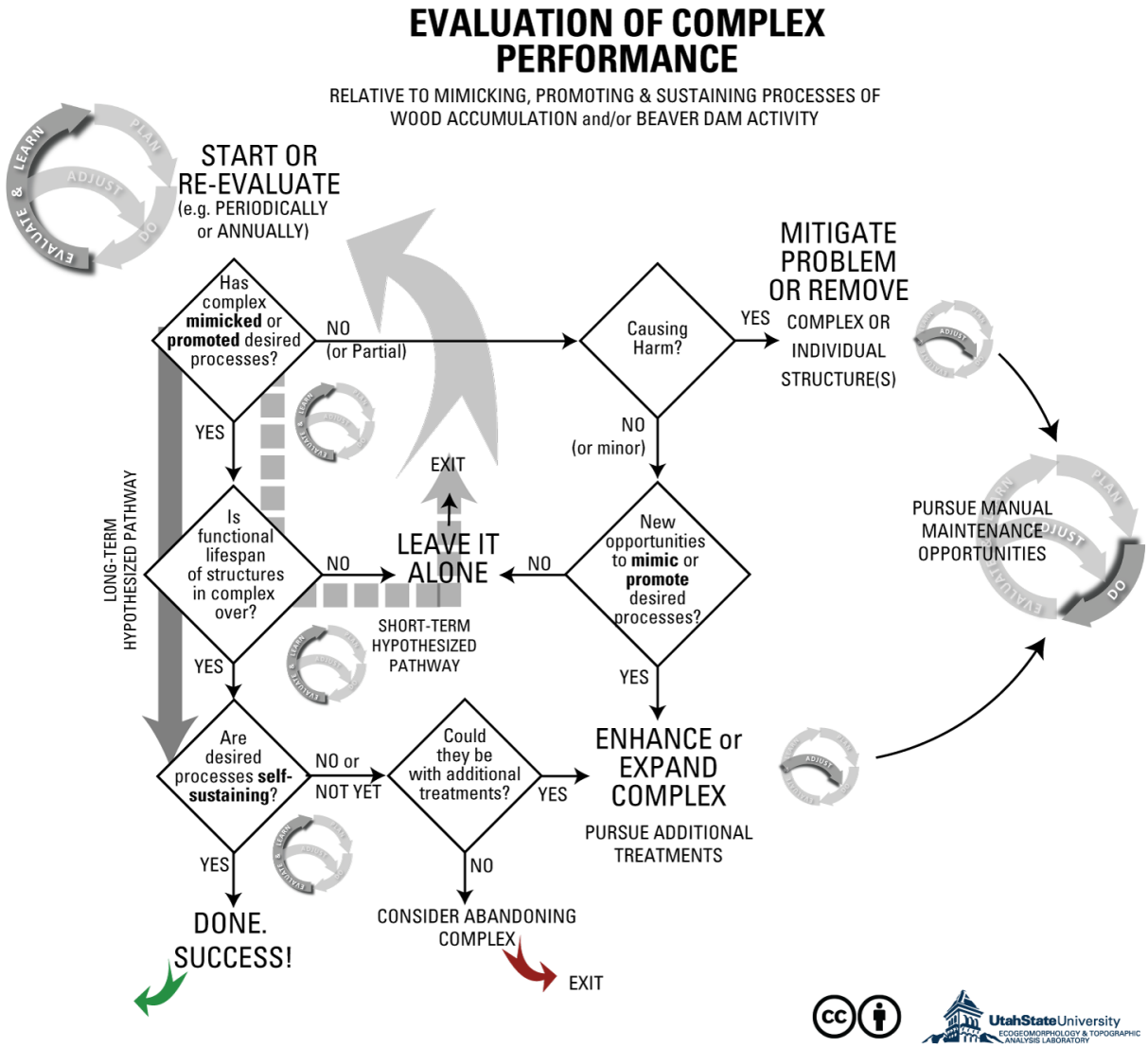


Figure 19- Detailed adaptive monitoring and maintenance for evaluation of high density large woody debris ($_{HD}$LWD) complexes. The primary long-term hypothesized pathway results in the achievement of a desired new dynamic stable state where more complex habitat is maintained by enhanced large woody debris recruitment processes.

SUMMARY – LOW-TECH EXTENSION OF CONSERVATION PLANNING PROCESS

In this chapter we took a typical restoration project planning process (embodied in the Conservation Planning Process of Figure 1) and elaborated what specific considerations are specific to low-tech process-based restoration. In each of the phases we introduced some screening questions to define explicit exit strategies from pursuing a low-tech restoration approach if your system is a) not structurally-starved, b) opportunities don't outweigh risks, c) problems not likely to be addressed by low-tech treatments, and or d) if low-tech is not proving to be a self-sustaining solution. However, beyond that we try to identify the key questions about the space for low-tech to work in the valley bottom, the current conditions, likely achievable conditions and how long it might take to achieve a self-sustaining solution. These questions are rooted in the principles of Chapter 2 (Wheaton et al., 2019), and critical to informing the design process of Chapter 5 (Shahverdian et al., 2019b).

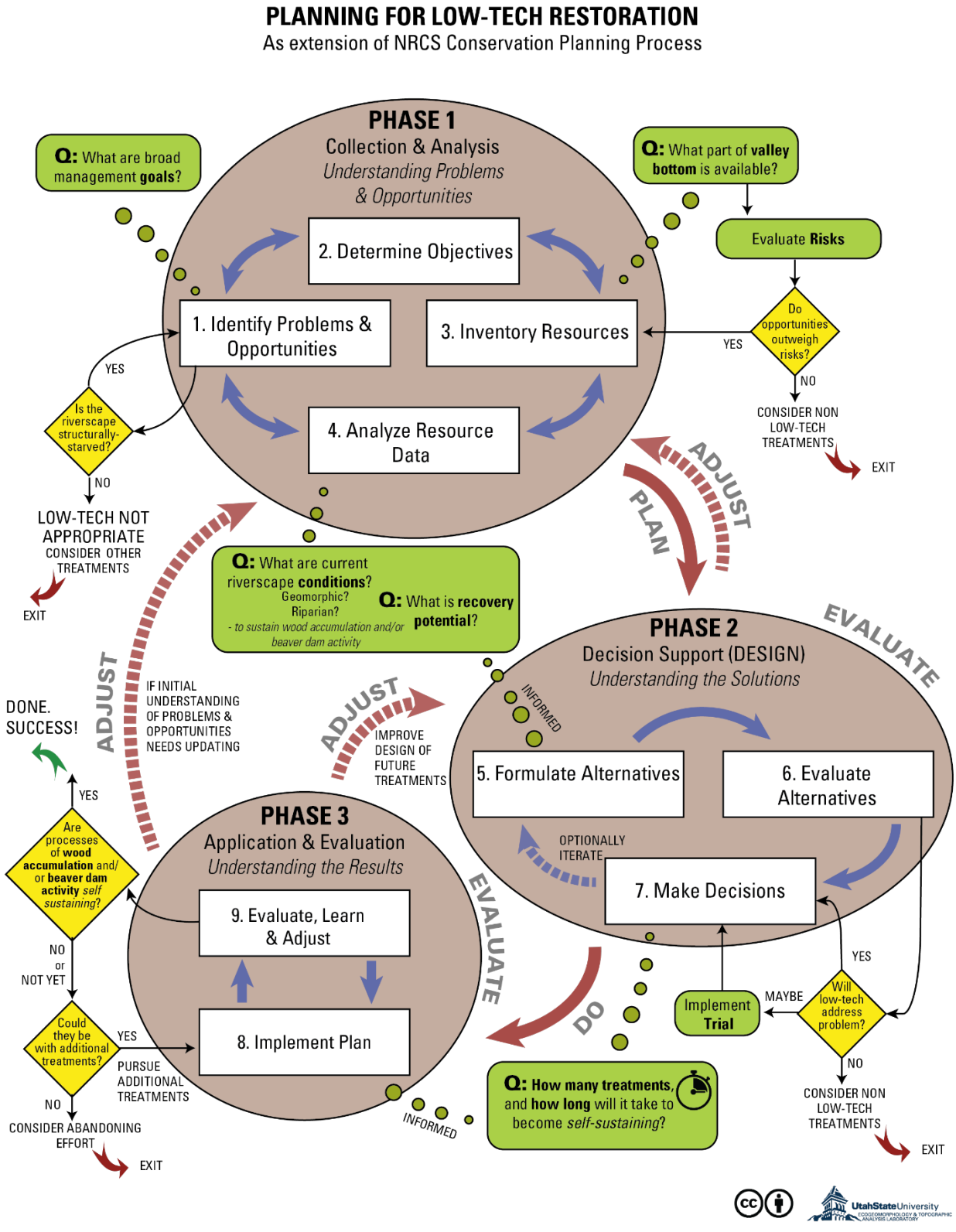


Figure 20 – Synthesis of Planning for Low-Tech Restoration – shown here as an adaptation of the NRCS Conservation Planning Process (Figure 1). Questions and considerations specific to low-tech restoration are shown in green, with critical decision points shown in yellow diamonds.

Chapter 3 – APPENDICES

APPENDIX 3A – PARALLELS BETWEEN DIFFERENT PLANNING FRAMEWORKS FOR RESTORATION

Table 2 - Nine planning steps, associated planning concepts, and adaptive management steps for planning, implementing, monitoring and evaluating a restoration project adapted from NRCS (2007a), Yochum (2016), Skidmore et al. (2011), and Bouwes et al. (2016).

NRCS Conservation Planning Process Steps	Planning Concept(s)	Adaptive Management Step and Actions	Riverscape Design Manual Chapter
1. Identify Overall Management Goals, Problems & Opportunities	- Identify the management goals and setting - Identify causes of impairment and related processes - Look upstream and downstream and where possible address watershed issues before reach scale issues - Don't assume the riverscape needs to be fixed – erosion and channel migration are natural	**Plan** - Identify management goals and problem	Chapter 1, 2, 3
2. Determine Initial Objectives	- Identify causes of impairment and related processes	**Plan** -Develop initial objectives	Chapter 1, 2, 3
3 & 4. Inventory and Analyze Resources (aka Assessments)	- Synthesis of previous assessments and planning efforts - Embrace uncertainty due to natural variability as an asset	**Plan** - Review past assessments - Develop conceptual models of riverscape function	Chapter 3
5 & 6. Formulate and Evaluate Alternatives	- Question constraints and remove rather than introduce new constraints - Evaluate alternative restoration strategies	**Plan** - Determine and evaluate restoration actions - Implement a trail to test conceptual models	Chapter 3,
7. Make Decisions & Select Restoration Action	- Design for resilient projects to protect restoration investment in the future.	**Plan** - Develop monitoring plan, benchmarks (triggers) for implementing maintenance and addressing risk	Chapter 3, 6
8. Implement the Plan	- Maximize natural processes – restore rather than constrain natural riverscape processes - Do no lasting harm during restoration	**Do** - Implement monitoring plan (including pre-project data) - Implement low-tech process-based restoration	Chapter 4, 5, 6
9. Evaluate the Plan	- Follow up and learn - Adjust to if necessary increase efficiency of future projects	**Evaluate, Learn, Adjust** - Evaluate monitoring data, update conceptual models and monitoring plan if necessary, and initiate maintenance as needed	Chapter 6

Restoration & Conservation Prioritization

There are numerous frameworks for prioritization that span the spectrum from quantitative structured decision making (also known as multi-criteria decision analysis) to decisions made entirely on the basis of stakeholder or decision maker judgement relative to management priorities. No single approach is uniformly better than another, but approaches vary in the degree to which the decision are transparently arrived at on the basis of specific evidence, versus more implicitly made. Regardless of the process, the important thing in a prioritization is that a conscious decision is made as to how specific reaches are ranked. In Figure 21, reaches throughout a 270-mile drainage network are individually prioritized. Such a ranking helps prioritize how limited resources of time (i.e., order) and money might be allocated to restoration of specific reaches.

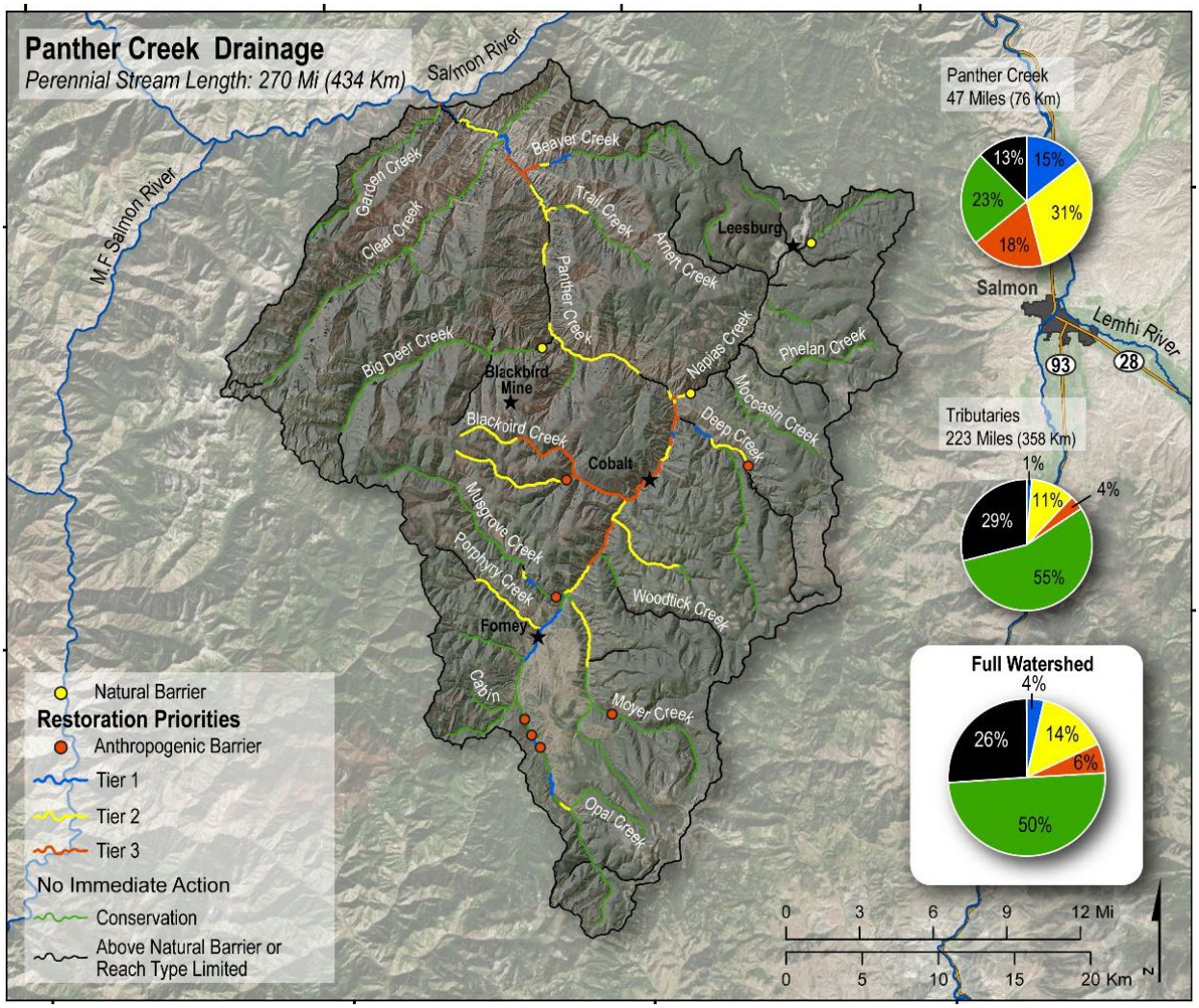


Figure 21 – Example of a watershed prioritization of restoration opportunities and mapping of conservation reaches. Example from: Hill et al. (2019a).

Potential Restoration Activities

Independent from the prioritization of specific restoration priorities, it is helpful to map where (on a reach-by-reach basis) specific restoration actions are feasible. Often times, low-tech restoration actions (e.g., mimicking and promoting beaver dam activity or wood accumulation) is most successful when combined with other management activities (e.g., grazing management of riparian areas, land use restrictions) and/or discrete, traditional restoration actions (e.g., mechanical removal of migration barriers and or levees).

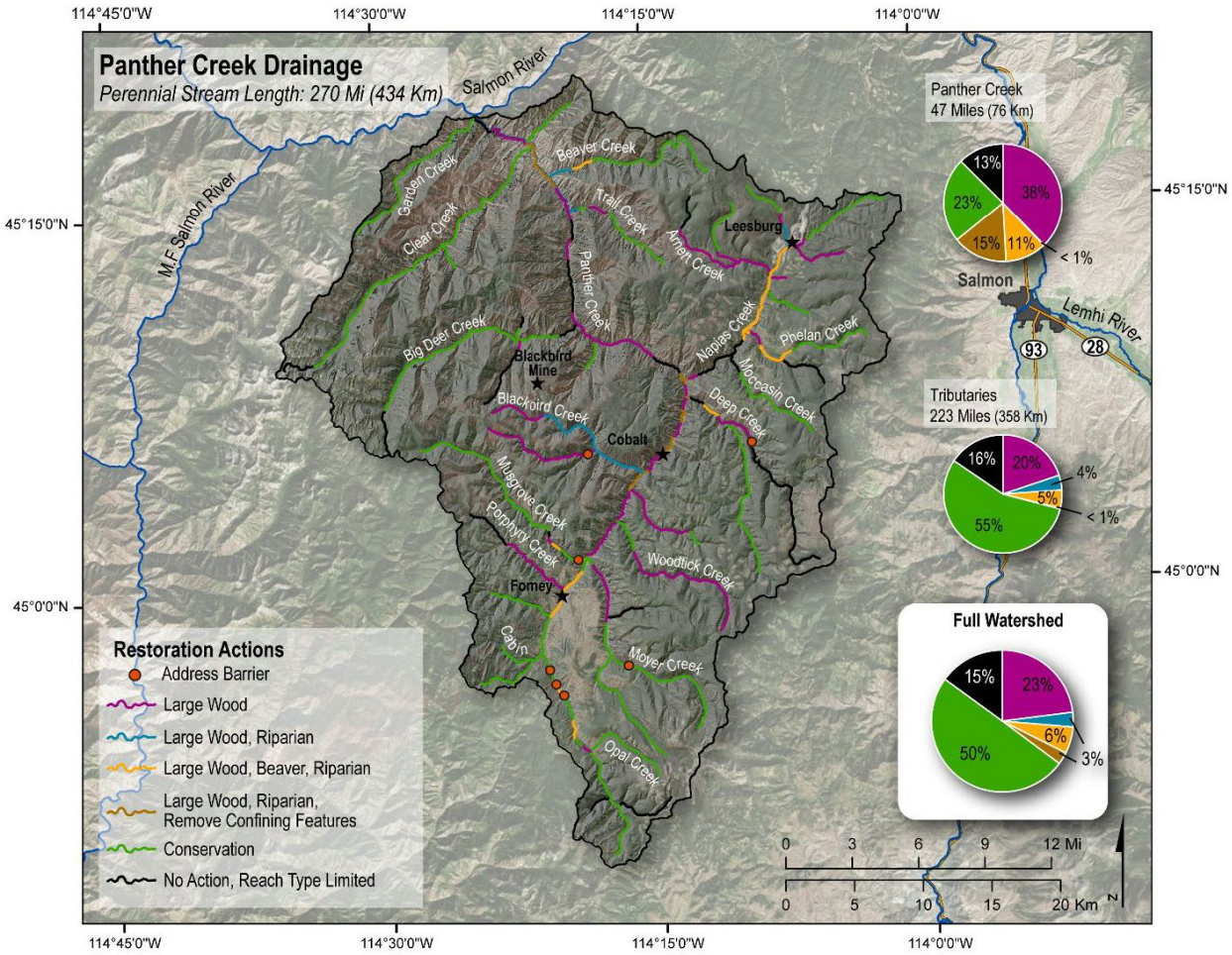


Figure 22 - An example of mapping the potential feasibility of specific types of restoration actions including low-tech treatments (i.e., mimicking and promoting wood accumulation and beaver dam activity). Example from: Hill et al. (2019a).

APPENDIX 3C: MAPPING VALLEY BOTTOM FOR ASSESSING SPACE

There are many methods to map valley bottoms. The most important things to remember are:

- The valley bottom includes the channel(s) and floodplain(s).
- The valley bottom can be considered the area that could plausibly flood in the contemporary flow regime, and may include areas that in current conditions (e.g., incision) are not likely to flood, but could again flood if recovered or restored to a better condition.
- Floodplain(s) may be differentiated between accessible and inaccessible areas. Inaccessible could still plausibly flood, but is not easily or practically accessible because of its stage. These inaccessible floodplains are not terraces, which are former valley bottoms that can no longer flood in the contemporary flow regime.
- The lateral extent of the valley bottom is used to set plausible limits on what is possible (e.g., maximum riparian extent, maximum extent of flooding, areas that could be impacted). Its precise boundaries do not need to be perfectly mapped, but rather approximately located to help estimate magnitude (e.g., of area) of opportunities and identify potential and real risks.

Valley Bottom Delineation with Valley Bottom Extraction Tool (VBET)

Correctly delineating the valley bottom and interpreting the valley-setting is critical to interpreting river character and behavior for a watershed assessment. By definition, a valley bottom is comprised of the stream or river channels and the associated low-lying, contemporary floodplain and represents the maximum possible riparian extent. If a network-scale assessment is being done, a geoprocessing algorithm to approximately map valley bottoms across broad network extents is necessary. One such tool is the Valley Bottom Extraction Tool (VBET: http://rcat.riverscapes.xyz). VBET uses geospatial data representing elevation and the stream network to create a valley bottom polygon (Gilbert et al., 2016) (Figure 23). The inputs are topography (e.g., a digital elevation model (DEM) and a drainage network. The tool can produce reasonable approximations of valley bottoms even with freely available national datasets like the 10 m resolution NED DEM (national elevation data digital elevation model), and the NHD (national hydrography dataset) of a drainage network. The tool produces a valley bottom polygon is used as an extent for the riparian condition analyses in the other R-CAT tools. The polygon can be manually edited to improve accuracy if important. While more precise mapping can be achieved with higher resolution inputs, a reasonable approximation can be produced over large areas.

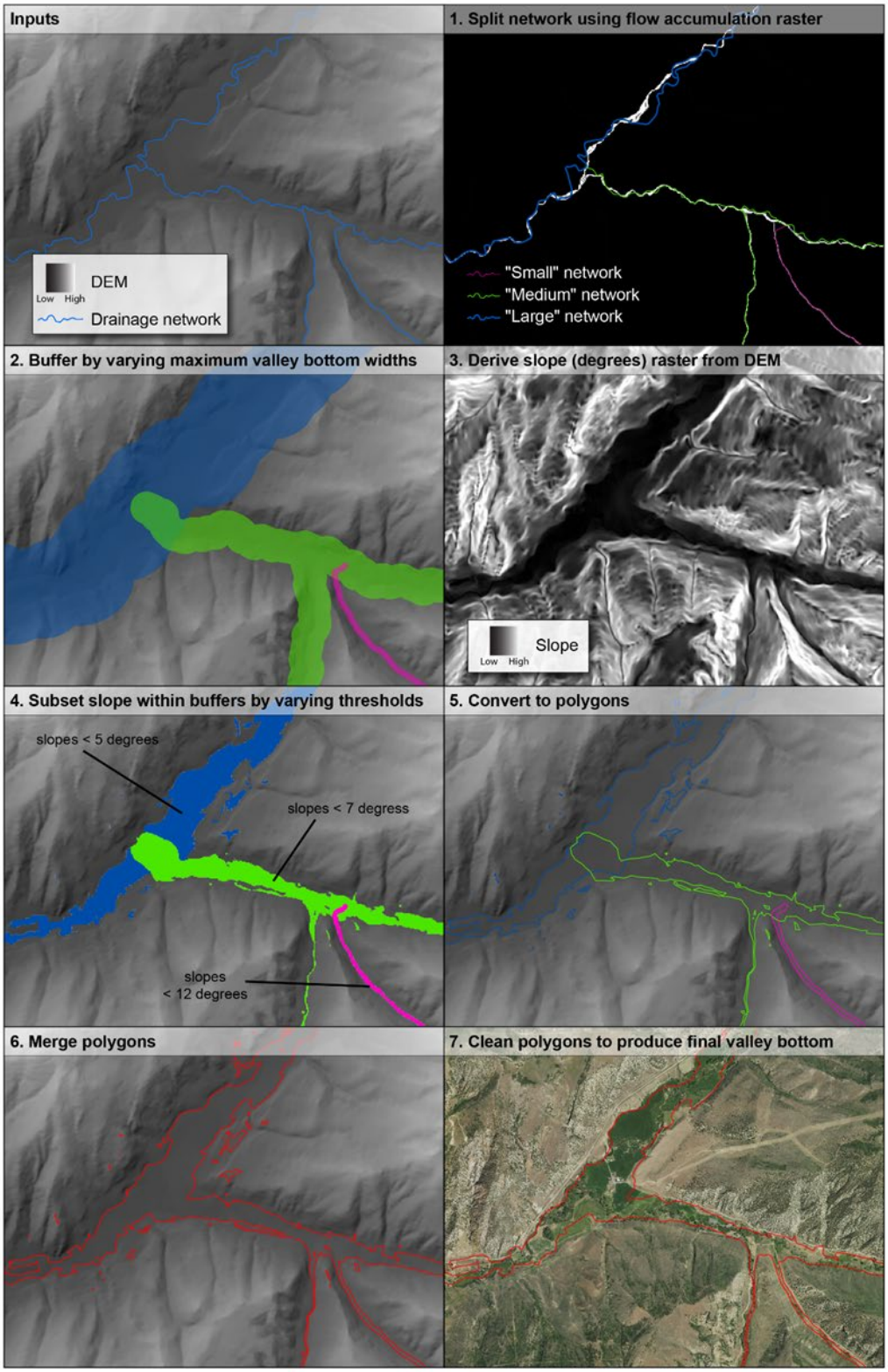


Figure 23 - Conceptual diagram of the Valley Bottom Extraction Tool (VBET) workflow showing the input data required and the seven processing steps. From: Gilbert et al. (2016).

APPENDIX 3D: ASSESSING RISK TO PROPERTY, INFRASTRUCTURE, AND PUBLIC SAFETY

Assessing risks to property, infrastructure, and public safety is a common part of traditional stream restoration planning (NRCS, 2007a). Generally, the more risk involved, the more caution is taken in the design. Low-tech restoration is generally considered 'low risk' relative to traditional restoration approaches because consequences of 'failure' are lower. Core principles of low-tech restoration, such as, giving the riverscape space and deferring decision making to the system, reduce the significance of uncertainty. However, it is still important to consider how any restoration project may affect property, infrastructure, and public safety. A risk assessment should always be considered and discussed with the landowner, manager, and/or stakeholders so that all parties are aware of potential risks. A simple checklist can be used to quickly flag potential issues and develop alternatives to reduce risks. Below, is an example developed by the USDA Natural Resources Conservation Service.

Risk Considerations Checklist for Low-Tech Stream and Meadow Restoration

Instructions

For each factor, select the characteristic that best describes the project site. If answers vary within project area, consider breaking site into multiple reaches and assessing each separately. This is not a comprehensive list, but rather, represents some basic considerations related to assessing potential risks to property, infrastructure, and public safety to discuss with the landowner/manager and stakeholders (green = lower risk, yellow = moderate risk, red = higher risk). For factors rating yellow or red, project planners may need to engage other technical specialists for additional review and analysis. Alternatives to mitigate or lower risks to acceptable levels should be evaluated in the planning process. In the notes, describe the situation and how risks are being reduced. In some cases, low-tech restoration approaches may not be appropriate based on constraints and risks.

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

Network-Scale Approximation of Risk to Infrastructure

Many freely-available datasets exist for approximate mapping of existing infrastructure, land uses, land cover and land ownership. Below in Figure 24 is an example from the Beaver Restoration Assessment Tool (http://brat.riverscapes.xyz), of the risk of beaver building dams where there could be undesirable impacts. This particularly example is based off considering proximity to roads, road crossings, irrigation canals, diversions, infrastructure and higher intensity land use, and then highlighting the overlay of those areas with places that could support beaver dam activity. Such an analysis can be done based off of freely available data. The idea with such analyses is not that areas with some or considerable risks need to be avoided entirely. It is simply that if those areas are targeted for low-tech restoration, then specific considerations need to be made to mitigate impacts, and there must be a willingness and acceptance amongst the stakeholders of those risks.

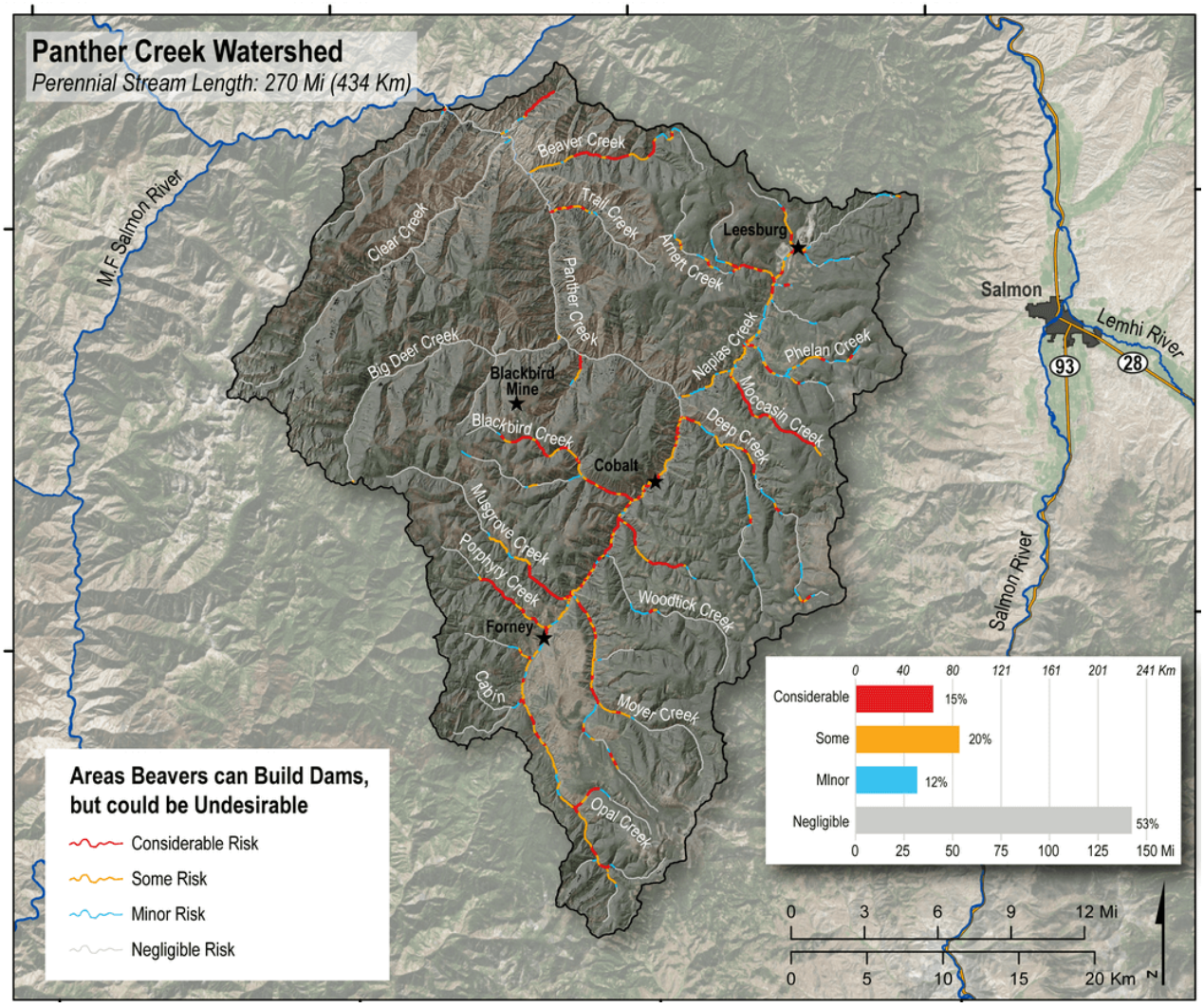


Figure 24 – Beaver Restoration Assessment Tool (BRAT) evaluation of areas with potential risk of beaver dam activity impacting roads, infrastructure or incompatible land uses.

APPENDIX 3E: ASSESSING RIPARIAN CONDITIONS TO SUPPORT WOOD ACCUMULATION

The Riparian Condition Assessment Toolbox (R-CAT; http://rcat.riverscapes.xyz) is a network level assessment tool consisting of the Valley Bottom Extraction Tool (VBET; Gilbert et al., 2016), Riparian Vegetation Departure index (RVD; Macfarlane et al., 2017), and Riparian Condition Assessment tool (RCA; Macfarlane et al., 2018). The questions the tool approximates answers to with remotely sensed data are all questions worth considering:

- What is the overall riparian condition? Indicators of this include:
    - What is the extent of departure of the extent of riparian vegetation in the valley bottom today compared to historic conditions?
    - What is the intensity of land use in the valley bottom?
    - What part of the valley bottom is still accessible by the channel(s) and active floodplain?

These questions can all be addressed qualitatively at a reach-scale over project extents and valuably inform the resource analysis questions of current conditions and their ability to grow woody vegetation, which could be recruited and support processes of wood accumulation. These same questions can be asked in a recovery

Riparian Vegetation Departure

Riparian vegetation condition controls the delivery of sediment, water, nutrients, and structure (e.g., wood). Much of the ability to conserve and restore riverscapes is dependent on riparian condition. Therefore, a watershed network assessment of riparian vegetation condition is essential for the development of stream restoration and conservation options. RVD index calculates riparian vegetation condition for each reach in valley bottom areas as the ratio of existing native riparian vegetation to an estimation of pre-European settlement vegetation coverage (Figure 25) (Macfarlane et al., 2017). Current riparian vegetation cover was estimated using the LANDFIRE Existing Vegetation Type (EVT) layer (LANDFIRE, 2018b) and historic vegetation was estimated using the LANDFIRE Biophysical Setting (BpS) layer (LANDFIRE, 2018a).

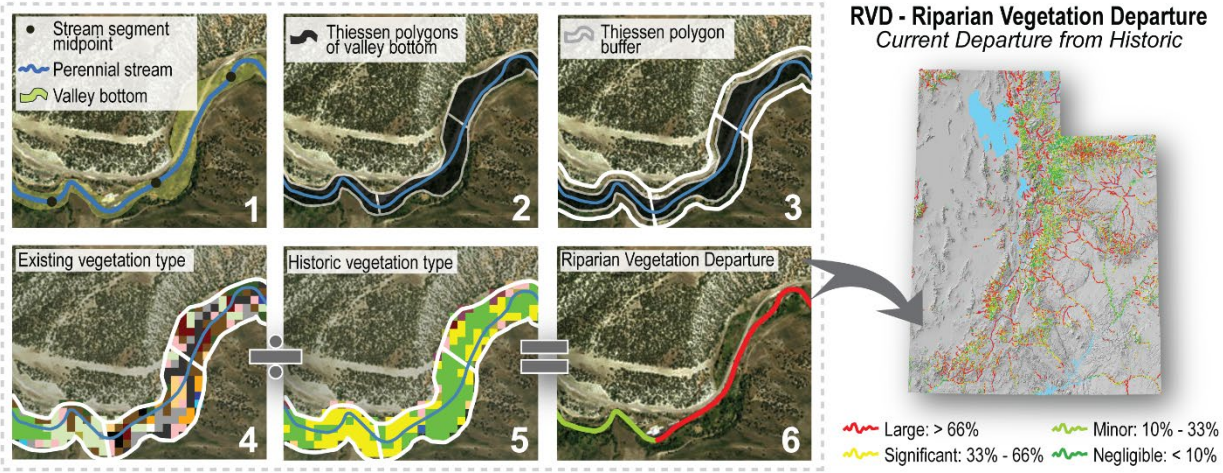


Figure 25 - A conceptual diagram of the riparian vegetation departure index showing how mid points of the drainage network (1) are used to generate Thiessen polygons (2) and how these polygons are buffered by the resolution of the vegetation data to ensure that vegetation data is completely contained within the valley bottom in headwater reaches (3). Riparian vegetation departure is calculated using the ratio of existing area of native riparian vegetation (4) to historic area of native riparian vegetation (5) and the output is a segmented drainage network containing riparian departure from historic condition scores (6).

Riparian Condition Assessment Tool – RCAT

The RCA tool was developed to assess impacts on riparian condition caused by three dominant stressors: (1) riparian vegetation departure from historical condition, (2) land use intensity within the valley bottom, and (3) floodplain fragmentation due to infrastructure within valley bottoms (Macfarlane et al., 2018). Each stream reach is attributed with

continuous values for the three stressors and the condition of each reach is then assessed using a fuzzy inference system. The tool calculates riparian condition, which ranges from 0 (poor) to 1 (intact), for each stream reach (Figure 26).

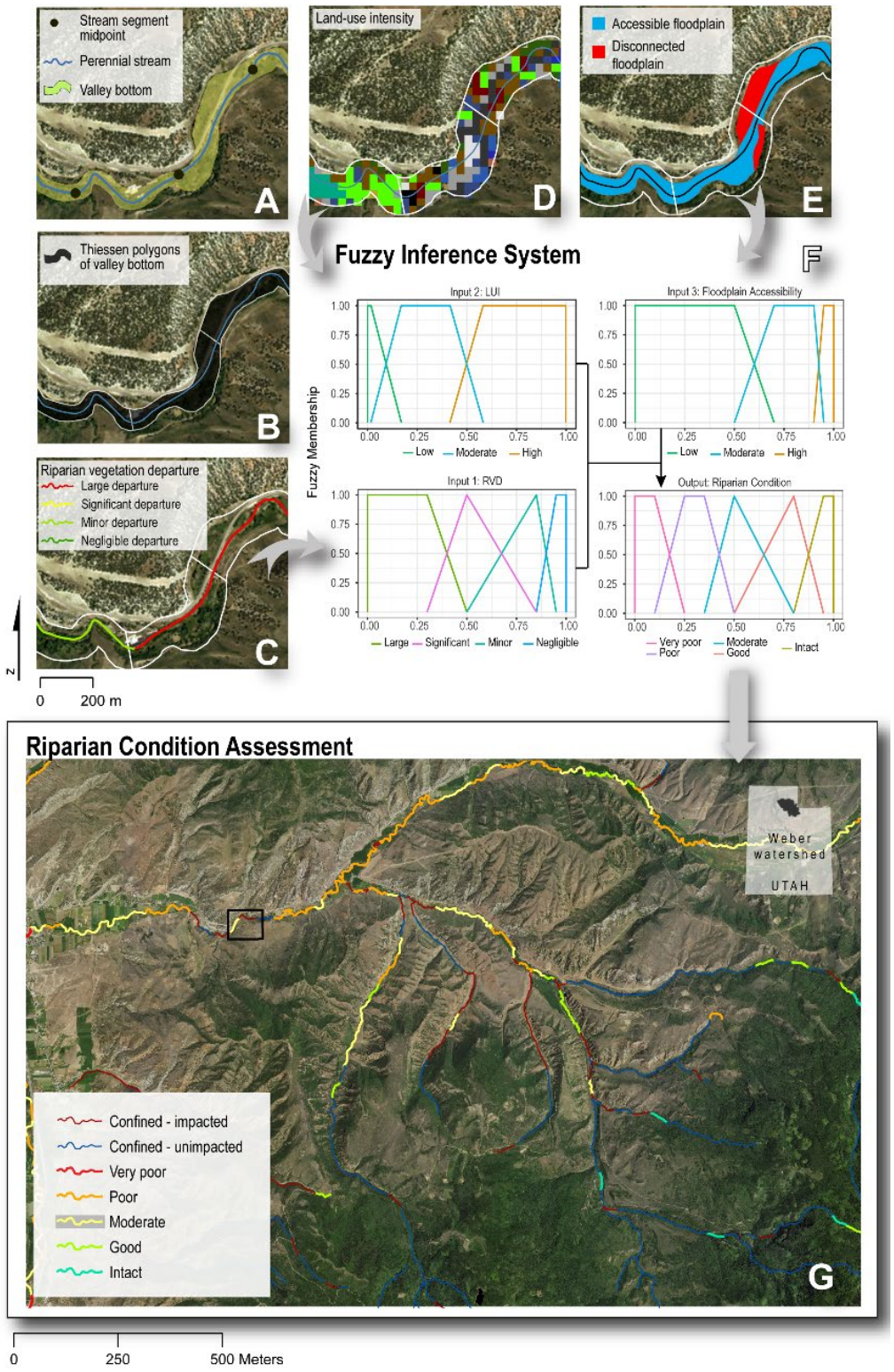


Figure 26 - Conceptual diagram of riparian condition assessment (RCA) tool showing how midpoints of a drainage network (A) are used to generate Thiessen polygons (B). Riparian vegetation departure index outputs (C) are combined with land-use intensity (D) and floodplain accessibility outputs (E) within a Fuzzy Inference System (F) to produce a segmented drainage network containing riparian condition assessment scores (G).

APPENDIX 3F: ASSESSING POTENTIAL FOR BEAVER DAM ACTIVITY

From a low-tech restoration perspective, the real question of interest is to what degree could beaver dam activity be a viable, self-sustaining activity in your riverscape (see Principles 2 and 9, Chapter 2: Wheaton et al., 2019).

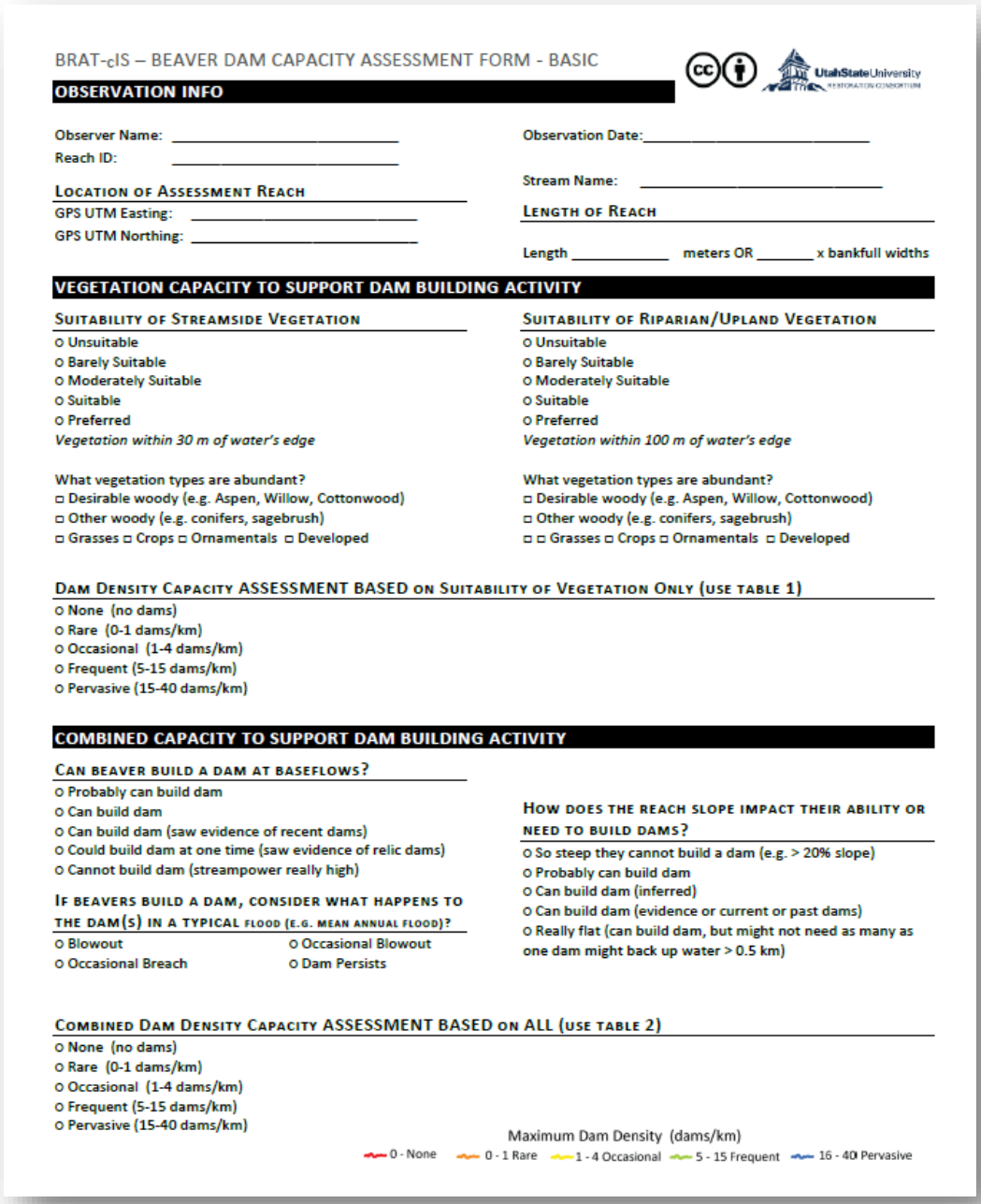
Beaver Restoration Assessment Tool

The Beaver Restoration Assessment Tool (BRAT: http://brat.riverscapes.xyz) is a decision support and planning tool intended to help researchers, restoration practitioners and resource managers assess the potential for beaver as a stream conservation and restoration agent over large regions and watersheds. At the heart of BRAT is a capacity model (BRAT cFIS and BRAT cIS), which estimates the upper limit of dam density (dams per mile) for individual stream reaches throughout a drainage network. BRAT focuses on predicting where beavers could build dams and to what extent (as opposed to the more general case of where beaver could make a living), because it is the dam building activity they do as ecosystem engineers, which we are typically most interested in.

The BRAT model can be run with freely available national data sets (or with higher resolution data), and is used to identify opportunities, potential conflicts and constraints through a mix of assessment of existing resources and scenario-based assessment of potential futures. The backbone to BRAT are spatial models that predict the capacity of riverscapes to support dam-building activity by beaver. By combining capacity and decision support approaches, researchers and resource managers have the information necessary to determine where and at what level reintroduction of beaver and/or conservation is appropriate.

How to Use the Capacity Inference System (BRAT cIS) Form

While running BRAT is a useful exercise for large scale planning and prioritization, the questions BRAT asks of the data can easily be asked along any stretch of riverscape, and answered with basic observations and common sense. When the BRAT capacity (i.e., how many dams per mile) are run with data, we use fuzzy inference systems to deal with categorical ambiguity and uncertainty in the input data. However, inference systems are nothing more than rule tables, and if the user is comfortable committing to specific categorical calls for the inputs that drive these capacity model, one can 'run' the model very simpler. That is all the BRAT capacity inference system (cIS) is. The Beaver Restoration Assessment Tool Capacity Inference System (BRAT cIS) Form and associated rule tables are a desktop or field-based assessment of beaver dam capacity (Figure 27).



BRAT-cIS – BEAVER DAM CAPACITY ASSESSMENT FORM - BASIC

OBSERVATION INFO

Observer Name: _____ Observation Date: _____

Reach ID: _____ Stream Name: _____

LOCATION OF ASSESSMENT REACH

GPS UTM Easting: _____

GPS UTM Northing: _____

LENGTH OF REACH

Length _____ meters OR _____ x bankfull widths

VEGETATION CAPACITY TO SUPPORT DAM BUILDING ACTIVITY

SUITABILITY OF STREAMSIDE VEGETATION

o Unsuitable
o Barely Suitable
o Moderately Suitable
o Suitable
o Preferred
Vegetation within 30 m of water's edge

What vegetation types are abundant?
□ Desirable woody (e.g. Aspen, Willow, Cottonwood)
□ Other woody (e.g. conifers, sagebrush)
□ Grasses □ Crops □ Ornamentals □ Developed

SUITABILITY OF RIPARIAN/UPLAND VEGETATION

o Unsuitable
o Barely Suitable
o Moderately Suitable
o Suitable
o Preferred
Vegetation within 100 m of water's edge

What vegetation types are abundant?
□ Desirable woody (e.g. Aspen, Willow, Cottonwood)
□ Other woody (e.g. conifers, sagebrush)
□ □ Grasses □ Crops □ Ornamentals □ Developed

DAM DENSITY CAPACITY ASSESSMENT BASED ON SUITABILITY OF VEGETATION ONLY (USE TABLE 1)

o None (no dams)
o Rare (0-1 dams/km)
o Occasional (1-4 dams/km)
o Frequent (5-15 dams/km)
o Pervasive (15-40 dams/km)

COMBINED CAPACITY TO SUPPORT DAM BUILDING ACTIVITY

CAN BEAVER BUILD A DAM AT BASEFLOWS?

o Probably can build dam
o Can build dam
o Can build dam (saw evidence of recent dams)
o Could build dam at one time (saw evidence of relic dams)
o Cannot build dam (streampower really high)

IF BEAVERS BUILD A DAM, CONSIDER WHAT HAPPENS TO THE DAM(S) IN A TYPICAL FLOOD (E.G. MEAN ANNUAL FLOOD)?

o Blowout
o Occasional Breach
o Occasional Blowout
o Dam Persists

HOW DOES THE REACH SLOPE IMPACT THEIR ABILITY OR NEED TO BUILD DAMS?

o So steep they cannot build a dam (e.g. > 20% slope)
o Probably can build dam
o Can build dam (inferred)
o Can build dam (evidence or current or past dams)
o Really flat (can build dam, but might not need as many as one dam might back up water > 0.5 km)

COMBINED DAM DENSITY CAPACITY ASSESSMENT BASED ON ALL (USE TABLE 2)

o None (no dams)
o Rare (0-1 dams/km)
o Occasional (1-4 dams/km)
o Frequent (5-15 dams/km)
o Pervasive (15-40 dams/km)

Maximum Dam Density (dams/km)
0 - None 0 - 1 Rare 1 - 4 Occasional 5 - 15 Frequent 16 - 40 Pervasive

Figure 27 - Page one of the Beaver Restoration Assessment Tool Capacity Inference System (BRAT cIS) Form. This form can be evaluated for any reach of a riverscape and the answers (capacity) are evaluated by using the look-up tables in Figure 33 and Figure 35.

The four questions that the BRAT cIS addresses, for a specific riverscape of interest, are:

1. Is there enough water present to maintain a pond?
2. Are enough and the right type of woody resources present to support dam building?
3. Can they build a dam at base flows?
4. Are dams likely to withstand typical floods?

These four questions are also the underpinnings of the BRAT Fuzzy Inference System (FIS) (Figure 28) described in detail in Macfarlane et al. (2015). BRAT's backbone is a capacity model developed to assess the upper limits of riverscapes to support beaver dam-building activities. Our estimates of beaver dam capacity come from seven lines of evidence: (1) a reliable water source; (2) stream bank vegetation conducive to foraging and dam building; (3) vegetation within 100 m of edge of stream to support expansion of dam complexes and maintain large beaver colonies; (4) likelihood that dams could be built across the channel during low flows; (5) the likelihood that a beaver dam on a river or stream is capable of withstanding typical floods; (6) evidence of suitable stream gradient; and (7) evidence that river is too large to allow dams to be built and to persist. With the BRAT FIS model, we approximate quantitative answers to those above mentioned questions with GIS data.

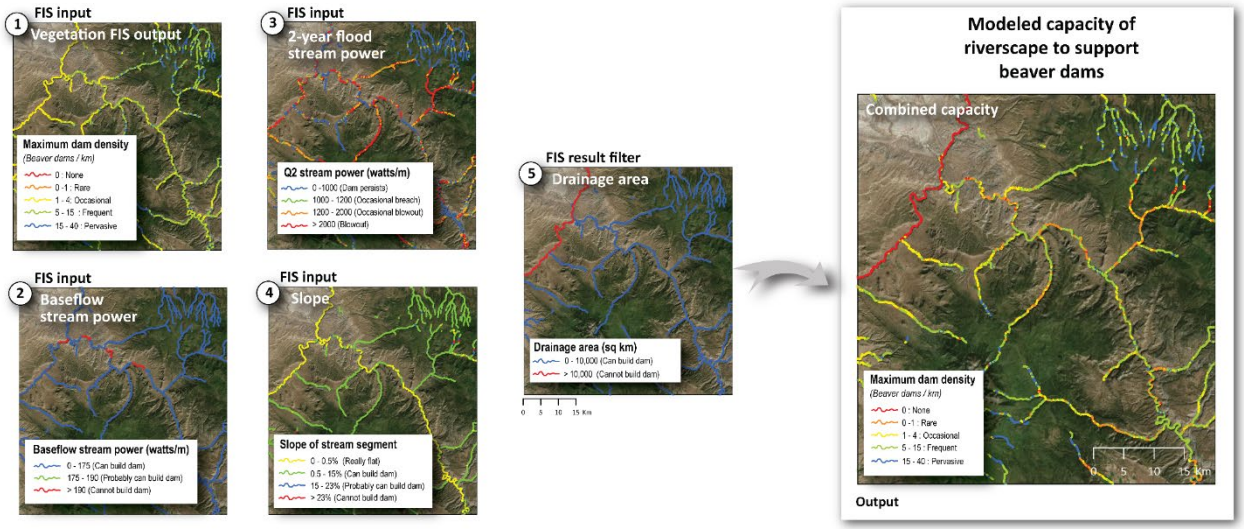
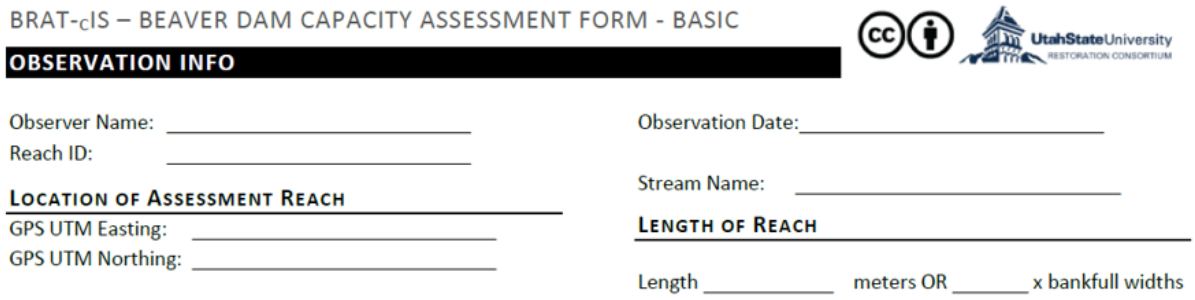


Figure 28 - Methodological illustration of inputs (1-5) and output for the combined capacity model of riverscapes capacity to support beaver dam-building activity. Model output is expressed as dam density (dams/km). From Macfarlane et al. (2015).

Both the BRAT cIS and BRAT FIS are rooted in the following:

- to build dams beaver need water and woody vegetation,
- the type and extent of vegetation matters most, and
- flow regime act to potentially limit capacity.

Using the BRAT cIS one can estimate in the field or at the desktop where beaver can build dams now and to what extent. The BRAT cIS also evaluates the maximum number of beaver dams a particular reach of river can support. This capacity estimate is assessed by answering the basic questions on the BRAT cIS form and running the simple inference system rule tables. The first section of the BRAT cIS form is the *observation Info*, which addresses the who, where and when of the data collection exercise.



BRAT-cIS – BEAVER DAM CAPACITY ASSESSMENT FORM - BASIC

OBSERVATION INFO

Observer Name: _____ Observation Date: _____

Reach ID: _____ Stream Name: _____

LOCATION OF ASSESSMENT REACH

GPS UTM Easting: _____

GPS UTM Northing: _____

LENGTH OF REACH

Length _____ meters OR _____ x bankfull widths

Figure 29 - The observation info portion of the Beaver Restoration Assessment Tool Capacity Inference System (BRAT cIS) form.

The second section of the BRAT cIS form is the *vegetation capacity to support dam building activity* (Figure 31) and addresses the question: Are *enough* and the *right* type of woody vegetation present to support dam building? This is ask for the streamside vegetation (i.e., vegetation within 30m of the water's edge) and for the riparian/upland vegetation (i.e., vegetation within 100m of the water's edge) (Figure 31).

VEGETATION CAPACITY TO SUPPORT DAM BUILDING ACTIVITY

SUITABILITY OF STREAMSIDE VEGETATION

o Unsuitable
o Barely Suitable
o Moderately Suitable
o Suitable
o Preferred

Vegetation within 30 m of water's edge

What vegetation types are abundant?
□ Desirable woody (e.g. Aspen, Willow, Cottonwood)
□ Other woody (e.g. conifers, sagebrush)
□ Grasses □ Crops □ Ornamentals □ Developed

SUITABILITY OF RIPARIAN/UPLAND VEGETATION

o Unsuitable
o Barely Suitable
o Moderately Suitable
o Suitable
o Preferred

Vegetation within 100 m of water's edge

What vegetation types are abundant?
□ Desirable woody (e.g. Aspen, Willow, Cottonwood)
□ Other woody (e.g. conifers, sagebrush)
□ □ Grasses □ Crops □ Ornamentals □ Developed

DAM DENSITY CAPACITY ASSESSMENT BASED ON SUITABILITY OF VEGETATION ONLY (USE TABLE 1)

o None (no dams)
o Rare (0-1 dams/km)
o Occasional (1-4 dams/km)
o Frequent (5-15 dams/km)
o Pervasive (15-40 dams/km)

Figure 30: The vegetation capacity to support dam building activity section of the Beaver Restoration Assessment Tool Capacity Inference System (BRAT cIS) form.

The vegetation assessment is based on beaver's preferences for woody vegetation to support dam-building activities (Figure 32). The proportion of building material in the following five dam building preference categories:

1. Unsuitable (0),
2. Barely Suitable (1),
3. Moderately Suitable (2),
4. Suitable (3), and
5. Preferred (4)

They are assessed as an area weighted average scored as a single value of: 0, 1, 2, 3 or 4 per reach. The vegetation preference question is asked for both the streamside and the riparian/upland fringe area independently.

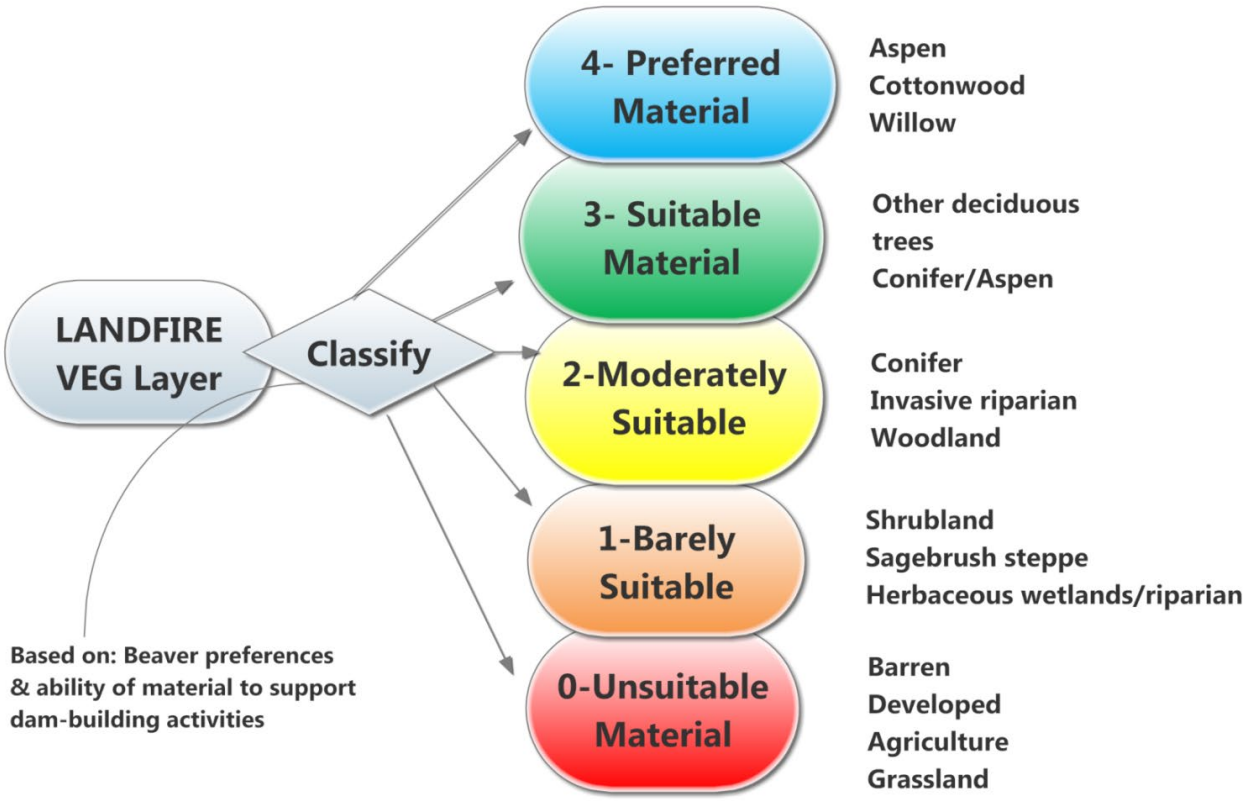


Figure 31 - Show beaver preferences for dam building materials lumped into 5 categories.

Figure 32 shows how to use the vegetation inference system rule table. The outputs are beaver dam capacity estimates based on the suitability of vegetation only and is reported as number of dams per mile (or km) (Figure 33).

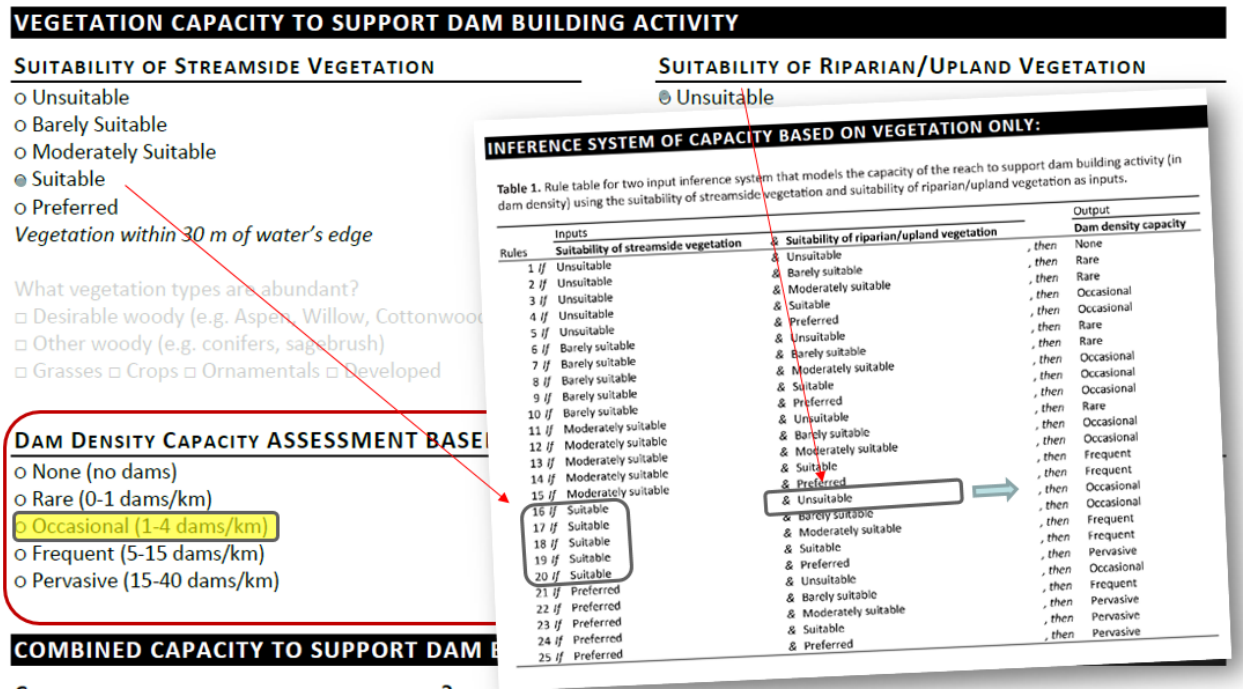


Figure 32: Illustrates how to use the vegetation rule table to assess beaver dam capacity.

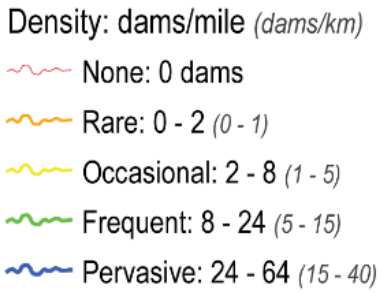


Figure 33: The beaver dam capacity output legend.

The third and final section of the BRAT cIS form addresses the combined capacity of the riverscape to support beaver dam building activity. The questions that this portion of the form addresses are: does hydrology (manifested as local hydraulics) limit beaver dam capacity? Specifically, can beaver build dams at baseflow? And are beaver dams likely to withstand a typical flood? (Figure 34). Figure 35 shows table 2 the combine inference system rule table that is used to assess combined beaver dam capacity. Once again, the outputs are beaver dam capacity estimates reported as number of dams per mile (or km) but this time are based on both the suitability of vegetation to support dam building and the potential limiting of capacity due to hydrology.

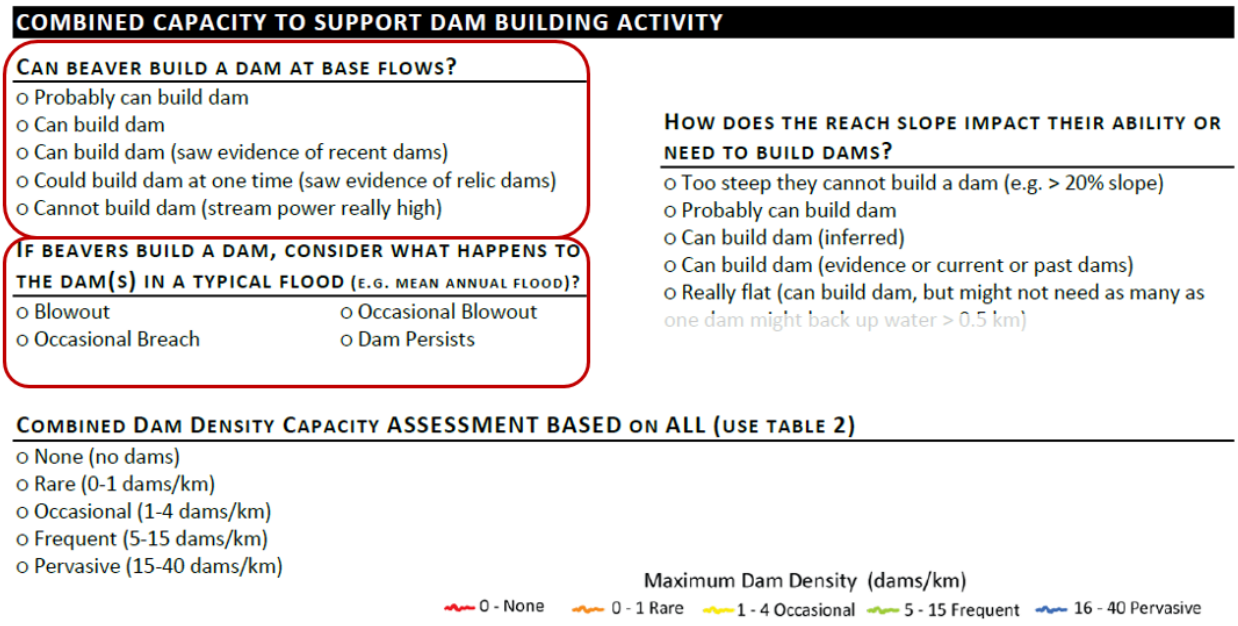


Figure 34: The combined capacity to support dam building activity section of the Beaver Restoration Assessment Tool Capacity Inference System (BRAT cIS) form.

COMBINED INFERENCE SYSTEM:

Table 2. Rule table for four input inference system that models the capaicty of the reach to support dam building activity (in dam density) uisng the vegetation dam density capacity (output of Table 1 model), the two-year flood stream power, baseflow stream power and reach slope.

	Inputs								Output
Rules	**Vegetation dam density capacity**	&	**2-year flood stream power**	&	**Baseflow stream power**	&	**Reach slope**		**Dam density capacity**
1	*if* None	&	-	&	-	&	-	*, then*	None
2	*if* -	&	-	&	Cannot build dam	&	-	*, then*	None
3	*if* -	&	-	&	-	&	Cannot build dam	*, then*	None
4	*if* Rare	&	Dam persists	&	Can build dam	&	NOT Cannot build dam	*, then*	Rare
5	*if* Rare	&	Dam persists	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Rare
6	*if* Rare	&	Occasional breach	&	Can build dam	&	NOT Cannot build dam	*, then*	Rare
7	*if* Rare	&	Occasional breach	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Rare
8	*if* Rare	&	Occasional blowout	&	Can build dam	&	NOT Cannot build dam	*, then*	Rare
9	*if* Rare	&	Occasional blowout	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Rare
10	*if* Rare	&	Blowout	&	Can build dam	&	NOT Cannot build dam	*, then*	None
11	*if* Rare	&	Blowout	&	Probably can build dam	&	NOT Cannot build dam	*, then*	None
12	*if* Occasional	&	Dam persists	&	Can build dam	&	NOT Cannot build dam	*, then*	Occasional
13	*if* Occasional	&	Dam persists	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Occasional
14	*if* Occasional	&	Occasional breach	&	Can build dam	&	NOT Cannot build dam	*, then*	Occasional
15	*if* Occasional	&	Occasional breach	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Occasional
16	*if* Occasional	&	Occasional blowout	&	Can build dam	&	NOT Cannot build dam	*, then*	Occasional
17	*if* Occasional	&	Occasional blowout	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Occasional
18	*if* Occasional	&	Blowout	&	Can build dam	&	NOT Cannot build dam	*, then*	Rare
19	*if* Occasional	&	Blowout	&	Probably can build dam	&	NOT Cannot build dam	*, then*	Rare
20	*if* Frequent	&	Dam persists	&	Can build dam	&	Really flat	*, then*	Occasional
21	*if* Frequent	&	Dam persists	&	Can build dam	&	Can build dam	*, then*	Frequent
22	*if* Frequent	&	Dam persists	&	Can build dam	&	Probably can build dam	*, then*	Occasional
23	*if* Frequent	&	Dam persists	&	Probably can build dam	&	Really flat	*, then*	Occasional
24	*if* Frequent	&	Dam persists	&	Probably can build dam	&	Can build dam	*, then*	Frequent
25	*if* Frequent	&	Dam persists	&	Probably can build dam	&	Probably can build dam	*, then*	Occasional
26	*if* Frequent	&	Occasional breach	&	Can build dam	&	Really flat	*, then*	Occasional
27	*if* Frequent	&	Occasional breach	&	Can build dam	&	Can build dam	*, then*	Frequent
28	*if* Frequent	&	Occasional breach	&	Can build dam	&	Probably can build dam	*, then*	Occasional
29	*if* Frequent	&	Occasional breach	&	Probably can build dam	&	Really flat	*, then*	Occasional
30	*if* Frequent	&	Occasional breach	&	Probably can build dam	&	Can build dam	*, then*	Frequent
31	*if* Frequent	&	Occasional breach	&	Probably can build dam	&	Probably can build dam	*, then*	Occasional
32	*if* Frequent	&	Occasional blowout	&	Can build dam	&	Really flat	*, then*	Occasional
33	*if* Frequent	&	Occasional blowout	&	Can build dam	&	Can build dam	*, then*	Frequent
34	*if* Frequent	&	Occasional blowout	&	Can build dam	&	Probably can build dam	*, then*	Occasional
35	*if* Frequent	&	Occasional blowout	&	Probably can build dam	&	Really flat	*, then*	Rare
36	*if* Frequent	&	Occasional blowout	&	Probably can build dam	&	Can build dam	*, then*	Occasional
37	*if* Frequent	&	Occasional blowout	&	Probably can build dam	&	Probably can build dam	*, then*	Rare
38	*if* Frequent	&	Blowout	&	Can build dam	&	Really flat	*, then*	Rare
39	*if* Frequent	&	Blowout	&	Can build dam	&	Can build dam	*, then*	Rare
40	*if* Frequent	&	Blowout	&	Can build dam	&	Probably can build dam	*, then*	Rare
41	*if* Frequent	&	Blowout	&	Probably can build dam	&	Really flat	*, then*	Rare
42	*if* Frequent	&	Blowout	&	Probably can build dam	&	Can build dam	*, then*	Rare
43	*if* Frequent	&	Blowout	&	Probably can build dam	&	Probably can build dam	*, then*	Rare
44	*if* Pervasive	&	Dam persists	&	Can build dam	&	Really flat	*, then*	Frequent
45	*if* Pervasive	&	Dam persists	&	Can build dam	&	Can build dam	*, then*	Pervasive
46	*if* Pervasive	&	Dam persists	&	Can build dam	&	Probably can build dam	*, then*	Frequent
47	*if* Pervasive	&	Dam persists	&	Probably can build dam	&	Really flat	*, then*	Frequent
48	*if* Pervasive	&	Dam persists	&	Probably can build dam	&	Can build dam	*, then*	Pervasive
49	*if* Pervasive	&	Dam persists	&	Probably can build dam	&	Probably can build dam	*, then*	Frequent
50	*if* Pervasive	&	Occasional breach	&	Can build dam	&	Really flat	*, then*	Frequent
51	*if* Pervasive	&	Occasional breach	&	Can build dam	&	Can build dam	*, then*	Pervasive
52	*if* Pervasive	&	Occasional breach	&	Can build dam	&	Probably can build dam	*, then*	Frequent
53	*if* Pervasive	&	Occasional breach	&	Probably can build dam	&	Really flat	*, then*	Frequent
54	*if* Pervasive	&	Occasional breach	&	Probably can build dam	&	Can build dam	*, then*	Pervasive
55	*if* Pervasive	&	Occasional breach	&	Probably can build dam	&	Probably can build dam	*, then*	Frequent
56	*if* Pervasive	&	Occasional blowout	&	Can build dam	&	Really flat	*, then*	Frequent
57	*if* Pervasive	&	Occasional blowout	&	Can build dam	&	Can build dam	*, then*	Pervasive
58	*if* Pervasive	&	Occasional blowout	&	Can build dam	&	Probably can build dam	*, then*	Frequent
59	*if* Pervasive	&	Occasional blowout	&	Probably can build dam	&	Really flat	*, then*	Occasional
60	*if* Pervasive	&	Occasional blowout	&	Probably can build dam	&	Can build dam	*, then*	Frequent
61	*if* Pervasive	&	Occasional blowout	&	Probably can build dam	&	Probably can build dam	*, then*	Occasional
62	*if* Pervasive	&	Blowout	&	Can build dam	&	Really flat	*, then*	Occasional
63	*if* Pervasive	&	Blowout	&	Can build dam	&	Can build dam	*, then*	Occasional
64	*if* Pervasive	&	Blowout	&	Can build dam	&	Probably can build dam	*, then*	Rare
65	*if* Pervasive	&	Blowout	&	Probably can build dam	&	Really flat	*, then*	Occasional
66	*if* Pervasive	&	Blowout	&	Probably can build dam	&	Can build dam	*, then*	Occasional
67	*if* Pervasive	&	Blowout	&	Probably can build dam	&	Probably can build dam	*, then*	Rare

Figure 35: Shows BRAT cIS table 2 the combined inference system rule table.

Example of Network-Scale BRAT Planning Assessment

The same basic questions that can be addressed at a reach-scale about the current or potential capacity to support beaver dam activity can be addressed at broad network scales as part of Phase 1 of the planning process using models like BRAT. The example in Figure 36 shows an estimate of existing capacity to support beaver dam activity based on freely-available, national data sets. Instead of using simple rule-tables (e.g. inference system Figure 32, Figure 35), the BRAT capacity model uses a fuzzy inference system to estimate capacity to support beaver dam building activity (Macfarlane et al., 2015).

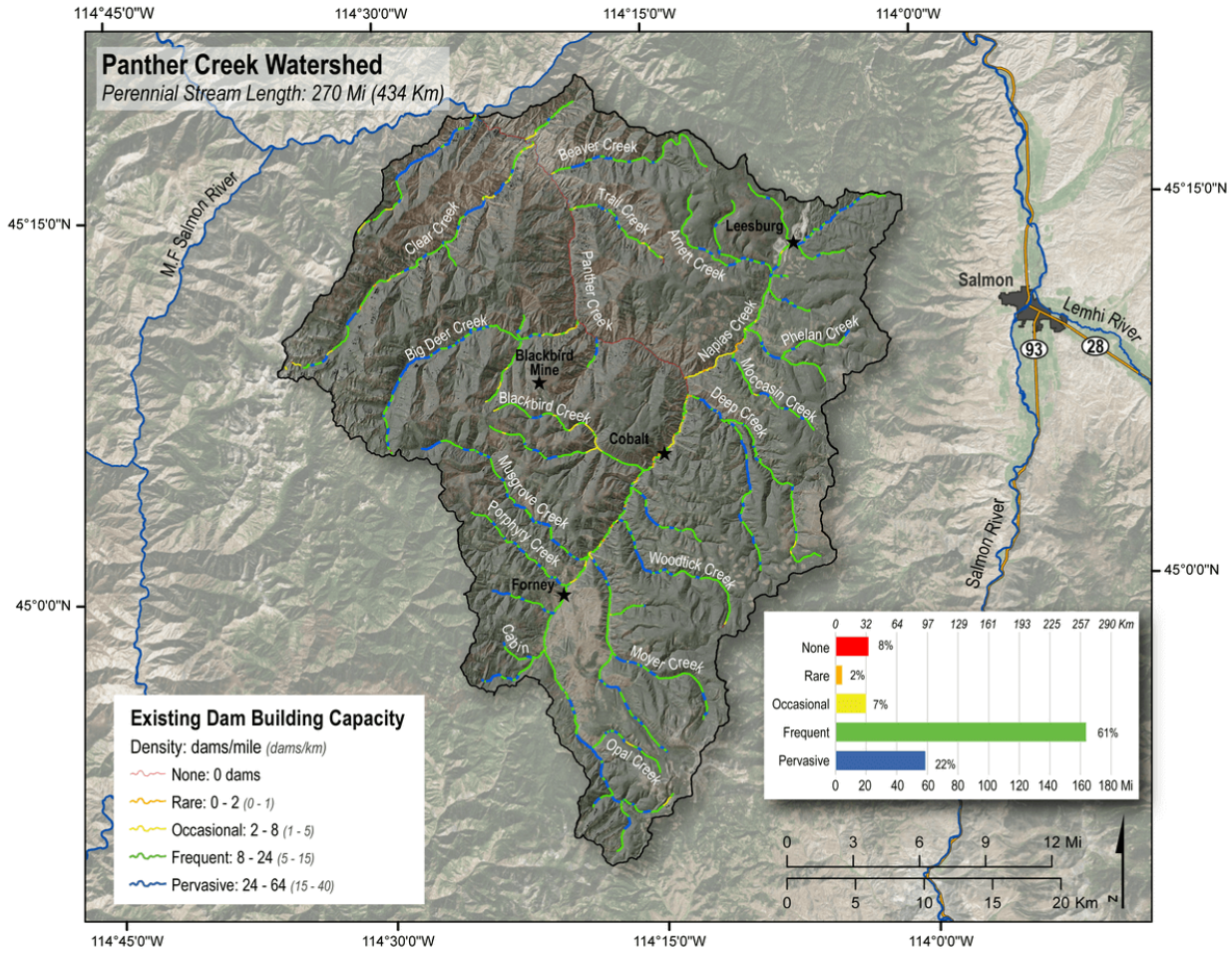


Figure 36 – Example of a network scale analysis of existing capacity to support beaver dam activity as part of a watershed planning and restoration prioritization process. Example from Hill et al. (2019b).

When considering beaver dam activity, a simple census of beaver dams can tell a lot about the proportion of capacity currently realized and help differentiate conservation potential from restoration potential. Figure 37 shows an example of such a census and helps make the point that in this watershed the vast majority of reaches are well below capacity. Those reaches that are near capacity are good goals for conservation (to sustain beaver dam activity processes). By contrast, the areas that have higher capacities (e.g. frequent or pervasive) and are found in areas with low or negligible risk of undesirable impacts by beaver dam activity (Figure 24 in Appendix D) are good candidates for restoration (Figure 38; see http://brat.riverscapes.xyz for more examples).

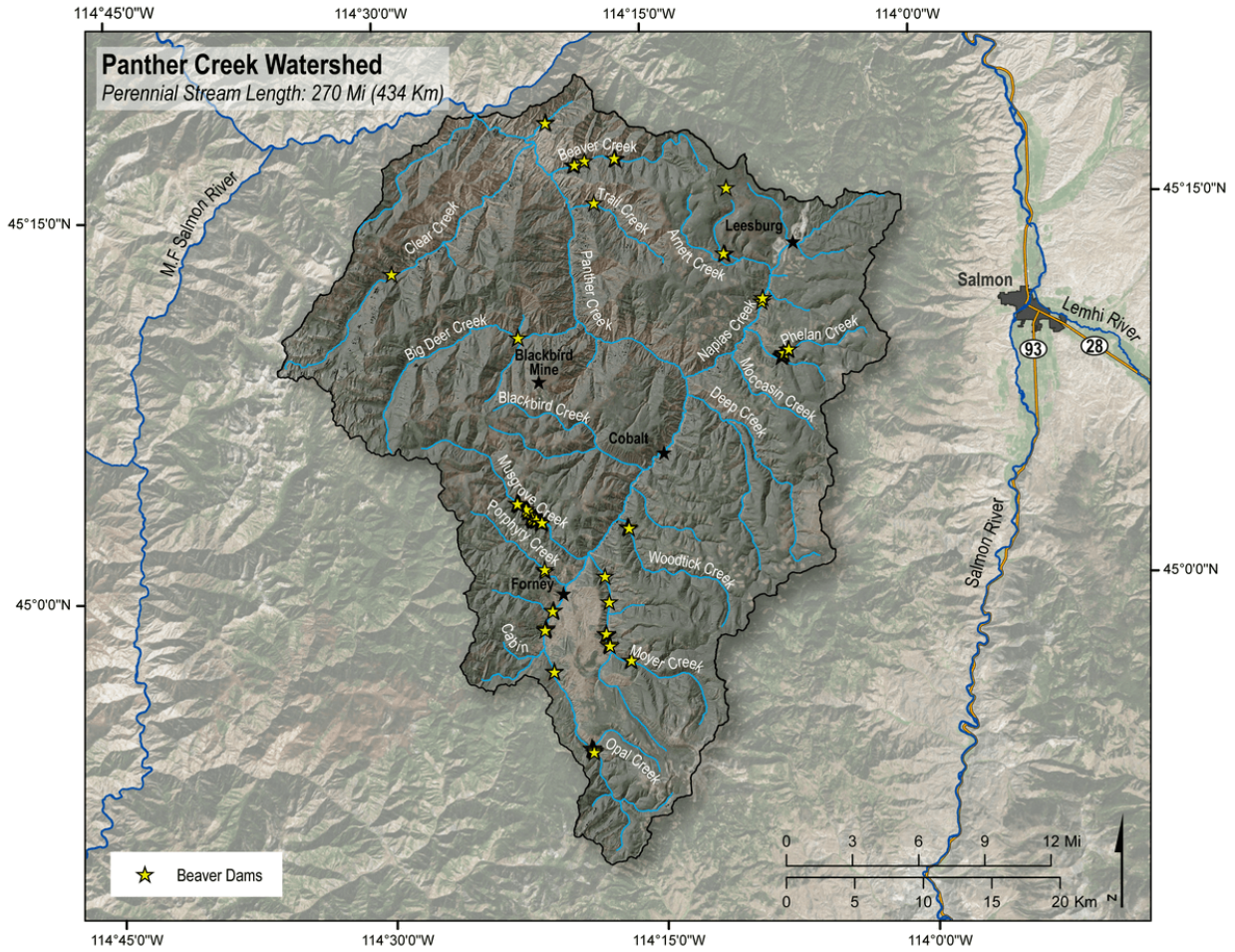


Figure 37 – An example census of beaver dam locations prepared from a desktop inventory of freely-available aerial imagery and/or field verification. Example from Hill et al. (2019b).

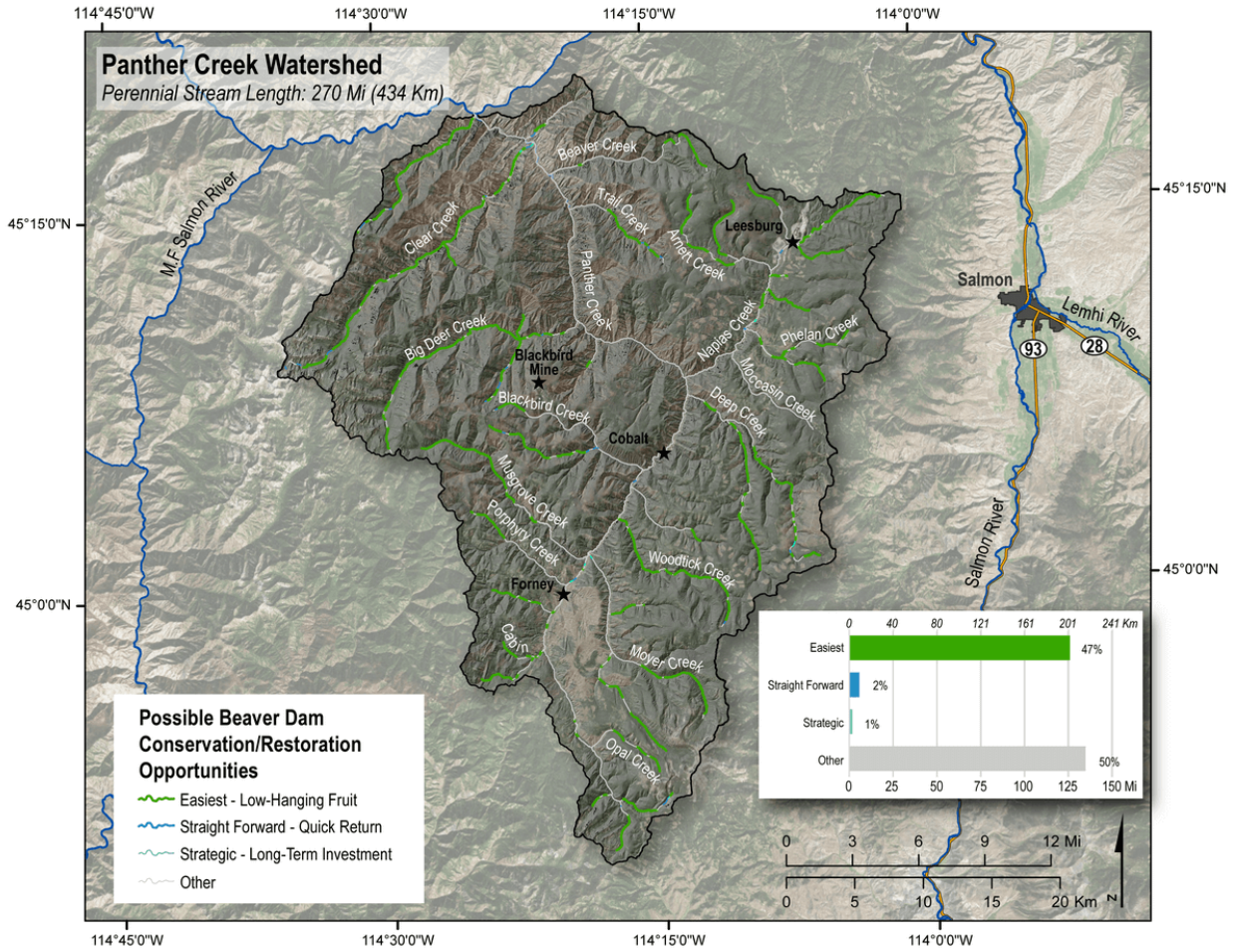


Figure 38 – Example of network scale assessment of conservation and restoration opportunities. Note that in this example 50% (135 miles) of the network is excluded on the basis of either having low capacity (Figure 36 ~ 40 miles) or having some to considerable risk of undesirable impact by beaver (Figure 24 ~ 95 miles). However, another 126 miles of the network in this example is flagged up as being 'low-hanging fruit' as the capacity is already high and risk is low. Approximately 3% of the network would require riparian recovery and improvement to be suitable for beaver dam activity.

APPENDIX 3G: STRUCTURE LEVEL ADAPTIVE MANAGEMENT

For most situations, adaptive management responses to evaluation and monitoring are best done at both the project level and the complex (group of structures) level. The same principles can be applied at the individual structure level, and we include it here to show an example of applying the thought process at the scale of individual structures. We intentionally do not highlight this in the main part of the chapter as it over-emphasizes the fate of individual structures. If low-tech restoration is to truly be effective, we need not focus on any single structure (i.e., Restoration Principle 6; Chapter 2: Wheaton et al., 2019). If projects have a small number of structures (e.g., < 50), it is easy to focus attention on individual structures. However, most projects should have so many structures that the fate of a single one is not critical to the success of the overall project. The primary goals should focus on the processes of wood accumulation and beaver dam activity, not the byproducts of debris jams (i.e., accumulations of wood) and beaver dams. Thus in any single monitoring event, one might inventory how many debris jams and beaver dams they saw, but tracking the fate of any single structure is less important. Figure 39 shows an evaluation and management response framework at individual structures, whereas Figure 40 casts that same process in adaptive management framework by explicitly laying out the designer or planner's hypothesized responses.

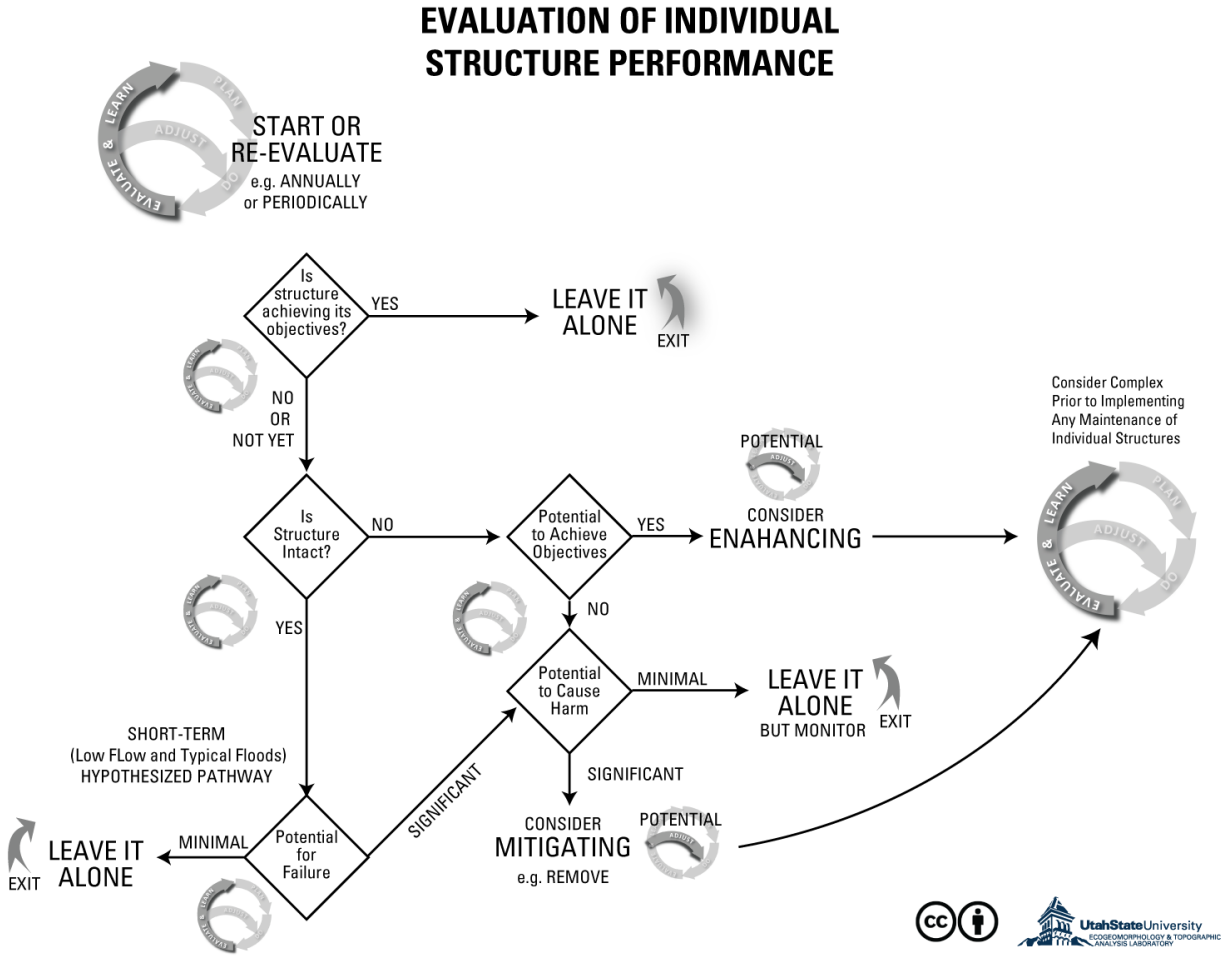


Figure 39 – An optional, detailed monitoring and maintenance workflow for evaluation of individual large woody debris (LWD) structures (e.g., PALS or BDAs). Modified from: Bouwes et al. (2016).

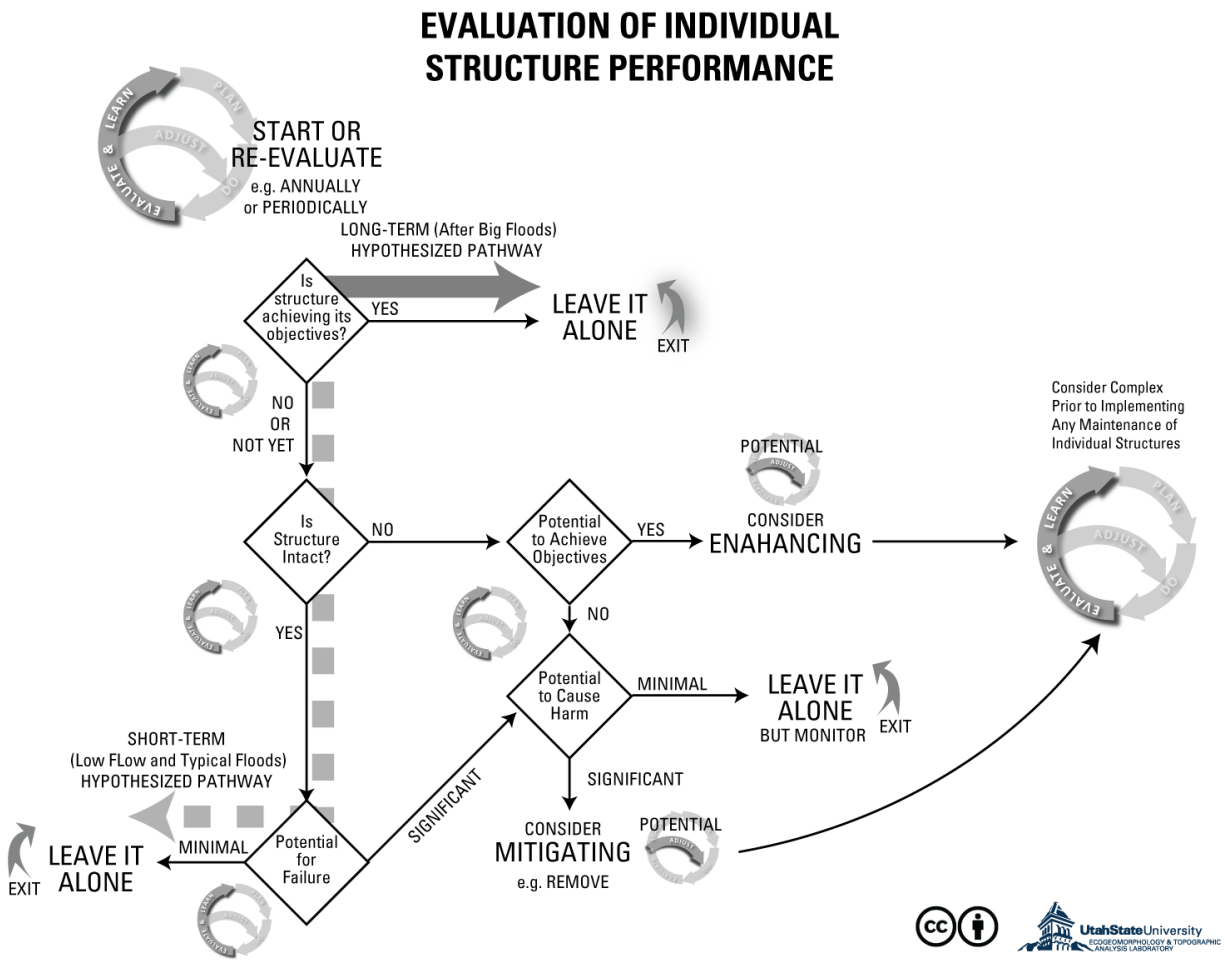


Figure 40 – The addition of short-term (dashed grey arrow) and long-term hypothesized pathways (solid grey arrow) is an example of what differentiates a structured maintenance decision making process (Figure 39) from a true adaptive management process. Evaluation and adjustments are made in both cases, but the addition of an explicit hypothesis about the expected outcomes allows hypothesis testing to take place as part of the evaluation and learning process. Note that the un-hypothesized pathways (e.g. structure not intact, significant failure, potential to cause harm) may not be what the project planner or designer predicts to happen. However, instead of ignoring these plausible outcomes, they can be explicitly recognized and management responses anticipated ahead of time. Including such questions (diamonds), triggers and decision points in an adaptive management plan is an excellent way to take on board stakeholder concerns without having to decide who is right or wrong. What can be agreed on instead, is that it is a potential concern, and what a reasonable response to mitigate that concern will take place if it is realized.

Chapter 3 - REFERENCES

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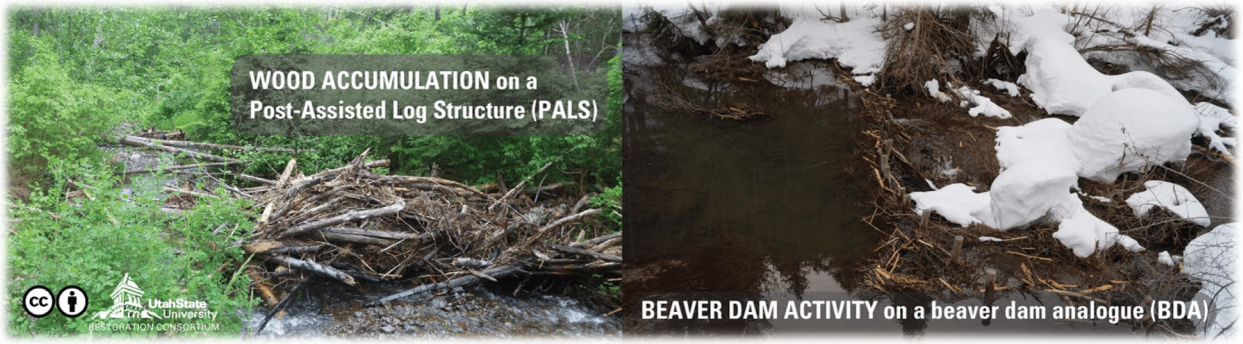
Chapter 4 – MIMICKING & PROMOTING WOOD ACCUMULATION & BEAVER DAM ACTIVITY WITH POST-ASSISTED LOG STRUCTURES & BEAVER DAM ANALOGUES



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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.

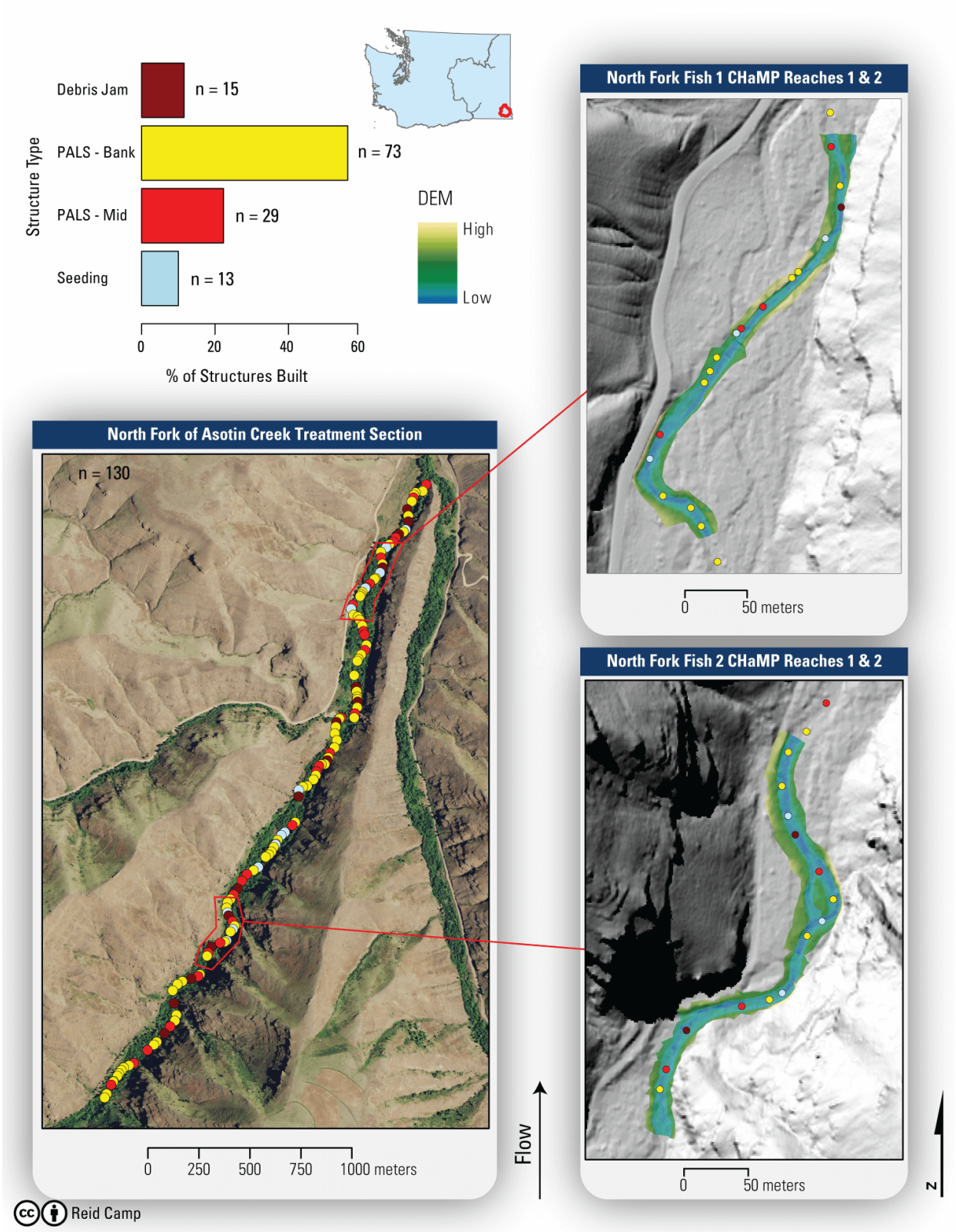

Figure 2 – An example of typical density of structure placement shown at the reach scale (upper and lower right) and at the riverscape scale in lower left. Not only are a high number of structures built, a diverse mix of structure types are used to achieve complex-level objectives (see Chapter 5 for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

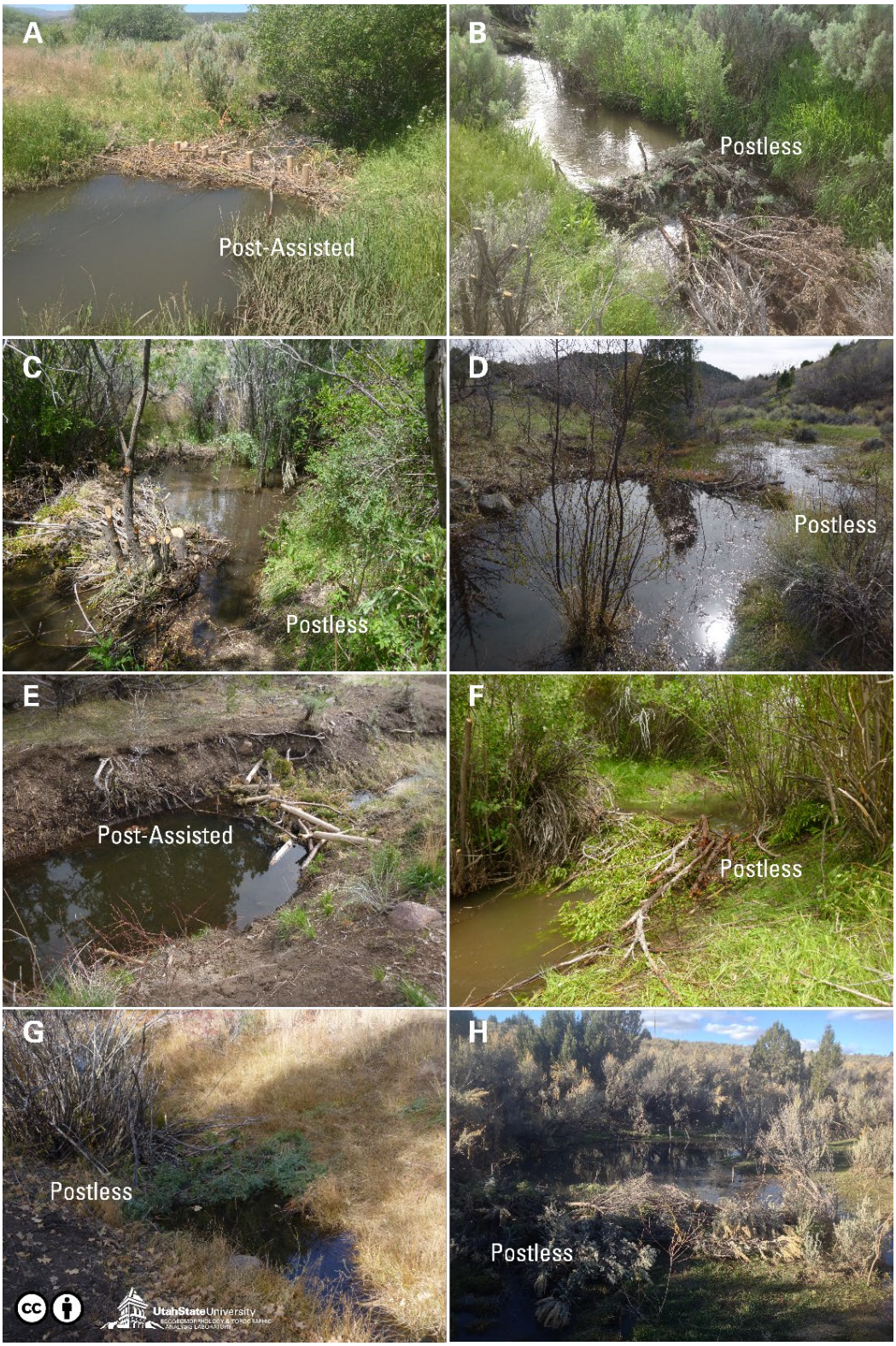

Figure 6 - Representative photos of the diversity of possible BDA shapes, sizes, locations, and building material. (A) post-assisted and willow weave (B) postless, sage and juniper (C) postless willow, using existing willow for stability (D) postless, juniper (E) post-assisted and juniper (F) postless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

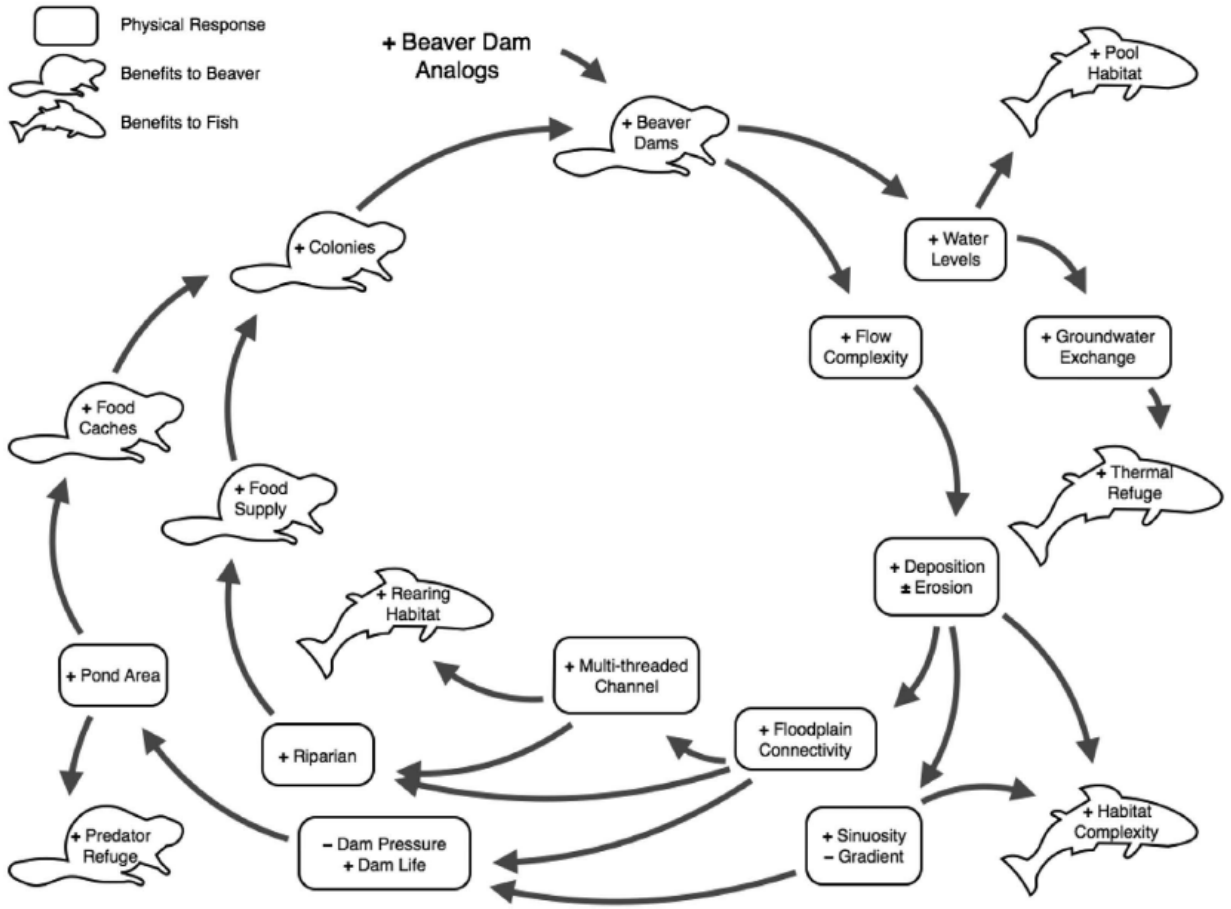

Figure 7 - From Bouwes et al. (2016b): Expected changes following the installation of beaver dam analogues (BDAs). Beaver-made dams and BDAs slow and increase the surface height of water upstream of the dam. Beaver ponds above, and plunge pools below dams change the plane bed channel to a reach of complex 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.

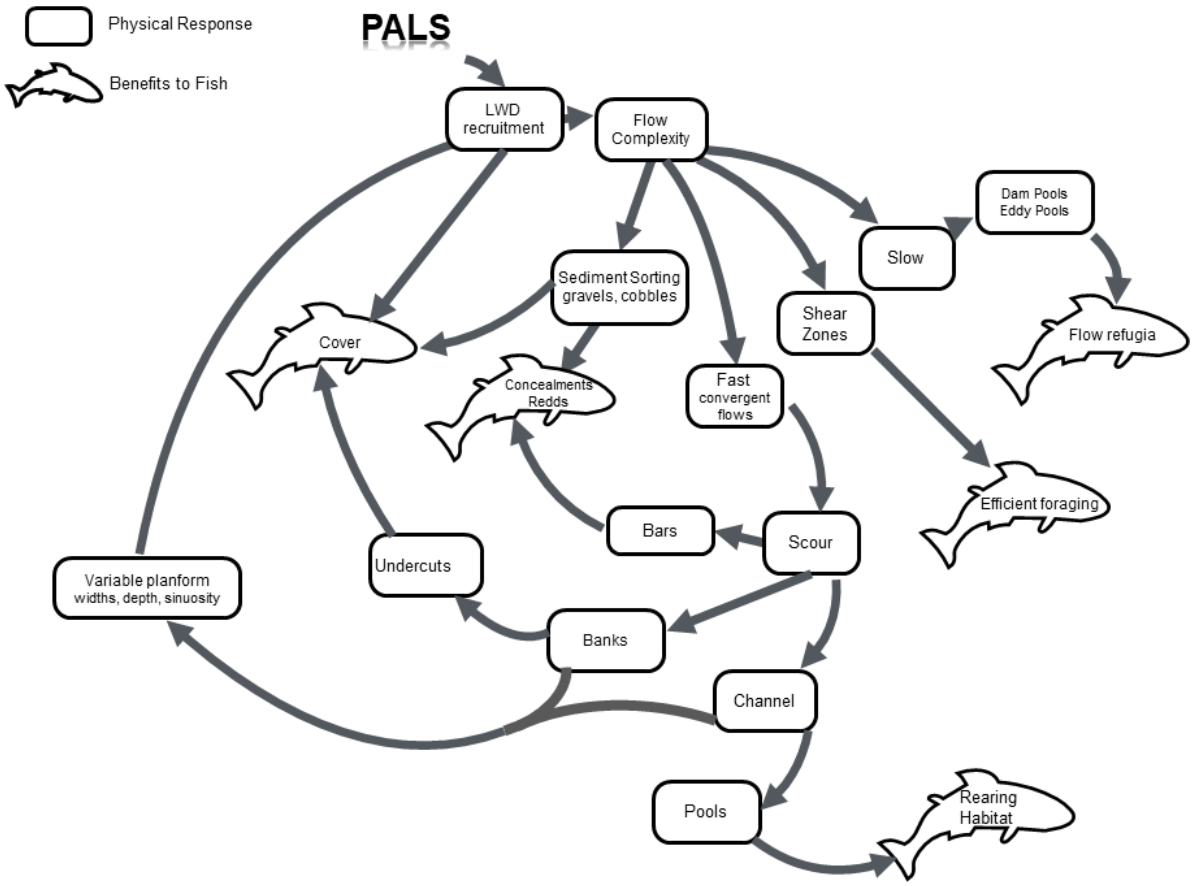

Figure 8 - Conceptual model used in the Asotin Intensively Monitored Watershed (IMW) study of the expected geomorphic and steelhead responses of adding post-assisted log structures (PALS). The increase wood loading by adding PALS is expected to increase flow complexity, creating: deposit and erosion 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.

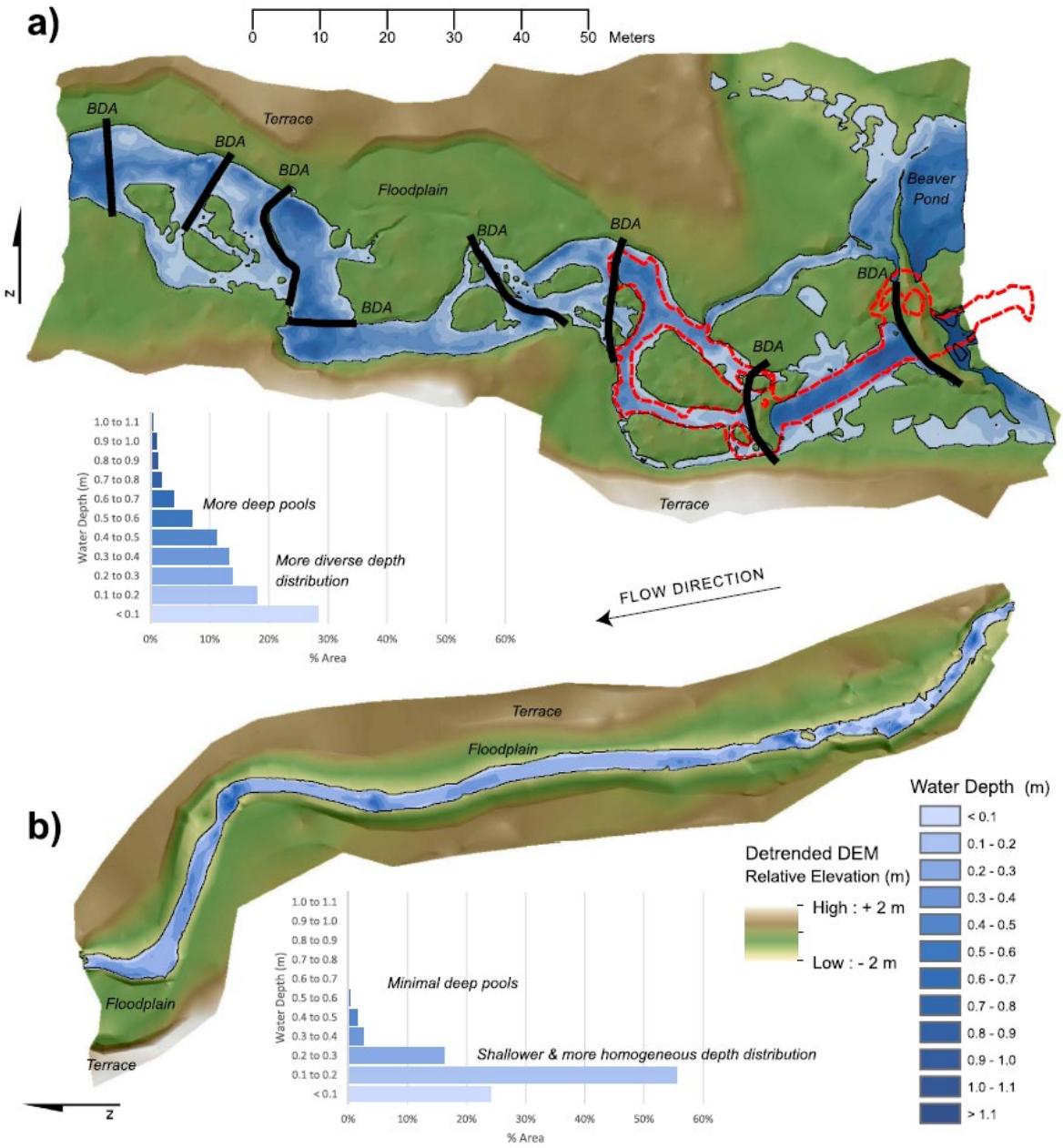

Figure 9 - Digital elevation models (DEMs) and water depth distributions for a A) typical reach with beaver dam analogues (BDAs) (i.e., successfully mimicking and promoting beaver dam activity) and B) without BDAs (i.e., structurally-starved control) from Bouwes et al. (2016b). Treatment area with BDAs 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.

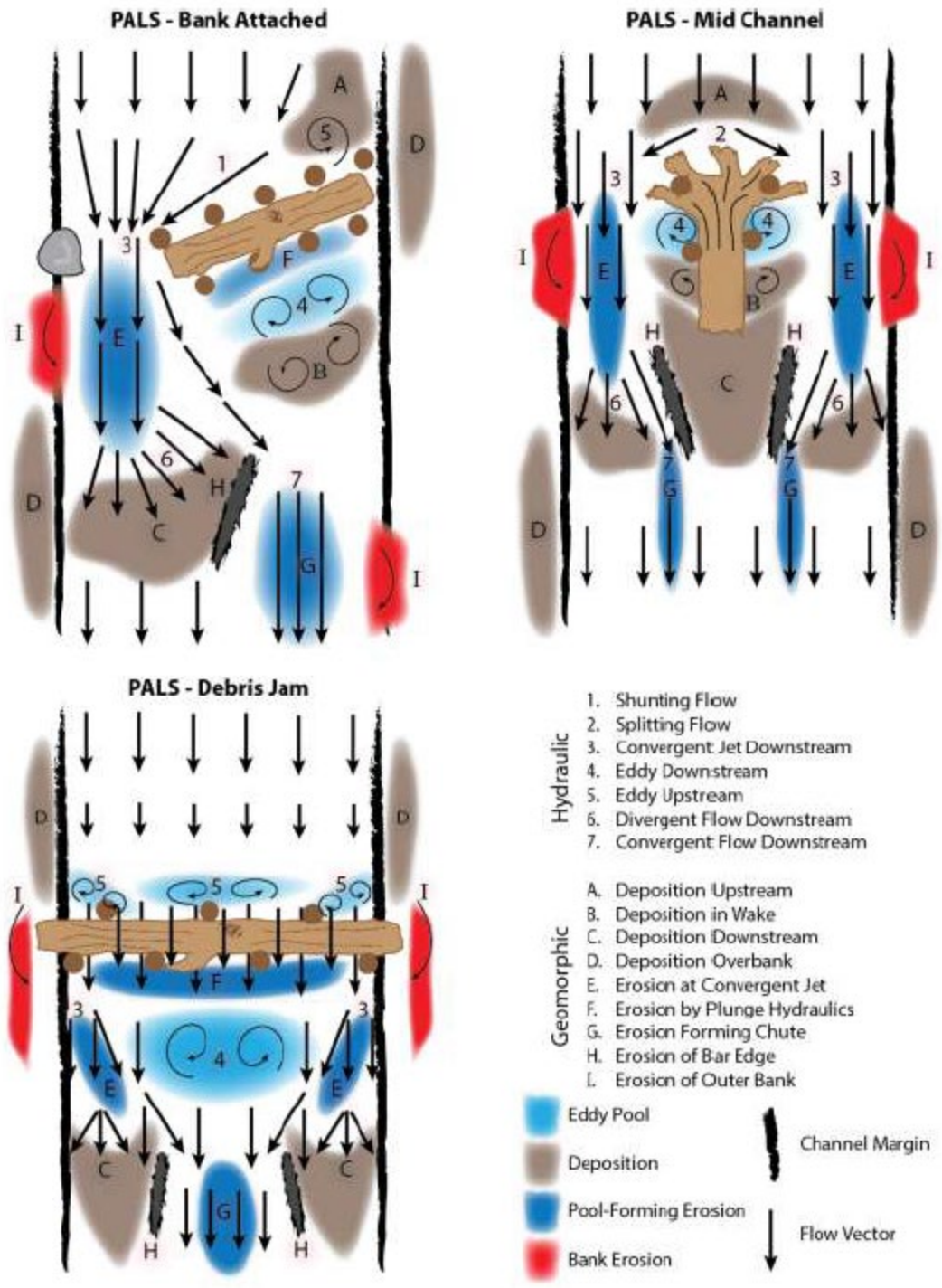

Figure 10 - Hypothesized hydraulic and geomorphic responses associated with bank-attached, mid-channel, and debris jam post-assisted log structures (PALS) from Figure 3.5 from Camp (2015a). Note: what is labeled as 'debris-jam' is referred to in this chapter as 'channel-spanning'.

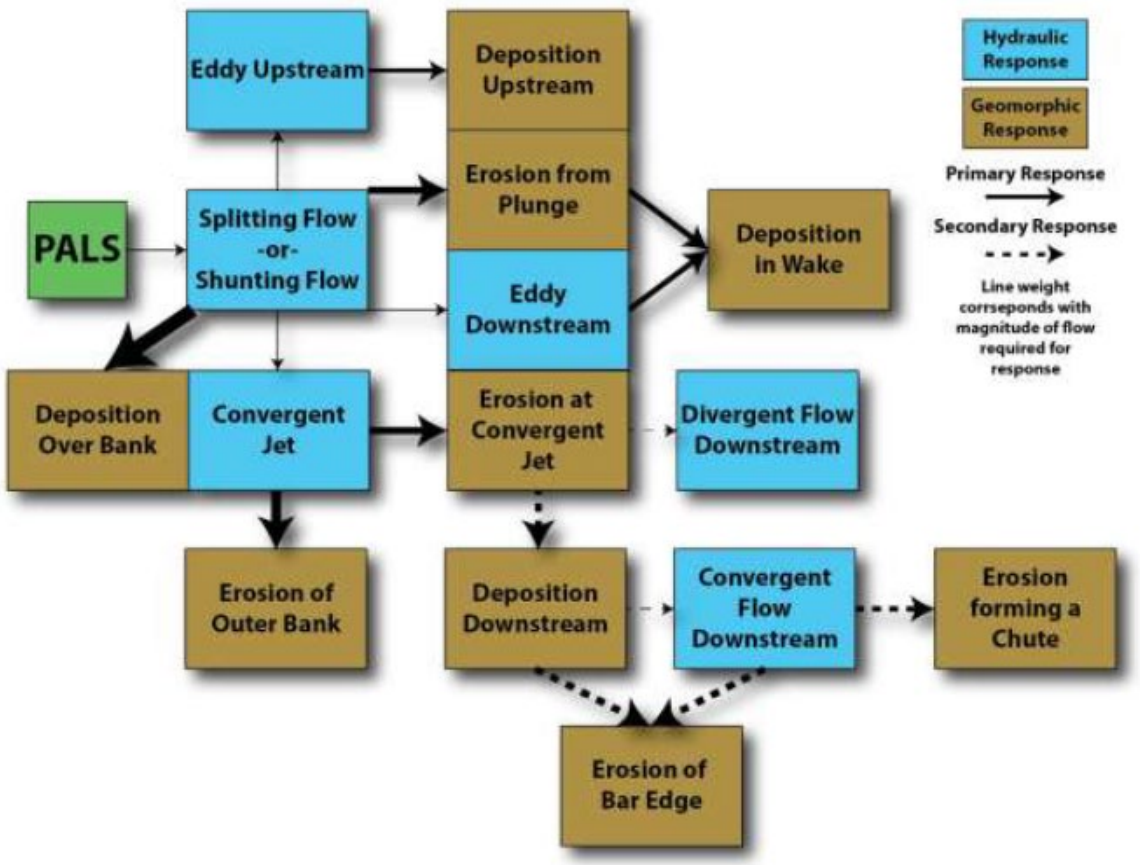

Figure 11 - Observed hydraulic and geomorphic responses associated with deflector and mid-channel PALS relative to the magnitude of flows from Camp (2015a). Deflectors (bank-attached) PALs shunt flow, and mid-channel PALS split flow (channel-spanning PALS not depicted). The thickness of the arrows (responses) 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.

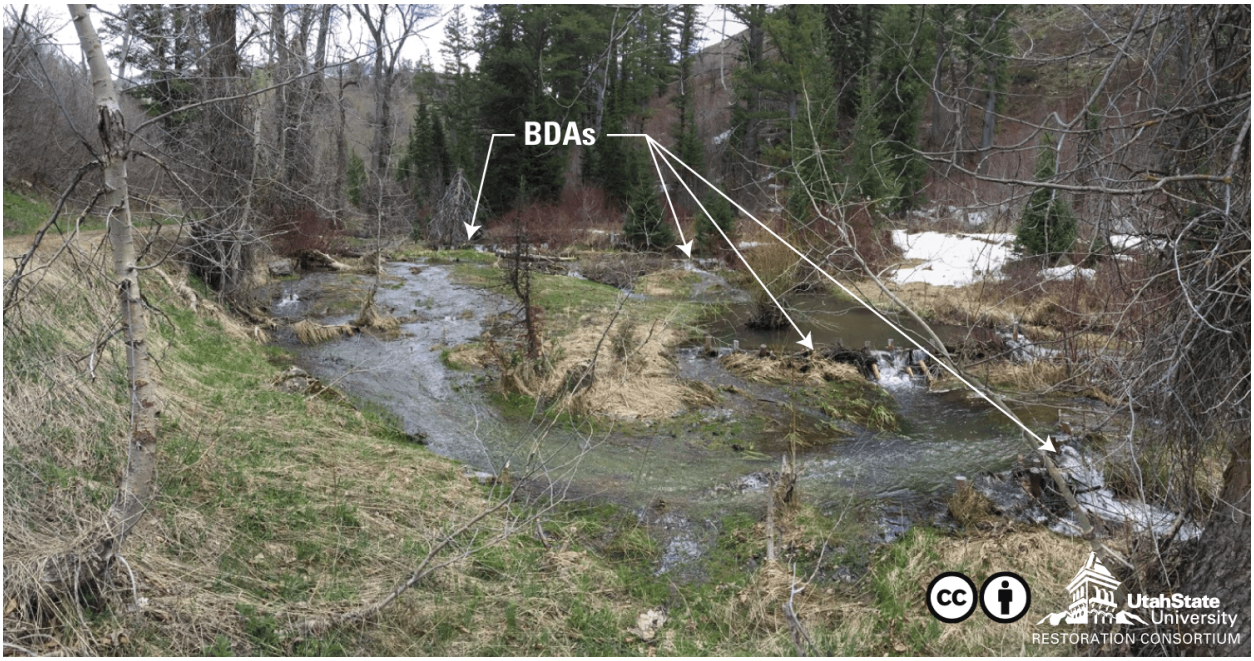

Figure 12 – Complex of four BDAs forcing overbank flows and inundation of the floodplain where the project goal was to restore the stream to perennial flows. The same magnitude flows (spring-runoff here) prior to installation of these BDAs had no overbank flow.

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).

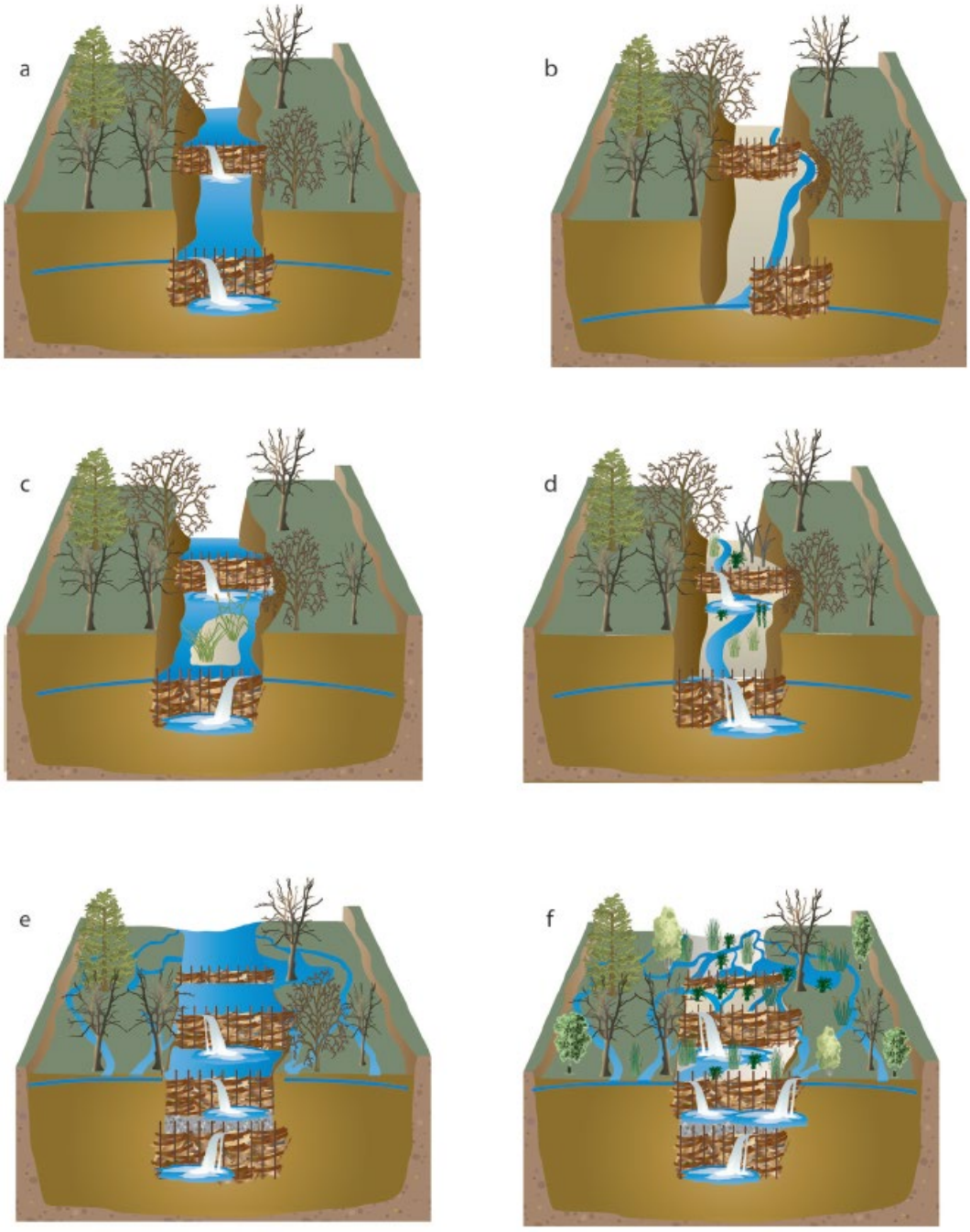

Figure 13 – Expected geomorphic responses following the Cluer and Thorne (2013) channel evolution model (from Stage 3 to 0) after the installation (a) of BDAs, their initial 'failure' by end-cutting (b), subsequent repair (c) and aggradation leading to floodplain reconnection in an incised system. Figure 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.

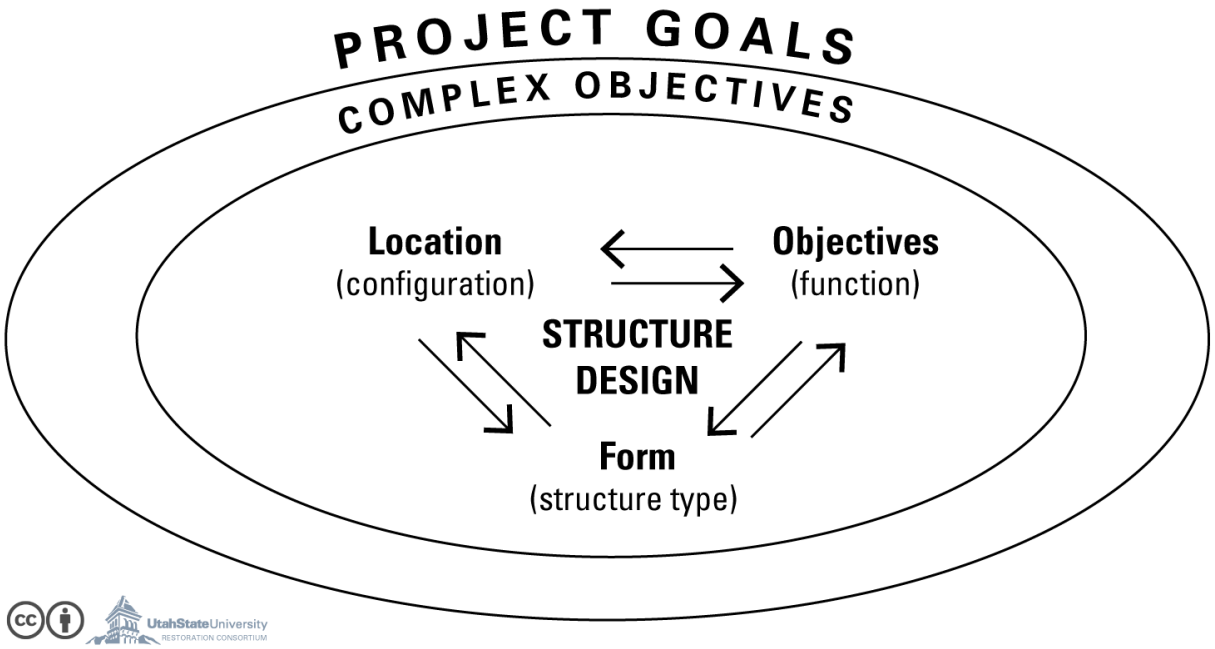

Figure 14 - Structure design is informed by relative location, (i.e., structure configuration within a complex), structure objectives (the function) and form (structure type, size, shape).

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.

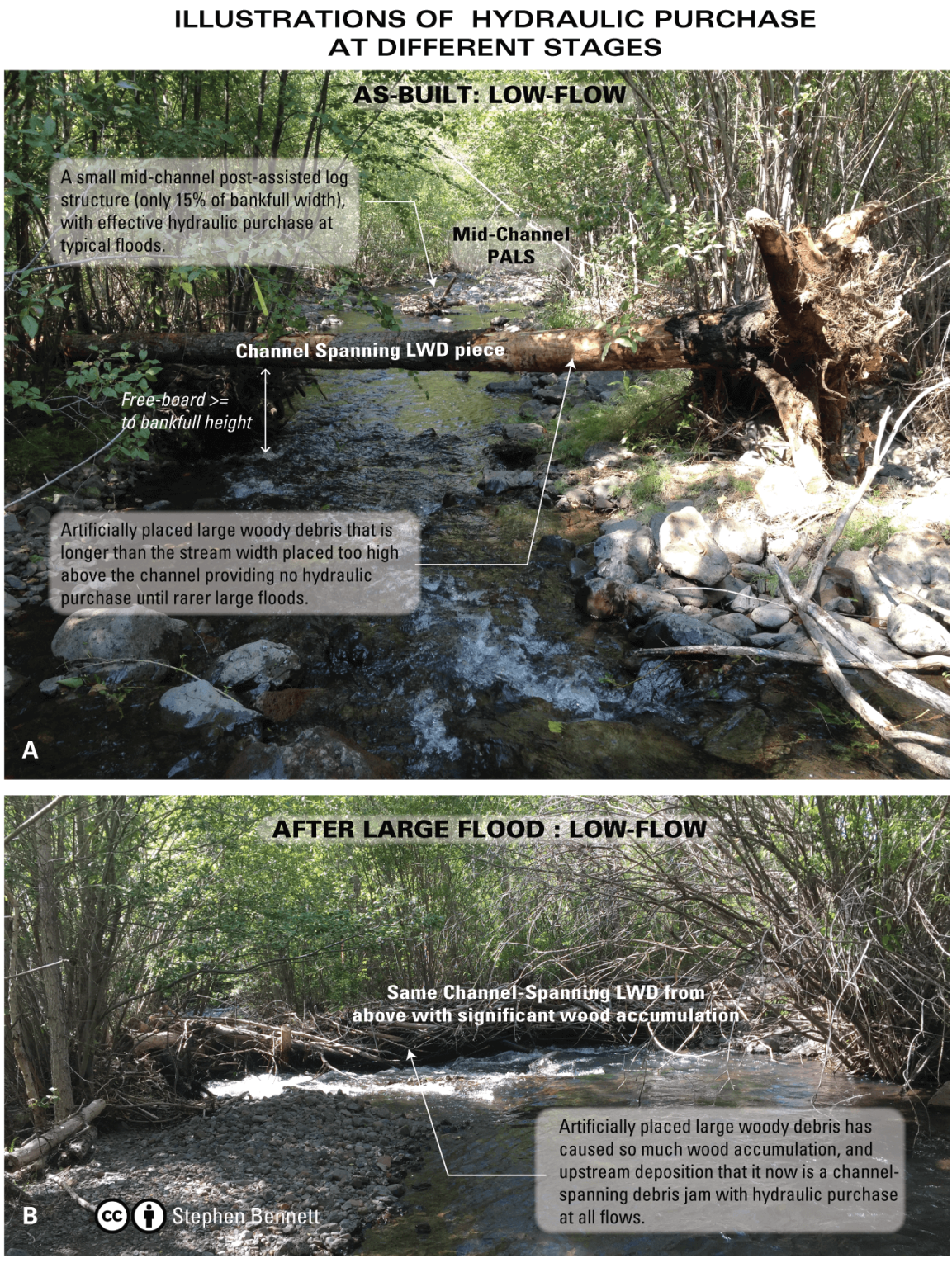

Figure 15 – A key placement consideration is defining at what flow stage the structure will engage with hydraulics or obstruct flows (i.e., hydraulic purchase). At the design stage, there is a choice about whether to build for immediate (i.e., low-flow) hydraulic purchase (e.g., mid-channel PALS in background 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).

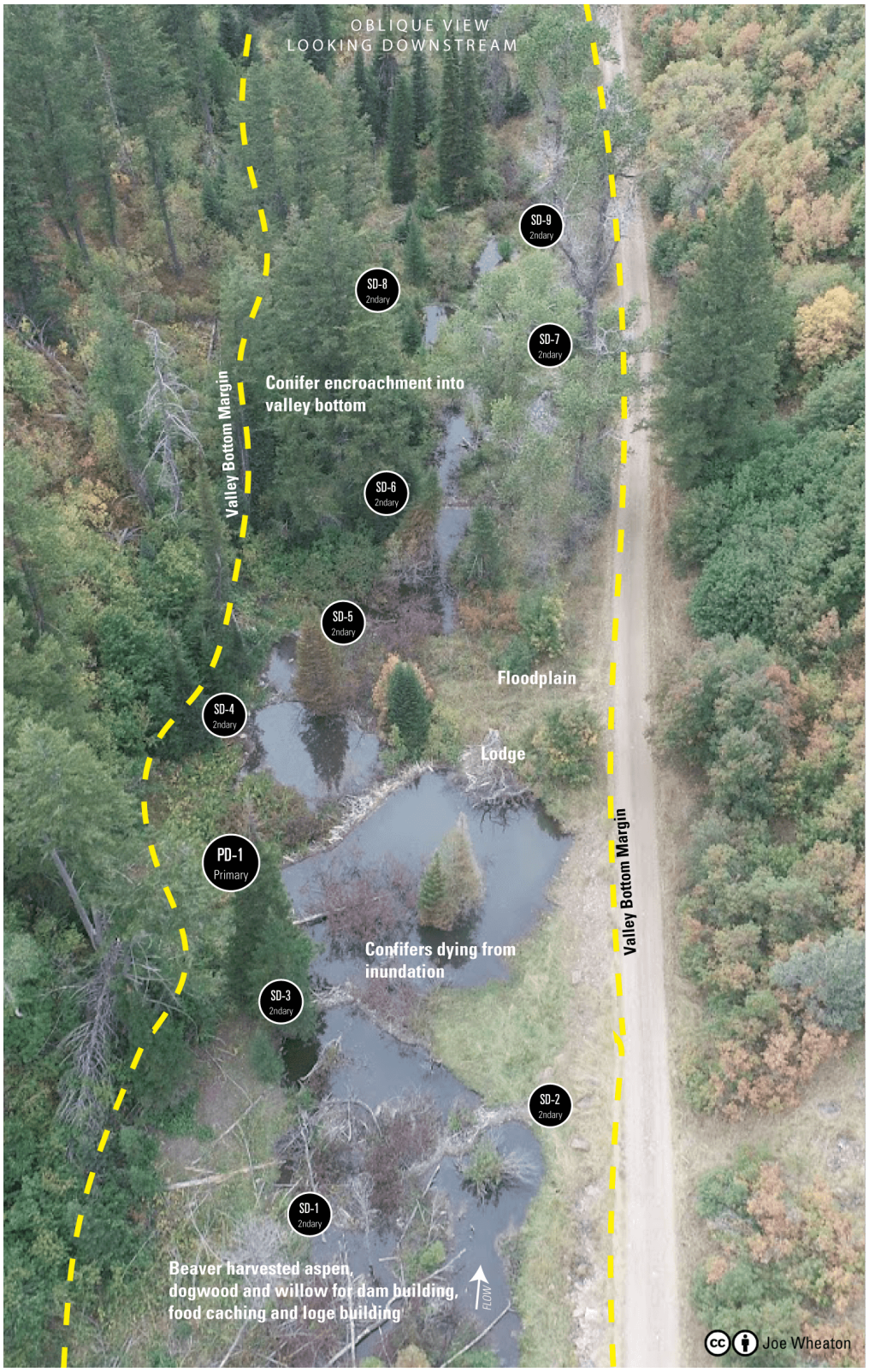

Figure 16 – The natural beaver dam complex should be the inspiration for designing a complex. Like natural beaver dams and accumulations of large woody debris, low-tech structures are more likely to achieve restoration goals when built to work together to influence hydraulic, hydrologic and geomorphic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

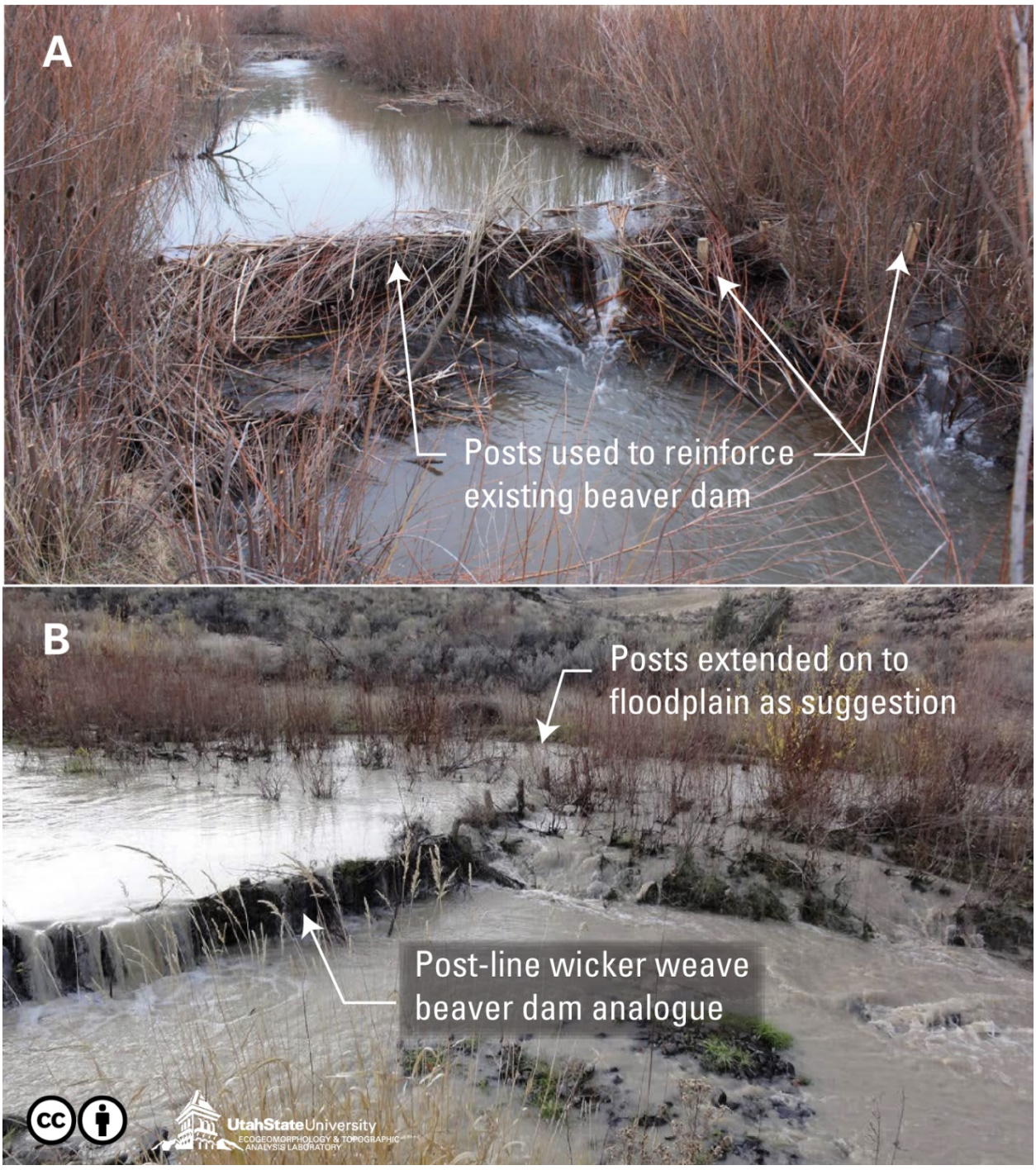

Figure 18 – Reinforced natural beaver dam (top) and post-line wicker weave BDA built in Bridge Creek (bottom).

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.

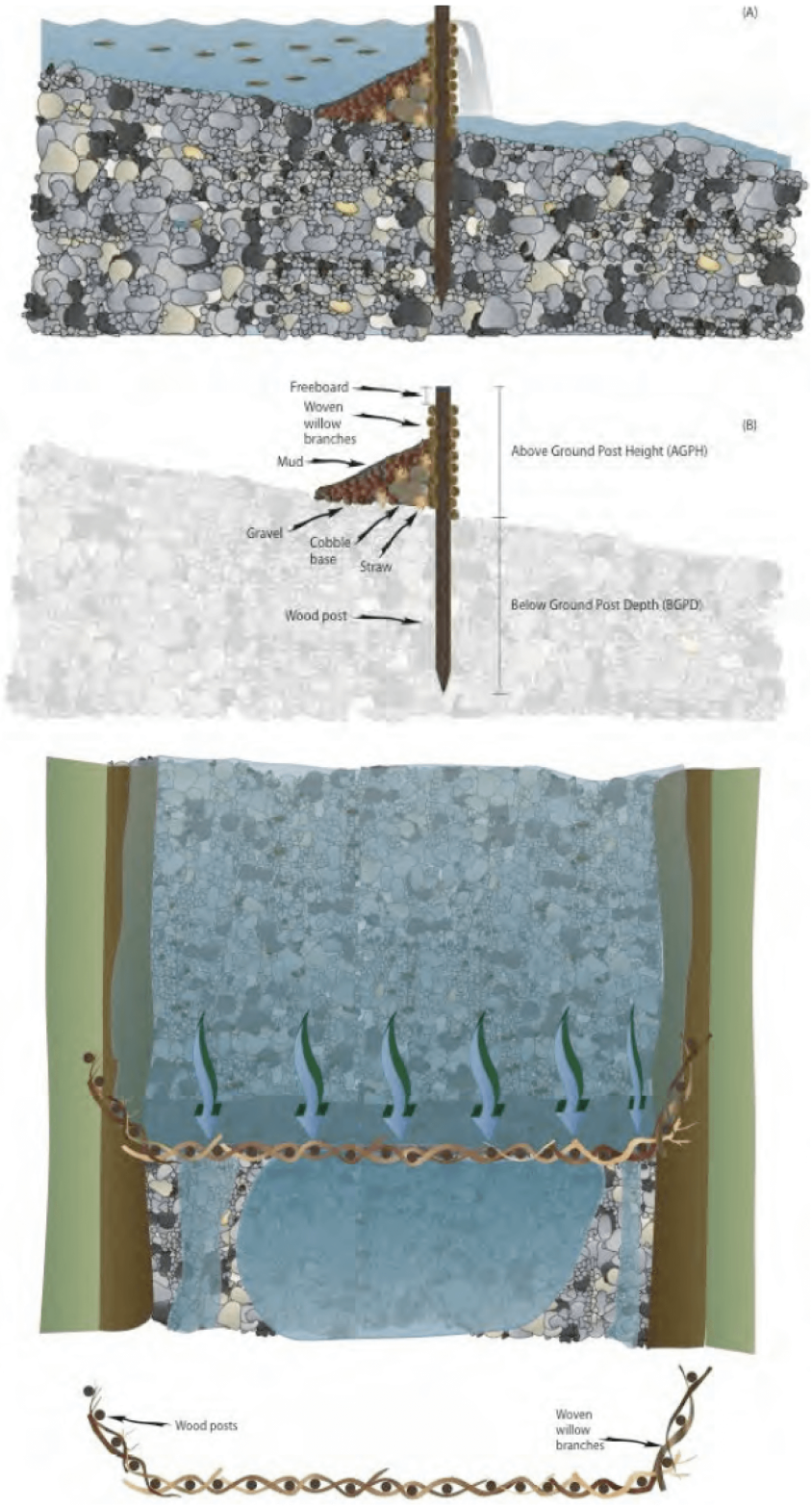

Figure 20 - Illustration of the one of the BDS structure types. Note the use of posts and a tight wicker weave between posts. Figure from Pollock et al. (2015). This is essentially a post-line wicker weave.

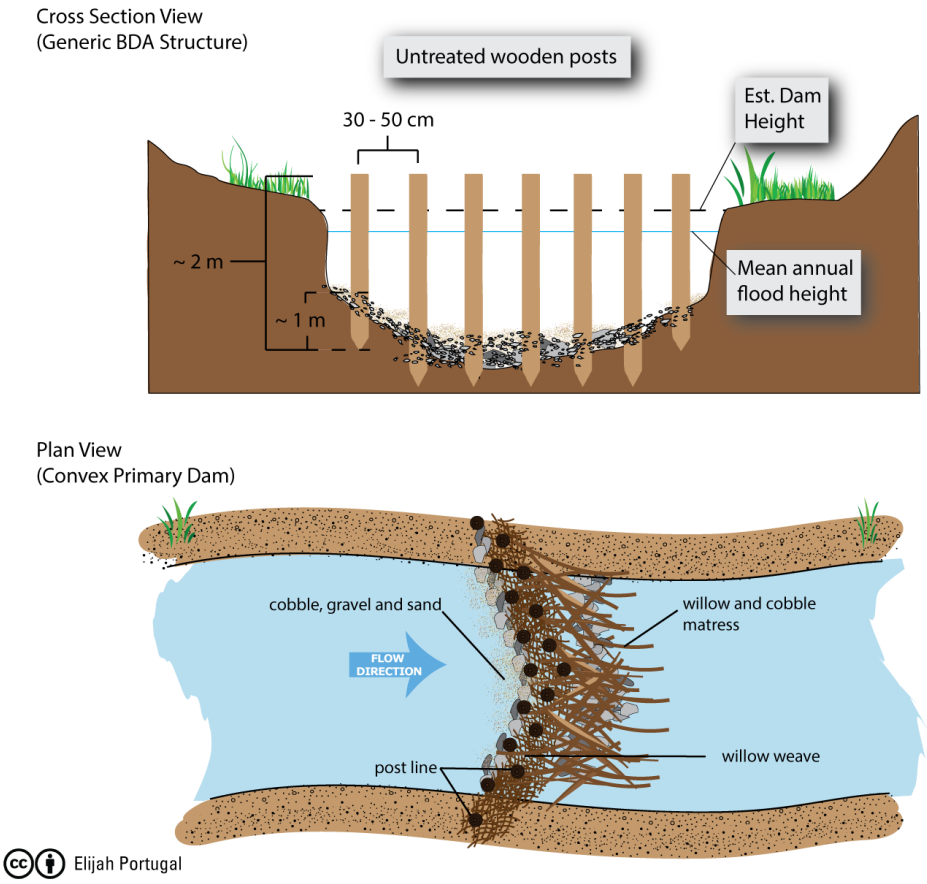

Figure 21 – Conceptual illustration of BDAs incorporating a downstream "mattress" and double post line. In practice BDAs can be built with or without posts and using a range of natural materials. Illustration credit: Elijah Portugal.

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).

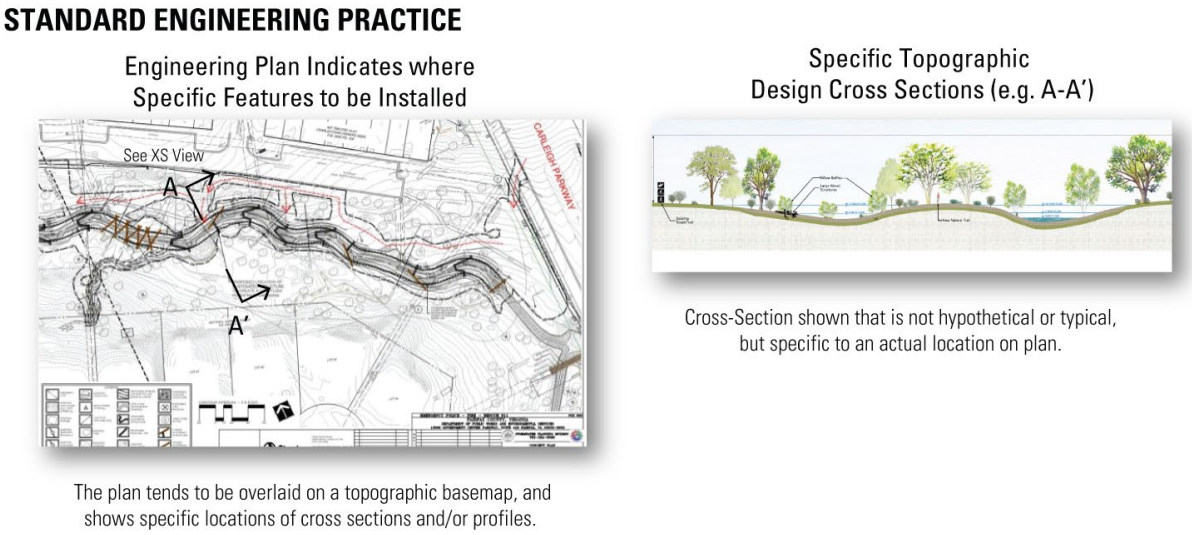

Figure 22 – In both standard engineering practice and low-tech practice, schematics as provided in this appendix are used. However, standard engineering practices tends to use plans on top of topographic basemap, from which specific topographic cross sections or elevation profiles are derived. In low-tech 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

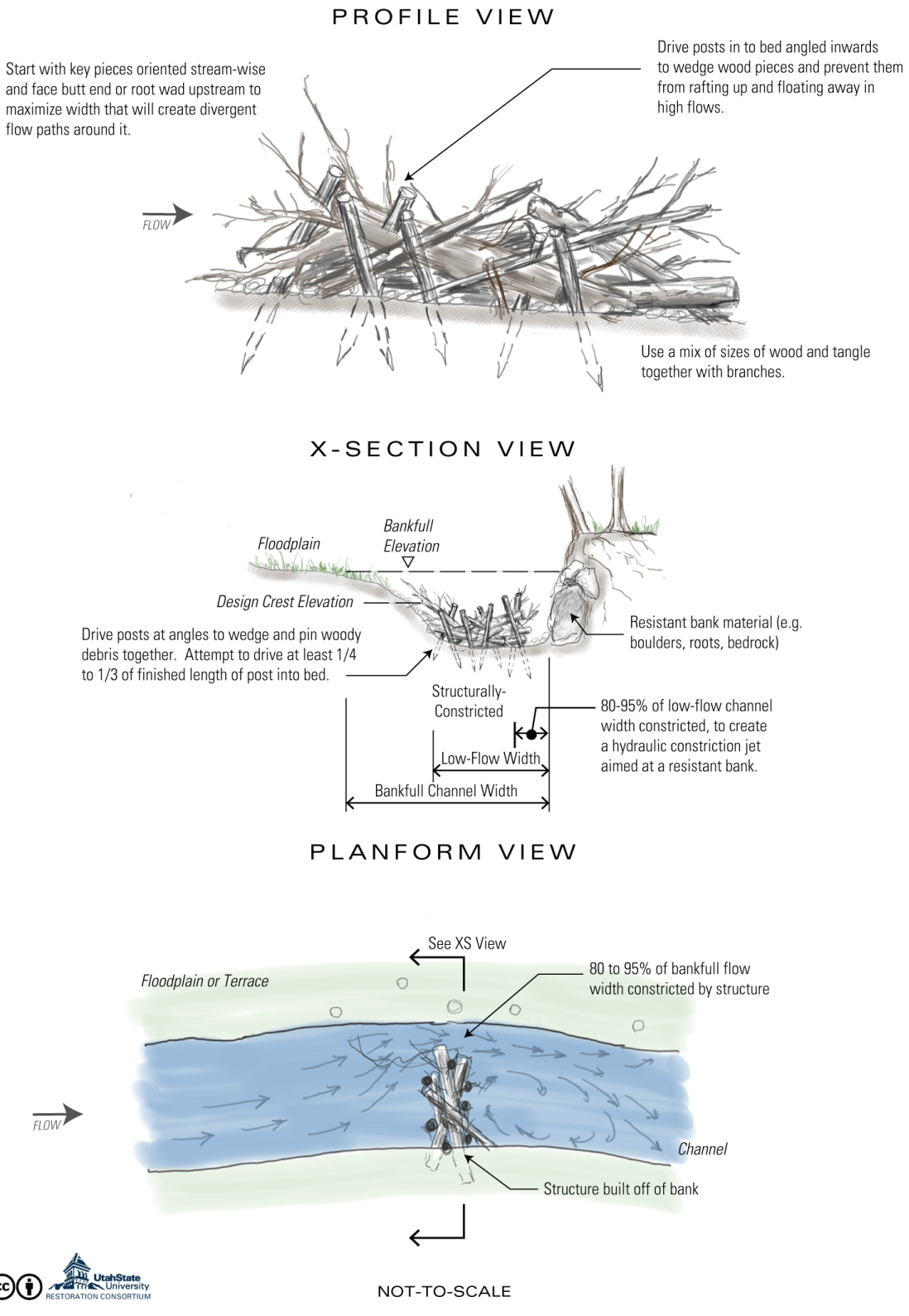

Figure 23 – Typical schematic of a bank-attached PALS directed at a resistant bank intended to force a constriction jet.

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

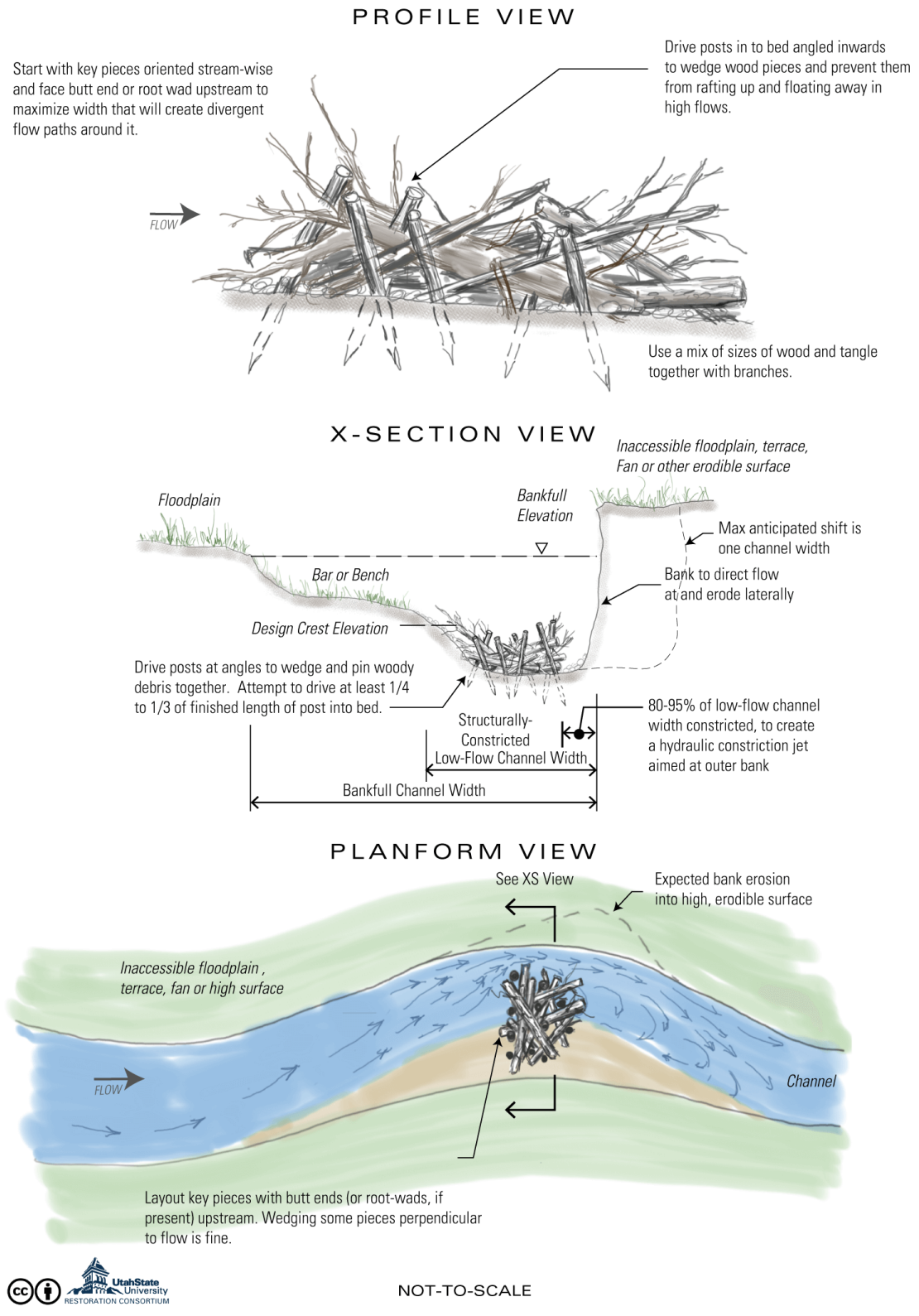

Figure 24 – Typical schematic sketches of a bank-attached PALS intended to blast and erode a bank to recruit sediment and/or wood.

Mid-Channel PALS

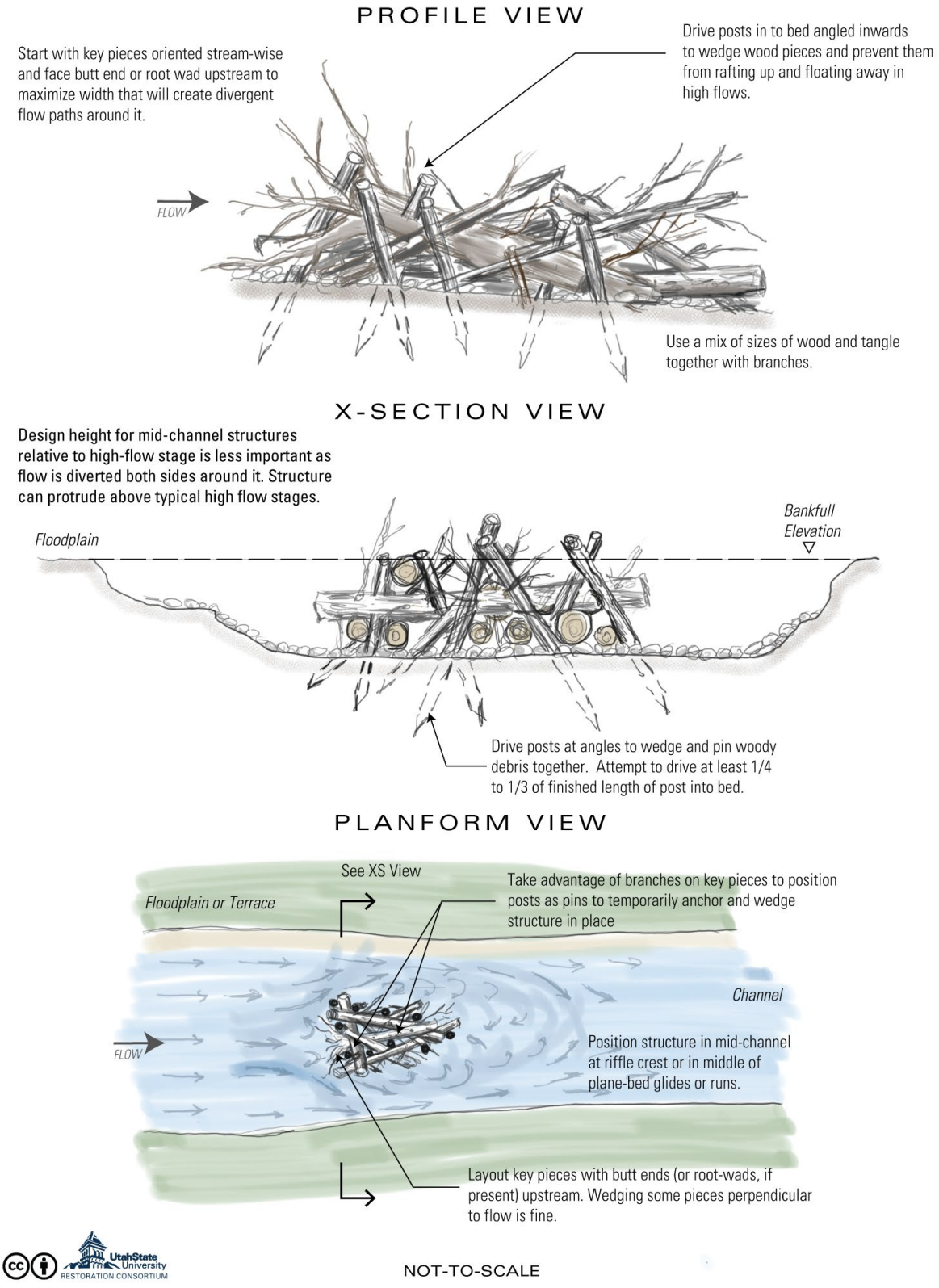

Figure 25 – Typical schematics of a mid-channel PALS.

Channel Spanning PALS

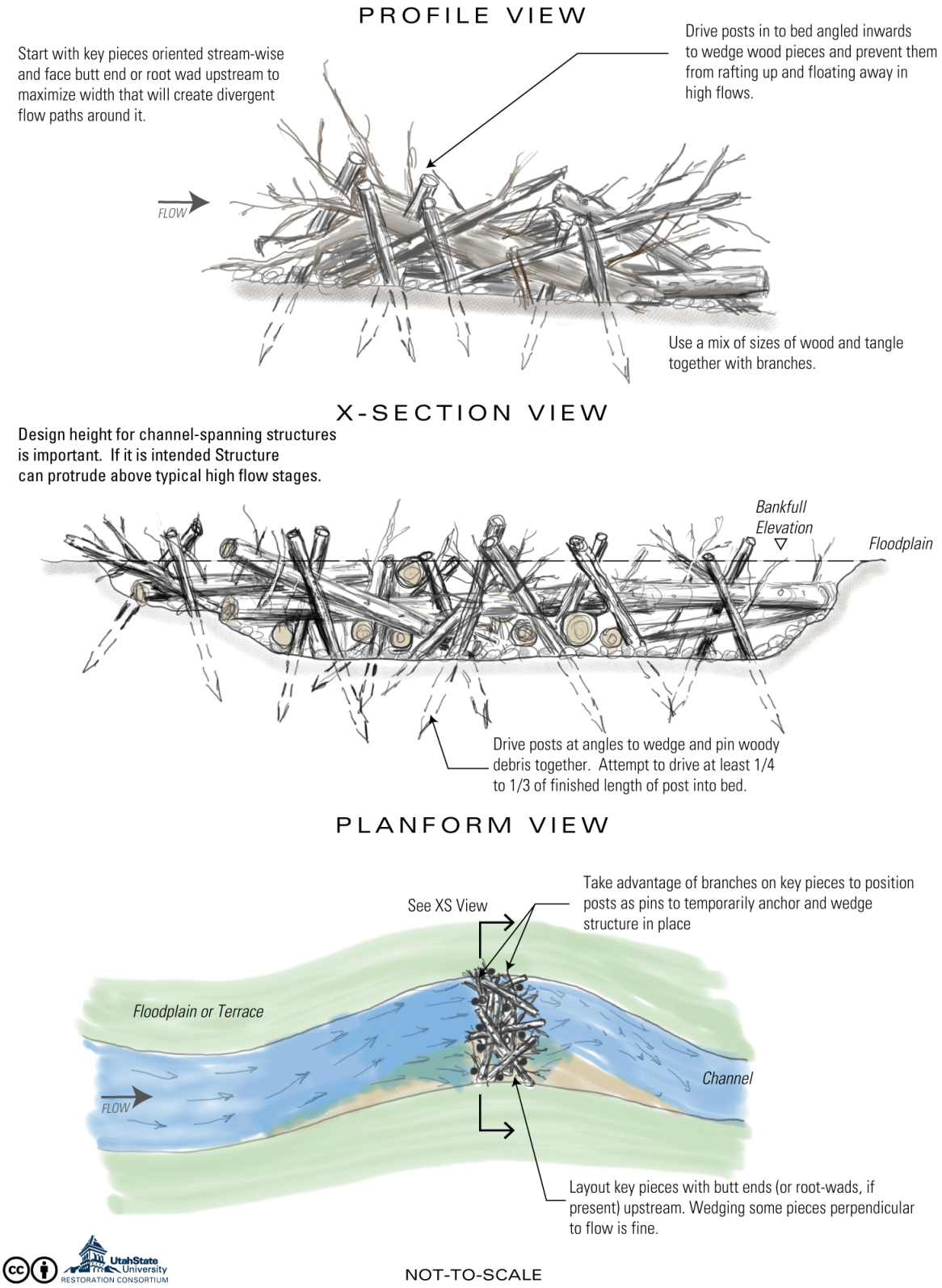

Figure 26 - Typical schematics of a channel-spanning PALS.

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.

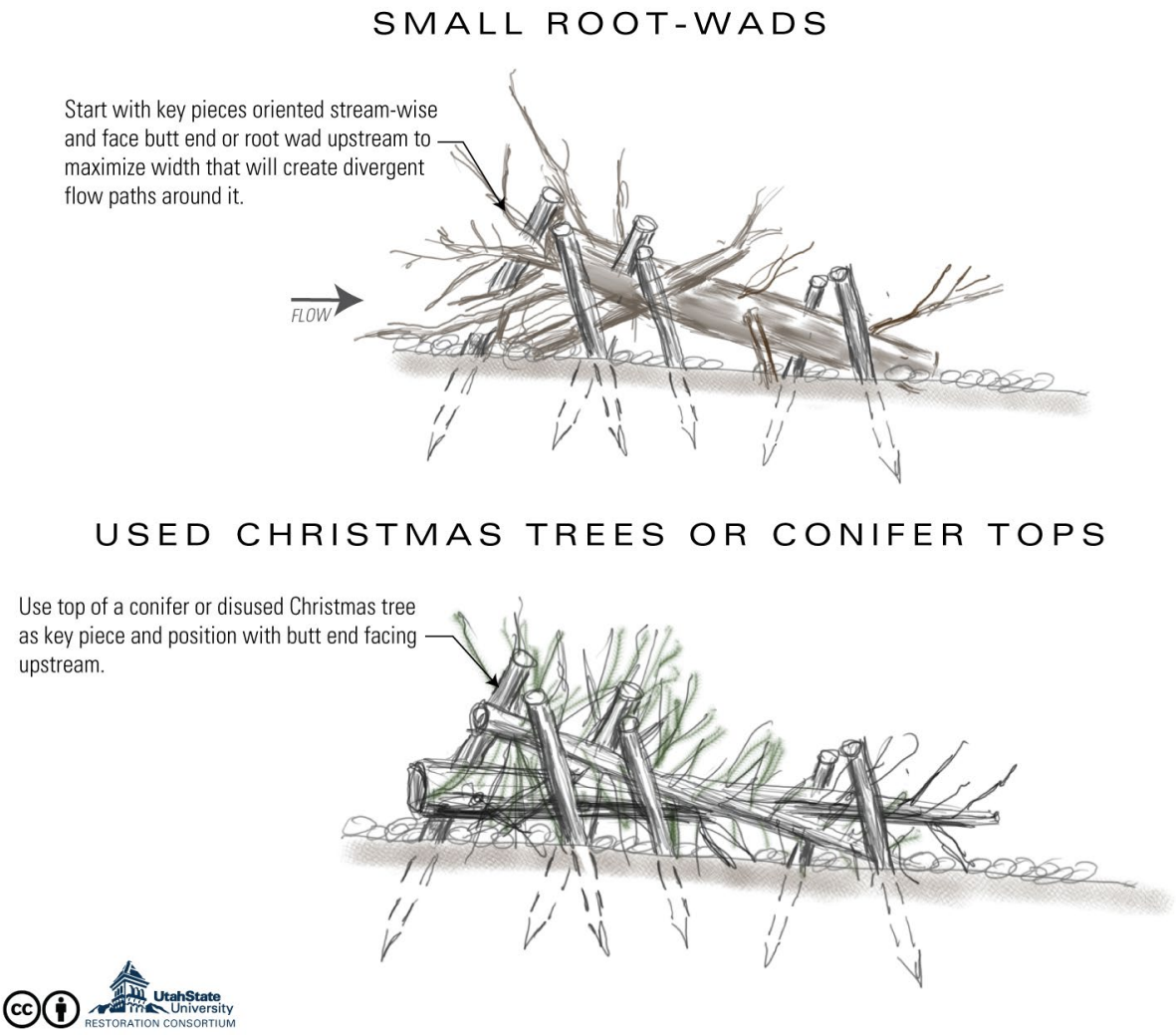

Figure 27 – Ideas for material substitutions with small root-wads and discarded/recycled Christmas trees or tops off of conifers. Smaller PALS like these can also be helpful to start with in streams and rivers with higher flow, to build something small and get it anchored, and then start piling on more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

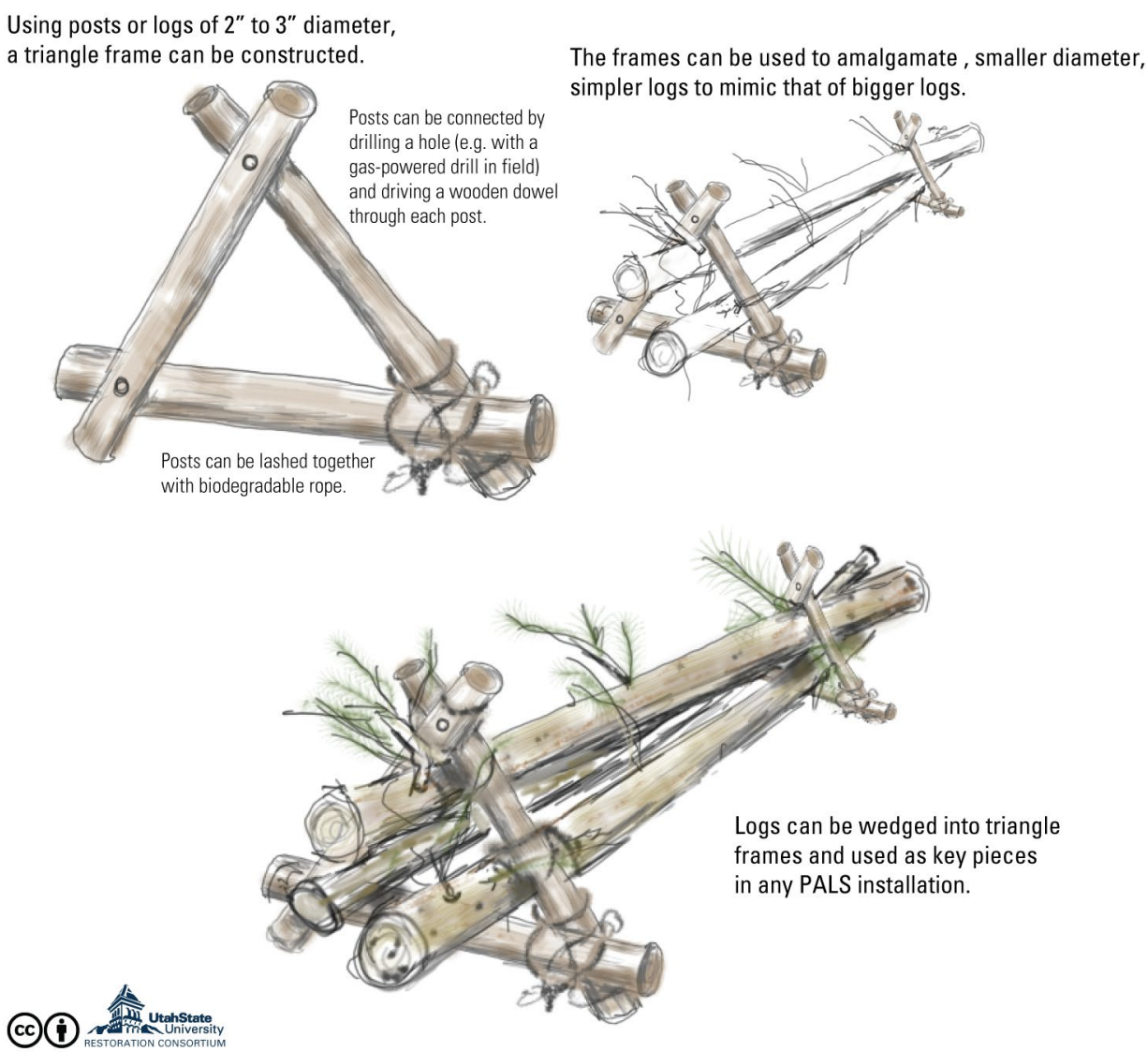

Figure 29 –Smaller logs can be effectively combined into bigger pieces with simple triangular frames. Frames can be sized to hold the smaller logs together, and connected with simple wooden dowels or, biodegradable rope lashing the frame and logs together. These structures can be especially useful where 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

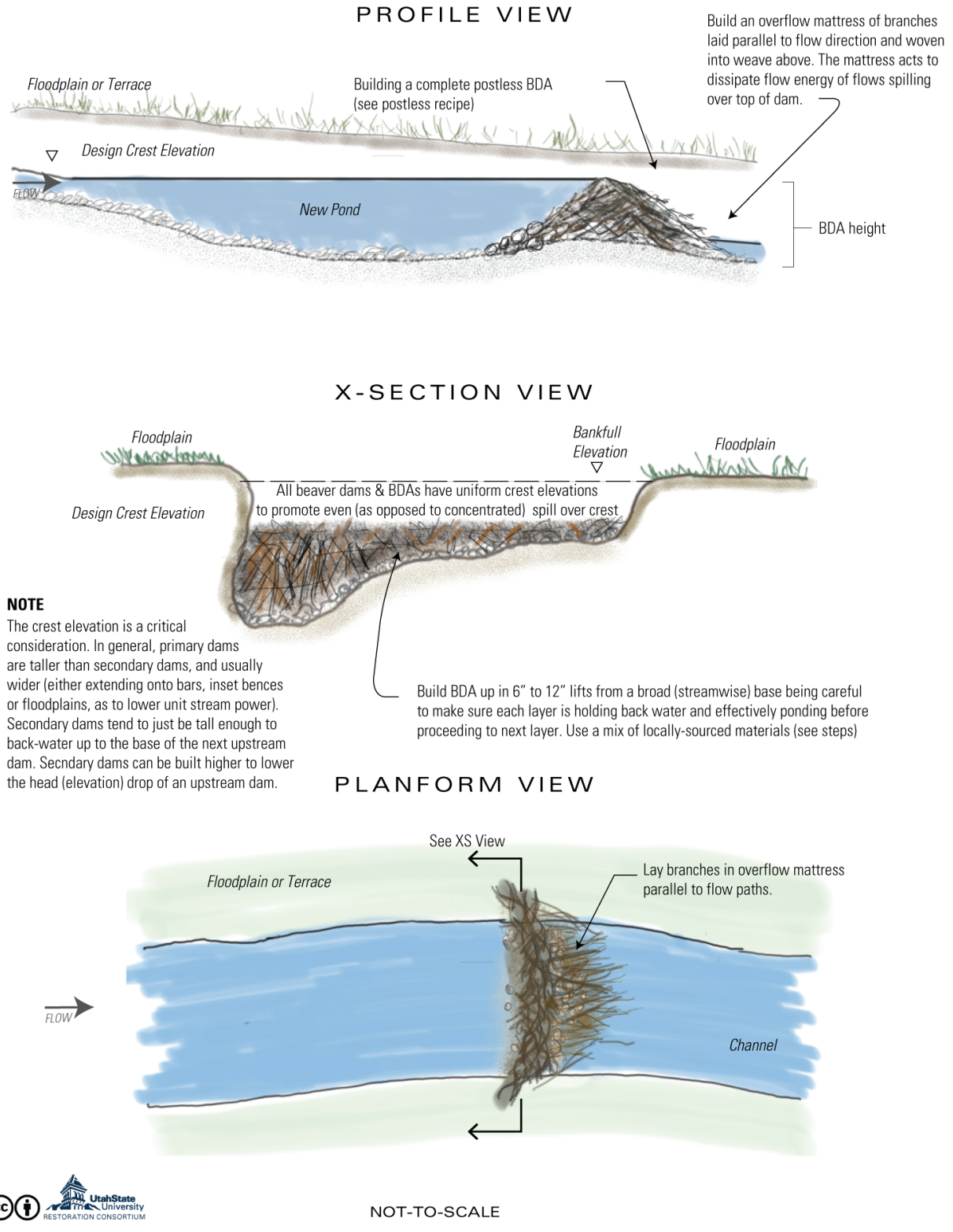

Figure 30 – Typical schematic sketches of a postless BDA.

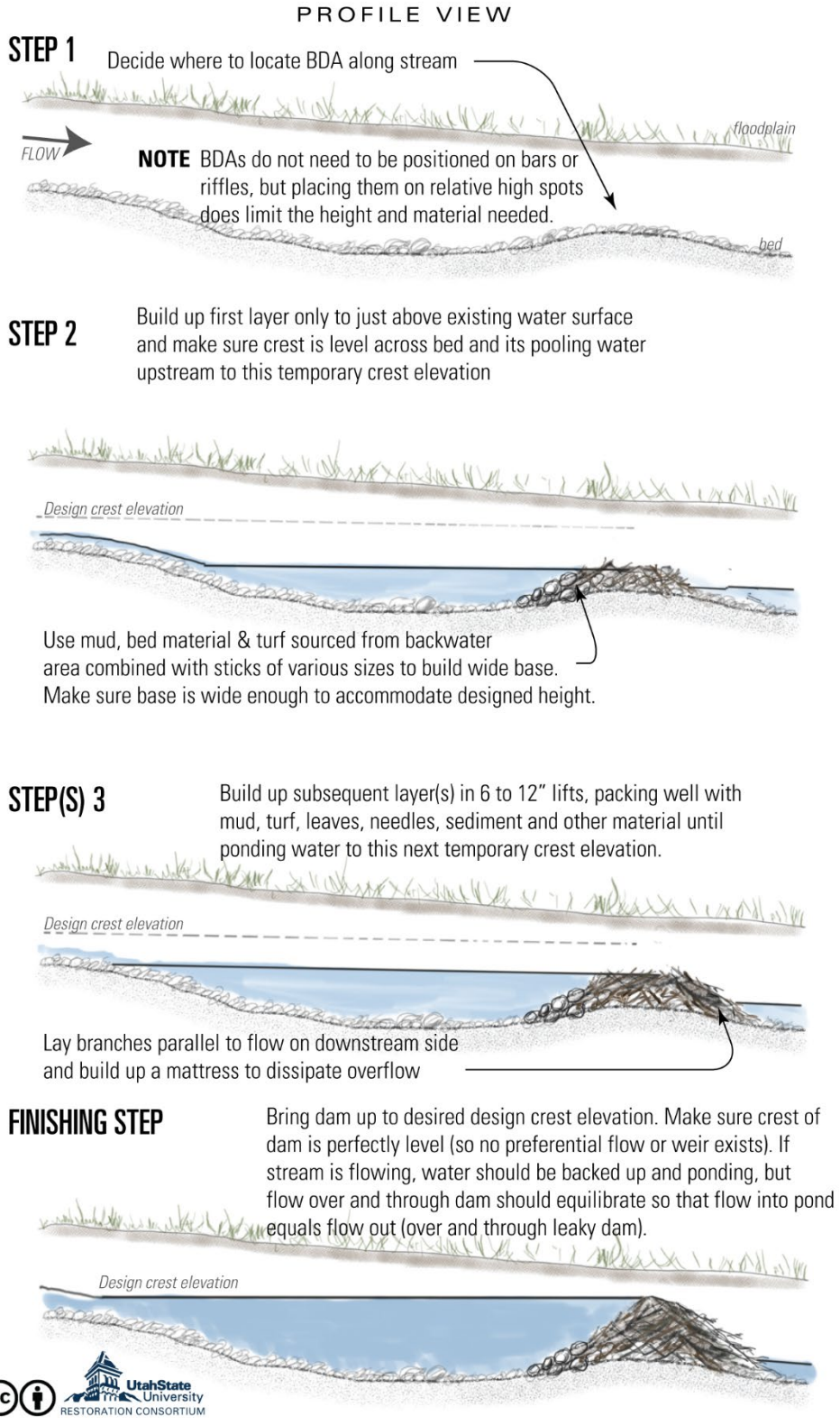

Figure 31 – Sequence for building postless BDAs, build up in 6" to 12" lifts, slowly, like beaver do. Make sure that your lifts are level, and water is backed up sufficiently that is flowing over the crest evenly (as opposed to through or under the dam), and the base is broad, before building up to your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

Postless BDA with Key Pieces Details

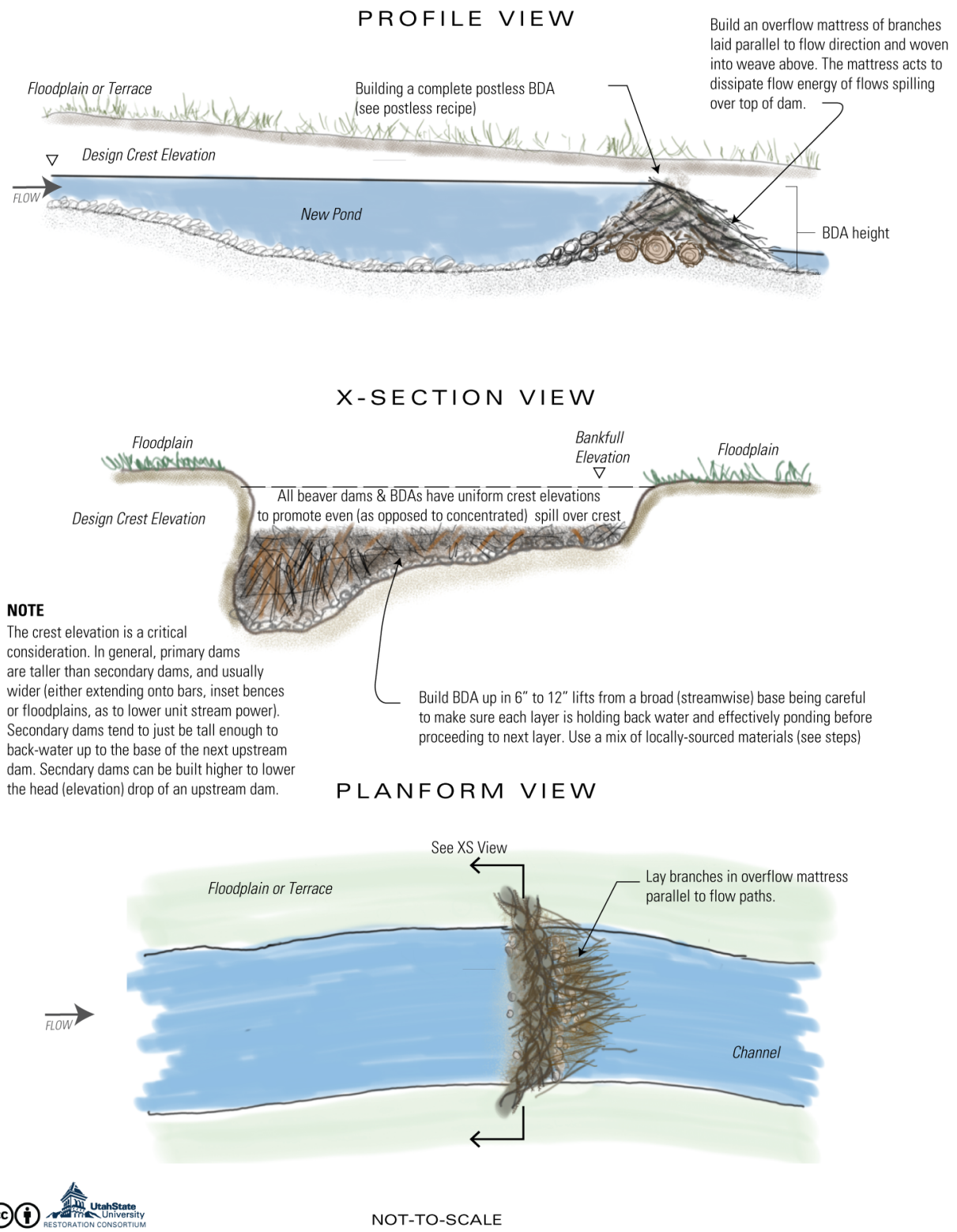

Figure 32 – Typical schematic sketches of a postless BDA with key pieces used in base.

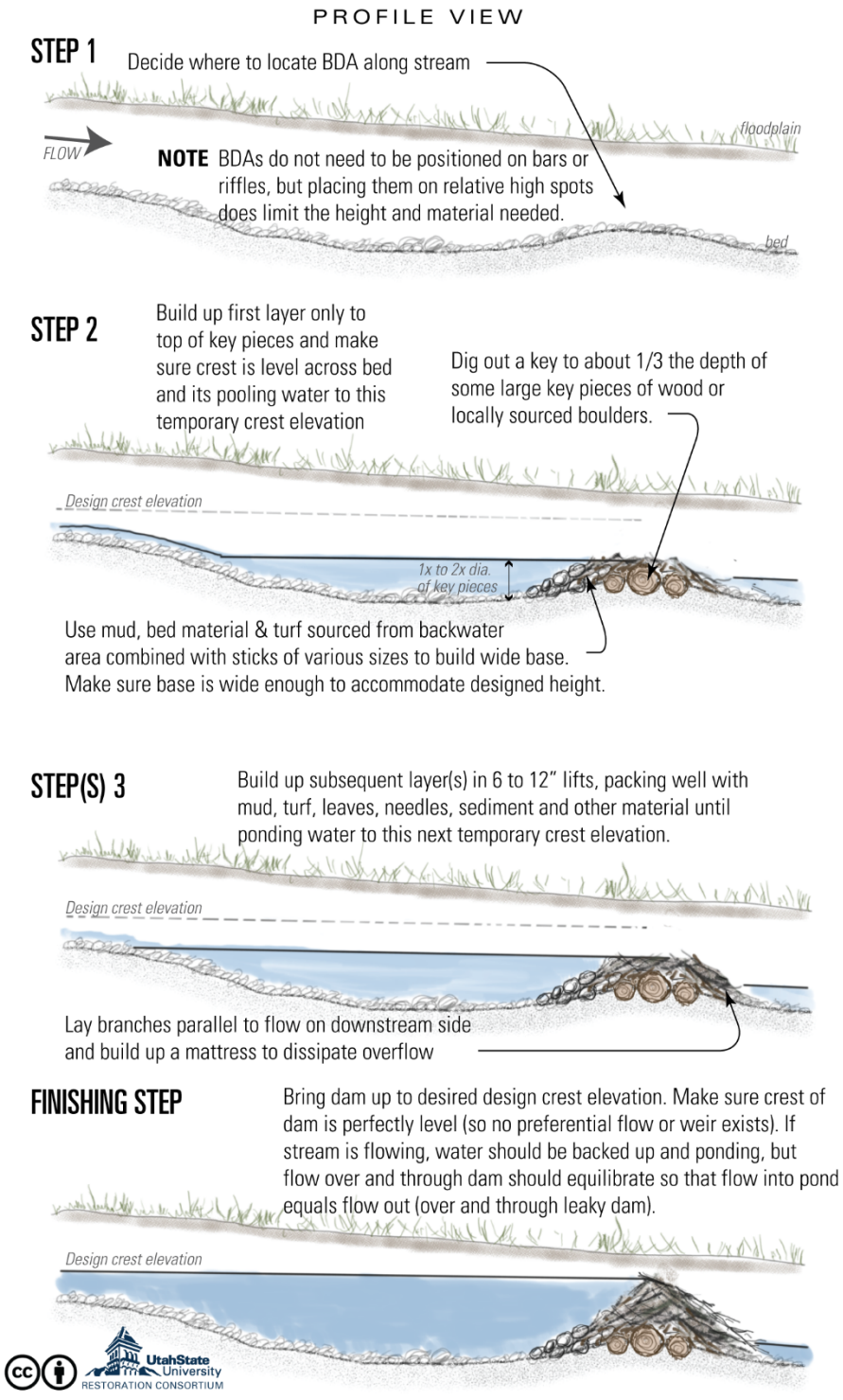

Figure 33 – Sequence for building postless BDAs with key pieces, build up in 6" to 12" lifts, slowly, like beaver do. Make sure that your lifts are level, and water is backed up sufficiently that is flowing over the crest evenly (as opposed to through or under the dam), and the base is broad, before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

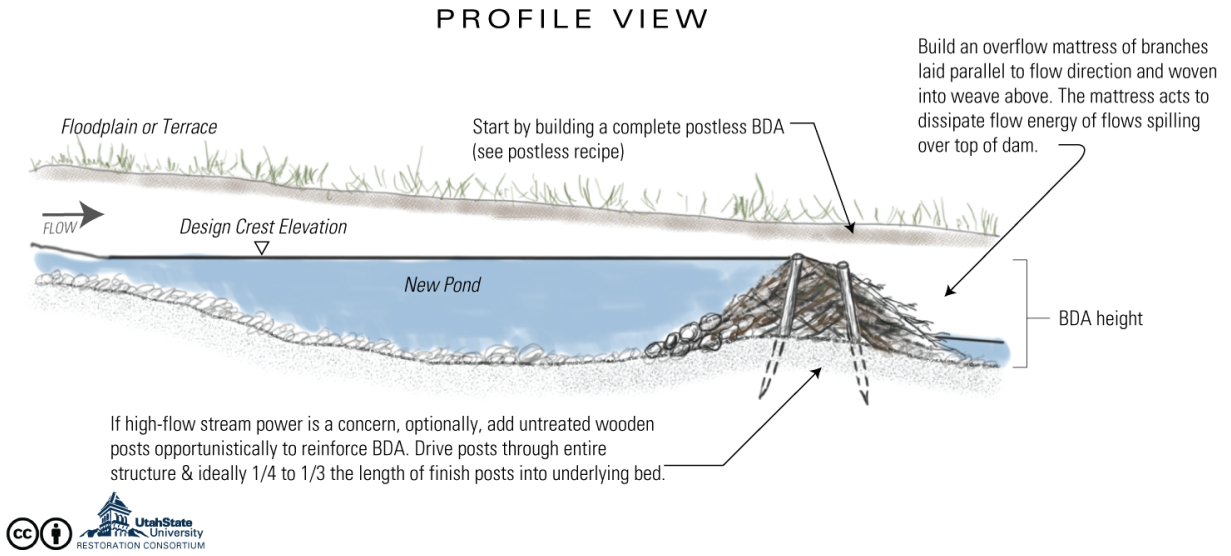

Figure 34 - Profile schematic of post-assisted BDA. If you think you need posts, our preferred approach is to build a postless BDA as per Figure 31, and then reinforce after the fact with some posts driven through the structure.

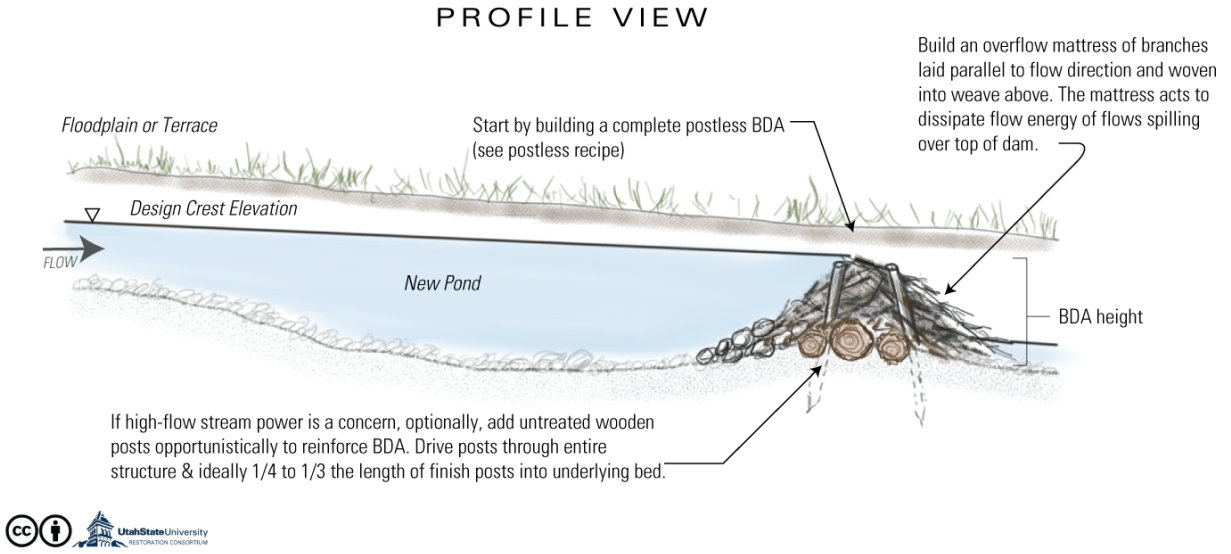

Figure 35 – Profile schematic of post-assisted BDA with key pieces. If you think you need posts, our preferred approach is to build a postless BDA as per Figure 33, and then reinforce after the fact with some posts driven through the structure.

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).

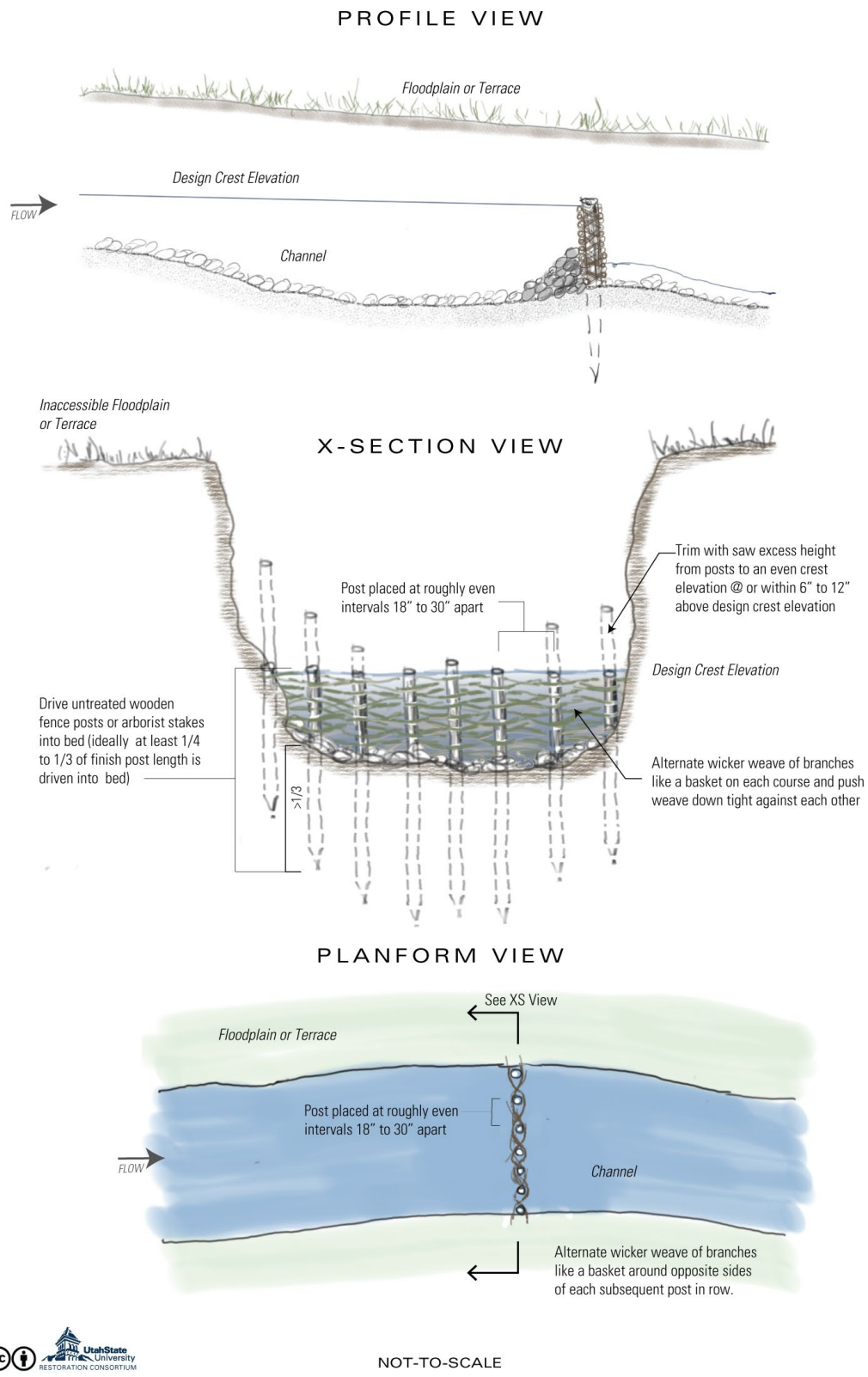

Figure 36 – Typical schematics of the first generation of wicker-weave post-assisted BDAs (similar to Figure 20) using a single row of posts and essentially building a vertical wall. We do not recommend this method, as the wall results in an overflow scour pool that can undermine the base, but in situations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

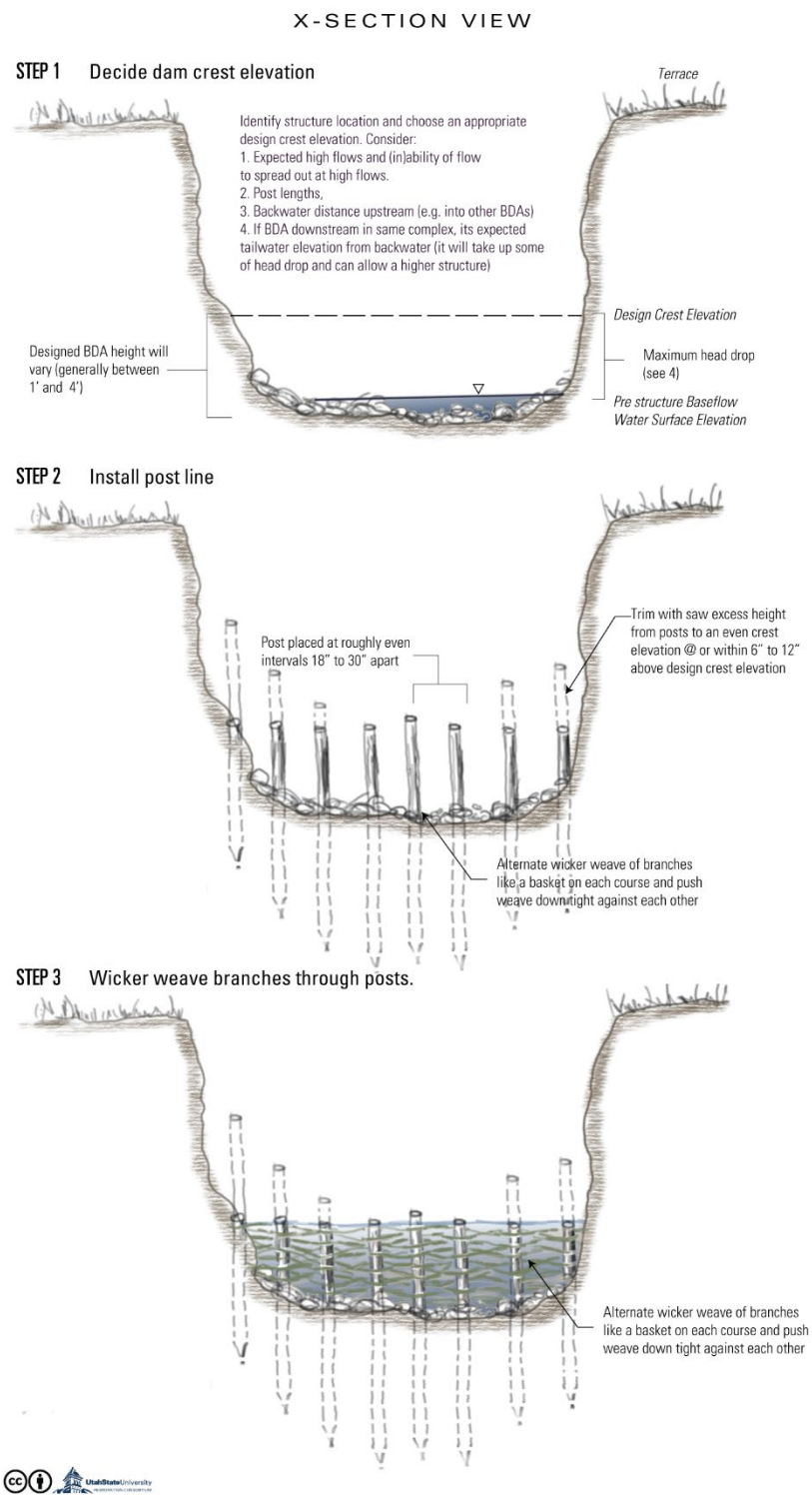

Figure 37 – Typical construction sequence for a post-line wicker weave BDA. First, a single row of posts is installed, and then the wicker weave is placed, and then an attempt is made to patch up the leaks.

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

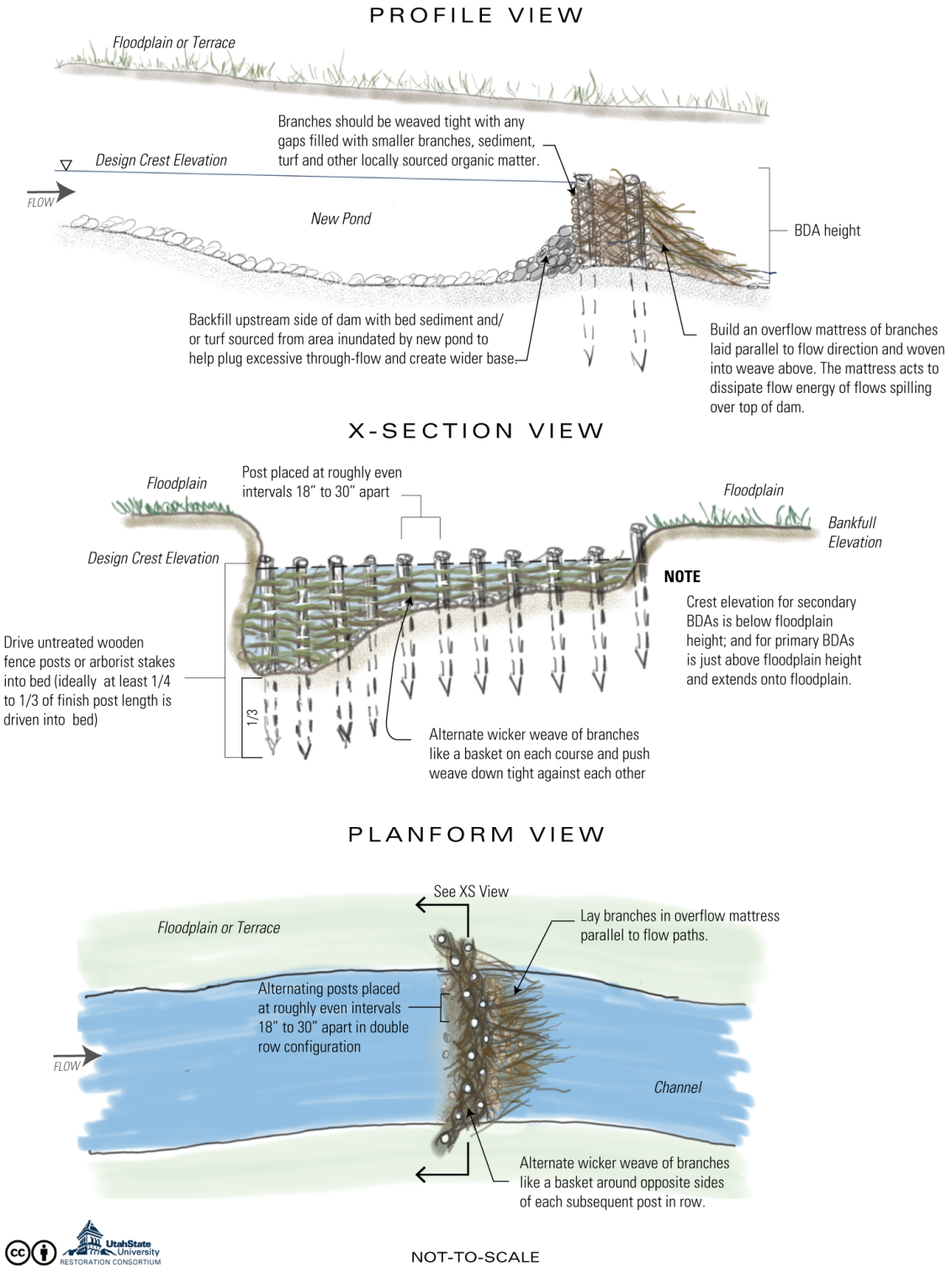

Figure 38 – Typical schematic sketches of a post-line wicker weave BDA, with simple improvements to include a double row of alternating posts, a convex downstream crest orientation, and most importantly an overflow mattress to dissipate flow over the top of the dam.

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.

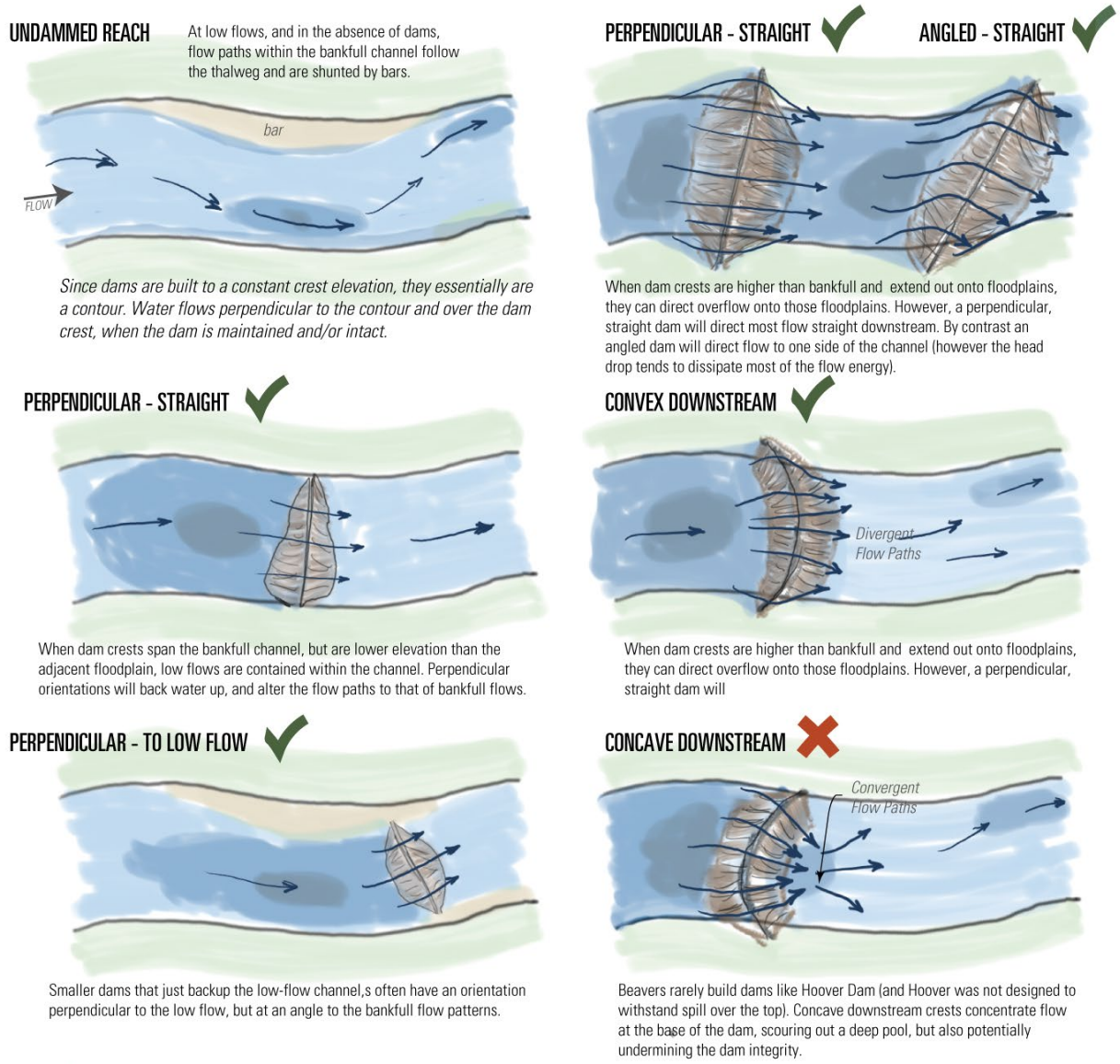

Figure 39 – BDAs can be built with various crest orientations (perpendicular, angled, convex downstream). Since a BDA crest is essentially a contour line (a line of equal elevation), flow paths will flow perpendicular over the crest. As such, if the intention is to direct flows in particular directions,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

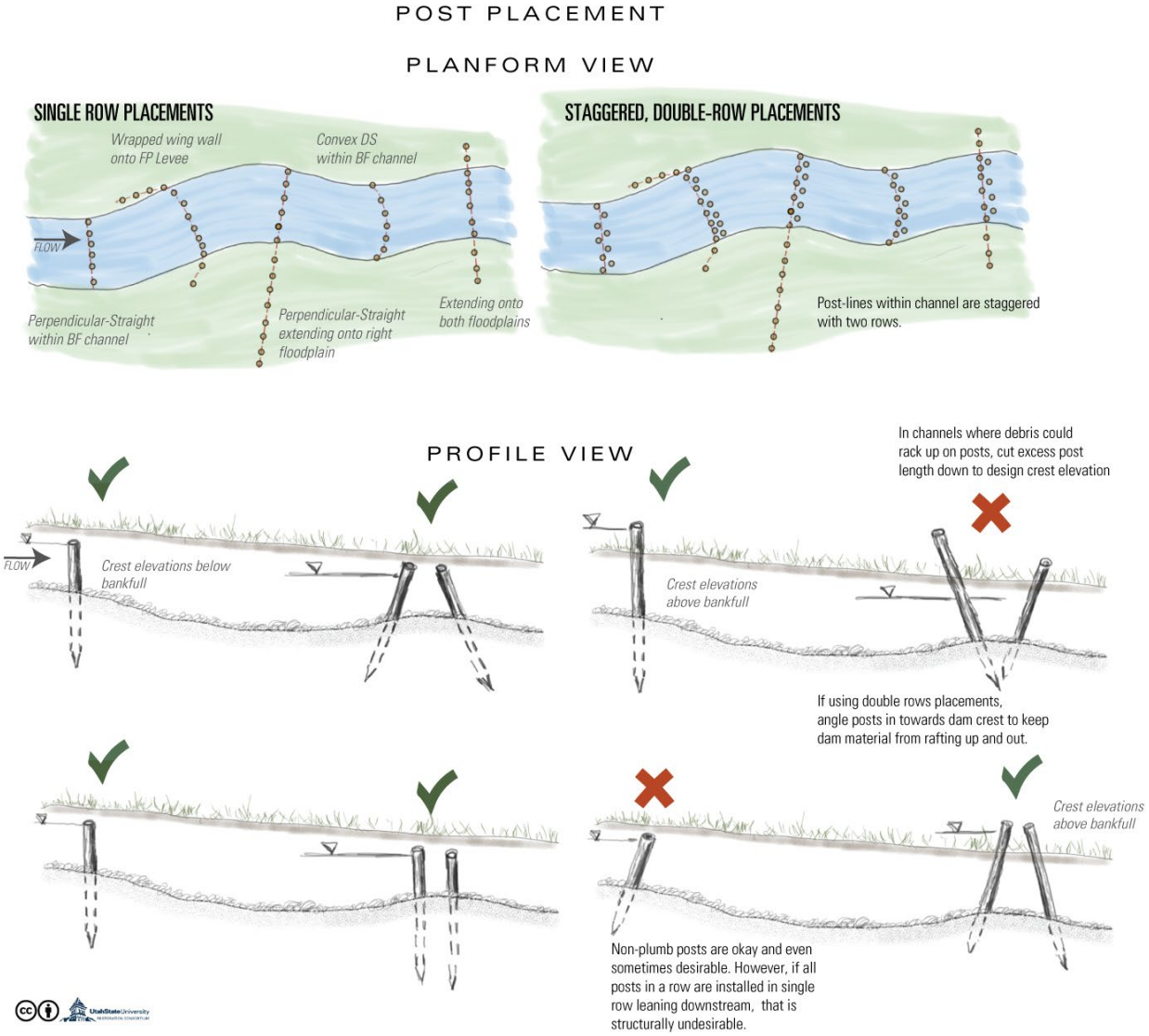

Figure 40 – Post placement considerations. When post are used in BDAs, consideration should be given to whether single-row or staggered double-row placements are used.

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Chapter 5 – DESIGNING LOW-TECH RESTORATION PROJECTS

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IMPLICATIONS FOR PRACTICE

- A complex is a group of structures designed to work together to mimic and/or promote specific processes to achieve one or more project objectives. Complexes are the building blocks of a low-tech restoration design.
- The low-tech restoration design process for complexes:
    - is rapid, low-cost, flexible, transparent, field-based, and generates clear and testable design hypotheses;
    - hypothesizes the hydraulic zone of influence (laterally constrained by the valley bottom) of the treatment, which helps set expectations for the extent of impact of the treatment relative to overall project goals and reach objectives for recovery potential;
    - identifies low-flow, typical-flood, and extreme-flood hypotheses (i.e., process-based responses), which articulate the connection between the processes initially mimicked, later promoted, and hopefully eventually taken over naturally by the system.
- Design of low-tech restoration projects focuses on the complex-scale rather than the individual structure to maintain focus on the scope of riverscape degradation due to structural starvation.

- The number of structures in a complex varies but is typically between 2 - 15 structures. The objectives of adjacent complexes can be the same or different depending on project goals and reach-scale recovery potential.
- Learning can be maximized and subsequent improvements, innovations and refinements to design and later phases of treatment or maintenance will be more informed when the low-tech process-based restoration designer articulates clear, testable design hypotheses at the complex-scale.

INTRODUCTION

The design process for low-tech restoration projects is a departure from engineering-based restoration design. Restoration design of low-tech projects are flexible, field-based, and do not require high-precision hydraulic, hydrologic, or topographic data. The purpose of this chapter is to describe the design process for low-tech restoration and provide practitioners a conceptual as well as a practical framework that will promote a clear articulation of objectives at different spatial and temporal scales, aid in developing realistic expectations, and ultimately increase the ability of projects to achieve their goals. In many instances, restoration objectives are more likely to be achieved using a phased approach over the course of multiple years, rather than as the result of a single treatment (Chapter 2: Wheaton et al., 2019). Practitioners can find efficiencies and maximize their learning when implemented within an adaptive management framework (Chapter 3: Bennett et al., 2019b). When multiple phases are used, it is important to clearly identify what information will be used to decide when no further restoration is required. In general, restoration should be considered complete when the processes of wood accumulation and/or beaver dam activity are self-sustaining (i.e., Principle 10).

This chapter is arranged as follows: we highlight the key restoration principles that guide the low-tech restoration design; we address the information required for designing a low-tech restoration project; we describe complexes (groups of restoration structures that are designed to work together); we provide guidance for designing restoration projects; and we illustrate how projects can be designed to achieve certain objectives using both theoretical and real world examples. Our objective in this chapter is not to describe details of individual types of restoration structures (Chapter 1: Shahverdian et al., 2019a: Appendix C; e.g., see Chapter 4: Shahverdian et al., 2019b for PALS and BDAS), but rather in keeping with low-tech restoration principles (see Chapter 2: Wheaton et al., 2019), to maintain the focus of restoration at reach scale and prevent an over-emphasis on the importance of individual structures.

KEY PRINCIPLES FOR DESIGNING LOW-TECH RESTORATION PROJECTS

We defined riverscapes and restoration principles for low-tech restoration in Chapter 2 (Wheaton et al., 2019). The Riverscapes Principles inform planning and design through an understanding of what constitutes healthy, functioning riverscapes and therefore what are appropriate targets for restoration. By contrast, the Restoration Principles are the foundation for specific restoration actions and provide guidance on how to develop designs that promote processes leading to recovery and resilience (Table 1). We highlight three principles that are particularly important in the design process: strength in numbers, it's ok to be messy, and let the system do the work.

Strength in Numbers – Focus on the Project and Complex, Not the Structure

While not all projects may have the opportunity to build 100s of low-tech structures, post-assisted log structures (PALS) and beaver dam analogues (BDAs) are intended to be implemented at high density over large areas. Focusing on the total number of structures and length of stream treated forces practitioners to more clearly link restoration treatments to restoration goals, which are unlikely to be achieved at the scale of an individual structure. Additionally, building more structures increases the redundancy in the system – structures that breach or blow out are likely to be retained within the restoration area if there are a large number of structures.

It's Okay to be Messy

Healthy streams are messy because natural beaver dams and wood accumulations are diverse, characterized by a wide range of shapes, sizes and residence times. At the project scale, building a diversity of structure types accommodates anticipated variability in stream flows and is more likely to encourage the processes (e.g., wood accumulation & beaver dam activity) that are crucial to meeting restoration goals. At the structure scale, building structures rougher, with less uniformity, tends to dissipate and/or more effectively deflect the forces they are subjected to, and makes them more effective at promoting wood accumulation and beaver dam activity.

Let the System do the Work

Structures force variations in hydraulics, which create energy gradients that amplify localized erosion and deposition. While installing structures is hard manual work, this is not the work of restoration. The processes they promote are the work. Those structures mimic wood accumulation and/or beaver dam activity initially, later promote the same processes (in high flows), and eventually those processes can continue to reshape and maintain habitat in perpetuity. Letting the system do this work with its stream power, harnesses energy beyond the energy to build low-tech structures. Moreover, if beaver like what they see, they continue the process. Thus, designing with low-tech restoration structures rely on the force of water to create changes rather than creating specific geomorphic forms. It is about making educated predictions about what processes will be provoked, and letting them happen.

GETTING STARTED – DESIGN AND REQUIRED INFORMATION

In this chapter, we assume that the following planning steps have been completed : Phase 1 - Step 1) Identify Problems and Opportunities, 2) Determine Objectives, 3) Inventory Resources, 4) Analyze Resource Data (Chapter 3: Bennett et al., 2019b). Low-tech design uses this information from Phase 1 to inform the design in Phase 2 (Figure 1) through Step 5) Formulate Alternatives and Step 6) Evaluate Alternatives. Project goals provide the guiding vision for all finer scale design decisions (e.g., complex and structure designs). In general, project goals are likely to be sufficiently broad and depend on a number of different processes such that they will require the use of multiple complexes with different objectives, each composed of a range of individual low-tech restoration structures.

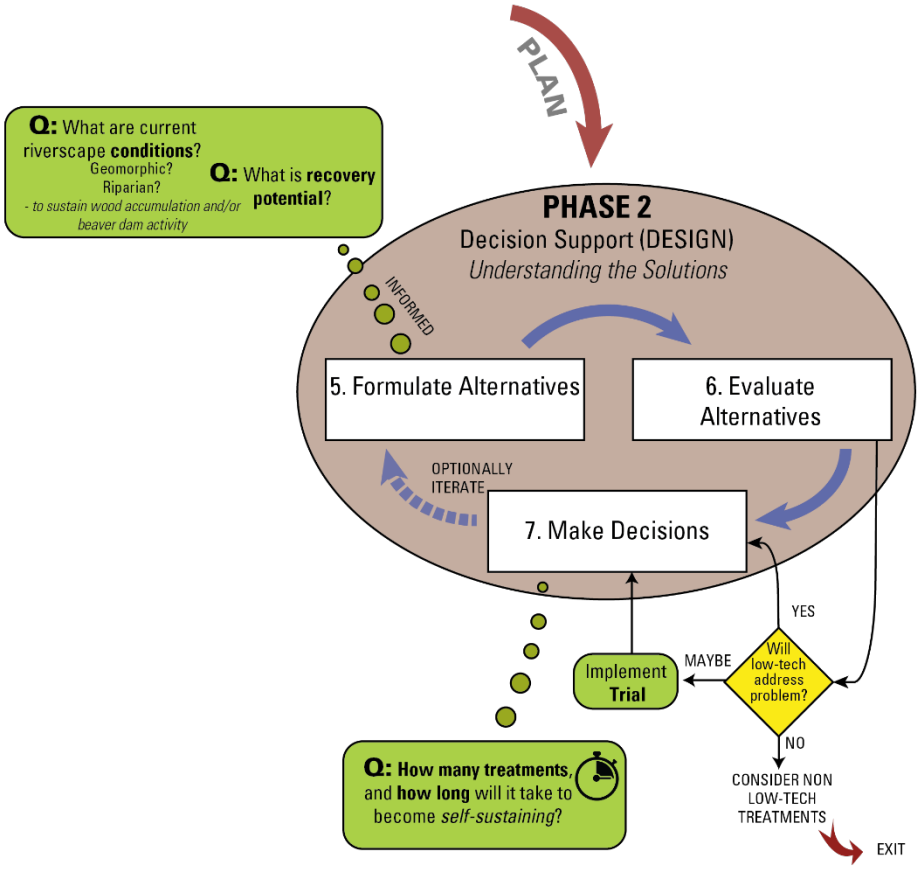

Figure 1 – This chapter is focused on design of low-tech restoration. The most critical information from Phase 1 of the Conservation Planning Process is the assessment of current conditions and upper limit of recovery potential. Coming out of Phase 2 (design), it should be articulated how far towards the recovery potential target the treatment associated with this design is expected to push things, and roughly how many treatments (and subsequent designs it might take).

Beyond the project goals, the most important information from the inventory and analysis of resources in Phase 1 is the:

- identification of valley bottom extents, and what proportion or parts of it can be considered or targeted for low-tech restoration
- evaluation of current geomorphic and riparian conditions within the valley bottom
- forecast of recovery potential (conditions plausibly achievable with restoration)

This should be done for the entire project area. If answers to these questions and inventory are not the same for the entire project area, the project area is sub-divided into as many reach segments as is necessary to describe different i) riverscape settings (Riverscapes Principle 3; Chapter 2), ii) anthropogenic constraints within the valley bottom, iii) current conditions, and iv) what those conditions could be elevated to and over how much of the valley bottom. If this process was not done formerly, the designer should at least be implicitly using a field-evaluated assessment of those factors to inform their restoration design.

A LOW-TECH DESIGN PLAN

A restoration design needs to communicate the objectives of the restoration project and clearly articulate how specific actions (e.g., building low-tech restoration structures) are likely to achieve those objectives. Clear articulation of project objectives and complex-scale design promotes transparency in the restoration process, ensures accountability, increases the capacity for learning and increases the likelihood of achieving broader project goals.

This initial part of the design process, sometimes referred to as the conceptual design, can be undertaken remotely, after having been informed by a field visit to determine reach scale conditions (Figure 2). A significant difference in the design process of low-tech projects, when compared to traditional engineering-based approaches is the use of a field-based design that does not require modeling or drawings. For experienced designers, the design of individual structures in the field should take 3-5 minutes. An experienced designer might spend 10 minutes to 1 hour to complete the design (structure types and configurations) for an entire complex depending on the total number of structures in the complex. Field designs can be documented using standardized forms to record relevant information and accelerate and simplify the process. We also recommend photo documenting pre-implementation conditions at all complexes and representative structures using geo-tagged photos.

The field design outlines the total number of structures to be built, their specific locations, and their specifications (i.e., type of structure, size, and orientation). Because the design of individual structures depends on site-specific characteristics, it must be done in the field. Note that the conceptual design lays out the complex objective, approximate length, and number of structures; however, the field design may alter these numbers based on conditions of their location. Complexes may abut one another or be separated by untreated sections. Complexes with the same goal might also be adjacent to one-another. In this case, the role of differentiating complexes may reflect a change in condition, or simply be to facilitate design and monitoring. We refer to the area that a complex influences as the zone of influence (ZOI). Delineating the complex ZOI is important to accurately identify and mitigate potential risks. Within a complex, identifying the ZOI of individual structures helps determine the spacing of structures. Minimally, a low-tech restoration design should include (Figure 2):

- **Location Map** – large scale (regional/state) map
- **Project-Scale Map(s)** – location within the drainage network, intent (design objective(s), and streamwise extent of complexes
- **Complex-Scale Map(s)** for each complex – structure types, zone of influence of complex (from this treatment), and valley bottom extent – (note locations of individual structures are optional)
- **Typical Structure Schematics** – typical construction details for standard structure types, and cross-sectional, planform and/or profile schematic sketches (Chapter 4: Shahverdian et al., 2019b)

The above, combined with field markers (e.g., flagging) at structure locations, transparently conveys design intent and scope, required to complete most permitting processes (see Chapter 6: Bennett et al., 2019a), and convey the necessary information to construction crews responsible for implementation. The majority of the above design process can be done in the field, and then the documentation finalized at the desktop. This keeps the design process agile, transparent, affordable and scalable. For trial implementations with lower numbers of structures, design costs (on a per structure basis) tend to be relatively expensive, though cheaper than engineering-based approaches. Generally, economies of scale are achieved as the total number of structures increases, since fixed costs, such as mobilizing project designers and field crews are constant, regardless of the number of structures built. In some instances, additional design plan components are worth considering, such as:

- **Structure Design Tables** – Showing individual structure attributes like crest lengths, orientation, position, obstruction type, stages influenced, shear zone types (see Table 1 in: Wheaton et al., 2015), and information for building material estimation (e.g., post quantities, fill materials). These tables are not necessary for permitting or design (see Chapter 6: Bennett et al., 2019a), but may prove helpful when building 100's of structures and/or when estimating materials needed to be imported from off-site or staged.
- **Narrative Report** – Where it is important to transparently communicate project goals, design plan, design objectives and intent to stakeholders, regulators, clients, partners or other audiences, a narrative report explaining and contextualizing the design plan package is helpful.
- **Adaptive Management Plan** (recommended) – An adaptive management plan can clearly articulate expectations, identify potential concerns or conflicting predicted responses, identify maintenance and/or mitigation triggers, as well as determine conditions that will demonstrate that the project has reached a self-sustaining state where further treatments are no longer necessary.

We have experimented with many different levels of documentation for low-tech restoration projects. We have found that the minimum design package described above strikes a balance of rigor, transparency and efficiency. Provided that project planning has been completed (Chapter 3: Bennett et al., 2019b) to ensure the appropriateness of low-tech methods, and the underlying restoration principles (Chapter 2: Wheaton et al., 2019) are used to inform project design, the design of low-tech restoration does not need to be a cumbersome and time-intensive process.

Spending too much time over-thinking and designing any single structure comes at the cost of building additional structures. Many engineering-based restoration design borrows from civil engineering and landscape architecture and require a topographic survey to provide a basemap, computer assisted drafting (CAD) to precisely draw designs and grading plans, and simple analytical design methods for estimating channel design variables, while using hydraulic modeling to estimate hydraulic response. This process increases design costs and over-emphasizes precision (Hiers et al., 2016) and stability (Hillman and Brierley, 2005) often focusing on the wrong risks (e.g., the 'failure' of any single structure). These designs often fail to consider the critical riverscapes principles and restoration principles (Chapter 3: Bennett et al., 2019b), or fail to clearly articulate hypothesized responses. Because process-based restoration does not impose a specific form on riverscapes, but instead mimics and promotes natural processes, clearly articulating the range of expected outcomes is essential.

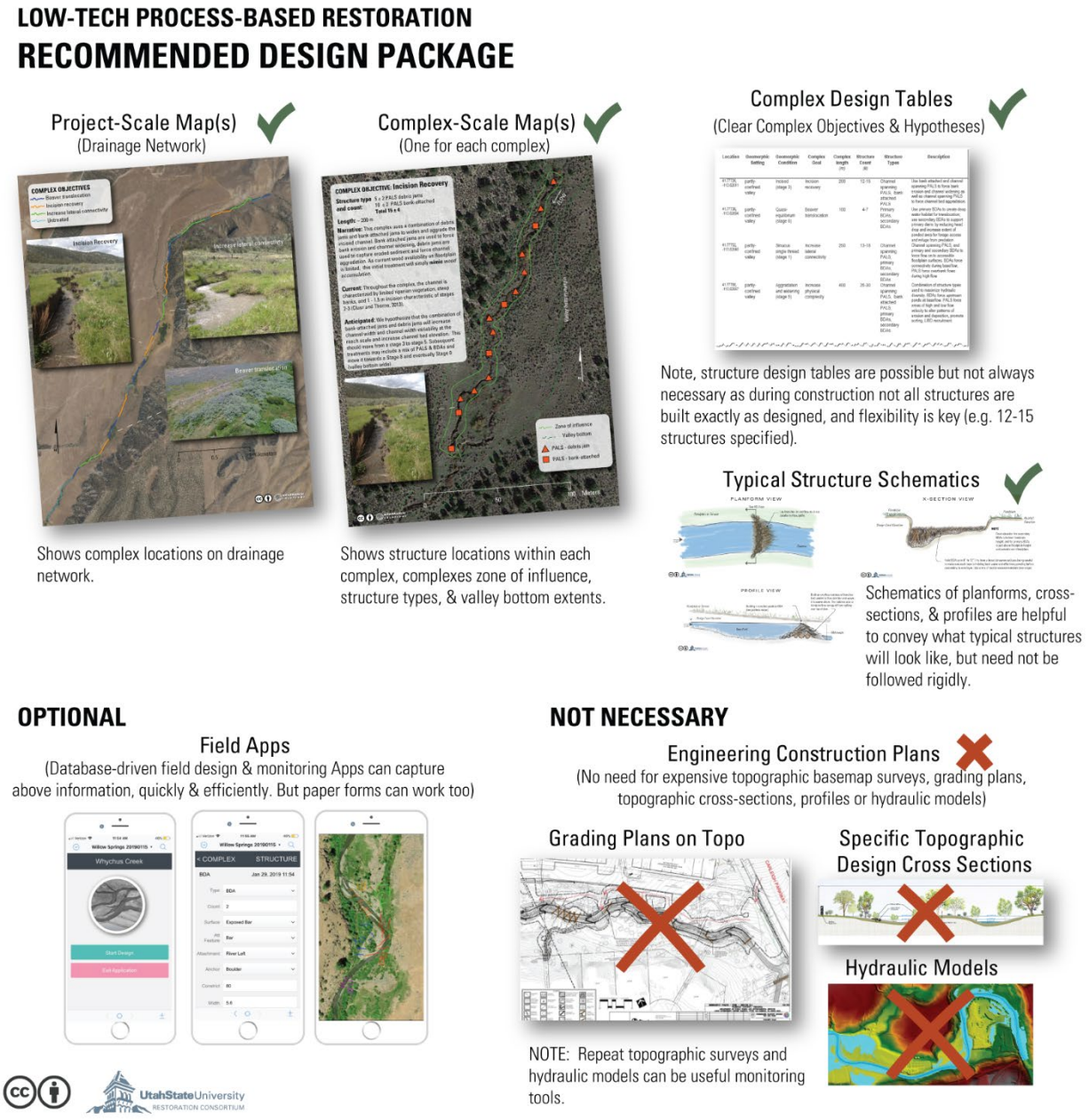

Figure 2 – The primary components of a recommended design package for low-tech process-based restoration.

Nested Spatial Scales

Low-tech restoration projects may cover large spatial extents and involve the construction of 100s to 1000s of individual structures. Smaller projects (e.g., < 1 mile), demonstrations and trials may cover 10's to 100's of individual structures. The restoration design process necessarily addresses different spatial scales, ranging from the individual structure to the entire project extent (Figure 3). In this chapter, we focus on design at the resolution of complexes and extent of projects. While individual structures are the building blocks of complexes (Chapter 4: Shahverdian et al., 2019b), the structure design is ultimately driven by:

- broader complex objectives,

- which are based on broader still reach-scale assessment of current conditions and recovery potential (Chapter 3: Bennett et al., 2019b),
- which, in turn, are driven by broader-scale project goals (Chapter 3: Bennett et al., 2019b).

Although it is possible to articulate specific objectives for individual structures, we suggest that it is more important to focus on objectives at the complex-scale, because it is the scale at which restoration objectives are more likely to be achieved. If Phase 1 of the Conservation Planning Process (Chapter 3: Bennett et al., 2019b) was completed, screening questions and assessments about the major risks and the appropriateness of low-tech process-based restoration methods were already evaluated. Thus, the design of complexes can be completed quickly. Depending on the scale of a project, the design may include an initial desktop (remote) analysis or may be completed entirely in the field. In contrast to more highly engineered restoration projects on larger rivers and/or with significant infrastructure concerns, low-tech methods, by their nature and because they are not seeking to impose a specific form (Chapter 2: Wheaton et al., 2019), do not require pre-project topographic surveys or hydrologic and sediment transport modeling.

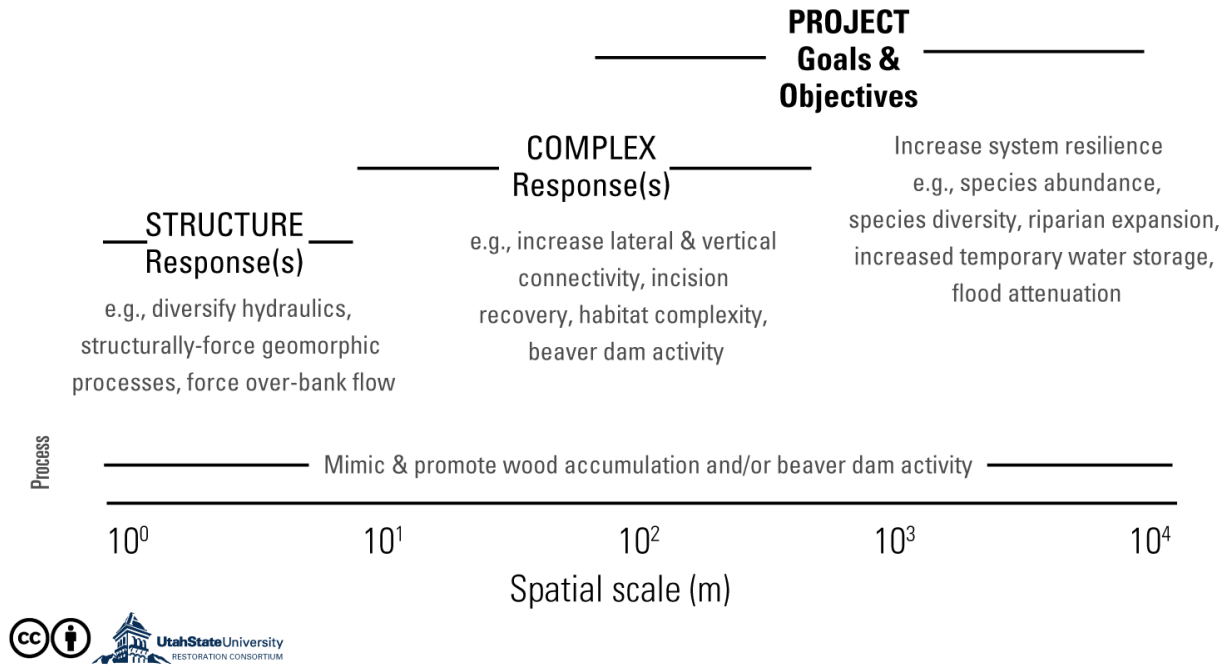

Figure 3 - Conceptual figure illustrating the overlap in spatial scale (extent) between individual structures, complexes and projects. The purpose of a restoration design is to articulate goals and/or measurable objectives at each of these scales and draw explicit linkages, such that individual structures can be linked to broader scale project goals. We suggest design begins at the complex scale, and work is done in the context of the reach-scale conditions and project scale recovery potential. Articulating objectives at the complex scale is critical because it informs the types and numbers of structures to be used based on reach type and conditions, and is the most practical scale at which data can be collected to address restoration effectiveness. Broader-scale project goals & objectives should be identified during the planning stage (Chapter 3: Bennett et al., 2019b).

Trial Projects and Designs

When evaluating design alternatives at each complex and thinking about what types of structural additions to use, it is always worth critically considering whether the proposed treatments are likely to address the identified problem (see yellow diamond in Figure 1). If other evidence exists from similar projects in similar settings to suggest the treatment should be effective, this can be used to justify the decision to proceed. If evidence does not exist, is inconclusive or stakeholders are concerned, a smaller-scale trial implementation may be a helpful way to test specific structure-types out in the context of your project (Chapter 3: Bennett et al., 2019b). Trial projects are smaller scale projects often consisting of 10s of structures (rather than 100s) that can be used to address a number of questions such as: "Are

channel-spanning structures, such as beaver dam analogues likely to breach?", "Does the stream need to widen before aggrading?", as well as logistic questions such as, "Is there sufficient on-site woody material to complete the project?" or "Does site access limit the use of particular equipment such as a hydraulic post driver?" As such, trial design is specifically dedicated to maximizing contrasts between different design alternatives to aid in the more efficient design and implementation in later stages. This can help build experience, test competing structure designs, and learn about logistical realities. If there are disagreements amongst the design team or project stakeholders about the "best" way to proceed, use a small-scale trial to build the competing designs and see what happens.

Phased Implementation

Based on the flow regime (available stream power and how frequently it occurs), restoration expectations can be generated based on how much might be accomplished from a single treatment, and how long it might take. Some restoration objectives are unlikely to be achieved by a single restoration treatment (Chapter 2: Wheaton et al., 2019). In many instances, stream restoration objectives are more likely to be achieved using a phased approach over the course of multiple years. Such an approach is most likely to be successful when implemented within an adaptive management framework (Chapter 3: Bennett et al., 2019b). For clarity, each subsequent phase should have its own design that is iteratively improved with adaptive management based on the evaluation of the response to the previous design(s). The remainder of this chapter focuses on restoration design of a single treatment. The same process applies each time, though subsequent treatments often do not require as extensive number of structures or material. Subsequent designs also tend to build off of past structures, wood accumulations and beaver dams to opportunistically accentuate those features and further accelerate the promotion of processes of wood accumulation and beaver dam activity. When multiple phases are used, it is important to clearly identify what information will be used to decide no further restoration is required (see 'exit' points in Figure 1). In general, low-tech restoration should be considered complete when the processes of wood accumulation and/or beaver dam activity are self-sustaining (Restoration Principle 10: Chapter 2: Wheaton et al., 2019).

DESIGN OF A COMPLEX

The design of a complex identifies complex objectives(s), the types of structures and configuration that will make up the complex (i.e., the form), the hydraulic zone of influence (ZOI), and articulates how the complex will meet its objectives (i.e., design hypotheses). Projects generally consist of reaches that reflect different conditions and opportunities, each reach with one or more complexes and each complex consisting of multiple structures.

In the context of a design, a complex is a group of individual structures designed to work together to achieve specific objectives. In nature, beaver often build a series of dams in a complex. The primary dam is generally larger, often spreading out onto a floodplain, and deep enough to support and underwater entrance to a lodge for the colony as well as a food cache. One or more secondary dams extend the foraging range upstream or downstream, and back water up to the base of the next upstream dam in the complex. An example of man-made complex of BDAs is shown in Figure 4, in which three BDAs were built to mimic a natural beaver dam complex and release translocated beaver into. Those BDAs were immediately colonized by the beaver released into them and promoted the expansion of all the dams (in both height and crest length) and construction of two lodges. The beaver then subsequently expanded that complex laterally, upstream and downstream with five more beaver dams, and then expanded and built their own new complexes upstream and downstream of the original complex.

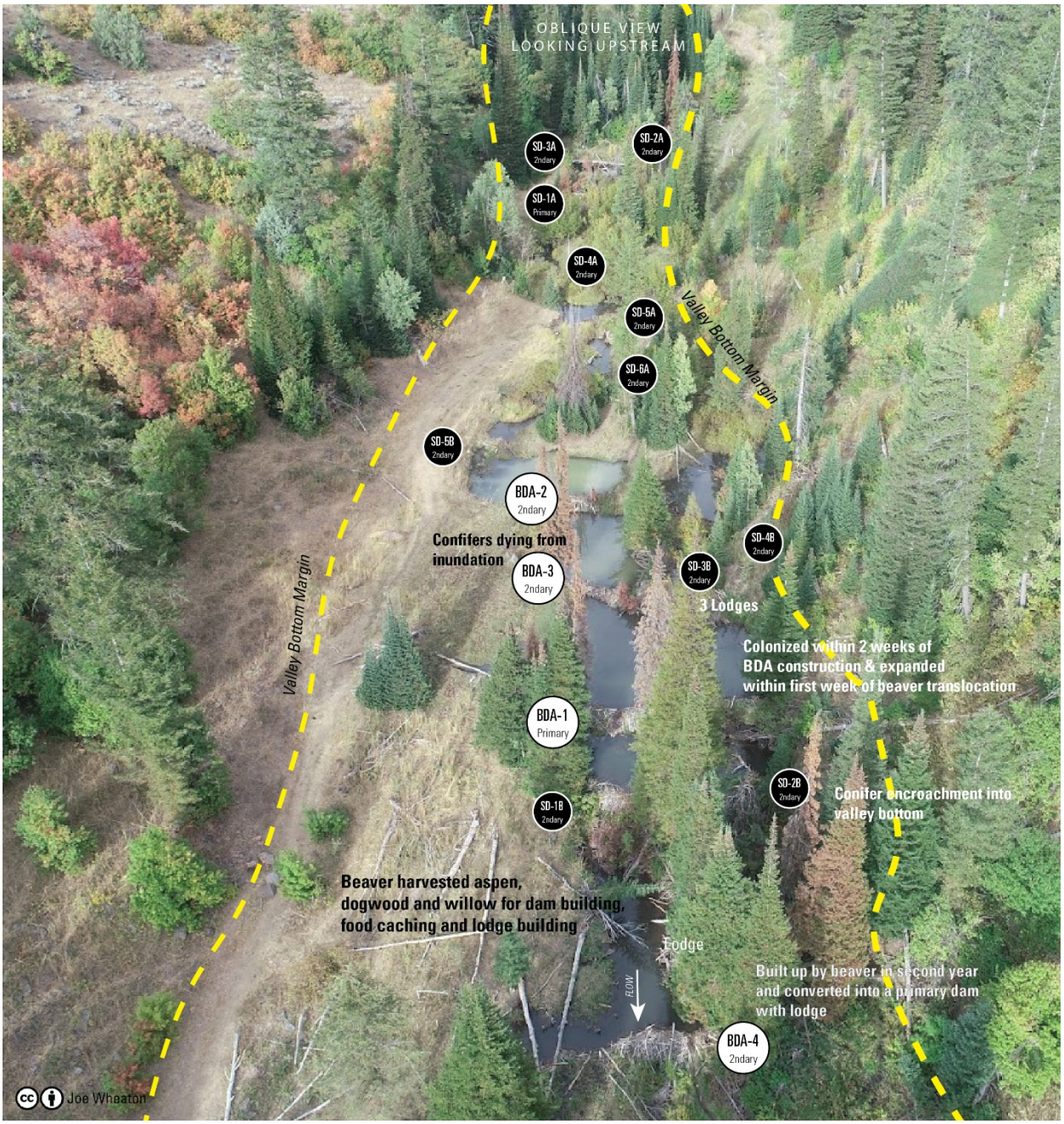

Figure 4 – Complex of four BDAs designed for beaver translocation (white circles), which was successfully colonized by beaver. Beaver built an additional 11 dams (black circles) within one year of translocation. Identifying the hydraulic zone of influence when designing low-tech complexes ensures that risks and opportunities are identified.

Complex Objectives

Common complex objectives include: increase channel-floodplain connectivity, increase instream complexity, create deep-water habitat for beaver translocation, and accelerate incision recovery. Some objectives, such as increased floodplain connectivity, will inherently promote increased surface and groundwater storage, and expanded riparian areas. The location and objectives of a complex are directly related to one another. For example, a complex built in an incised channel will likely be designed to accelerate incision recovery by channel widening and aggradation. It will not, by contrast, be designed to promote increased channel-floodplain connectivity. The structure types and their

configuration used in a complex are based on an understanding of the different ways in which individual structures can influence hydraulic and geomorphic changes (Chapter 4: Shahverdian et al., 2019b). There are multiple complex configurations that can be used to achieve any particular objective. Complexes may abut one another or be separated by untreated sections (Figure 6). Complexes with the same objective may also be adjacent to one another. In this case, the role of differentiating complexes may reflect a change in condition, or simply be to facilitate design and monitoring. Later in this chapter we provide examples of complex designs.

Often a complex will contain a diversity of structure types to achieve overall project goals. The diversity of forms, objectives, and locations of different complex types is vast, and we cannot possibly anticipate or cover designs for each of them. Rather, application of the principles treatment (Chapter 2: Wheaton et al., 2019) and mechanisms by which the building blocks (i.e., the structures) promote hydraulic, hydrologic, and geomorphic change will help facilitate efficient complex designs. However, here, we provide examples of how designs for common complex objectives: increased instream complexity, habitat improvement for beaver translocation; incision recovery; increased channel-floodplain connectivity. We do not provide explicit complex form (structure types and configurations) here. The specific locations of individual structure types and their relationship to other structures in a complex depends on intra-reach conditions that are site-specific. However, specific complex objectives tend to be correlated with certain structure types (Figure 5). In other words, a complex designed for beaver translocation is unlikely to use bank-attached PALS because they would not create the deep-water habitat required by beaver. Similarly, a complex designed to promote incision recovery would tend to utilize more PALS than BDAs because they are a more efficient structure type for promoting channel widening and aggradation.

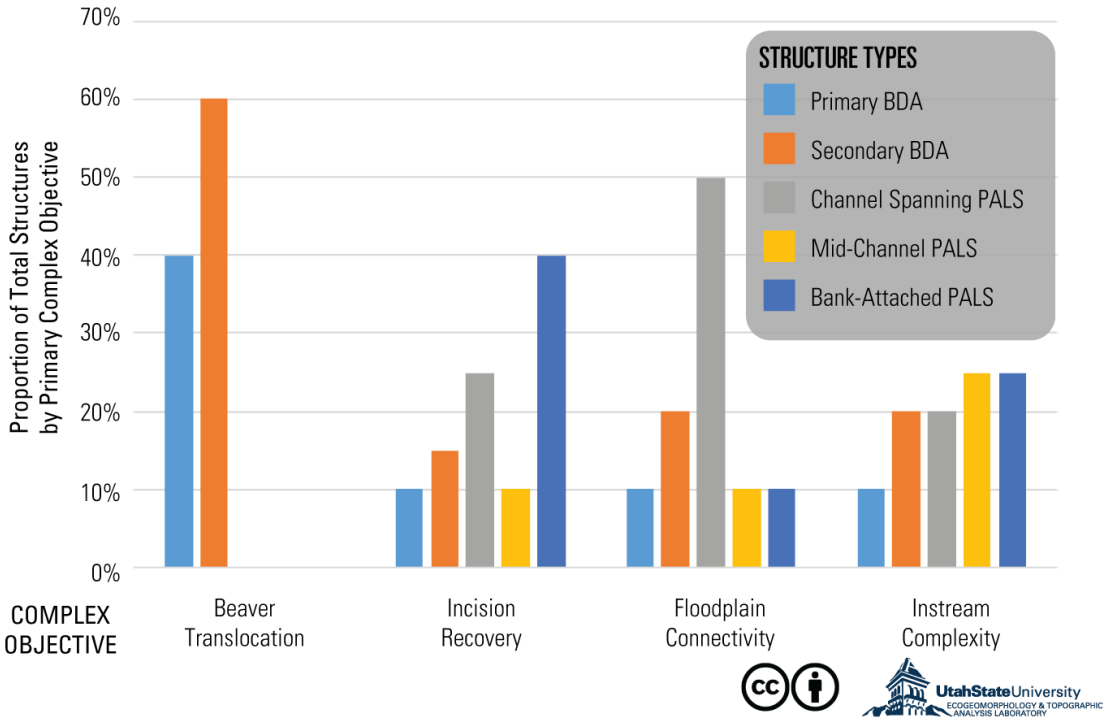

Figure 5 - Conceptual depiction of how the distribution of structure types varies with complex objective. The types and number of structures relative to one another vary depending on the complex objective.

Figure 6 – Conceptual complex design at project scale. The objective of each complex has been identified and is based on reach-scale attributes. Inset photos show different conditions within the project area (total length ~ 4 mi (~6 km) that determine the objectives of each complex. Channel incision (inset left) can be addressed by a complex designed to force channel widening and aggradation. In areas with accessible floodplain but no woody riparian vegetation (inset, top right) complexes can restore immediate channel-floodplain connectivity. Areas with abundant woody riparian vegetation (inset, bottom right) are suitable for beaver translocation and complexes can be designed to create immediate deep-water habitat for translocation. Complexes are represented as lines rather than points to better depict their longitudinal extent on the channel network. When mapping at higher resolutions, we recommend mapping complexes as polygons to represent their anticipated hydraulic zone influence Figure 8 and Figure 9 . Note that complexes may or may not be adjacent to one another, such that one complex begins where another ends. Furthermore, two complexes with the same goal may be adjacent to one another. The specific types and locations of individual structures is necessarily determined in the field.

Field-Based Design

The design process relies heavily on field assessments. However, once a field visit has been performed to identify or confirm reach-scale conditions, a conceptual design can be completed remotely (Figure 8 and Figure 9. The field design outlines the total number of structures to be built, their specific locations, and their specifications (i.e., type of structure, size, and orientation). Because the design of individual structures depends on site-specific characteristics, it must be done in the field. A significant difference in the design process of low-tech projects, when compared to traditional engineering-based approaches is the use of a field-based design that does not require topographic basemaps, modeling or CAD drawings. Note that the conceptual design lays out the complex location, objective, and approximate number of structures; however, the field design may alter these numbers based on field conditions. Chapter 4 (Shahverdian et al., 2019b) describes structure level design considerations for the specific cases of post-assisted log structures and beaver dam analogues. For experienced designers, the design of an individual structure in the field should take 3-5 minutes. Therefore, an experienced designer might spend 10 minutes to 1 hour to complete the design (structure types and configurations) for an entire complex depending on the total number of structures in the complex. Field designs can be documented using standardized forms to record relevant information and accelerate and simplify the process. We also recommend photo documenting pre-implementation conditions at all structure sites using geo-tagged photos. Complex designs can be documented using both maps (Figure 8 and Figure 9) and tables (Table 1).

Table 1 – Example of specific information to collect for a group of different complex designs. Complex design may also include maps showing complexes throughout the project area. Structure types are discussed in length in Chapter 4 (Shahverdian et al., 2019b). Stage refers to stream evolution model stages defined by Cluer and Thorne (2013). Note, location may be specified as coordinates at top of complex or bottom of complex.

Location	Geomorphic Setting	Geomorphic Condition	Complex Objective	Complex length *(m)*	Structure Count *(#)*	Structure Types	Description
41.77726, -113.82011	partly-confined valley	Incised (Stage 3)	Incision recovery	200	12-15	Channel-spanning PALS, bank-attached PALS	Use bank-attached and channel-spanning PALS to force bank erosion and channel widening; as well as channel-spanning PALS to force channel bed aggradation
41.77736, -113.82094	partly-confined valley	Quasi-equilibrium (Stage 6)	Beaver translocation	100	4-7	Primary BDAs, secondary BDAs	Use primary BDAs to create deep-water habitat for translocation; use secondary BDAs to support primary dams by reducing head drop and increased extent of ponded area for forage access and refuge from predation
41.77752, -113.82048	partly-confined valley	Sinuous single thread (Stage 1)	Increase lateral connectivity	250	13-18	Channel-spanning PALS, primary BDAs, secondary BDAs	Channel-spanning PALS and primary and secondary BDAs to force flow on to accessible floodplain surfaces. BDAs force connectivity during baseflow, PALS force overbank flows during high flow
41.77788, -113.82067	partly-confined valley	Aggradation and widening (Stage 5)	Increase physical complexity	400	25-30	Channel-spanning PALS, bank-attached PALS, primary BDAs, secondary BDAs	Combination of structure types used to maximize hydraulic diversity. BDAs force upstream ponds at baseflow. PALS force areas of high and low flow velocity to alter patterns of erosion and deposition, promote sorting, large woody debris recruitment

Hydraulic Zone of Influence of Complex

We refer to the area that a complex is capable of influencing as the hydraulic zone of influence (ZOI). Delineating the complex hydraulic ZOI is important in order to accurately identify and mitigate potential risks as well as developing realistic expectations for achieving complex goals. We delineate the hydraulic ZOI based on annual peak flows. In other words, we identify the maximum upstream, downstream and lateral extent of surface water influenced by restoration. Upstream extent is determined by the backwater formed by the upstream-most structure, while downstream extent may be determined by how the complex forces overbank flows that may not return to the channel for 10s of meters below the final structure. Similarly, the lateral component of the hydraulic ZOI is determined by reach-scale topography. Reaches with accessible floodplain are more likely to have a greater lateral ZOI than incised reaches. For complexes in incised reaches, practitioners may also want to identify the geomorphic ZOI to better predict and monitor the geomorphic changes associated with restoration. We use the hydraulic ZOI, rather than the geomorphic ZOI, during the design process because it is more conservative and allows us to better identify risks and opportunities. Within a complex, identifying the hydraulic ZOI of individual structures helps determine the spacing of individual structures.

CONSIDERATIONS FOR COMMON COMPLEX OBJECTIVES

Increase Instream Complexity

Because many streams are structurally starved, plane-bed, single thread, low sinuosity reach types are far more common than they were historically. In simplified riverscapes, critical habitat features are further apart, and aquatic organisms cannot fulfill daily, seasonal, and life-stage specific activities. Furthermore, low complexity streams are often characterized by impaired flow and sediment regimes, and the physical processes necessary to create and maintain habitat are degraded (Shahverdian et al., 2019b).

A complex designed to increase instream complexity would likely utilize a variety of low-tech structures (Figure 7). Utilizing a variety of structure types would promote greater hydraulic and therefore geomorphic complexity. Some structures, such as BDAs, would create immediate pond habitat and areas of slow-moving deep water, while others, such as bank-attached PALS, would create areas of shallow, fast-moving water. Furthermore, different structure types will be activated during different flow conditions; BDAs create immediate changes in hydraulics, while some PALS may require annual peak flows to force geomorphic change. Channel-spanning structures are more likely to cause deposition of bars and formation of plunge pools, while bank-attached structures are more likely to force scour pools and bank erosion. The structures will also act as cover from predators for fish.

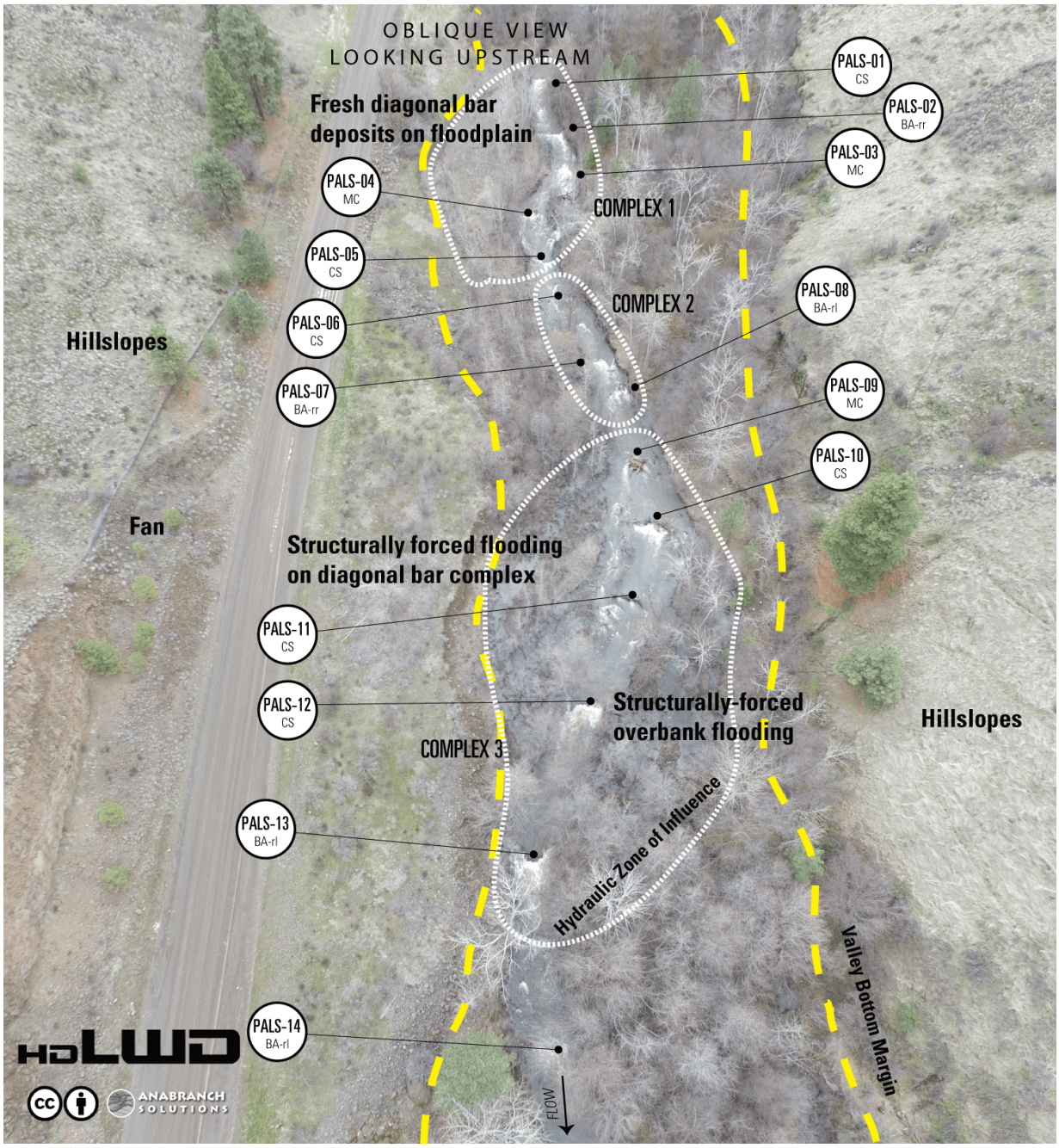

Figure 7 – Series of complexes designed to increase instream complexity and lateral connectivity. Each complex is composed of different types of PALS that force different hydraulic responses. During annual high flows (shown in photo) structures force overbank flows.

Habitat Improvement for Beaver Translocation

In recognition of influence their dam building activities have on riverscapes, translocating beaver has regained popularity in the past decade (Woodruff and Pollock 2015). As an ecosystem engineer, beavers modify hydrological connectivity, sediment transport, channel morphology, floodplains, nutrient cycling, and riparian vegetation producing ecosystems services such as resilience to drought and fire, flood control, water storage, water quality benefits, and increased livestock forage. And because beavers blur the line between aquatic and terrestrial systems, habitat improvement projects impact a broad range of species including fish, amphibians, reptiles, birds, and wildlife.

Common practices of releasing beavers have resulted in both poor survival and high emigration from the project area (McKinstry and Anderson, 2002; Petro et al., 2015). McKinstry and Anderson (2002), suggested that ponds may increase their survival but that the building of ponds was impractical. BDAs can be used to create immediate deep-water habitat for beaver translocation and increase survival and decrease emigration.

A complex designed to improve habitat for beaver translocation would rely on the use of BDAs to create extensive deep-water habitat. Primary BDAs are used to create ponds capable of sustaining an underwater entrance to a lodge or bank den. In colder regions, ponds must be deep enough to prevent freezing solid during the winter months. In general, this requires selecting locations where a structure is capable of creating laterally extensive, deep-water habitat. Secondary BDAs are used to expand ponded areas upstream and downstream of the primary dam to increase safe access to forage.

To maximize the likelihood of successful translocation, it is important to create multiple opportunities for beaver. Therefore, rather than simply building a single primary BDA, we recommend building a complex consisting of several BDAs (Figure 8). When beaver are translocated to the middle of the complex, they will encounter deep-water habitat if they move upstream or downstream.

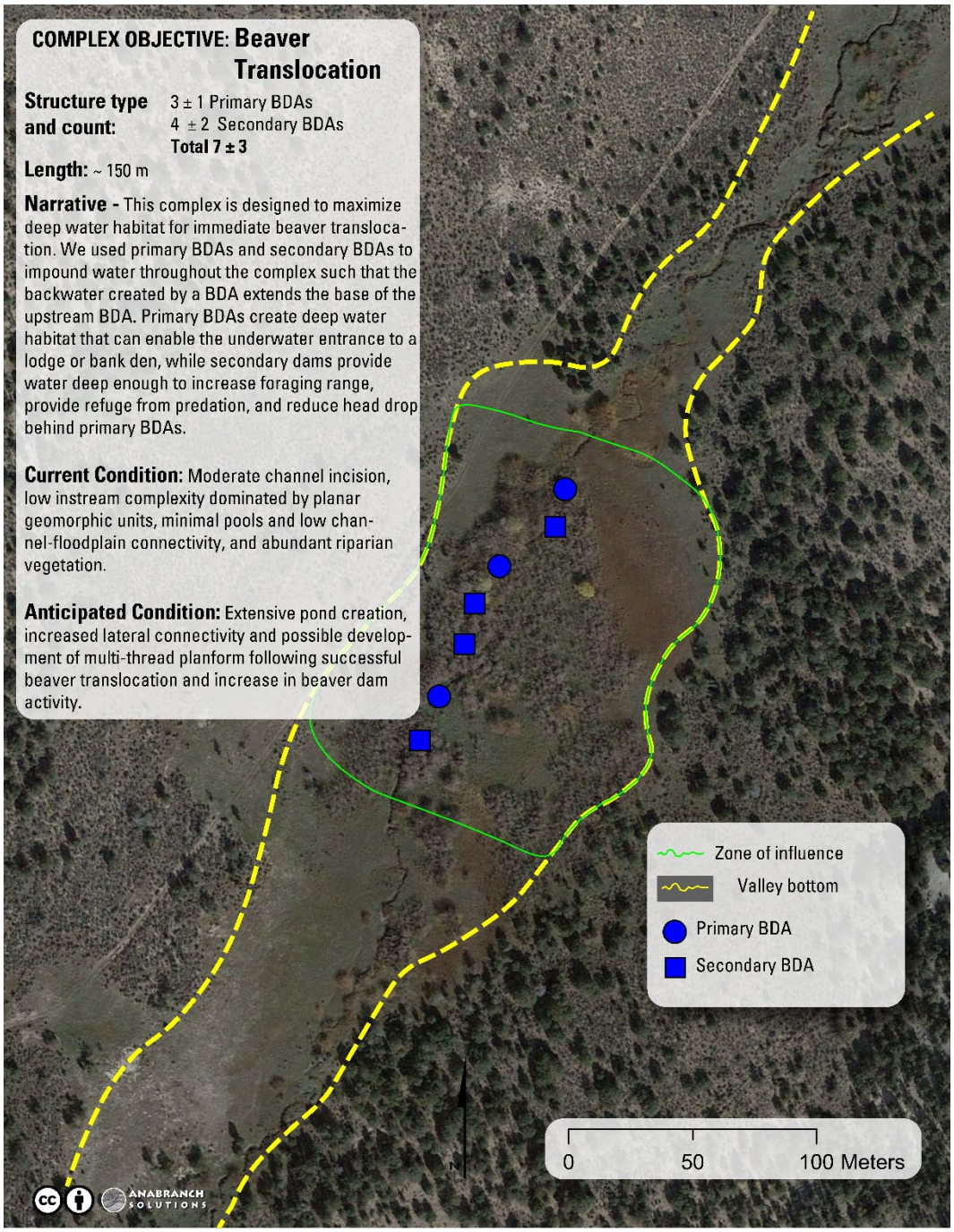

Figure 8 - Complex designed to create beaver habitat for translocation. Unlike complexes designed to create pool habitat for other species (e.g., trout), this complex is intended to create deep ponds that allow for an underwater entrance to a lodge or bank den, as well as extensive pond areas to allow safe extension of foraging range. Dams are spaced such that the backwater from one dam reaches the next upstream dam allowing beaver to travel safely throughout the complex and reduce the risk of predation. Building multiple dams also gives translocated beaver options, and reduces the chance of emigration from the release site. The zone of influence (ZOI) delineated in this design figure represents the maximum possible extent affected given successful beaver translocation and dam building activity. It does not represent the immediate footprint of BDAs themselves. For restoration design, delineating the ZOI is important in order accurately identify and mitigate potential risks.

Incision Recovery

Channel incision is a common problem that results in degraded stream conditions that may persist for decades (see Chapter 1: Shahverdian et al., 2019a). The stage of the evolution of an incised channel for a particular reach will dictate the complex design. Local (i.e., sub-reach scale) factors such as channel geometry, local sediment sources, and bank material will also influence complex form.

If a complex is targeting a reach that is in the aggrading stage, the design might be rather simple - build a series of BDAs that are capable of forcing overbank flows onto inset floodplains after the channel aggrades behind the structure (Figure 9). If large woody materials are readily available (i.e., minimal costs in staging) and high flows are sufficient to deliver debris that can rack up onto channel-spanning PALS, then these structures might be more efficient (i.e., less time and money, more structures) in achieving the same results. The height of the structures needed to reconnect the floodplain might also be too high to withstand the forces at high flows and might require building in stages. Trial structures might help identify some of these issues before full implementation occurs.

Often streams do not fit discretely into a single stage, but rather a mosaic of stages can be found throughout the project area. A complex might contain channel sections in both the widening and aggrading stages. Therefore, bank-attached PALS may be used to widen the channel and create inset floodplains. The material eroded from the opposite bank might be used to aggrade downstream channel-spanning structures strategically located near inset floodplains. Larger bank material will aggrade the channel bed more quickly than fine sediments, so bank-attached structures might be located to harvest coarse alluvium for downstream fill if the material in the erodible bank is observable. A channel-spanning structure might be built downstream of structures forcing water onto an inset floodplain, to capture the return flows to prevent head-cutting through the wetted floodplain. Strategic location of different structure types and sizes with different functions can greatly increase the efficiency of a complex to move channel incision to a dynamic stable equilibrium (i.e., Stage-0).

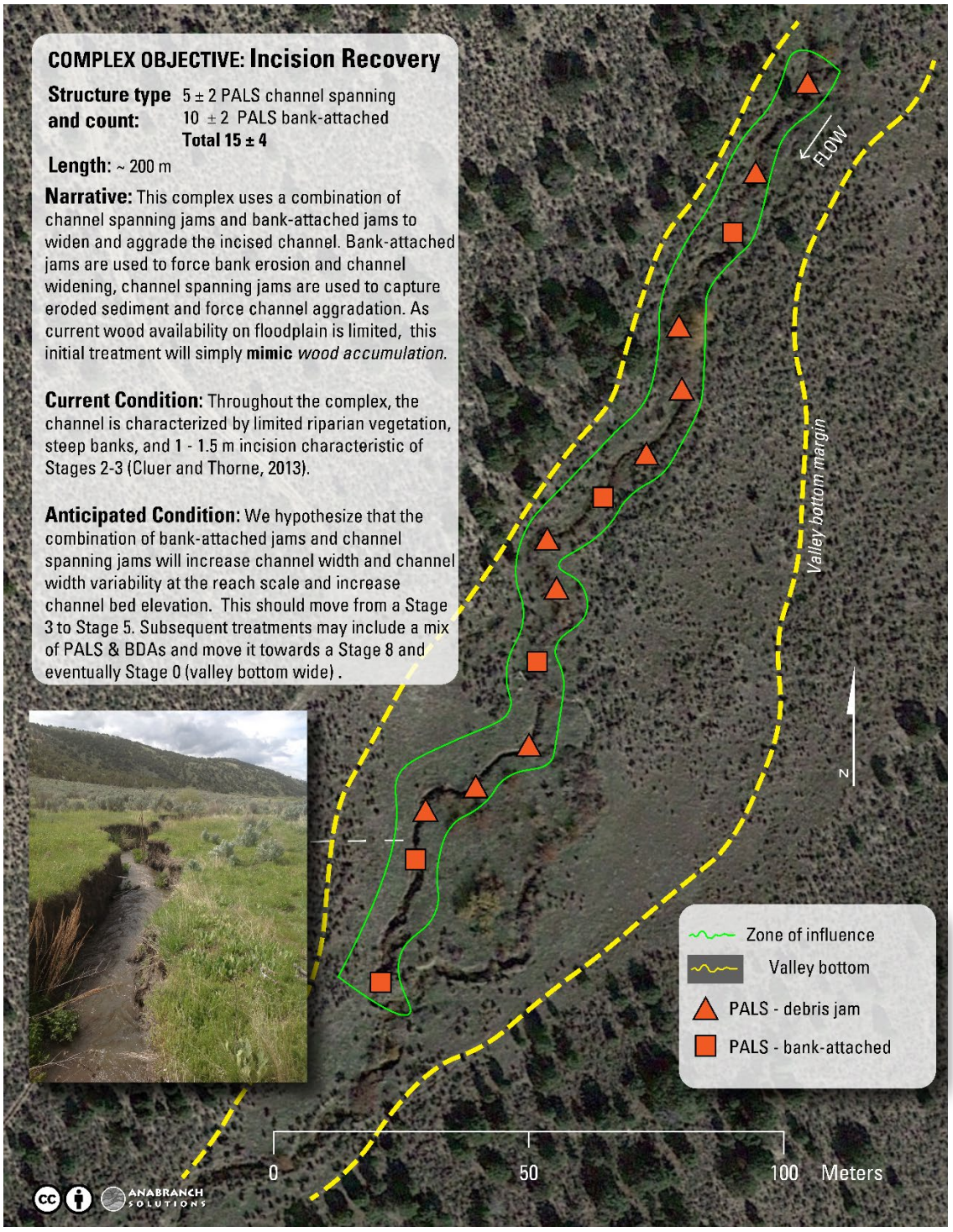

Figure 9 - Example of complex design that notes the locations and types of structures to be used. In practice, this information would be recorded using a standardized form that would direct construction crews to the specific location of each structure and then provide a detailed construction design. The zone of influence (ZOI) here denotes the maximum extent of potential channel widening due to one phase of restoration. In practice, this extent is unlikely to be reached during the first phase of restoration, and depends on high flow conditions. For projects where complex design and construction occur concurrently, the locations of individual structures may not be mapped until after construction.

Increase Channel-Floodplain Connectivity

Many restoration projects attempt to reconnect disconnected channels to their floodplains with a goal of creating a desired dynamic equilibrium stable state (i.e., Stage-0). Properly functioning floodplains can support riparian vegetation that will provide future material for either beavers or large wood in streams. Generally, channel-spanning structures are more effective at forcing overbank flows than bank-attached structures, though bank-attached structures will still increase roughness and result in some increase in lateral connectivity.

A complex designed to increase channel-floodplain connectivity therefore will likely rely on channel-spanning structures, including primary and secondary BDAs and channel-spanning PALS. BDAs may be capable of forcing channel-floodplain connectivity during baseflow conditions, while PALS are more likely to influence lateral connectivity during high flow conditions. As with all low-tech restoration complexes, building a variety of structure types, shapes and sizes can help address uncertainty in flow conditions as well as structure response to different flow conditions. When building structures in a complex designed to increase channel-floodplain connectivity, identifying discrete features such as high flow channels, low banks and side channels may greatly increase the ability to force lateral connectivity and increase the quantity of habitat. Multiple structures are much more likely to keep the floodplain connected although occasionally a well-placed structure can force a very disproportionate amount of water onto newly wetted surfaces.

THE IMPORTANCE OF TIME AND FLOW CONDITIONS

We articulate specific hypotheses for different flow conditions when designing low-tech restoration (Figure 10). We formulate hypotheses for different flow conditions rather than for different time periods (i.e., short, medium and long term) based on the understanding annual flow characteristics may exhibit high variability. Developing restoration hypotheses based on the flow regime and specific flows (e.g., baseflow, typical annual flood, and rarer large floods) helps create realistic expectations for project managers and funders. Because low-tech restoration designs may require high flow conditions to “do the work”, articulating the likely response of projects to different flow scenarios allows practitioners to better communicate project objectives and manage expectations.

Low-tech restoration design is an ongoing process, where future restoration opportunities are based on the results from previous efforts. The design process for multi-year projects therefore responds to outcomes of earlier phases of implementation. In this way, low-tech restoration can take advantage of new restoration opportunities that may not be available during the initial phases of restoration (e.g., floodplain reconnection may not be possible until some amount of channel aggradation has taken place). It is also critical to identify metrics that can indicate when restoration is complete (i.e., when restoration goals have been achieved). Developing these metrics can help guide project design in subsequent phases of a multi-year implementation.

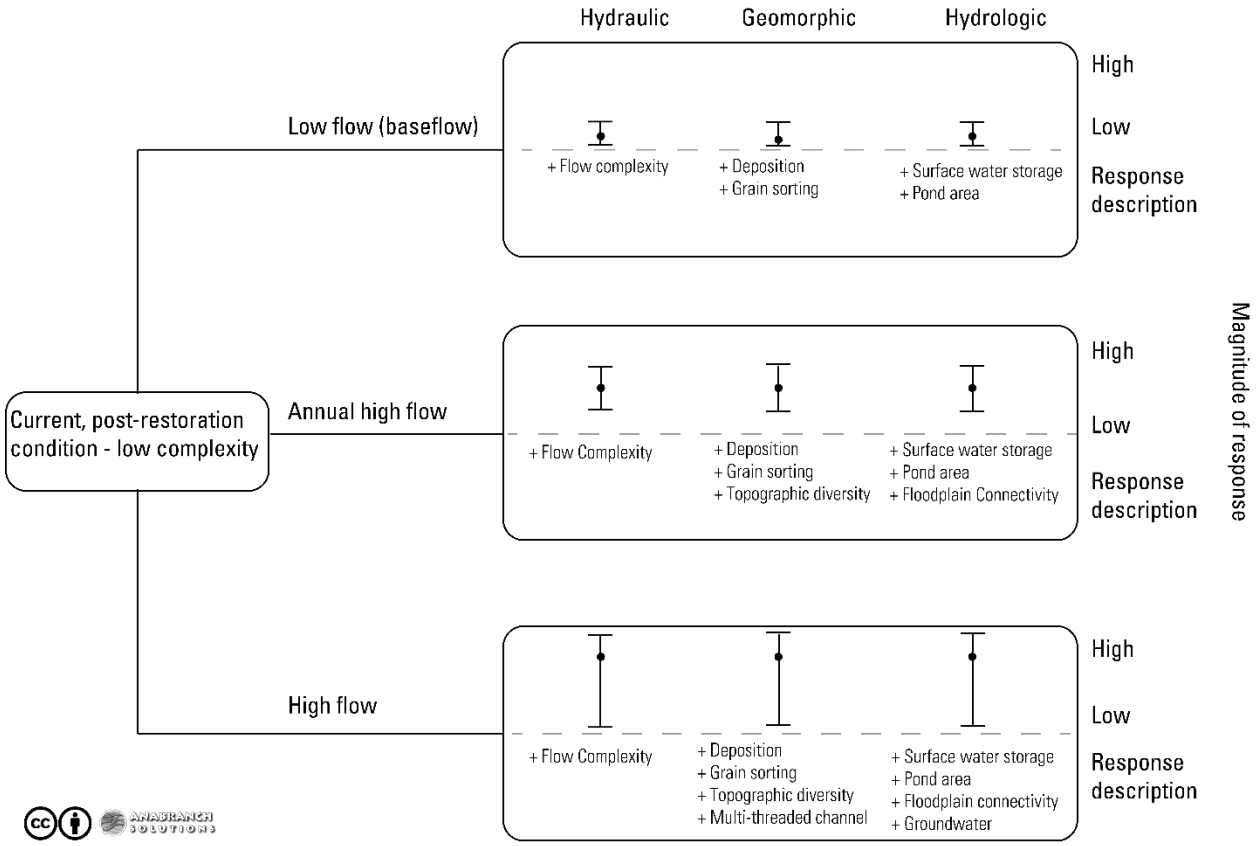

Figure 10 - Conceptual hydraulic, geomorphic, and hydrologic responses to different flow conditions. At all flows, complexes increase the amount of flow complexity by forcing convergent and divergent flow and producing deep water and shallow water areas with variable flow velocities. Hydraulic responses are likely to correspond to flow stage, with limited response during low flow, and greater response during high flows. Higher magnitude hydraulic responses lead to greater magnitude and range of geomorphic and hydrologic responses. Note that the bars indicate the range of possible response, and the marker dot denotes the hypothesized mean response. Responses assume one treatment (i.e., no maintenance or continued restoration efforts). In practice, continued efforts may be required to achieve restoration objectives. Dashed line represents no change, + denotes an increase, text below dashed line describes the responses.

CONCLUSION

The design of low-tech process-based restoration projects relies heavily on a field-based design process. Low-tech restoration structures such as PALS and BDAs are intended to be built in complexes — groups of structures that work together to promote specific hydrologic and geomorphic processes. Focusing on the complex-scale, rather than on individual structures, and articulating specific complex objectives forces practitioners to focus on the scale most likely to help achieve restoration objectives.

There are many potential audiences for a restoration design, including: land managers, contractors, researchers, and regulatory officials. Each of these groups have specific needs and expectations when funding, approving or implementing stream restoration projects. For land managers, clear objectives and pathways to achieving those objectives are necessary to ensure that restoration is aligned with broad-scale land management objectives (Chapter 3: Bennett et al., 2019b). For contractors, specific complex and structure designs are necessary to implement restoration on-the-ground. For researchers, having a better understanding of baseline conditions (e.g., through photo points) as well as the complex objectives enables development of appropriate monitoring strategies. Lastly, for regulators (e.g., US Army Corp of Engineers, state water agencies etc.), clear design plans will enable better understanding of low-tech restoration projects and facilitate project approvals.

Chapter 5 - APPENDIX

APPENDIX A - THE TOPOGRAPHIC PARADOX

Design in engineering-based river restoration practice is intimately tied to a topographic survey. A topographic survey is the gold-standard as the basemap on which traditional civil engineering design is based. When earthwork and grading is involved, the ability to design with topography is critical, and the difference between the design surface and original grade surface allows estimation of cut and fill volumes (e.g., Figure 11, http://gcd.riverscapes.xyz). Moreover, topographic surveys can facilitate multi-dimensional hydraulic modelling (Nahorniak et al., 2018), and ecohydraulic modelling of fish habitat (Wheaton et al., 2004), and be up scaled to evaluate population-scale life cycle models (e.g., Wheaton et al., 2017). We have conducted thousands of high-resolution topographic surveys and subsequent analyses in what, for six years, was the largest stream habitat monitoring program in the world – the now defunct Columbia Habitat Monitoring Program (Bangen et al., 2014a; Bangen et al., 2014b; Bouwes et al., 2011).

One of the ironies of low-tech restoration design is that we are explicitly promoting outcomes and processes that will sustain a greater degree of topographic heterogeneity within the riverscape valley bottom, yet we explicitly discourage requiring topographic surveys for design. If project objectives are to create topographically complex habitat by structurally-forcing hydraulics and geomorphic processes, what better way to illustrate the effectiveness of restoration than by pre- and post- topographic surveys? Indeed, topographic surveying can precisely and convincingly demonstrate changes in topography that result from restoration. In this appendix, we show three examples illustrating these ideas:

- Figure 11 shows before and after topographic surveys, where an avulsion across the inside of a meander bend was forced by a beaver dam. The repeat surveys were differenced, and the geomorphic processes of erosion and deposition were mapped and quantified using DEM (digital elevation model) differencing (using our GCD Software).
- Figure 12 shows before and after topographic surveys where a high-density large woody debris restoration treatment using PALS transformed a structurally-starved system dominated by planar geomorphic units (runs and rapids), to a physically complex system with structurally-forced bars, riffles and pools. The geomorphic units are derived directly from topography (Bangen et al., 2017; Wheaton et al., 2015), using our GUT (geomorphic unit tool).
- Figure 13 is a conceptual histogram of elevation for pre- and post-restoration conditions in an entrenched channel from Shahverdian et al. (2017). The hypothesized geomorphic mechanisms of redistributing elevation from a strongly bimodal (peaked for high floodplain surface and plane bed channel surface) are smeared out via these processes into a much more variable elevation surface. This is clear way of testing the ideas posed in Pollock et al. (2014).

From a scientific, adaptive management and/or monitoring perspective, all three of these examples are repeatable and worth studying and documenting (Lautz et al., 2019). However, from a restoration practice perspective, such quantification is usually unnecessary. These responses all follow the Riverscapes Principle 2 and the structurally-forced pathway to complexity (see Chapter 2: Wheaton et al., 2019). These responses all do not require precise topographic survey document. They can be seen and verified in a qualitative fashion (Camp, 2015). If these processes take place over the entire valley-bottom such that the system is transformed back to Stage 0 (see Chapter 1: Shahverdian et al., 2019a), then they can be approximated for free with remotely sensed satellite imagery (e.g., Silverman et al., 2018). If we spend limited restoration resources on design, implementation and monitoring at the structure scale, we will miss the opportunity to restore more miles of structurally-starved riverscapes. We do need research and monitoring to document these responses, vet them in the peer reviewed literature, and give practitioners the confidence to proceed. However, as researchers who have made their careers by measuring and analyzing high-

resolution topography, we believe it is unnecessary for design of low-tech process-based restoration. Moreover, this manual and the principles (Chapter 2: Wheaton et al., 2019) underlying the low-tech design process are based on our experiences from decades of studying topography and can be used to justify this approach, but are not necessary for each project.

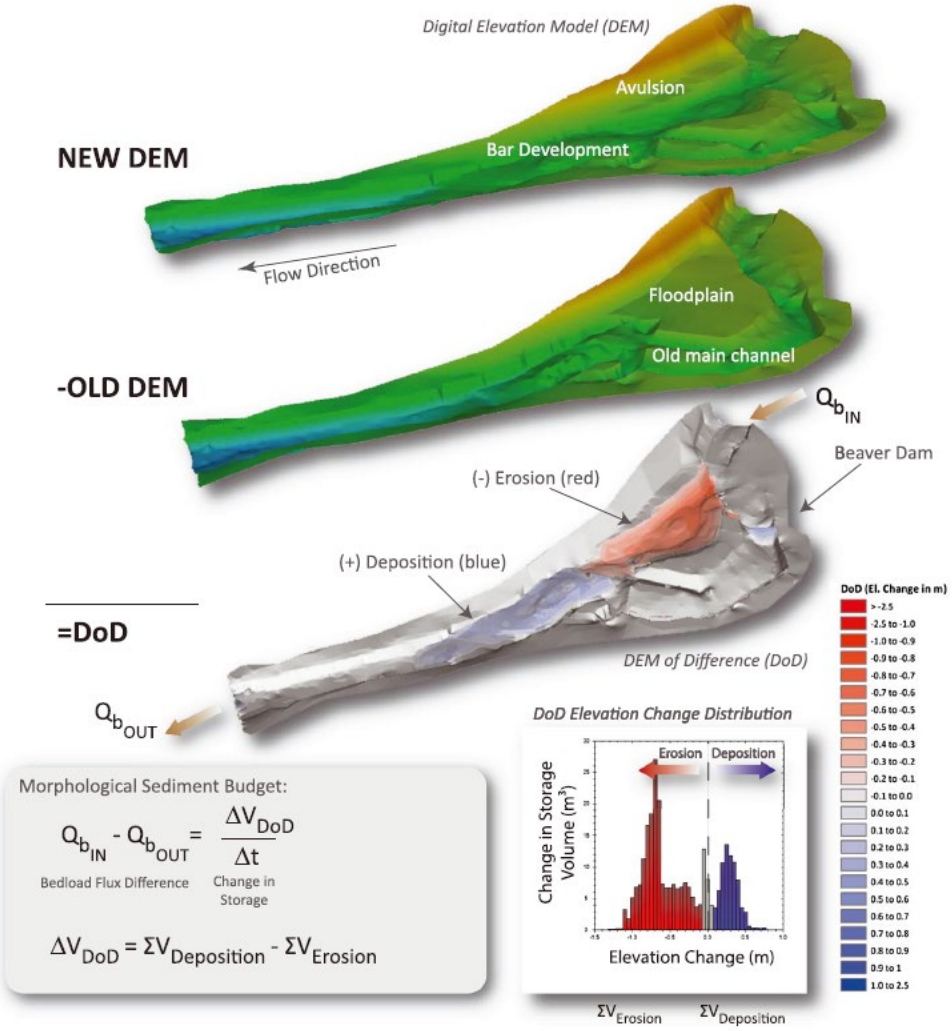

Figure 5. Concept of DEM differencing for morphological sediment budgeting. As repeat monitoring takes place into the future, pairwise comparisons of more recent DEMs (New DEM) and previous year's DEMs (Old DEM) can be made using a simple cell-by-cell subtraction of DEM elevation values. This results in a distribution of negative (red) and positive (blue) DoD values, which correspond to erosion and deposition respectively. These elevation change values can be multiplied by cell area and summed to estimate the total volume of erosion and deposition. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 11 – Topographic maps as digital elevation models (DEM) are an excellent basis for monitoring, but are unnecessary for the design of low-tech restoration projects. Differencing DEMs allows estimation of earthwork cut and fill for grading associated with designs, as well as monitoring geomorphic adjustment with post-project monitoring and repeat surveys. This figure 5 from Bangen et al. (2014b) illustrates the application of DEM differencing using geomorphic change detection (http://gcd.riverscapes.xyz).

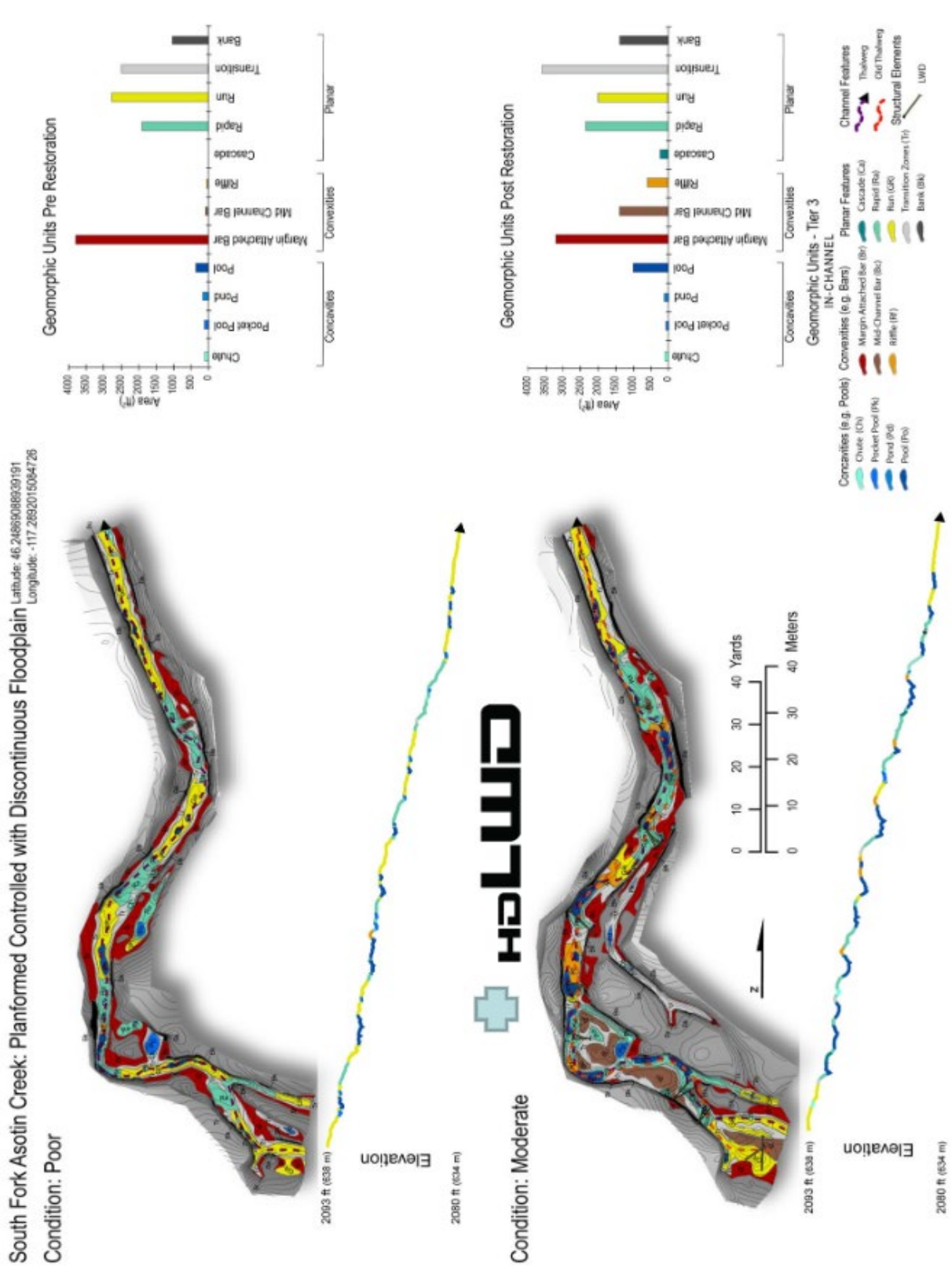

Figure 12 – Example of structurally-forced hydraulic diversity with the addition of high-density large woody debris (HDLWD – i.e., lots of post-assisted log structures). The creation of new pools, growth of bigger structurally-forced pools, and forcing of new bars and riffles at the expense of rapids and runs (i.e., plane bed habitat) illustrates how restoration can create structurally-forced complexity. From: http://gut.riverscapes.xyz

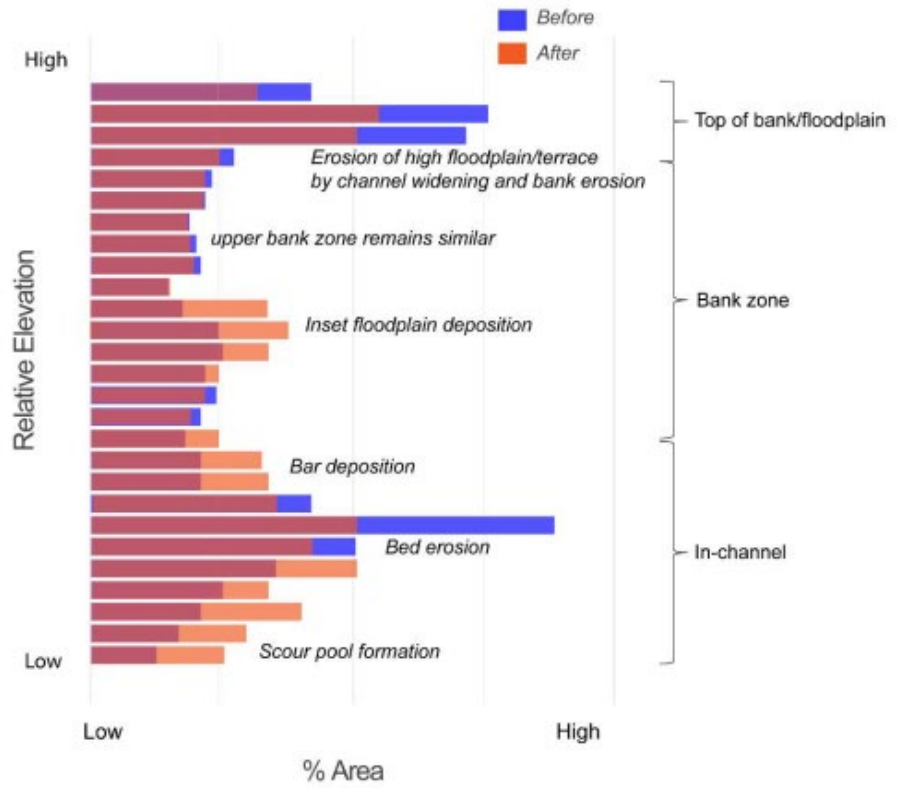

Figure 13 – Example of a conceptual diagram of the current distribution of elevations and the hypothesized results after restoration. The top figure shows a histogram (before and after), and the photos below show pre-treatment conditions (left) and post-treatment diversification of surfaces from structural-forcing (right). Photos are taken at different locations within the same reach. Note that the orange is semi-transparent in order to see the 'before' conditions. From Shahverdian et al. (2017).

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Chapter 6 – LOW-TECH RESTORATION PROJECT IMPLEMENTATION

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IMPLICATIONS FOR PRACTICE

- Key phases of restoration project implementation include obtaining regulatory consultations and permits, construction, monitoring and adaptive management.
- Application of beaver dam analogues (BDAs) and post-assisted log structures (PALS) as low-tech tools for process-based restoration is an emerging approach that may require working closely with local regulators to increase awareness of the practice and expected outcomes.
- Unlike traditional restoration practice where construction is generally done by specialized contractors or heavy equipment operators, low-tech structures are often hand-crafted and can be built by a much broader range of practitioners (e.g., from volunteers and conservation corps crews to professionals). This allows more people to participate in restoration, however, it involves additional safety and logistical considerations.

INTRODUCTION

In this chapter, we provide guidance relevant to implementation of low-tech process-based restoration of riverscapes on both i) the necessary consultation and permitting part, and ii) the fun part - construction. The construction stage of low-tech restoration can truly be a community effort – landowners, youth groups, volunteers, conservation corps, managers, and anyone that doesn't mind hard, wet and dirty work can join in (Maestas et al., 2018). Throughout this manual we have stressed that low-tech restoration is simple, scalable, and does not require advanced degrees, or certifications to implement, provided the underlying principles are understood, and basic planning has been completed (see Chapters 1-3: Bennett et al., 2019; Shahverdian et al., 2019a; Wheaton et al., 2019). Hence, in this chapter we assume the reader has already concluded their riverscape is structurally-starved (see Chapters 1 and 3: Bennett et al., 2019; Shahverdian et al., 2019a), understands the guiding low-tech principles (see Chapters 1 and 2: Shahverdian et al., 2019a; Wheaton et al., 2019), completed project planning (see Chapter 3: Bennett et al., 2019), designed complexes (see Chapter 4: Shahverdian et al., 2019c), and selected specific locations, structure types, and structure dimensions (e.g., PALS & BDAS, see Chapter 5: Shahverdian et al., 2019b). While more detail has been provided in those preceding chapters to robustly support those phases, those planning and design phases are generally done by a smaller number of people. A much larger audience (or workforce) will become involved in the construction and implementation described in this chapter. In this chapter, we present two key aspects of implementation: i) consultation and permitting, and ii) construction. We also comment briefly on the evaluation aspect of implementation, which is covered in more detail in Chapter 3 (Bennett et al., 2019).

Individual states, counties, and local municipalities have specific regulatory and permitting requirements. Management agencies, such as Bureau of Land Management (BLM), USDA Natural Resources Conservation Service (NRCS) and US Forest Service (USFS), also have their own internal consultation and approval processes. There are too many specific individual permitting examples to cover comprehensively here. Instead, we provide the reader general guidelines and suggestions to approaching the consultation and permitting process.

In the construction section, we review the basic steps of implementing a restoration project focused on installing woody debris structures. Much of the construction review will be familiar to seasoned restoration practitioners. However, we provide this construction review because there may be more "novice" practitioners using low-tech restoration than other more traditional forms of restoration that rely on licensed engineering contractors to do the work. We also point out practical and logistical considerations that may be less obvious to practitioners that are used to more mechanically-based "hard-engineering" restoration (Bisson et al., 2013). We remind readers that low-tech restoration should be reflective of the guiding principles (see Chapter 2: Wheaton et al., 2019), use of locally available materials, and generally seek to restore more miles of stream, with less focus on individual structures – and more focus on using many structures (strength in numbers) to let the system do the work.

The idea of maintenance may be new and somewhat confusing to some practitioners but is explicitly part of an adaptively managed Conservation Planning Process (Figure 1). Maintenance (or subsequent treatments in successive phases) are a critically important part of low-tech and a distinguishing feature that is lacking in traditional restoration – namely that the structural deficit in riverscapes is of such magnitude that no restoration action can address it in one treatment (see Chapter 3 mainteance and evaluation: Bennett et al., 2019; see Chapter 1 scope of the problem: Shahverdian et al., 2019a). Low-tech restoration is well-positioned to address scope of structural deficits because it seeks to add structure to promote processes directly related to recruitment, transport and accumulation of woody debris in riverscapes (not impose form on a riverscape). The low-tech approach essentially injects pulses of structure into the riverscape in an attempt to promote self-healing. By evaluating the effect of the pulse of structure, practitioners can gauge when natural processes have healed enough that more injections of structure are no longer needed. This is a very different but arguably more effective and efficient way of restoring a riverscape because treatments can be ramped up as needed rather than trying to fix the entire system in one step – which is not practically feasible.

We have also assembled a number of resources for practitioners – especially those new to low-tech restoration. Please visit the riverscapes website for more information (http://lowtechpbr.restoration.usu.edu). The riverscapes website will be updated periodically with new information, lessons learned and training opportunities.

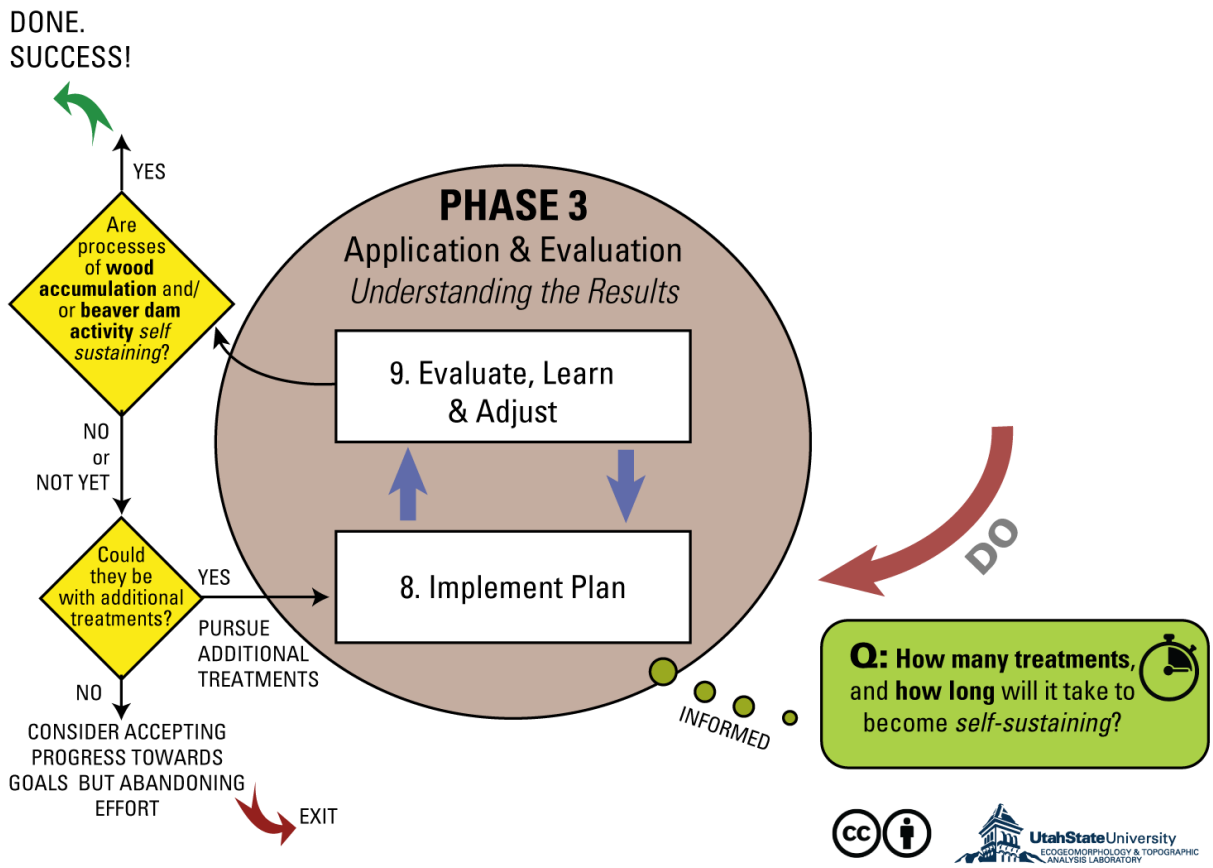


Figure 1 – The implementation and evaluation aspects of low-tech process-based restoration correspond to Phase 3 of the Conservation Planning Process (see Chapter 3 for more information). Each design that is produced in Phase 2, corresponds to one implantation event. For most (not all) low-tech restoration, it may take multiple treatments a) to achieve project goals, and b) before processes of wood accumulation and/or beaver dam activity are self-sustaining.

CONSULTATION AND PERMITTING

Low-tech structures (e.g., beaver dam analogues (BDAs), post-assisted log structures (PALS); see also Appendix 1 in Chapter 1 for many others: Shahverdian et al., 2019a) are different from a permitting standpoint than more traditional engineering-based structures (e.g., engineered log jams, J-hooks, cross veins, etc.), because they are not designed or constructed to be relatively permanent, but instead designed to promote processes. Most BDAs and PALS are designed and constructed to have a design life of <1 year, despite often having lifespans in excess of decades. This means they are not certified by an engineer to sustain a specific magnitude flood tied to a recurrence interval high-flow (e.g., 25, 50 or 100 year recurrence interval floods). Individual structures are meant to be dynamic wherein change is not only expected, but explicitly the design objective (e.g., may fill up with sediment, breach, or move; see Chapter 4: Shahverdian et al., 2019c). However, when constructed in large numbers, many structures are expected to persist for several years and the wood from structures that move is expected to accumulate on downstream structures (e.g., strength in numbers Restoration Principle 6, see Chapter 2: Wheaton et al., 2019). The design process for low-tech restoration is simple, primarily performed in the field, and we recommend that permits are sought for groups of structures called (see Chapter 5: Shahverdian et al., 2019b). Thus, when submitting a permit application practitioners are encouraged to describe the locations, goals and objectives of each complex (and overall project), building materials,

approximate number and type of structures, and corresponding typical dimensions of the structure types being used (e.g., height and percent constriction of the channel). If required, as-built surveys can be provided to the regulators after construction confirming the final design specifications of the treatment.

Stream restoration projects require consultation with various regulatory agencies to obtain necessary clearances and permits prior to implementation. Requirements and processes vary by state, project funding source, land ownership, project location, treatment type, etc. Regardless, the consultation process for most stream restoration projects can take considerable time and should begin early in project planning. For a more comprehensive overview of permitting, refer to Chapter 17 of Part 654 Stream Restoration Design of the National Engineering Handbook by NRCS (2007).

Given the wide variation in regulatory requirements and protocols across the country, we do not attempt to provide detailed permitting guidance here. Practitioners are highly encouraged to reach out to local regulators and partners to become familiar with the consultations and permits that might be required for a specific project. Below, we provide a non-comprehensive list of some common regulatory entities related to low-tech stream restoration that often require coordination and consultation:

Federal

- **U.S. Army Corps of Engineers (Corps)** – The Corps administers permits for Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act which commonly apply to instream restoration projects occurring in 'waters of the U.S.'
- **U.S. Fish and Wildlife Service (USFWS)** – USFWS regulate inland, and NOAA Fisheries regulate anadromous fishes under the Endangered Species Act (ESA). Consultation may be required where federally-protected species may be affected by project actions.
- **National Oceanic and Atmospheric Administration Fisheries Service (NOAA Fisheries)** - NOAA Fisheries, along with USFWS, administers the Endangered Species Act. Consultation may be required where federally-protected species may be affected by project actions.
- **National Environmental Policy Act** – If the project has a federal nexus (funding, participants, on federal land), then the proposed work must also be in compliance with the National Environmental Protection Act (NEPA). A federal agency will take the lead for evaluating the NEPA component.

State/Local

- **State Historic Preservation Office (SHPO)** – The SHPO manages and administers programs for the protection of the state's historic and cultural resources, in accordance with the National Historic Preservation Act. Most restoration projects require consultation due to ground-disturbing activities.
- **Department of Water Rights, Water Resources, or Engineers Office** – Depending upon the location, some states require consultation with the agency overseeing water rights when implementing instream restoration projects.
- **Department of Fish and Wildlife** - Depending upon the location, some states require consultation with the state fish and wildlife agency when implementing instream restoration projects. Many states establish 'work windows' that guide timing of project implementation to minimize adverse impacts to species of concern. Some states also have requirements related to fish passage and stream habitat management.
- **County and municipal governments** – Although rare, some local governments require stream alteration permits or other coordination for restoration work. Counties in some states require shoreline permits, though some states provide exemption for fish and wildlife habitat enhancements.
- **State Departments of Land or Ecology -** State Departments of Land or Ecology regulate more general physical and ecological impacts (not just water, or fish/wildlife) and may require permits for stream alteration.

Since BDAs and PALS are relatively new to stream restoration, it may be necessary for project planners to coordinate and communicate closely with local regulatory agencies to help improve overall understanding of the low-tech process-based restoration approach and expected outcomes. Below we provide guidance for project planners:

- **Understand the intent of the governing regulations**. The intent of most regulations relevant to restoration is to protect the environment, critical infrastructure, cultural resources and/or the health and safety of the public.
- **Provide the regulator with the information they need to approve the project**. What questions do they have to ask and answer to make an interpretation regarding your application and/or issue a permit or exemption? Make their job easier by providing a complete application, organized around the questions they have to answer.
- **Establish a rapport with regulators and earn their trust**. Invite your regulators to come and see what you are trying to do and, to the extent appropriate, become a collaborator in what you are trying to achieve. The goals of low-tech restoration and governing regulations from which they are issuing permits often share a lot in common.
- **Communicate regularly and clearly** – Do not be afraid to ask questions and communicate the intent with the regulators. Seek guidance on the permitting processes.
- **Be realistic about timeframes** – Each agency has a different workload and different standard for how long a permit process takes. While some agencies can turn things around quickly (< 2 months), allow for 6-12 months or more depending on how complex the project is.
- **Request a permit for complexes not structures** – If your permitting agency will allow it, do not submit overly precise structure-by-structure design details. Focus on complexes of structures working in concert with each other to achieve broader scale objectives within a reach. For example, you might state that 'Complex B is designed to mimic a beaver dam complex, promote aggradation of an incised channel, and floodplain reconnection through widening the incision trench and letting the river build its own inset floodplain in place of the eroded terraces. Complex B spans 150 yards and will consist of 2-4 bank-attached PALS towards the upstream end, a large primary BDA, and 3-5 secondary BDAs downstream'. The range of structure types and numbers, give flexibility in precise implementation yet convey intent, scope and impact.
- **Even if a permit is not required, let the regulator make that decision** –In most jurisdictions, low-tech restoration will not trigger the need for a permit if it is in ephemeral streams or gullies. It is still good practice to notify, ask or apply with the regulatory agency, and let them make that determination.
- **Permit for Staged Implementation & Maintenance** – Low-tech restoration is often not completed in a single treatment. For efficiency, it may help to apply for a permit asking that cover several years to allow for maintenance or further treatment.
- **Attend Local Permitting Workshops** – To provide a better understanding of the permitting process, many local and state agencies provide free workshops for practitioners. These workshops often include presentations and guidance from government personnel that are likely to review your permit application. They will describe what they look for in a quality application and give tips for navigating the regulatory process.

We provide examples of some permit applications for projects using BDAs and PALS to help low-tech project planners see the types of typical information submitted and how treatments are described on the manual website (http://lowtechpbr.restoration.usu.edu/manual/chap06/permitting).

CONSTRUCTION OF LOW-TECH RESTORATION STRUCTURES

Some forethought on logistics, prior to implementation, enables the construction of a greater number and density of structures, which is essential to achieving restoration goals. As with any construction process, safety and efficiency are paramount concerns. Those experienced with construction and hand labor will not necessarily need the considerations and references provided here. We highlight some of our lessons learned regarding logistical considerations, crew dynamics, safety procedures, and construction equipment based on experience building thousands of BDAs and PALS since 2009. Much of what follows is common sense, but without direct experience building low-tech structures, it might not be obvious to all participants. We organize this section into sub-sections on:

- Building materials for low-tech structures
- Building low-tech structures
- Tools and equipment for building low-tech structures
- General construction guidance (logistics, crews, safety)

One of the main requirements of low-tech process-based restoration methods is to build a large number of structures over a large spatial extent – such that treatment scales match the scope of the problem (Process-Based Restoration Principle 3 from Beechie et al. (2010)).

Building Materials for Low-Tech Structures

The majority of low-tech structures discussed in this manual are built with a primary building material of wood (e.g., beaver dam analogues (BDAs), post-assisted log structures (PALS); see also Appendix 3 in Chapter 1 for many others: Shahverdian et al., 2019a). Other secondary building materials include smaller organic matter (e.g., turfmats, leaves, small branches), soil, and/or alluvium (sediment transported by water, making up channel substrate and valley fill deposits). Some low-tech structures (e.g., Zuni bowls, one rock dams) are made entirely with rock (Maestas et al., 2018). As Restoration Principle 7 encourages (Chapter 2: Wheaton et al., 2019), always use natural building materials that could plausibly be found in that riverscape environment. From a pragmatic perspective, if these can be sourced on site that dramatically simplifies logistics and keeps costs down.

Some structurally-starved riverscapes still boast abundant woody riparian plants or intersect uplands with abundant woody vegetation. In those fortunate circumstances, everything needed to build can be found onsite and locally sourced. This keeps cost down. Some of those environments are also prime candidates for wood replenishment techniques design (Saldi-Caromile et al., 2004) like selective felling (Carah et al., 2014) and grip-hoisting (Micelston, 2014). However, in many structurally-starved riverscapes, part of that starvation is due to the fact they no longer have abundant woody vegetation. While longer-term restoration goals may focus on improving such conditions, immediate low-tech restoration implementation still needs a source of wood. Moreover, low-tech restoration often helps 'fix' the hydrology problems (Restoration Principle 4; see Chapter 2: Wheaton et al., 2019), which, in turn, accelerates riparian recovery. When combined with better land use practices (e.g., improved grazing management), it becomes easier to grow and sustain a source of wood.

We elaborate on four aspects within this subsection of building materials: sourcing woody materials, procuring wooden post, staging woody material and moving of building materials.

Sourcing Woody Building Materials

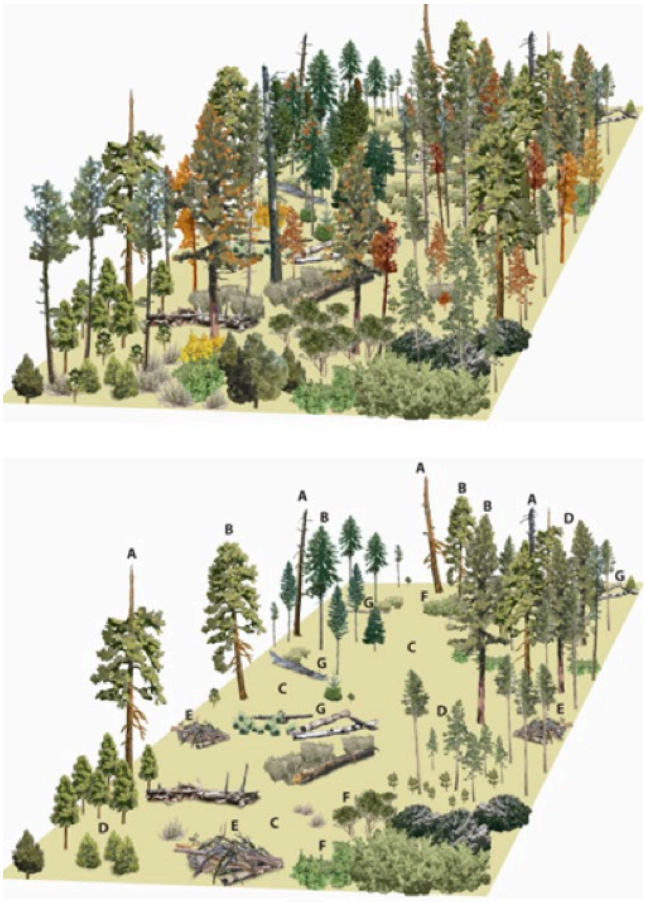


Figure 2 - Forest and riverscapes restoration efforts in the same watersheds and areas can be complimentary efforts. Fuels reduction to improve forest health and fire resilience efforts can produce lots of woody material and brush that has no commercial value, but works great as building materials in PALS and BDAs. Figure 4 & 5 from Strong et al. (2016).

Many potential sources for woody materials can be found to create high-density large woody debris ($_{HD}$LWD) treatments (e.g., PALS and wood replenishment) or BDAs. If possible, try to locate a free source and one that either eliminates or minimizes the need to haul or transport material from offsite. If native riparian vegetation is abundant enough on site it can support some harvest (most of which grows back vigorously from coppicing), it can be used as a source of wood. Be sure to relay your intent to use riparian vegetation or woody debris from the floodplain during the consultation process. However, there is no need to use only riparian species. Conifer encroachment into riparian areas and riverscapes is a massive problem across the west and is directly related to riparian degradation. Sometimes wood of the appropriate size for PALS (4 – 20' in length and 4-16" diameter) is available as a waste product from timber harvest (i.e., slash), forest thinning, fuels reduction or fire salvage from state and federal land management agencies or private timber operations. We strongly recommend trying to integrate range or forest management with your stream restoration project and combine fuels management with riverscapes restoration (Figure 2).

Examples of this type of integration include conducting forest thinning operations in forests, and juniper removal in rangelands, and using the woody material to build structures (Kormos et al., 2017; Strong et al., 2016). Scott Nicolai, habitat biologist with the Yakama Nation in Washington State summed up the intent – "We are essentially conducting reverse logging" … bringing woody material back to the streams as cost-effectively and efficiently as we can (see his grip hoisting guidelines in Appendix B).

Throughout the sage-steppe of the Western US, fire suppression has helped facilitate expansion of pinyon-juniper (PJ) communities into sagebrush habitats and promoted much higher stand density in PJ woodlands than would have naturally occurred. PJ woodland expansion and infill has negatively impacted species of concern, watershed hydrology, and other ecosystem functions (Miller et al., 2017). In response, conservation partners across private and public lands have greatly accelerated PJ removal efforts to improve sagebrush rangelands, sage grouse habitats, and watershed health (Figure 3). There is a tremendous opportunity to couple these upland restoration efforts with low-tech riverscapes restoration in the valley bottoms by using these as sources of wood to feed the structurally-starved riverscapes. We have had excellent luck in combining forces with such efforts to do both upland and instream riverscapes treatments (Shahverdian and Wheaton, 2017) as part of holistic watershed restoration efforts (Figure 3).

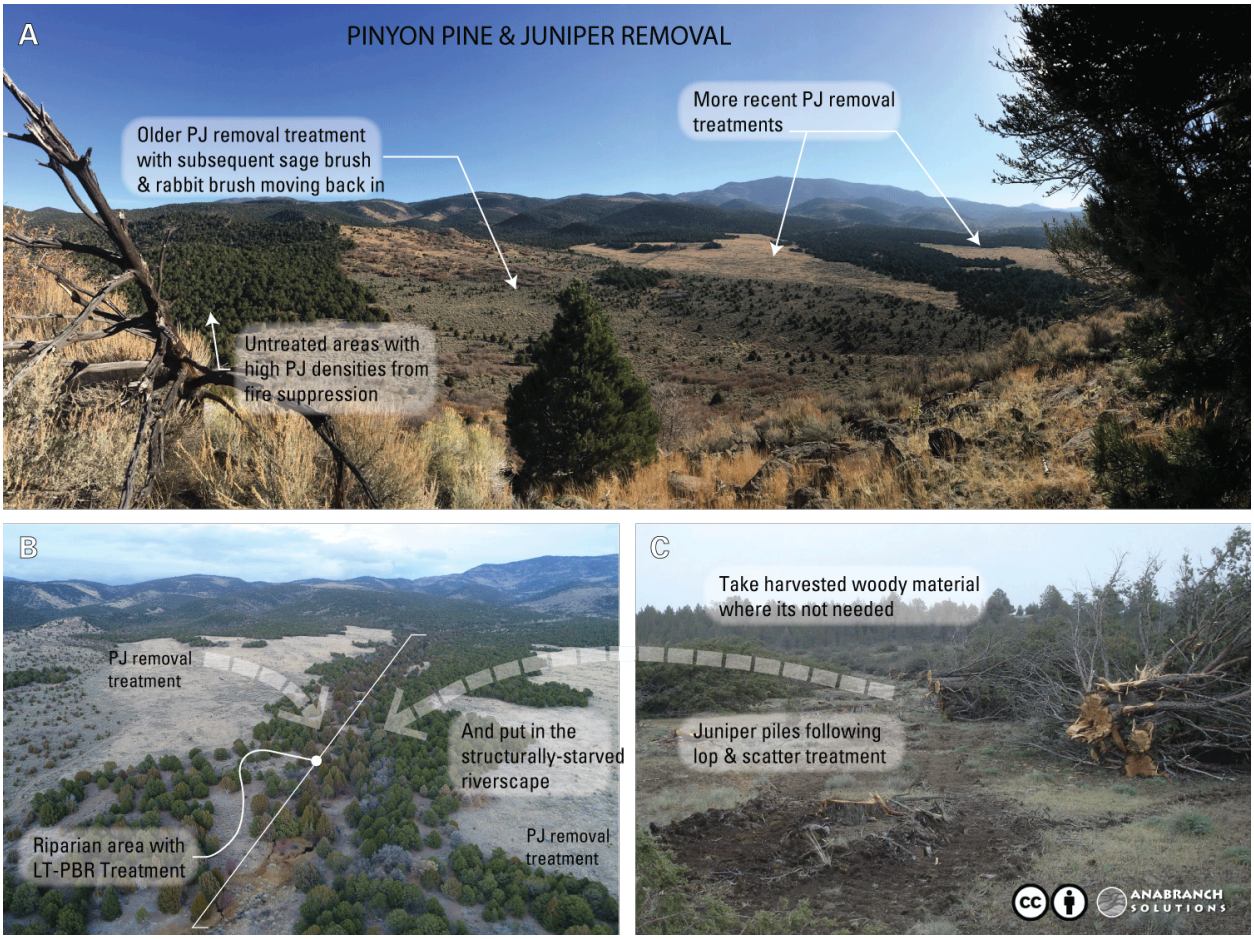


Figure 3 – Examples (A & B) of PJ (pinyon pine and juniper) removal at watershed-scales. Most of the material from such projects is (C) typically piled and burnt, wood chipped, or hauled off site. Occasionally, some of the material can be used for posts or small-scale commercial applications. Given the proximity of many of these projects to structurally- starved riverscapes (like the one shown in A & B), and the suppression of riparian vegetation from conifer encroachment into valley bottoms, it makes sense to take some of the material harvested and put it into the structurally-starved riverscapes with low-tech restoration.

One other example of unwanted excess woody material comes from invasive riparian vegetation management of riparian areas. Encroachment of riparian areas with non-native invasive vegetation like tamarisk in the southwest is a common problem (Shafroth et al., 2008). As long as the material is dead, and the risk of regrowth or spread from that woody material is negligible, such material can make an excellent source of wood (but be sure to consult with local permitting agencies). We have done this with tamarisk in partnership with the Bureau of Land Management (BLM) and Utah Division of Wildlife Resources (UDWR) on the San Rafael River (Laub et al., 2015; Shahverdian et al., 2017).

Woody material may also be gathered from yard waste facilities, Christmas tree collection, and local landowners. Special care should be taken to avoid material that is contaminated by fertilizers, insecticides, herbicides, or other potentially harmful substances. With all wood that you source, make sure it is a size that one to three people can handle and carry. This might mean cutting larger pieces into manageable sizes, and it generally means avoiding too large of diameter of wood unless directly felling or grip-hoisting into the channel.

Wooden Posts

PALS are typically built with wooden posts that are driven into the streambed to temporarily secure woody material in place. BDAs can be built in post-assisted variants, but for the majority of situations postless BDAs will work. If a PALS is going to last at a particular location, its stability is more a function of the accumulation of other material and partial burial of the structure than the type of posts you use. The posts are not meant to last forever, and it's better to have something that will break down in 1 to 10 years. Never use pressure treated posts, as the chemicals will leach into the stream (Figure 4 B). A large variety of options exist for posts (Figure 4).

Figure 4 – Posts are used to provide temporary stability or pins when building many low-tech restoration structures (e.g., post-assisted log structures). Many commercially available fence post options are available, but a premium price is charged for consistency, larger diameter, and straight poles (e.g., peeler cores and lodge pole (A, G, J, K). Rough logs (C, N), smaller diameter tree stakes (H, I) are cheaper, and often available from fuels reduction (F) or non-commercially viable slash from timber harvest operations. Since posts are driven into substrate, they need to be pointed at tips (A, E, H-N). Pointing can be done by supplier (typically with a machine – e.g., M) or by an experienced chainsaw operator with four cuts (L & N).

A variety of post type and size (length and diameter) can be used. In general, use the smallest and least expensive posts required to achieve the structure goal. Posts length is a function of structure height. Generally, posts should be driven as far as possible and a minimum of 25% to 33% of the exposed length of post above the bed. In general, posts bought commercially and sold as fence posts are 6 to 8' in length and nominally 3 to 4" in diameter (e.g., Figure 4 A, G, K and J). Trimming the post to the required length can increase safety because the post driver does not have to be lifted as high.

We have paid between $4 and $8 a post for untreated fence posts. By contrast, we have been available to secure posts for as little as $1.50 to $3.00 a post directly from small-scale mills when we are willing to go for odd sizes (smaller diameter is often easier to drive), odd lengths, and irregularities. Another cheaper option that works well are tree stakes or arborist stakes in diameters of 1" to 2" (Figure 4 H & I). Order more posts than are required for each structure as it is likely that some of the posts will be unusable because of defects or excessive diameter. Another option is making your own posts from onsite or freely available materials (e.g., Figure 4 C, D, F & N). Do not forget to factor in labor costs and time and compare these to commercially sourcing posts.

Staging Woody Material

Regardless of the material you will use, staging it near your restoration structures ahead of time is often necessary (Figure 5). The staging can often occur outside the work window or when crews are available, and it can greatly speed the construction of structures if most of the woody material is near the work site and ready to roll or drag into the stream. Staging the material at each structure ahead of time also helps to determine how much woody material you need to complete the entire project. Even small streams can use large quantities of material – in our experience, the amount of available building material is often the limiting factor. If you are constructing BDAs, other material (e.g., sod, mud, rocks) gathered onsite is also required to help pool water upstream of the structure. However, staging piles create very favorable conditions for rattlesnakes, so make sure crews are alert and aware of the possibility of interaction with snakes.

Whereas the construction of low-tech structures is primarily done by hand without the aid of heavy equipment, if staging areas have good vehicular access, having some heavy equipment to help load, unload, pile and stage material can be a helpful time saver.

Figure 5 – Staging of woody building materials secured from off site into floodplain (A) and terrace (B) areas with easy access for unloading and loading, and subsequent moving into riverscapes treatment areas.

Moving Building Materials by Hand

By comparison with traditional restoration where heavy equipment can be used to move material and place it, most of the work of moving and placing after staging is done by hand. A helpful way of thinking about wood is in terms of how many people it takes to carry and safely place. In Figure 6, a three-guy/gal piece of wood shown as this < 12" diameter log takes three people to carry it safely. In Figure 7, most of the wood and material being brought in can be safely carried by one person. If larger key pieces are necessary for a structure's design, then two to three people can carry them from the source or staging area to the structure location. However, efficiency is maximized when the majority of pieces used are one-guy/gal wood. Plus, a lot of smaller material can be effectively combined to emulate the role of a larger piece of wood.

*Figure 6 - Most materials will be moved by hand, so it is essential it **can** be moved by hand. Most of the material you work with is easiest if it is one-guy/gal wood (i.e., it can be carried by one person). The terms 2-guy/gal and 3–guy/gal have real physical meaning. In some cases, 'bigger' wood can be simulated by creatively combining a bunch of smaller pieces together, meaning more can be done by less people. However, after moving enough 2-guy/gal or 3-guy/gal wood, you will want to make sure you use it sparingly and only where necessary. Note limbs removed on underside of log to lie in contact with the stream bed (i.e. increased hydraulic purchase).*

Figure 7 - Team work in moving woody material from its source areas or staging areas to structure locations can save time and backs.

Building Low-Tech Structures

Typical time for building a structure varies widely by type of structure, amount of material needed, the efficiency/experience of the crew, and whether that material is readily available. Having enough laborers to move material from source areas to staging areas or directly to where it will be placed is critical for efficiency). When the placement of material into its final resting place is simply a dropping, felling, chucking, or tossing operation, placement can be a matter of seconds. When the placement is for PALS (pos-assisted log structures), and involves packed, woven, stomped, pounded, driven, laid, intertwined, tied, pinned material, this takes on the order of minutes for each piece, and 10s of minutes to an hour for bigger structures that involve more pieces and more posts. Plus, posts have to be driven into support the PALS (Figure 8). Thus, PALS that are mid-channel tend to be quickest (often 10 to 30 minutes), whereas channel spanners can take longer (often 15 to 120 minutes) and bank-attached are often similar to channel-spanners, as we tend to constrict 80 to 95% of the channel width. BDAs are much more labor intensive then PALS because the act of plugging to hold water back takes more time. Small secondary BDAs can be built in as little 30 minutes, but most BDAs take between 45 and 120 minutes and some large primary dams can take as long as half a day.

Figure 8 – A crew of three building a post-assisted log structure.

One of the reasons that BDAs take so much longer to build is, if you mimic the plugging work of beaver on dams, you are building more than just a wood structure. You are actually making a carbon fiber mess, which has some wood, branches and sticks, but may also include all sorts of sizes of sticks, twigs, leaves, grass, turf, root-mats and other organic matter. They also include lots of sediment. A range of size of materials and textures helps fill voids and more effectively hold back water in these leaky dams. Getting a bucket line of this smaller sized material (e.g., Figure 10) can be a highly effective way of speeding up the process. This 'other' material should always be sourced locally on site. Source areas should be carefully chosen as to not be counter-productive. For example, a good area to source bed material and sediment would be from the bed upstream of a BDA that will be inundated with water (this just creates more capacity). By contrast, it makes less sense to source the sediment right at or downstream of the structure as this could undermine its integrity.

There are many ways to build structures. The reader is referred to Chapter 5 Appendices D & E for examples of typical schematics (i.e., cross section, planform and profile views), as well as installation instructions for PALS and BDAs (Shahverdian et al., 2019b). These are available for use in reports, permit applications and for practitioners to adapt (Figure 9). Just like cooking, sometimes recipes are helpful for getting started. However, once the practitioner is more experienced creative substitutions of ingredients (materials) and clever adaptations are encouraged. When building lots of structures, there is room for experimentation.

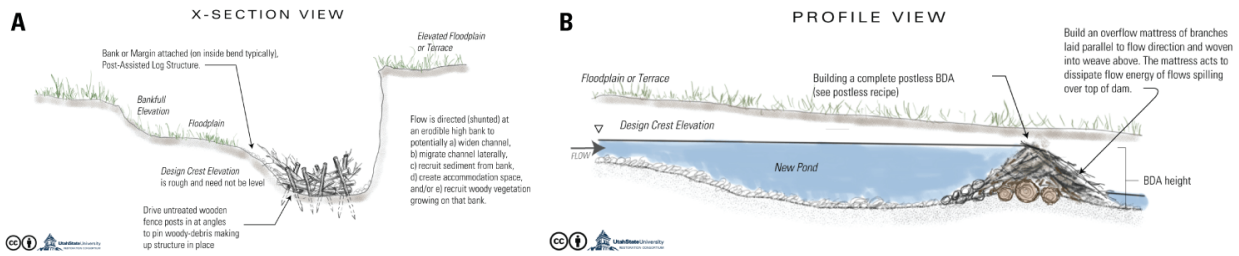


Figure 9 – Examples of schematics for PALS and BDAs available in Appendices D & E of Chapter 5 and on the website (http://lowtechpbr.restoration.usu.edu/resources) to help. A) Example of typical cross section for bank-attached PALS used as a 'bank-blaster'. B) Example of postless BDA profile schematic.

Figure 10 – For BDAs, mud, bed sediment, turf mats, leaves and organic matter are very useful for plugging up leaks and making the BDA hold back water. It is helpful to have lots of 5-gallon buckets, a few shovels and a small crew to get a bucket line from the source area to the crew members packing the dam material.

Tools & Equipment for Building Low-Tech Structures

A plethora of tools, methods and equipment can be used in low-tech restoration. One of the exciting aspects of low-tech restoration can be working with new partners and collaborators who bring different experience and creativity in problem-solving and solutions to the process of adding structural elements. Crews generally work to add woody material, use fill material if it is a BDA to create a pond (Figure 11), and optionally drive posts to secure wood. In this sub-section we review a range of tools and equipment that can be helpful.

Figure 11 – Example of the construction process of a beaver dam analog including driving posts, and adding woody material, packing in fill material.

Hand Tools – Cutting & Digging

We find the following hand tools are useful for construction of BDAs, PALS and other low-tech restoration structures and woody additions:

- Shovels, picks, digging bars and 5-gallon plastic buckets – for digging, gathering and moving materials
- Clippers, handsaws, chainsaws, brush cutters – for cutting and harvesting shrub and woody material, trimming posts; chainsaws can also be used for felling trees to create instant wood structures

One of the handiest reference resources for ideas on tools is the USFS's Handtools for Trail Work (Hallman, 2005). The manual includes resources on:

- Tools for Sawing
- Tools for Chopping
- Tools for Digging
- Tools for Brushing
- Tools for Lifting and Hauling

Pay attention to what experienced laborers, arborists, and landscapers use and ask them for ideas and how to use them effectively.

Chainsaws

Chainsaws are an invaluable tool for speeding up a huge variety of tasks with adding structure (wood) back into streams. A non-exhaustive list of these tasks includes:

- Felling trees either directly into place or from nearby source areas (e.g., riparian areas or nearby hillsides)
- Pruning branches from live trees as source structure material
- Limbing branches from a fallen tree to make a simpler log for placement or moving
- Limbing branches from just one side of a fallen tree or wood in PALS so that 'underside' comes in direct contact with the stream bed (i.e., increasing 'hydraulic purchase'; see Chapter 2: Wheaton et al., 2019), and leaving the branches on other side to stick up and out (acting as posts almost to weave other material in)
- Cutting logs and branches to size to fit in structure or as key pieces
- Cutting a channel-spanning log that has no hydraulic purchase until above bankfull flows so that it has hydraulic purchase at low or sub-bankfull flows
- Pointing tips of posts for driving with a chainsaw by taking four angle cuts (Figure 4; L and N)
- Trimming the tops of posts driven into bed to design crest elevation where and if there is concern that posts might rack additional debris at high flows in undesireable ways (sometimes this is desired)

Only experienced chainsaw operators or those who have undergone safety training or received a chainsaw operator certification should be allowed to operate a chainsaw onsite. Minimizing the number of people onsite using chainsaws at any given time and keep the chainsaw operators out of the area the rest of the crew(s) is/are working. We frequently employ sawyers from fire crews or timber harvest professionals for chainsaw work. We recommend:

- Having the sawyer(s) work in front or ahead of time of crews in cutting, staging and prepping material at structure locations, such that when crews arrive all additional cutting can be done with hand saws and/or loppers
- Having the sawyer(s) work with the construction manager, foreman or designer to identify the source areas and quantities to do their work efficiently
- Having a sawyer available (especially when running multiple crews) to cut specific logs to size for placement in a structure
- Having a sawyer come back through after initial structure construction and trim posts or other features down to design crest elevations

Some agencies have specific guidelines and requirements for who can operate chainsaws and how they can be used on projects under their jurisdiction (e.g., USFS Saw Policy). Make sure you are aware of, and in compliance with, the relevant policies and regulations in the area you work.

Log Haulers

Hand log-hauling tools (e.g., Ironton wooden handle Timber Carrier) are useful for moving logs to the structure location by rolling instead of carrying or dragging (Figure 12).

Figure 12 – Hand operated log haulers (e.g., this one is a LogRite Buck Arch) can make the work of moving 2-guy/gal or 3-guy/gal pieces of wood a one-person job.

ATVs and ORVs

All-terrain vehicles (ATVs) and off-road vehicles (ORVs) with trailers are very useful for staging posts and cut branches if access allows (Figure 13). ATVs and ORVs can also be used in combination with a log hauling tool (e.g., LogRite Buck Arch) to haul logs to the structure locations. If access allows, an ATV or ORV can be used to transport the hydraulic post driver and generator between structures during construction.

Figure 13 – Where ATV access is feasible, ATVs can be a very handy way of moving materials between staging areas and structure locations.

Trailers

It is often beneficial to have multiple sizes of trailers to serve different roles. A large trailer is best suited for hauling posts and materials to the project site or staging area (Figure 14). Whereas a smaller trailer that can be towed using an ATV or hand truck is best suited for hauling material to a structure where access may be limited (Figure 13).

Figure 14 – Low-tech restoration is primarily about getting structure (e.g., wood, branches, logs, trees, sticks, posts) back in riverscapes. To add large amounts of structure requires moving and staging lots of material and trailers are an invaluable tool for doing that if the material cannot be sourced immediately adjacent to the location structures are being built.

Boats

Moving materials by floating is a common trick of beaver, and a great way to let the water do the work. Since some of your building materials are naturally buoyant, it can be very efficient to float posts and large woody debris pieces downstream to the structure location if the stream has sufficient water depth and/or flow. Boats are another great way to float materials and equipment around (Figure 15). If riparian density or steep banks make access difficult, a wide canoe or duck boat with a flat, plastic bottom can be an efficient way to haul posts and small logs. Using a boat is also very efficient for hauling the hydraulic post driver, generator, accessory hand tools and extra posts (Figure 15 A, C & D). We do not recommend using metal boats in shallow streams because they are more prone to cracking and puncturing.

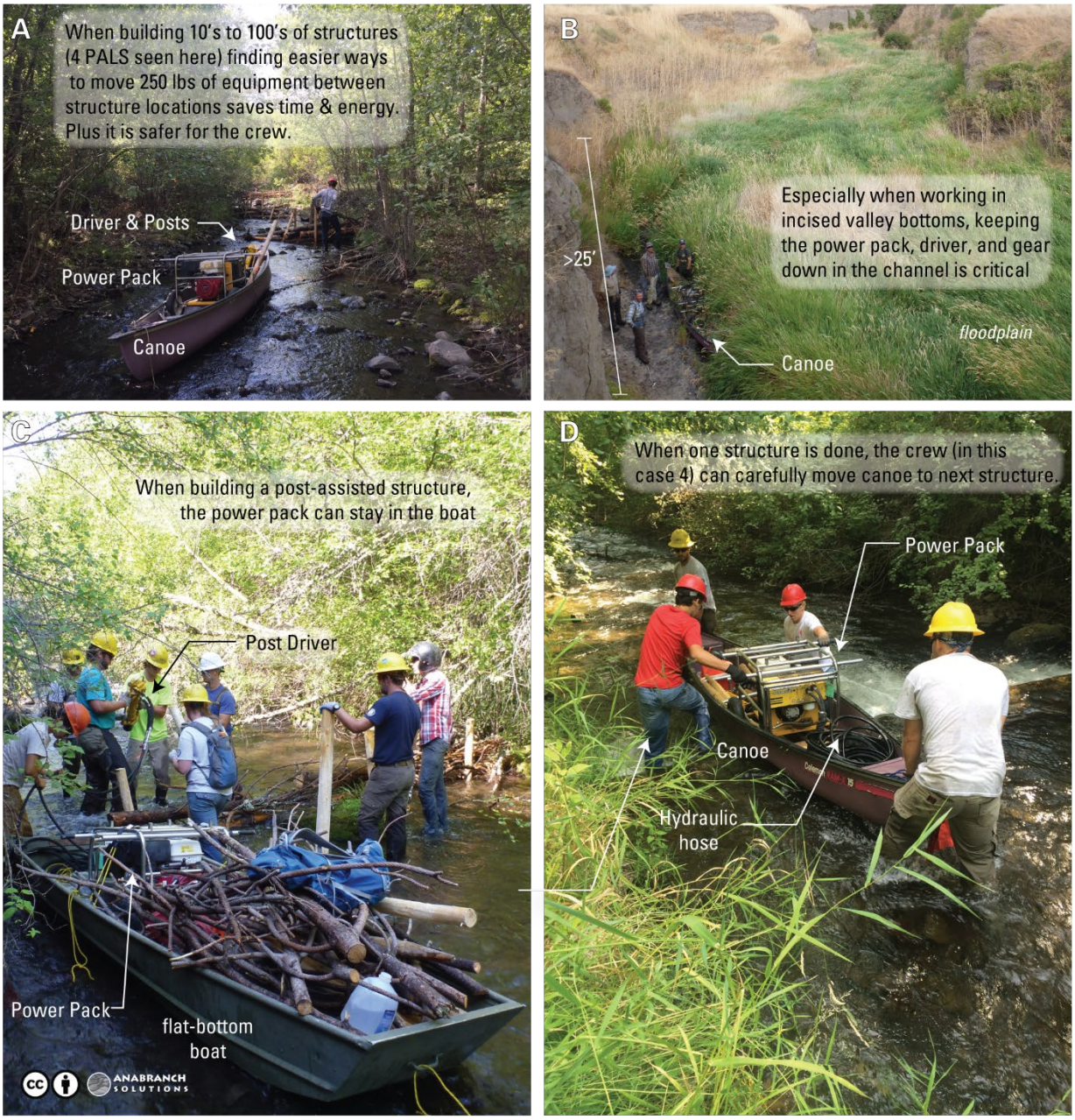
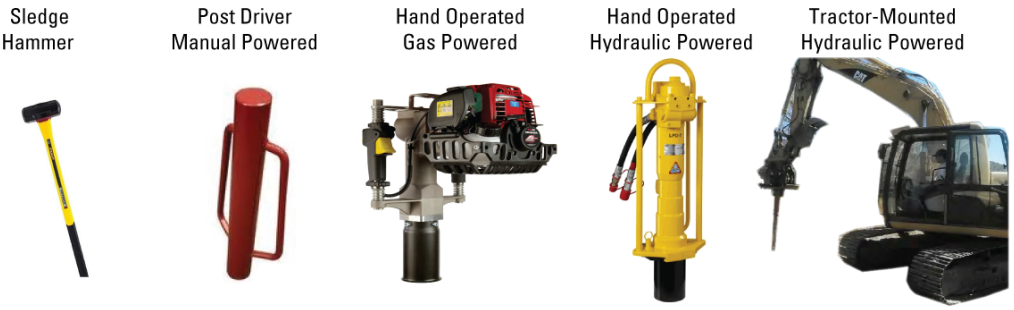


Figure 15 – Using small boats in small streams to float the power pack, driver and hydraulic hoses saves time and backs. This is taking a cue from beaver, they often build secondary dams to extend their forage range to woody material –floating building materials is easier than dragging or carrying (let the water do the work).

Post Drivers

For things that need to be driven or pounded (e.g., wooden posts), options span the spectrum using a sledge-hammer (dangerous and often will not work on larger diameter posts or for as many), to having a hydraulic powered post driver mounted on the front of a skid steer, mini-excavator, tractor or excavator (Appendix A, Figure 24). For low-tech restoration, we tend to discourage the use of tractor-mounted post drivers (Figure 16) as they lead to over building, more complicated permitting requirements, expensive mobilization costs, higher skilled- labor and riparian/land impacts associated with equipment access. Really small diameter posts (e.g., tree stakes, tipped branches; Figure 4 H & I) can be driven with a manual post driver, or a hand-operated, gas-powered driver (Figure 23). However, such gas-powered post drivers work in a limited range of circumstances and rarely work for fence post diameter posts (i.e., 2.5" to 4").

POST DRIVER OPTIONS



Equipment Cost	*$*	*$*	*$$*	*$$$*	*$$$$*
Operator Expertise	*Unskilled*	*Unskilled*	*Moderate*	*Moderate*	*Skilled*
Ease of Deployment	*Easy*	*Easy*	*Easy*	*Moderate*	*Difficult*
Max Diameter of Post	*0.5 - 2"*	*0.5 to 2.5"*	*1" to 2.5"*	*1" to 4"*	*1" to 6"*
Effectiveness / Scalability	*Low*	*Low*	*Moderate*	*High*	*High (access limited)*

Figure 16 – Post drivers come in a huge variety of options, but each have tradeoffs in terms of equipment cost, operator expertise required, ease of deployment, maximum diameter of posts they can drive (varies with substrate) and their overall effectiveness and scalability when doing 10's to 100's of structures over many miles of streams.

Hydraulic Powered Post Drivers

Figure 17 - Moving the power pack (Atlas LP 13-20) and hose that drives the hydraulic post driver is at least a two-person job if it can be rolled, and is often easier with three or four. It typically takes three to four people to lift and/or carry it short distances.

We have found hydraulic post drivers with portable power packs (Figure 17) to be the most versatile over a wide range of conditions. Hydraulic post drivers use an external source of power to generate the hydraulic pressure for their operation. In the case of tractor mounted post drivers, the power comes from the engine of the tractor, skid steer or excavator. By contrast, portable power packs like those shown in Figure 22 can provide the power supply. Such power packs are heavy (between 100 and 275 pounds) and can be rolled short distances (< 0.5 mile). While hydraulic power can make the job of driving posts easier, it does come at the expense of needing to move a heavy power pack, 50+ pounds in hoses, and 75 pound driver (see Figure 13 and Figure 15 for ideas of how to minimize effort in those movements).

Various manufactures of hydraulic power packs exist. We have good luck with used the Atlas Copco LP 13-20 DEL (unit weight: 256 lbs, 6.7 KW output). We also recommend the Atlas Copco Hydraulic LP 13-30 P generator to power the post driver (unit weight: 200 lbs, 9.6 KW output), which is lighter but higher power output (and more expensive). This model comes with rugged off-road tires and handles for manual transport. We have used the Skidtrill P38 (unit weight: 97 lbs, 5.2 KW output), and is easier to move around than the larger Atlas Copco Our colleagues at the USFS have found it quite versatile and useful, but in some situations (e.g., embedded cobble bed) it may be underpowered. As with any small engine, they require regular maintenance and upkeep. While in the fray of implementation, equipment maintenance can sometimes be overlooked, which may lead to season-ending malfunctions. Consider incorporating regular maintenance into your implementation schedule or assign someone the role of 'equipment chief' to ensure your vital equipment remains in good condition.

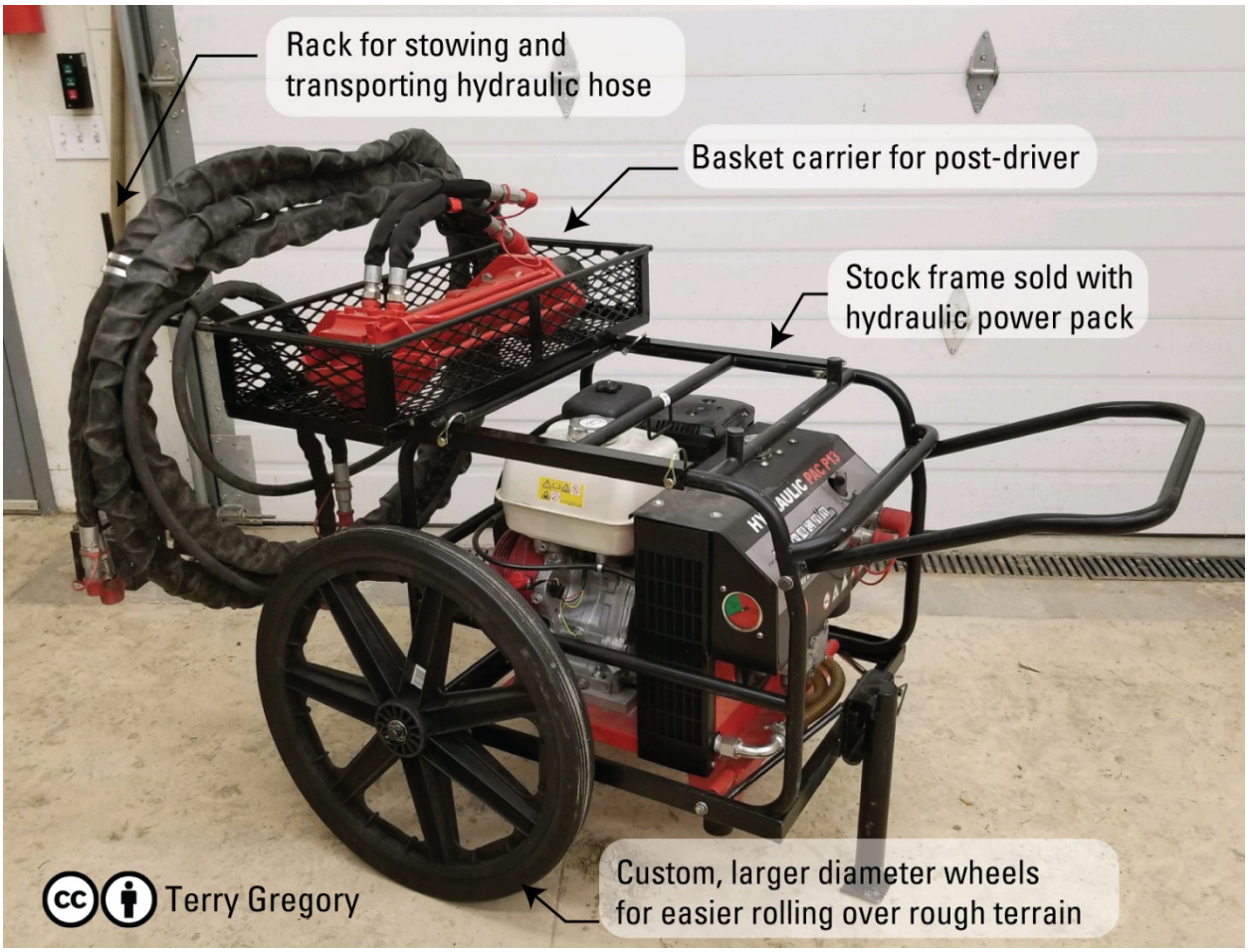


Figure 18 - Example of customizations that can be made to a stock hydraulic power pack and its transport frame to make it easier to move between installation locations. The stock 6" to 8" wheels are replaced with a larger 20" wheel, and a basket carrier is added for transporting the post driver (tends to be 50-90 lbs) and a rack for stowing excess and/or transporting the hydraulic hose. These customization were made by Idaho Fish and Game's Terry Gregory.

Hydraulic Hose Lines

Figure 19- An extension hydraulic hose line can add versatility in how far the post driver can be positioned away from the power pack and minimize the number of times you need to move the power pack.

When working in streams, you should always use an environmentally friendly, biodegradable hydraulic fluid (typically based on vegetable oil) in case of a spill. Research available products to ensure the hydraulic fluid is truly environmentally friendly as the marketing for some products can be misleading. Use long hydraulic lines or extension hose (30-60') to connect the post driver to the generator (Figure 19). This allows for leeway in how close the ORV needs to be driven to the structure location. Similarly, long hydraulic lines serve the same purpose when using a boat during construction. Be aware that longer hoses may reduce the amount of power delivered to the driver, so consult with the product supplier to determine an appropriate hose length.

Post Drivers

We generally use the Atlas LPD-T driver (weight: 75 pounds; post diameters from 1.5" to 3.94"). The 'T' stands for trigger, and these are manually triggered on the post driver handle by the operator driving the post. They also make a smaller Atlas LPD-LD-T driver (weight: 38.5 pounds; post diameters from 0.4 to 2.36"). Atlas does sell guide-adaptors for different diameter posts and these can be invaluable to have at hand if you are using a range of diameters of posts (machine shops can also make you one). We have spent a lot of labor trimming 4" posts with a chain saw to fit into a 3.5" diameter receiver, when it is much safer and cheaper to simply have an extra adaptor. If you use the Skidril, they make HP16 HP18 and HP20 driver models, which range from 50 to 85 pounds and span a range of diameters. Care should be taken never to 'dry fire' the post driver (i.e., engage without the hammer in contact with the post) as this can ruin the internal workings of the driver (an expensive repair or replacement).

Figure 20 – Best practices for working with a manually operated hydraulic post driver are illustrated above in a small stream.

The post driver head is heavy and should not be operated by one person. Remember when you are working in a river – it is slippery and easy to fall. Move slowly, communicate with your crew members, and work together. DO NOT lift the post driver above your shoulders (Figure 20). Work together to 1) tilt the post you want to drive below your shoulder, 2) lift the post driver onto the post, and 3) stand up and position the post in place. The crew manager or designate should be directing this operation and getting the "all clear" from the crew before beginning to drive the post into the stream bed. Proper PPE includes hard hats (in case driver or post falls), gloves, ear protection (the drivers are loud),

and eye protection. Hazards to be aware of include: dropping the post driver on someone, the post driver and post falling onto someone, the post driver breaking the posts (this can happen when not paying attention to if the post is still actually driving into the bed, and continuing to operate the driver), tripping on hydraulic hose, and getting hands pinched or crushed.

Griphoists

Griphoists are hand-operated, simple machines that can be extremely effective for stream restoration (Figure 21). They are light enough to be packed into remote locations, allowing practitioners to implement low cost restoration over a much broader area. Small models are rated at 2,000 pounds of pulling power and weigh less than 20 pounds, excluding the wire rope. The largest model weighs approximately 70 pounds, is rated at 8,000 pounds of pulling power, and can be rigged to tip over large diameter trees with rootwads intact. When properly maintained, griphoists are extremely reliable. They have been used for instream restoration for decades (Flosi et al., 1998). The New York – New Jersey Trail Conference published 'Rigging Handbook for Trail Work' (Micelston, 2014), which has guidelines for using griphoists and rigging.

Figure 21 – Griphoists are an effective tool for creating a mechanical advantage and pulling in or over live-trees, dead snags, and/or down trees. A) Example of griphoist being used to pull a tree into a creek. B) A whole tree pulled down across a channel with a griphoist. C) A tree pulled over with its root-wad intact, can be repositioned and dragged into position in a creek. D) When done with supervision and safety in mind, even sixth graders can crank on the griphoist and use the mechanical advantage to move some big material. Slides from Scott Nicolai (Yakama Nations) from a Cheap & Cheerful Restoration Workshop with the Snake River Salmon Recovery Board.

Since they are manual tools, griphoists are most effective when source wood is in close proximity to the stream. Regulatory guidelines will typically preclude significant source wood removal within 30-50 feet of the stream ordinary high water mark. At this distance, a six-person crew of experienced laborers can typically recruit 10-20 full length, previously felled trees to the stream with griphoists per work day. Tipping, extricating and transporting large trees with intact rootwads (for example, a 28" DBH, 100' tall douglas fir) can require several griphoists, blocks for 2:1 mechanical advantage, and can take an entire work day per tree to recruit to the stream. However, these large "key pieces" can provide geomorphic benefits for many decades, and may still warrant the effort required for their placement. See Appendix B for further guidance.

General Construction Guidance

Experienced laborers and contractors may already be familiar with the topics in this section on general construction guidance. However, less experienced groups, volunteers and anyone in charge of supervising or training laborers may find these sub-topics a useful guideline. We provide them here as a reference to help low-tech restoration define a minimum standard of practice.

Construction Crew

Each project should have a designated construction manager onsite for all construction activities. When the construction manager is not directly overseeing construction activities they should designate a crew member (e.g., crew lead) to do so. When building structures, we find having a crew of at least 3 and up to 6 people is helpful. Too many people can become a safety concern. Running multiple crews simultaneously can work really well for rapidly treating large areas. With multiple crews, make sure that each crew has a clear zone in which they are working and understands what their tasks are. Always have someone responsible for overseeing construction – not participating in it. This person primary task is to look out for everyone's safety, think ahead about staging and logistics, and constantly reflecting on basic questions like:

- Are proper safety procedures being applied?
- Are the complex and structure designs being followed?
- Are there opportunities to improve safety, efficiency and effectiveness in the future (e.g., next structure, tomorrow, next week, or next project)?

Regardless of whether volunteers or a licensed contractor are doing the installation, there are some basic considerations:

- Consider having the construction manager review the safety operations with the crew before starting construction and regularly thereafter (weekly, bi-weekly or monthly depending on state regulations.)
- Report all accidents to the construction manager and project manager; document these incidents with a log and follow up on the incident as necessary.
- Designate a person to be the safety officer – whether they are the construction manager, crew lead, or the responsibility is delegated to a crew member. Every crew member should be aware of, and vocal about, potentially unsafe actions or situations. The safety officer is responsible for ensuring everyone is wearing appropriate personal protective equipment (PPE), resupplying PPE and safety equipment as necessary, and correcting unsafe behavior.
- Have fully stocked first aid kit(s) on site and in each vehicle at all times; review with the crew emergency protocols.
- Never work alone. Always pair up when working.

Safety

Communication and Procedures

Pre-project and regular safety meetings essential to avoid or minimize accidents. Instill in everyone on the job site the importance of looking out for themselves and each other to stay safe. The construction manager should be in regular communication with all crew leads (if running multiple crews) and ensure that they are taking similar precautions.

Low-tech restoration involves hard manual labor that can inadvertently lead to injury. Treat the work site like any professional construction site; communicate with other crew members, work together, and keep clear of areas where people are using chainsaws, operating off-road vehicles (ORVs), or moving large woody debris. The construction manager should be flexible so that operating procedures can be adapted and improved to make construction safer, more efficient and more effective.

Safety Training & Certifications

At a minimum, you need to comply with any safety training and certification requirements for your own and partner organizations. Consider the following:

- First Aid (e.g., Red Cross) – For all crew members
- Wilderness and Remote First Aid (e.g., Red Cross) – Since you are often working in remote areas
- ATV or OHV Safety Training – For anyone using an all-terrain vehicle (ATV) or off-highway vehicle (OHV) certification (e.g., https://www.offroad-ed.com/, https://atvsafety.org/atv-ridercourse/)
- Chainsaw Safety Training – For anyone using chainsaws

Personal Protective Equipment

All crew members should wear the appropriate Personal Protective Equipment (PPE). At a minimum, each crew member should wear closed-toed work boots, full pants, gloves, hardhat, and eye and ear protection. One of the most frequently overlooked PPEs are hardhats. The Occupational Safety and Health Administration (OSHA) provides details on work site safety.

Keeping Crews Fed and Hydrated

A critical part of keeping crews safe is keeping them alert, and that means keeping them well fed and hydrated. Especially when working with inexperienced laborers or volunteers, the construction manager should make sure that crews are well-fed and hydrated. Always provide clean drinking water and have plenty of extra available (including extra water bottles) in case any individual is not prepared. The construction manager should provide clear expectations to individuals about what food and drink they need to bring themselves and what will not be provided. However, just like having first aid kits on hand, keeping extra snacks, food and beverages is critical. Also, construction managers and crew leads should promote a culture of taking care of each other by regularly (hourly at least) making sure all crew members are hydrated, and regularly having breaks for having a snack, eating lunch, hydrating or simply resting. These breaks are not just important for safety but can be critical for crew morale too. Domitrovich (2013) outlines helpful guidelines for wildland firefighter health and safety that are equally helpful for low-tech restoration construction crews.

Environmental Safety and Fire Risk

Precautions should be taken to ensure construction has as little negative impact to the environment as possible. Low-tech process-based restoration approaches already benefit from relying mostly on hand labor, thus negating the types of impacts associated with large mechanical equipment (e.g., removing riparian vegetation for temporary access roads). However, accidents or lack of preparation could lead to harmful environmental disturbances that are counter to your goal as an implementer. Use approved biodegradable hydraulic fluid in all post drivers and chain-saws and refuel and store fuel outside the riparian area.

The instream work window is often during summer months when fire risk is highest. Therefore, when small engines are used for construction, make sure a fire extinguisher is readily available to stifle small fires caused by sparks from the exhaust or heat from the engine. Vehicles can also start fires if their hot engines make contact with dry vegetation. Make a routine of checking the Industrial Fire Precaution Level (IFPL) daily to ensure you are remaining lawful during high fire risk periods. For example, you may be required to have a designated 'fire watch' personnel (they are not allowed to work, just watch for fires), or stop using combustible engines after 1pm. Violating IFPL restrictions may be cause for shutting down your entire project, and no one wants to start a forest fire anyway.

When refilling gas, diesel, oil, or other environmentally harmful fluids into engines, take special precautions to prevent spills. Use a funnel for easy filling, and an absorbent mat underneath the equipment to catch any spills.

EVALUATION

As highlighted in the Conservation Planning Process of Figure 1 (see Chapter 3: Bennett et al., 2019), the evaluation component of any restoration project is critical. Evaluation of project outcomes is more than just monitoring. A common compliant amongst scientists and researchers is that restoration projects and outcomes are not properly monitored and evaluated and therefore the same mistakes continue to be made (Lautz et al., 2019; Pilliod et al., 2018). We contend that evaluation can take many forms from implicit, qualitative and non-documented, to explicit, quantitative and over-documented. It is easy to just do monitoring for monitoring's sake and focus on monitoring because it can be done, as opposed to what it will tell us. With the trend in conservation and restoration towards S.M.A.R.T. objectives (see Chapter 3), it is all too easy to set precise, but arbitrary targets (Hiers et al., 2016). However, overly specific and precise targets may not allow enough latitude for natural processes and variability to take place. Some form of post-project evaluation through time is critical. From a practical perspective, there are three helpful questions to consider when deciding what level of evaluation is necessary:

1. What level of evaluation is warranted to decide if actions like: maintenance of existing structures, additional treatments, or mitigation of unintended consequences are needed?
2. Who is doing the learning? Is the evaluation through adaptive management to help inform project stakeholders and help the practitioner learn? Or is the evaluation to contribute to broader community learning amongst a peer group of practitioners? Or is the level of documentation required something that requires peer-reviewed science, vetting and dissemination in the peer-reviewed literature?
3. How much are project funders willing to pay for cost of knowing, and how much evidence is required to support an evaluation?

None of the above are to suggest that monitoring should not be done. At a minimum we suggest some site revisits to take repeat photographs, and most importantly, evaluate the key question posed in of Figure 1 (see Chapter 3: Bennett et al., 2019):

- Are the processes of wood accumulation and/or beaver dam activity self-sustaining?

The entire low-tech process-based restoration approach is predicated on the Riverscapes and Restoration Principles (see Chapter 2: Wheaton et al., 2019), and the idea that overall project goals and objectives will be met if the river has the room to do its work in self-sustaining ways. There are situations where the answer to this key question is glaringly obvious (e.g., a situation where there were no beaver or beaver dams prior to restoration, and now there are 100s maintained by dozens of colonies). There are many other situations, where it may not be clear yet (keep watching and critically evaluating), or more treatments might be necessary to get to self-sustaining.

Remember, in the Conservation Planning Process, high risk situations have already been identified and, most likely, avoided or specific provisions to mitigate those risks were put in place. Thus, the consequences of not achieving a self-sustaining state are relatively minimal. Low-tech actions are relatively inexpensive compared to many traditional approaches that have had no demonstrable effect at the scale of riverscapes systems, ecosystems or populations. Thus, if all that was wasted was a little time, a little money and a little sweat equity, at least no harm was done. More importantly, these systems and the ecosystems and human communities that depend on them are worth trying to fight for.

CONCLUSIONS

The consultation and permitting process for low-tech restoration is similar to that for traditional restoration. However, because the normal levels of disturbance and impact associated with traditional construction are avoided, there is possibility for a streamlined permitting process. For many regulators, this is a new and unfamiliar practice, so share with them these resources if they are unfamiliar and be patient. Communication early and often is crucial.

Unlike traditional restoration practices, where construction is generally done by specialized contractors or heavy equipment operators, low-tech structures can be built by a much broader range of practitioners. This allows more people to participate in restoration, however, it involves additional safety and logistical considerations. One of the main goals of low-tech process-based restoration methods is to build a large number of structures over a large spatial extent – such that treatment scales match the scope of the problem (Process-Based Restoration Principle 3 from: Beechie et al., 2010). Ultimately, scaling up low-tech construction efficiently may in some instances be most efficiently done by specialized contractors, hired laborers, or in-house agency labor crews (e.g., conservation corps crews, fire crews, sawyers, etc.) with training and experience. A good construction manager, can make effective use of volunteers – especially for small projects. However, for larger projects laborers and contractors can and should be paid fair wages for this important work.

Chapter 6 - APPENDICES

APPENDIX A – POST DRIVER INFORMATION

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

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

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

Application

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

Comments

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

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

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

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

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

Application

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

Comments

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

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

ANABRANCH SOLUTIONS

Figure 22 – Fact sheet produced by Nick Weber at Anabranch Solutions on Portable Power Packs and drivers (combined these are hydraulic post drivers). We are not endorsing any specific brand or manufacturers, but provide these for informational purposes only-as these are readily available and have been used extensively in low-tech restoration.

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

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

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

Application

Pneumatic units require air compressor

Comments

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

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

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

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

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

Application

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

Comments

Handy for T-posts and maintenance of structures.

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

ANABRANCH SOLUTIONS

Figure 23 – Some pneumatic and gas-powered alternative to hydraulic post drivers (Fact sheet by Nick Weber of Anabranch Solutions). We are not endorsing any specific brand or manufacturers, but provide these for informational purposes only as these are readily available and have been used in low-tech restoration extensively.

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

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

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

Application

Good for tough jobs when road access is available

Comments

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

Figure 24 – Hydraulic drivers are available for mounting on skid steers, tractors, backhoes, excavators and mini-excavators. Here's one example from Kencove. We are not endorsing any specific band or manufacturers, but provide these for informational purposes only as these are readily available and have been used extensively in low-tech restoration.

APPENDIX B – WOOD REPLENISHMENT WITH GRIPHOISTS

Scott Nicolai (Yakama Nation Fisheries Habitat Biologist) has been using griphoists to replenish structurally-starved streams with abundant quantities of large wood since 2008. His recommendations and "lessons learned" include the following:

Wood Replenishment with Griphoists

Restoration Managers should:

1. Use Washington Department of Fish and Wildlife's Stream Habitat Restoration Guidelines (SHRG) Chapter on Large Wood and Log Jams that discusses "Large Wood Replenishment" for project design (Saldi-Caromile et al., 2004).
2. Coordinate with public land managers well in advance of planned implementation.
3. Select "source wood" sites carefully – select trees from overstocked stands (see securing building materials). If allowed, remove some sub-dominant trees that are fairly large diameter and length relative to stream size and power.
4. Remember that grip-hoisting is strenuous work - bring a large lunch, wear sturdy clothes. It may be possible to cancel gym memberships!
5. Work with silviculturists as necessary to select appropriate trees for removal.
6. Use the griphoists to assist with tree felling as needed to avoid hang-ups and increase safety.
7. Consider using this technique as a volunteer activity. For example, it may be possible to use members of High School Sports Teams for a day of griphoist work. Strong emphasis on safety is obviously critical.
8. When seeking permits, encourage allowance for a flexible work window. This technique is extremely low impact.
9. Have workers "baby-sit" the larger branches as trees are moved, otherwise most may break off enroute to the stream.
10. Prior to work, a redd survey is needed if fish spawning is possible at the treatment site.
11. Have workers watch cable passage through blocks (aka pulleys) as necessary to avoid cable hang-up.
12. Position the trees in the wetted channel whenever possible, in order to keep the trees wet, thereby reducing buoyancy during high discharge.
13. Protect "tail hold" trees from girdling by using large straps instead of chokers for anchorage.
14. Lubricate griphoists per manufacturer's recommendations at the end of each work week.
15. Try to place a lot of trees instream – follow SHRG guidelines but DON'T BE TIMID! More trees = greater stability, greater habitat benefit.
16. Showcase results – both good and bad - whenever possible. As restoration practitioners, we all need to learn from the successes and failures of others.
17. Look for opportunities to share equipment with other restoration entities. Grip hoists are extremely durable when maintained properly.
18. Consider using wire grips ("mules"). They can save time on complex rigging applications.
19. Use all necessary personal protective equipment.
20. Know the working load limit of all rigging equipment. These limits must be strictly obeyed.
21. Griphoists, helicopters and heavy equipment get along well together! Employ griphoists for final placement, and "tweaking" of wood that was previously staged via these "petro fuel burners". Griphoists can be extremely beneficial in this regard.

22. Paint all equipment that is small enough to lose a bright fluorescent color. This includes griphoist handles, blocks, mules, shackles, repair tools.

Restoration Managers must always take heed of the following:

1. Do not propose this technique in streams with bankfull widths that are greater than the length of the average tree, unless the activity is coordinated with placement of larger key pieces via other means, or where risk to infrastructure is deemed insignificant by all involved land managers and regulatory agencies.
2. Do not exceed working load limits of any equipment.
3. Do not work alone.
4. Do not implement projects without a "heads up" project manager, who is managing for safety and project efficiency.
5. Safety First, Safety Always.

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Chapter 7 – CALL TO ACTION, ADDITIONAL RESOURCES & CONCLUSIONS

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CALL TO ACTION

Scaling restoration to match the scope of degradation will require a re-imagination of what's possible and an expansion of the restoration toolbox to include low-tech process-based approaches that get more people off the sidelines and into riverscapes restoration. In the American West alone, it is estimated that conservatively between 50,000 to 100,000 miles of perennially flowing riverscapes are degraded (USEPA, 2016), depending on definitions of degradation, choice of indicators of stream health, or the bar we set for stream recovery. The impairments to riverscapes are well understood and documented (Allan, 2004; Montgomery and Wohl, 2003), but the sobering scope of this degradation is often not emphasized enough. The grand challenge is what to do about it. As practitioners, scientists, land owners, and resource managers, do we standby, continue to observe and accept this degradation? Do we settle for the economic, social and environmental consequences that go along with these more vulnerable riverscape states? Or do we re-imagine what these riverscapes could be and invest in re-establishing sustainable and resilient riverscapes and, in turn, the communities and ecosystems that depend on these riverscapes?

In the Fourth National Climate Assessment, the U.S. Global Change Research Program USGCRP (2018) highlight that investing in proactive adaptation like low-tech process based restoration (e.g., using beaver as a climate adaptation strategy) produces benefits that far exceed the costs of such restoration efforts. Specifically, USGCRP (2018),

"Proactive adaptation initiatives including changes to policies, business operations, capital investments, and other steps yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security." Low-tech restoration is about more than just improving riverscape health for the sake of the riverscape. Low-tech restoration is critical to rangeland health and productivity (Donnelly et al., 2016), the viability of rural communities, the stewardship and sustainability of working lands, water security, and resiliency to extreme events like floods, droughts, and fires (Randall, 2018). However, just like considering other issues of national significance (jobs, education, health), the focus needs to be on how we target efforts to those most in need and expand the footprint of such investments to maximize their impact for the greatest number of riverscapes.

The seriousness of this degradation problem is reflected in a US ecological restoration economy that directly employs over 126,000 people and is worth $9.5 billion/year (overall economic impact estimated at $24.8 billion/year; Note: US GDP is $19.3 trillion; BenDor et al., 2015). Despite annual investments in the billions of US dollars in riverscape restoration efforts (Bernhardt et al., 2005), the restoration industry has barely scratched the surface of the scope of degradation (Bernhardt et al., 2007). The return on the investment from 'business as usual' restoration and the lack of measurable results is worrying (Hiers et al., 2016). We can and need to do more with this societal investment to actually produce measurable improvements in riverscape health and resilience. We assert that understanding the four Riverscapes Principles (Chapter 2: Wheaton et al., 2019), and following the six Restoration Principles (Chapter 2: Wheaton et al., 2019) will produce measurable returns such as population-level responses and increased riverscape resilience. The key is scale. We need to be treating riverscapes over spatial extents that are large enough to produce system-level changes visible from space (i.e., Restoration Principle 6: 'There is strength in numbers').

Current stream restoration practice costs an average of $65,000 to $450,000 per mile (median: $270K per mile), and the median length of restoration projects is < 0.5 mile (Bair, 2004; Bernhardt et al., 2007). These are respectable per project monetary investments, but the size of the projects is far too small to reverse over 200 years of riverscape degradation, land use impacts, and systematic structural starvation – in short, the scale of restoration does not match the scale of degradation. We need to make restoration investments that are smarter, and 'partner' with the natural processes to let the system do much of the work required to restore riverscapes (Restoration Principle 7). This approach is far more likely to lead to self-sustaining riverscapes (Restoration Principle 10). This requires a process-based perspective and an honest look at the bigger picture. We cannot afford to continue to disproportionally overspend on small projects (i.e., spatial extent of < 2 miles of riverscapes), ignore the scope of the problem (i.e., 50-100,000 miles of degradation), or expect measurable increases in populations of imperiled fish and wildlife – our approach needs to change.

Together, we can build the partnerships and communities of restoration practitioners, land-owners, volunteers, and resource managers; and harness the power of riverscapes to heal themselves to tackle this massive riverscapes problem head-on. It will require working together, pooling resources strategically, and keeping focus on the broader scale targets. The approach outlined in this manual is not about building perfect structures that last for decades. This is about feeding structure quickly and efficiently to a structurally-starved system with a specific focus on the processes of wood accumulation and beaver dam activity. The additions of structure will mimic natural structural elements and initially promote complexity and riverscape connections. Eventually, our restoration interventions will be no longer be necessary as the system will be self-sustaining. We can build these communities of restoration practitioners that can rise to the challenge and take pride in finding creative and innovative solutions. Go big!

ADDITIONAL RESOURCES

Workforce

To 'go big', existing practitioners will need to expand their current skill sets, and a community will need to build a workforce tackling this problem with low-tech restoration. While we are relying most on stream power to 'do the work', we also need an army of laborers to prepare the initial treatment(s) of structures that help mimic and promote the processes the system needs to recover. As of 2019, that workforce capacity is currently not fully-trained, mobilized or available to rise to this challenge. However, the workforce could be built quickly. The interest and enthusiasm is promising. This design manual is intended to help practitioners involved in planning (Chapter 3: Bennett et al., 2019a) and designing (Chapter 4: Shahverdian et al., 2019) low-tech restoration projects do so more efficiently, with the bigger picture in mind. Those planning and design costs can scale up to larger footprint projects very efficiently. In other words, the cost of planning and design is relatively expensive (on a per mile basis) when just applied to small footprint projects. However, those costs can become extremely affordable (on a per mile basis) when put to designing projects on the order of 10's and 100's of miles. The labor-force that could help implement those treatments (Bennett et al., 2019b), will need to be built. We forecast that over the next 3-5 years, as this low-tech practitioner community grows and finds it stride, most projects will be relatively small-footprint trials (e.g., ~ 25-100 structures over 0.5 to 2.0 miles(0.8 to 3.2 km)). These projects are critically important in an adaptive management 'learning-by-doing' sense and for building the local understanding and comfort level with this sort of work. The low-tech labor is hard but rewarding work that will take economic incentives to encourage a skilled labor force to engage. Given the lack of jobs paying living-wages in many of the rural communities these riverscapes intersect, we (i.e., governments, taxpayers & voters) could decide to invest not just in the riverscapes, but the people connected to these lands to stimulate rural workforce development and economic growth.

Innovation, Shared Lessons & Expectation Management

We do not envision the low-tech process-based Restoration Principles (Chapter 2: Wheaton et al., 2019) changing too much over time. However, the specific low-tech restoration actions, various flavors and recipes of different structure types and some of the technology to make planning, design, monitoring, community building and adaptive management easier will evolve and improve rapidly over the next 5 to 10 years. Practitioners will find creative variations and local adaptations that work really well in certain situations, and backfire in others. Collectively, we hope the low-tech restoration community will leverage various forums to share their experiences (good and bad) and what they are learning from them. As practitioners ourselves, our biggest strides forward and biggest innovations on low-tech restoration to date have grown out of our own 'failures', mistakes and willingness to try something new. In fact, the idea of postless BDAs was one that some thought was crazy, but we quickly learned by trying it, that it can work really well. We have found efficiencies in how to build, source materials and stage construction all from trying things that others thought were too obvious or simple to try doing. Do not be afraid to try out new ideas at small scales to test new ideas (e.g., in trials). The community will need to find the limits of a low-tech process-based restoration approach to structurally-starved riverscapes. Not everything will work the same everywhere (e.g., Riverscapes Principle 3; Chapter 2: Wheaton et al., 2019). Regardless of the platforms for building this community (e.g., workshops, conferences, webinars, social-media, field-tours, peer-reviewed publications, making project reports and data publicly available an easily discoverable), we hope that this community can build confidence in themselves and each other by transparently sharing experiences. We have tried to provide a rationale for how and why to move past the antiquated notion of 'failure' focused on individual structures and an obsession with wrong risks (i.e., built structures changing or adjusting). Paradoxically, by focusing less on the risk of restoration causing damage, and more on processes and deferred decision making (Restoration Principle 9; Chapter 2: Wheaton et al., 2019), liability and unintended consequences are actually minimized. We need to re-define expectation management for restoration projects from a 'one and done' approach focused on stability of structures and imposing form on riverscapes, to an approach that uses simple, low-tech designs and methods to promote riverscape processes, with an acknowledgement that maintenance (i.e., more treatments) will likely be required to fully restore self-sustaining processes.

Leveraging Technology to Do Low-Tech Restoration

Different types of low-tech restoration structures have been around for over a century. However, installing many of these structures together over broad scales, while applying low-tech process-based Restoration Principles (Chapter 2: Wheaton et al., 2019) is a relatively new practice. As such, we have developed some web-based resources to accompany this manual at http://lowtechpbr.restoration.usu.edu that can be updated through time as more is learned and shared about low-tech process-based restoration. These web-based resources will grow over time but include the types of things to make the tasks of planning, designing, building, monitoring low-tech project easier. Many of the example reports, figures, forms, etc., that have Creative Commons licenses can be adapted and reused by anyone. These include:

- **Examples** – of permit applications, planning reports, design reports, adaptive management plans, all intended to be copied and adapted as templates to get practitioners started
- **Field Forms** – for design and monitoring. Paper copies to print or tweak, and eventually data-base driven Apps
- **Models & Tools** – for assessing conditions, recovery potential and tracking responses to restoration
- **Contractor Lists** – an incomplete but growing list of contractors and firms that are doing low-tech restoration
- **Low-tech Structure Recipes** – schematics and construction details to include, tweak and adapt for individual designs and/or permit applications
- **Discussion board** – there is a new discussion board associated with this low-tech manual (currently empty), which the community can use if it chooses to: https://github.com/Riverscapes/PBR/issues
- **Twitter handle** - #lowtechPBR to share your experiences with low-tech PBR.
- **Workshops** – We have taught over 20 workshops on low-tech process-based restoration, and are continuing to offer more through the Utah State University Restoration Consortium (http://restoration.usu.edu). These workshops are available for both University credit and Continuing Education Units, which can be applied towards a graduate certificate in Restoration of Aquatic Ecosystems. We also have an undergraduate major in Management and Restoration of Aquatic Ecosystems, where students learn about the principles of low-tech process based restoration and design and build their own projects.

Part of the idea behind the website is to push beyond the infancy and amateur stage that much low-tech process-based restoration is at, and help set both the standards of practice and build a community of practice (a social science term from the psychology of learning) where the manual and website are meant to introduce an idea, language and methods that will be practiced and refined by a community. This community of practice is made up of learners at all stages (novice to apprentice to expert), is meant to be a self-sustaining and always innovating as a community. There needs to be some infrastructure and acknowledged effort in order to advance the community (professional development, continuing education, outreach) - that is, the process of becoming a practitioner of LT-PBR is, like LT-PBR, not a one and done endeavor, it is a lifestyle, a profession, and thus requires continual care and feeding.

CONCLUSIONS

In this manual, we laid out the need for, and an approach to, low-tech process-based restoration of structurally-starved riverscapes. Riverscapes represent the entire valley bottom, and healthy riverscapes rely on connected channel(s) and floodplains. With the systematic removal of structural elements like wood accumulations and beaver dams, those 'connections' are less frequent in both time and space. Subsequently, the vast majority of riverscapes in the American West (and elsewhere) are now structurally-starved. These riverscapes are nowhere near their potential, and they are more vulnerable to disturbances of increasing frequency and severity like droughts, floods and fires. From the perspective of riverscape health and the ecosystems that depend on riverscapes, there is plenty of merit in finding more cost-effective, scalable restoration approaches to address these challenges. Investing in improving the resilience of these riverscapes also makes strategic sense from the perspective of sustaining the long-term viability of communities, economies, and industries that depend on the ecosystem services and water resources these riverscapes provide.

Figure 1 – The future of low-tech restoration is promising. Looking over the shoulder here of the next generation that could help initiate the reshaping of our riverscapes into resilient systems, we see promising signs. In the background are posts sticking out of the water from a BDA this boy helped build, and that beaver are now maintaining. In the foreground, we see beaver's latest remodeling, a dam built so tall that it completely drown out the constructed BDA. While not precisely predictable, this is the essence of process-based restoration— where the process of beaver dam activity was initially mimicked (with BDAs), promoted (reintroducing beaver), and beaver have taken over that process in a self-sustaining way.

To scale up restoration efforts to the scope of riverscape degradation, we need to work smarter and more efficiently. The key is working with an understanding of how healthy riverscapes function and recognizing the processes that shape and sustain healthy riverscapes. The four Riverscape Principles we laid out in Chapter 2 (Wheaton et al., 2019) summarize this understanding. By contrast, the six Restoration Principles laid out in Chapter 2 (Wheaton et al., 2019) help contextualize the role low-tech restoration actions play in the bigger picture, by emphasizing: i) the specific processes to mimic and promote, ii) the scale they are needed at, iii) that the system has to do the real work of restoration, and iv) that the long-term goal is self-sustaining. The subsequent planning (Chapter 3: Bennett et al., 2019a), design (Chapter 4: Shahverdian et al., 2019), permitting, construction and adaptive management (Chapter 6: Bennett et al., 2019b) are tailored to focus on complexes (groups of structures), and what processes they are collectively intended to mimic and promote. This de-emphasis of the structure itself translates to: i) shorter expected structure design life, ii) quicker structure design and implementation, and iii) subsequently, the ability to build more structures and treat more miles than society can afford with engineering-based approaches alone. This focus will be crucial to seriously tackling the true scope of riverscape degradation. However, instead of dismissively setting aside the work that riverscapes themselves can play in shaping their own more resilient futures, this entire approach relies on an understanding and appreciation of what riverscapes can do for themselves. It recognizes the critical role that practitioners can play in initially mimicking, quickly promoting and eventually simply stepping aside to let natural processes find sustainable solutions.

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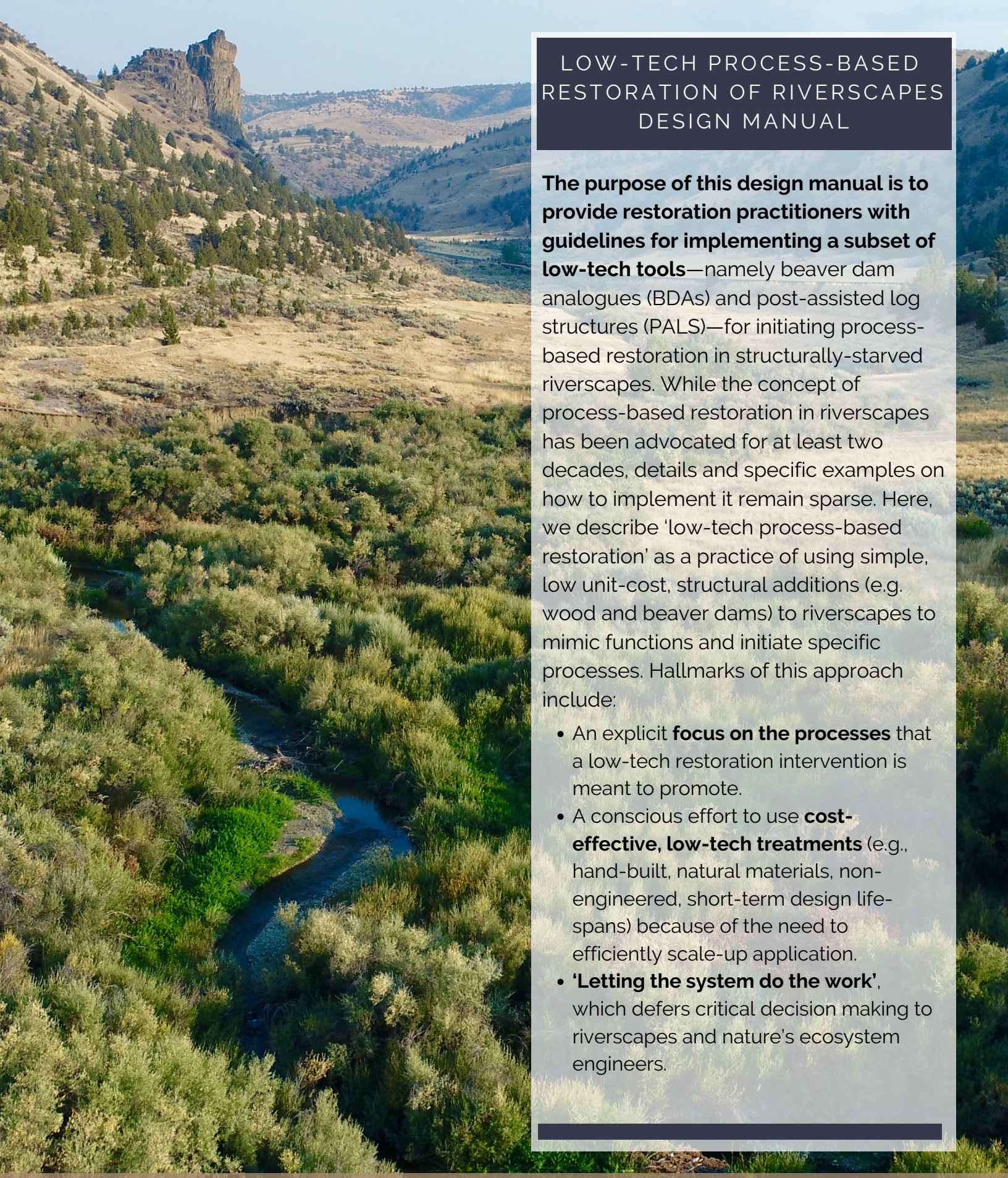

LOW-TECH PROCESS-BASED RESTORATION OF RIVERSCAPES DESIGN MANUAL

The purpose of this design manual is to provide restoration practitioners with guidelines for implementing a subset of low-tech tools—namely beaver dam analogues (BDAs) and post-assisted log structures (PALS)—for initiating process-based restoration in structurally-starved riverscapes. While the concept of process-based restoration in riverscapes has been advocated for at least two decades, details and specific examples on how to implement it remain sparse. Here, we describe 'low-tech process-based restoration' as a practice of using simple, low unit-cost, structural additions (e.g. wood and beaver dams) to riverscapes to mimic functions and initiate specific processes. Hallmarks of this approach include:

- An explicit **focus on the processes** that a low-tech restoration intervention is meant to promote.
- A conscious effort to use **cost-effective, low-tech treatments** (e.g., hand-built, natural materials, non-engineered, short-term design life-spans) because of the need to efficiently scale-up application.
- **'Letting the system do the work'**, which defers critical decision making to riverscapes and nature's ecosystem engineers.

find more resources at:
lowtechpbr.restoration.usu.edu