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The Use of Large Wood in Stream Habitat Restoration

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Photo credit: Trevor Lucas, Pacific States Marine Fisheries Commission.

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

PREFACE

Restoration practitioners and government agencies implement large wood projects throughout California to enhance instream and floodplain habitats for salmonids and many other species. The California Department of Fish and Wildlife provides guidance on how to implement large wood and other stream restoration projects in the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 2010). Since its publication, the science, techniques, and complexity of large wood projects have expanded greatly. This report updates the previous description of large wood projects, describes the assessment and planning required, and the construction techniques needed for the implementation of large wood projects in California. This report combines a review of current literature on the subject with input from California Department of Fish and Wildlife scientists and engineers, and others with experience and expertise in the restoration of large wood in California's streams and rivers.

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INTRODUCTION

Natural unaltered riparian zones supply large wood to a stream through various processes. This large wood provides an instream structural element important to salmonid habitat. Unfortunately, in California there are few examples of riparian zones or streams which are unaltered by human land use activities. This has left a legacy of streams deficient in the large wood which is necessary to create and maintain salmonid habitat. Carah et al. (2014) defines large woody debris as "trees, logs, root wads, and large tree branches that fall into streams and interact with water, sediment, and organisms in the channel." To facilitate the reestablishment of stream processes, the addition of large wood is a restoration technique that benefits streams on a range of scales (Cederholm et al. 1997; CDFG 2004; Opperman et al. 2006; Jones et al. 2014; NMFS 2014; Roni et al. 2015). Large wood projects aim to improve channel and floodplain function, provide habitat to salmonids, and add nutrients to the stream. This administrative report provides a planning process, design guidance, and construction techniques that will help facilitate successful large wood projects.

ROLE OF INSTREAM LARGE WOOD

The impact of large wood on a stream depends on the geomorphology of the stream, the stream size relative to the dimensions of the wood, and the hydrology of the stream. In streams small enough for large wood to remain relatively stable within the channel, large wood traps other large wood, small wood, and bedload. These structural elements serve to inhibit channel incision. By maintaining the bed elevation within channels, large wood retains connectivity of streams to their respective floodplains. Floodplain connectivity provides a range of biological and geomorphic benefits. Floodplain connectivity spreads the power of the stream flow over a larger area and reduces channel incision. During high-flow events, flooded floodplain habitat provides refugia for adult and juvenile salmonids. Large wood can force flow around wood accumulation and generate streambank erosion, supplying sediment to the stream and inducing meandering. Large wood can also increase the pool frequency from the typical five to seven channel widths apart to approximately two channel widths apart (Collins and Montgomery 2002). In larger streams, wood mobilized by high flows can form large wood accumulations in main channels, forcing the stream to send more water into high-flow channels traversing floodplains. Large wood accumulations can also lead to bar formations and allow vegetation to propagate within the stream channel on point and mid-channel bars.

Large wood in streams serves an important role in creating and maintaining salmonid habitat. As adult salmonids return to their natal streams to spawn, large wood provides winter concealment habitat and low-velocity resting places. Gravel deposition and sorting associated with large wood creates spawning habitat. In-channel wood provides juvenile salmonids with cover and protection from predation, as well as refuge from high-flow velocities. Large wood accumulations promote gravel deposition upstream, and bed scour to form pools downstream, enhancing preferred habitat for juvenile salmonids. Pool scour creates sediment deposits that serve as spawning habitat and maintains the hyporheic zone, where shallow groundwater mixes with surface water, cooling the overall water temperature. Large wood accumulations also trap fish carcasses, contributing nutrients such as carbon, nitrogen and phosphorous to the stream. Wood in streams supports a food resource for invertebrates that in turn provides food for juvenile salmonids.

While hardwoods are the dominant tree species in many anadromous fish streams in California, most large wood projects in California take place in coastal watersheds dominated by conifers such as Douglas fir or redwood. Hardwoods such as alder, willow, maple, and ash are smaller and decay more rapidly than Douglas fir or redwood. While their residence within a stream channel may be short lived, hardwoods provide many of the same habitat benefits as conifers, including pool formation, cover and shelter (Opperman et al. 2006). Hardwoods that fall but remain rooted on the streambank can continue living and growing after they fall, remaining stable in the channel. Hardwoods that fall into streams and do not remain rooted still provide habitat benefits. Deciduous trees serve as obstructions that can trap and retain smaller mobile debris (Montgomery et al. 2003).

Large riparian hardwood trees such as willow, oak, sycamore, and cottonwood, play a significant role in the formation and maintenance of pool habitat for South-Central California Coast steelhead (*Oncorhynchus mykiss*). Thompson et al. (2006) found most habitat for South-Central California Coast steelhead was influenced by standing hardwood trees. Standing hardwood trees form fish habitat by stabilizing wood jams consisting of fallen limbs or whole trees that fall into streams. Fallen trees when rooted continue to function, creating pool habitat and shelter for juvenile steelhead.

ECOLOGICAL AND HISTORICAL CONTEXT OF LARGE WOOD IN STREAMS

Large wood recruits naturally into a stream from the near-stream riparian zone through several processes including windfall, mortality, streambank erosion, debris flows, debris avalanches, debris torrents, and landslides. The stability of wood in a stream is dependent on the size and gradient of the stream, bed morphology, channel confinement, the size of the wood and the resistance of the wood to decay. Stream and wood size have an inverse relationship, where the relative mass of the wood piece compared to the stream channel width determines stability These large, stable wood elements are called key pieces, or key logs. A key piece is a functional piece of natural wood with sufficient mass, with a shape that contributes to the formation of a stable obstruction that alters flow and forms channels. Collectively, a key piece and its "recruited" pieces of trapped wood form large wood accumulations. Key pieces become important local hydraulic and geomorphic controls and will be discussed further within the report section, "Construction Considerations-Specifications of Large Wood."

The amount of large wood in stream channels and the ability of a stream to recruit large wood from adjacent riparian forests has been greatly diminished in many watersheds due to anthropogenic activities. Such activities include channel clearing for navigation, anadromous fish passage, flood control, and removal of riparian trees for timber harvesting and agricultural development. The impacts of these activities on the volume of in-channel large wood, as well as the species composition and age structure of riparian forests, persists in many watersheds today. Protecting riparian zones and preserving naturally occurring instream wood is the most cost-effective way to improve fish habitat. In watersheds where timber harvest may occur, the California Forest Practice Rules administered by the California Department of Forestry and Fire Prevention (CAL FIRE 2015) manage riparian areas to provide shade, protect streambanks, and ensure future recruitment of large wood. These management practices are anticipated to benefit anadromous salmonid conservation over time (Swales 2010).

The California Department of Fish and Wildlife (CDFW) regulates the removal of wood from streams. Wood removal activities (except on federal or tribal lands) require a Notification of Lake or Streambed Alteration[1] (LSA). Any party interested in removing in-stream logs that threaten bridges, culverts, or private property; or for use as firewood, saw logs, or specialty wood products; or to improve fish passage, must complete an LSA Notification. Persons seeking to modify large wood accumulations to improve fish passage must first consult with CDFW, as these large wood accumulations are often beneficial fish habitat and may not inhibit fish passage. In addition, other federal, state, or local permits may be required.

NEED FOR AND EFFICACY OF LARGE WOOD RESTORATION

Large wood provides several ecological functions to the stream channel and is considered a crucial component of essential habitat in the recovery of anadromous salmonids, including Coho Salmon (*Oncorhynchus kisutch*). Large wood in the estuarine environment stabilizes substrate and provides cover and shelter from predators. Large wood has the same function in the freshwater environment and is the key element in establishing and maintaining pools and spawning habitat, as well as providing habitat for aquatic invertebrates (CDFG 2004).

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

It is generally acknowledged (Boyer et al. 2003; CAL FIRE 2015) that restoring riparian and upslope processes impacted by past practices is necessary to ensure long-term recruitment of wood to the stream channel. Declining fish populations may not be able to persist over the decades or centuries necessary for large trees to mature and recruit naturally into the stream. In the short term, large wood projects can provide immediate benefits to stream channel form, function and aquatic habitat in those watersheds and riparian areas that remain in the early stages of recovery and are lacking large wood.

It is reasonable to expect that large wood structures will adjust and shift with time and stream flow and accumulate additional large and small wood. Over the years, structures are subject to fill and scour, and the wood will lose durability as it decays. In a well designed and implemented project, most of the wood should remain in the system and enhance fish habitat for the design life of the project. Large wood that does not remain in the project reach, but simply washes downstream and through the system, will not provide the desired project benefits (USBR and USACE 2015).

Various studies document the retention rate and biological response of large wood projects. Carah et al. (2014) evaluated wood projects in 11 Mendocino County streams treated with wood between 2007 and 2012. Logs were either installed with no added stability or wedged between trees for added stability. A total of 1,973 pieces of wood were placed in stream reaches with gradients less than 3% and bankfull widths between 12 and 63 ft. The overall retention rate of logs over the short term (6 years or less) was 92%, and all key logs were retained. Logs greater than 1.5 times bankfull width were not transported outside the project reaches. Additionally, treated areas showed an increase in pool frequency and volume, as well as additional accumulations of wood. Jones et al. (2014) evaluated 91 large wood projects without rigid anchors in western Oregon and concluded that "large wood projects may play a role in maintaining and improving stream complexity and Coho Salmon rearing capacity in coastal basins of Oregon, potentially compensating for the lack of natural recruitment of wood to the streams." Roni et al. (2015) reviewed 22 studies of wood placed in streams and reported that more than 75% of project elements remained in place and provided habitat benefits for a decade or longer. That same review found a positive biological response to large wood projects, particularly for adult and juvenile Coho Salmon and Rainbow Trout (*O. mykiss*).

RESTORATION OPPORTUNITIES

Restoring stream processes involves improving the physical connection between the channel, floodplain, and hyporheic zone, thus reestablishing natural diversity in the flow and sediment regimes (Powers et al. 2019). Large wood projects should seek to restore the stream to a Stage 0 or Stage 1 channel or move the stream from the current stage in the Stream Evolution Model toward a more desirable Stage 7 or Stage 8 channel (Figure 1; Cluer and Thorne 2014). Many California streams are currently

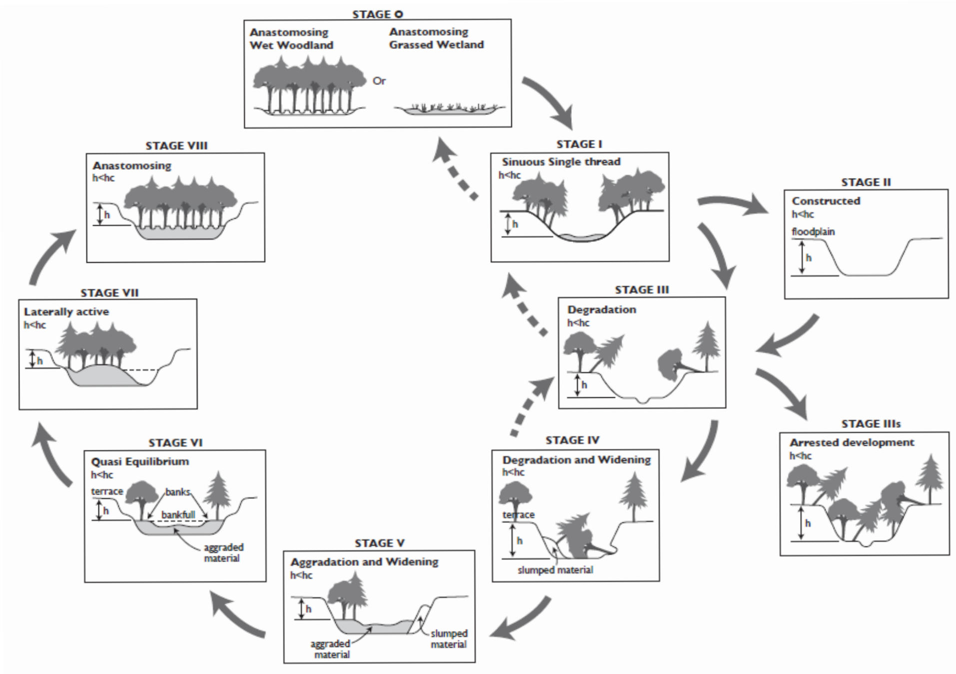

Figure 1. Stream Evolution Model (Cluer and Thorne 2014).

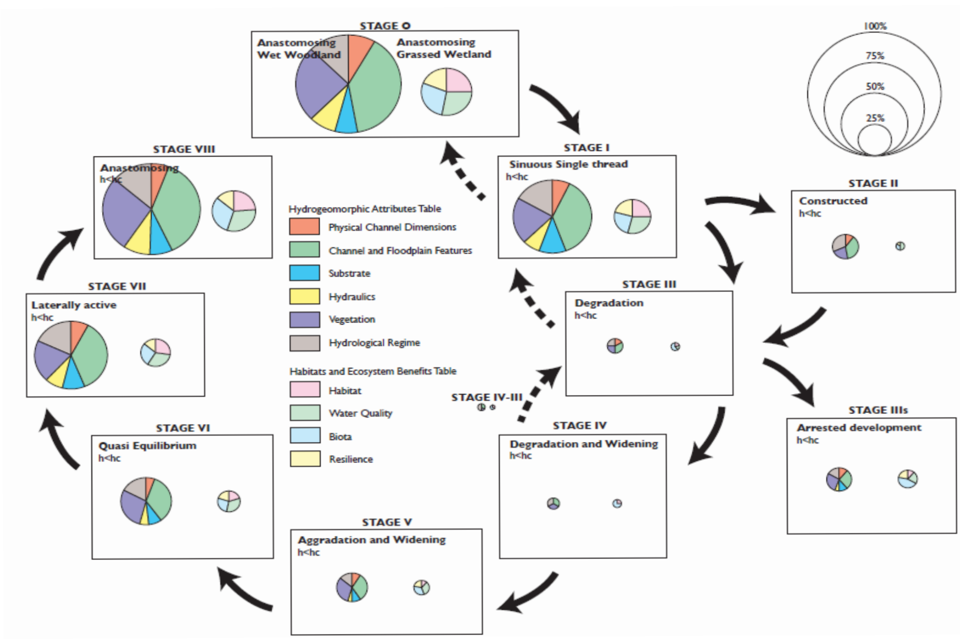

Figure 2. Habitat and ecosystem benefits provided by each stage of the Stream Evolution Model (Cluer and Thorne 2014).

incised and fall in the Stage 3 or Stage 4 category where the addition of large wood alone may not yield substantial habitat benefits. In incised channels, restoring habitat and stream function requires addressing the cause of the incision. Once the cause of the incision is addressed, reach-scale restorative actions to restore channels toward the most desirable Stage 0 can be implemented. Figure 2 describes the habitat and ecosystem benefits provided in each stage of the Stream Evolution Model (Cluer and Thorne 2014).

The goal of many large wood projects is to improve cover and provide scour to enhance habitat for salmonids. Well-placed wood structures also improve the geomorphic function of a stream, and its associated floodplain and riparian zone. Past land-use activities have resulted in channel incision and streams characterized by Stage 3 of the Stream Evolution Model. Channel incision is a qualitative term that describes the condition in which a channel has degraded to such an extent that it disconnects from its floodplain and off-channel or side-channel habitat areas. Levee construction also disconnects a channel from its floodplain. Streams disconnected from the floodplain tend to have higher peak flows and lower base flows. Channel incision affects the riparian corridor by lowering the water table that supplies water to the roots of riparian plants. Steep side slopes associated with an incised channel commonly slough and fail resulting in the undermining and washing away of riparian vegetation (Figure 3). Large wood structures designed to reverse the impacts of channel incision provide a tool to ameliorate those impacts (Figure 4).

It is essential to consider what opportunities to improve geomorphic function are present along a proposed stream reach. Reversing the effects of channel incision requires a reach-scale effort that may take more than one treatment. Adding large wood to a channel reduces water velocities, traps additional wood, and promotes sediment deposition and meandering (Figure 5). Collectively, these elements lead to more complex instream habitat and improved geomorphic function. Improved functionality provides benefits to salmonids beyond providing cover. These include gravel sorting for spawning habitat, water velocity and temperature refugia, and an increase in available food from additional benthic macroinvertebrate productivity that occurs on inundated floodplains. Note: not all incised channels were originally connected to a floodplain. Many small mountain streams are naturally entrenched as a function of geomorphic forces associated with mountain building.

Abbe and Brooks (2011) emphasize that "large wood projects should be designed to accommodate the physical and biological processes to which the project will be subjected and emulate natural self-sustaining structures." Large wood projects involving key logs consist of either single or multiple log structures which are added to the channel with no added stability. Where key logs are not available, some form of stabilization is required. This can include wedging logs between trees, weighing logs down with ballast (native streambank material, gravel, boulders, or large wood

Figure 3. Incised channel. Photo credit: Scott Monday, CDFW.

Figure 4. Large wood added to stream. Photo credit: Scott Monday, CDFW.

Figure 5. Large wood structure that trapped additional large and small wood, reduced stream velocity, and retained sediment. Photo credit: Scott Monday, CDFW.

placed above the bankfull channel height) or logs rigidly anchored (use of exterior anchors) to trees, bedrock, pilings, or a combination of these types of stability. A detailed description of stabilization techniques is included in this report under section, "Stabilization Methods."

Opportunities for habitat improvement using large wood placement can present themselves in a variety of ways, particularly in low-risk settings away from infrastructure such as forested lands. Habitat improvement includes a reduction in channel capacity through dense spacing of key logs, moving flow out onto the floodplain, raising water surface elevations to create access to existing side channels and cut-off oxbows, and raising the water table to support the riparian zone. This often requires multiple treatments spaced over several years after evaluating the results of the previous efforts. In areas where infrastructure is set back from the stream, it is possible to use wood structures to induce sinuosity in previously straightened streams.

In low-risk areas, with willing landowners or land managers and where there are key pieces of wood and other large and small wood available, it is possible to do extensive wood loading. Taking advantage of these opportunities takes careful planning and design. The rewards in terms of improvement to fish habitat are usually worth the time and effort.

CONSTRAINTS AND RISK CONSIDERATIONS

Knutson and Fealko (2014) state, "rivers are dynamic in nature, and all structures within a river channel are exposed to risks associated with fluvial processes." Large wood structures are constructed out of material that is buoyant, variable in quality and shape, and which deteriorates over time. As such, some degree of dislodgement is not unusual. For some projects, dislodged wood is not a problem, but for others there are undesirable impacts. The projects that have the greatest constraints are also the ones for which dislodgement of the wood structures is problematic.

It is important to note that large wood projects, like all restoration projects, can have unintended effects on the riverine and biotic communities. Large wood structures can destabilize streambanks by re-directing stream flow, which may be a desired outcome in a remote location, but problematic in areas with vulnerable infrastructure. If improperly placed, wood intended to provide cover in a pool might slow down the flow and create sediment deposition. A large wood structure can cause a large wood accumulation that leads to channel avulsion or inhibits fish passage. It is essential that large wood projects be supported by a written analysis that identifies why, how, and where to place the structures on the landscape to increase the chance of benefitting the fish and riverine conditions they are intended to bolster. Potential constraints to consider are discussed below.

PROPERTY OWNERSHIP

Large wood projects have the potential to cause flooding, streambank erosion, or result in direct damage to property. These problems may not occur at the structure location, but may be upstream, downstream, or across the stream from the structures. Property ownership should be determined for the entire project reach, including the area directly upstream and downstream from the project. Whether the reach is entirely within the property of one landowner or land manager, or if there are multiple landowners, should be identified. Written access permission must be secured from all landowners or land managers if the project is on their property. In addition, it is important to contact all landowners or land managers who may possibly be affected by the project, fully explain the benefits and risks of the project, and obtain written permission to conduct the project.

INFRASTRUCTURE

Logs that dislodge from a large wood structure may block a culvert, potentially causing the culvert to wash out, or become lodged on a bridge abutment or deck, creating scour that could threaten the integrity of the structure. Downstream property such as irrigation diversions, storm drainage outfalls, and docks may also be impacted by dislodged wood. These impacts may occur a long distance downstream of the project reach. Scour created by a structure may undermine the structural integrity of utility lines buried under the stream or river. If a large wood accumulation captures large wood and sediment, there is potential for the structure to cause flooding to upstream properties.

RECREATIONAL ACTIVITIES

Large wood projects are potential hazards to river recreationists such as kayakers, rafters, swimmers, and anglers. These structures may also pose a hazard to curious adults or children who choose to climb or play on or around them. There is also the possibility of personal injury to those installing the project if rigid anchoring was used to secure the structure.

PROJECT PLANNING

RISK ASSESSMENT

Large wood projects are either considered high or low risk through an evaluation process. Low-risk projects include projects where there is low-risk to public safety, infrastructure, or private property. Public property and large tracts of privately owned lands are good locations for these projects. Low-risk projects include structures with key-piece-sized logs with no added stability, and key-piece-sized logs wedged between live trees to add stability. They also include structures constructed of wood that do not meet key log criteria, that are pinned to live trees or anchored to bedrock in the streambed or streambank. The high-risk category includes all large wood projects, regardless of the size of stream or length of wood, in areas where public safety, infrastructure, or private property are at risk. Licensed engineers must design, approve, and stamp projects that fall into the high-risk category. Those responsible for the design must conduct the appropriate stability and scour calculations.

A written risk and constraints assessment is required for all large wood projects. The location of the project should be identified in the assessment, with a description of how the project was determined to be low- or high-risk. For all large wood projects, it is desirable to consult with CDFW early in the planning process, including a field visit to the project reach. The field visit with knowledgeable CDFW staff should include a discussion of project constraints and potential alternatives.

WATERSHED AND STREAM SELECTION

The need for a large wood project on a stream or watershed can be determined by researching reports that identify a lack of large wood as a limiting habitat factor for anadromous salmonids. Watershed assessments are discussed in the California Salmonid Stream Habitat Restoration Manual, Part II (Flosi et al. 2010). Several watershed assessments specific to California coastal watersheds have been completed by the CDFW Coastal Watershed Planning and Assessment Program. These watershed assessment reports include background information, findings, limiting

TABLE 1. Habitat indicators (modified from NMFS 2014).

Habitat Indicator	Good	Very Good
Primary Pool Depth	2–3.3 ft	>3.3 ft
Primary Pool Frequency (per reach length)	41–50%	>50%
Key Log Piece (pieces† per 330 ft of channel length)	2–3	>3
Large Wood <20 ft wide‡ (pieces per mile)	54–84	>85
Large Wood 20–30 ft wide‡ (pieces per mile)	37–64	>65
Large Wood >30 ft wide‡ (pieces per mile)	34–60	>60

† Key Log Pieces:

- Length: for logs with root wads attached, length of a key piece must be 1.5 times the bankfull width of the stream. If no root wad is attached, the length of the log must be two times the bankfull width (ODF and ODFW 2010).
- Diameter: should be equal to or greater than half the bankfull depth (USBR and USACE 2015) or meet the key log diameter based on stream width in Table 2, whichever is greater.

‡ The number of pieces of wood in streams with a bankfull channel width of less than 20 ft, between 20 and 30 ft, or greater than 30 ft. Large wood is defined as all wood pieces greater than 12 in in diameter and a minimum of 20 ft long (CDFG 1998). In first and second order streams, a primary pool is defined to have a maximum residual depth of at least 2 ft, occupy at least half the width of the low-flow channel, and be as long as the low-flow channel width (Flosi et al. 2010).

factor analysis, and improvement recommendations. For watersheds that do not have a complete watershed assessment, individual stream habitat inventories may have been completed using the methodologies described in the California Salmonid Stream Habitat Restoration Manual, Part III (Flosi et al. 2010). Stream habitat inventories document the presence, absence, and condition of numerous aquatic habitat parameters, usually including a tally of pieces of large wood greater than 12 in in diameter and over 20 ft in length within the bankfull channel. The lengths, depths, and widths of pools, riffles, and flatwater habitats are also usually summarized. If no inventory exists, one must be completed prior to moving forward. A local CDFW regional office can provide the most recent information on a stream of interest. Also, the Stream Inventory Reports found in CDFW's Document Library[2] may be useful.

[2] https://nrm.dfg.ca.gov/documents/ContextDocs.aspx?cat=Fisheries--StreamInventoryReports

Instream large wood provides benefits to all species of resident and anadromous salmonids. For streams inhabited by Coho Salmon, the National Marine Fisheries Service (NMFS 2014) lists important indicators of aquatic habitat suitability related to channel complexity (Table 1). A large wood project may be appropriate for Coho Salmon streams where habitat inventories identify indicators that fall below the threshold of the good channel complexity indicator category.

SITE CHARACTERIZATION FOR ALL PROJECTS

After identifying all constraints, completing the risk assessment, and identifying the need for the project, the next step in the process for all projects is to conduct a preliminary field site characterization. Preliminary field site characterization identifies specific stream reaches that have the geomorphic attributes and riparian vegetation necessary to support a successful large wood project. Typically, large wood projects consist of numerous sites or features within a project reach.

The site characterization consists of a written geomorphic description of the stream reach in terms of planform, confinement, bed forms, and floodplain characteristics. Measuring the slope of a channel can determine how impactful large-wood structures may be to that reach. Large wood has the most significant impact on moderate-slope (1–3%) alluvial channels (Saldi-Caromile et al. 2004). Stream slope also has a bearing on structure spacing and size. Structures can be smaller in height or spaced farther apart in lower-gradient slopes and still have a significant impact on channel form.

Bankfull width and depth should be measured at one representative cross-section to determine the entrenchment ratio in a reach. This gives the designer a better understanding of the opportunities and constraints for restoration. Rosgen (1996) defines entrenchment as the vertical containment of a stream. To calculate the entrenchment ratio, the width of the flood-prone area (determined at twice the maximum bankfull depth) is divided by the width of the bankfull channel. An entrenchment ratio less than 1.4 defines an entrenched stream so disconnected from its floodplain that flood flows rarely inundate the floodplain. This means that flow greater than bankfull is constrained within streambanks and not distributed across the floodplain; consequently, the considerations regarding location, structure height, and orientation take on different significance. Wood structures placed in such a site will be subject to greater stream power and flow depths than in channels with less entrenchment. In entrenched streams, no stabilization is necessary if placing wood that meets the length and diameter criteria for a key log. Wood that does not meet the key log criteria may be utilized if it is anchored to increase stability.

It is also important to determine if the stream is stable, aggrading, or degrading. If the stream is aggrading or degrading, the cause of the instability should be determined. If the stream is aggrading due to a discrete influx of sediment, large wood structures could help sort the sediment or narrow the stream to facilitate sediment transport through the reach; however, if the sediment load is too great, large wood could become buried and ineffective. If the stream reach is degrading, or there is a head cut located downstream, a large wood structure that has successfully trapped transient wood could begin to back up sediment and become a barrier to fish passage. In reaches with wood structures on degrading streams, periodic monitoring for fish passage and distribution should be conducted. If the degradation has largely already taken place, large wood structures are a tool for trapping sediment to build up the streambed and potentially reconnect side channels or floodplains to the stream. To aid in determining if the stream is aggrading or degrading, the design team should review historical and current aerial photographs, looking for increasing or decreasing channel sinuosity. In the field, recent sediment deposits, channel braiding, and streambank erosion, particularly bare vertical banks, undercut banks, and sloughing, should be noted. For further information on determining vertical channel stability, see Castro (2003) and Castro and Beavers (2016).

The preliminary site characterization should include a description of substrate composition (i.e., sand, gravel, cobble, bedrock etc.) and a qualitative assessment of scour potential, as indicated by residual pool depths and depth of alluvial cover. Gravel and finer bed materials indicate that cover, sediment sorting, and scour could be appropriate project objectives, while coarser substrate would lead to project objectives of sediment deposition and reduced stream power. Any bedrock outcroppings in the channel bed should be noted and existing pool depths in the project reach measured. The presence of bedrock indicates that scour potential could be limited, but bedrock may also provide additional anchoring locations. Subsurface conditions will determine the appropriateness of using piles or posts. It is particularly important to know if bedrock or boulders are present when considering installing piles or posts as an anchoring technique. Exploratory trenching and/or boring in the streambed is necessary to determine subsurface conditions if planning to install piles or posts. Sand and bedrock streambeds are inappropriate for boulder ballast as boulders are very mobile in these settings.

The preliminary field site characterization should also include a description of the streambank composition, layering, bedding, geometry, and potential for erosion. The more erodible the streambank is, the more potential exists for a large wood project to facilitate streambank erosion. This may be an acceptable or desired outcome, but it is important to recognize that large wood structures placed adjacent to streambanks underlain by un-cemented deposits of small gravel, sand, and silt are vulnerable to flanking, resulting in the flow going around the structure. If bedrock is present, a qualitative assessment of its durability should be made. Bedrock used to anchor a structure must be uniformly sound, hard, and durable. The bedrock should be free from cracks, seams, and other defects that can increase its susceptibility to deterioration from chemical dissolution, cycles of freezing and thawing, and cycles of wetting and drying (i.e., slaking). If trenching is required to key the structures into the streambank for stability, a characterization of streambank material is important. Presence of bedrock in the streambank indicates that trenching may be difficult.

Sediment supply. The geomorphic assessment should include a qualitative description of sediment supply, composition, and transport. Depending on the objectives of the project, it is necessary to know the likelihood and relative significance of streambed aggradation or degradation. If the objective of the large wood structure is to encourage sediment deposition over exposed bedrock, boulders, or cobble, it is necessary to make streambed material observations upstream and downstream of the project reach to determine if there is adequate bedload to deposit over the bedrock, boulders, or cobble. The design team should be looking for gravel bar deposits in these reaches, particularly those that are regularly reworked by the stream (i.e., they lack mature vegetation, and the gravel is loose on the surface), and not just isolated patches of gravel.

Along with the geomorphic description, the type and extent of riparian vegetation should be included in the characterization. Roots from riparian vegetation provide strength and stability to streambanks. A wide riparian buffer zone can safeguard the project from creating streambank erosion and prevent the structure from flanking. The size, location and species of riparian trees affect the ability to wedge or anchor logs. Thus, the riparian trees that are to be used as anchors should be identified and listed, including those to be felled into the stream.

If the plan incorporates downed on-site wood, the length, diameter, and species of wood should be identified and listed, as this influences residence time in the channel and the need for anchoring. Downed wood must be sound before including it in a planned project, and the landowner or land manager must provide permission to use this wood. It should be determined how and what method will be used to procure and move on-site wood. If moving the wood requires heavy equipment, it is important to evaluate access for the equipment and the potential for site disturbance to move the wood and place it in the stream.

Other site constraints may determine whether large wood projects are appropriate. For example, dams within the watershed affect stream flow, sediment supply, and transport of large wood. Access to the site and general location can have a large impact on cost, depending on whether access will be from an existing road or if the project includes construction of a new road. Transportation costs can be prohibitive if access for large trucks is difficult and if the distance to the site is far from the delivery point of equipment and materials. The need to move equipment to the construction site or in and out of the stream channel is another consideration. Moving heavy equipment may damage riparian vegetation or require building access roads to move materials or the heavy equipment to the site. Care is required to avoid disturbing areas with invasive plant species for fear of distributing them to a wider area. In some cases, there is a strong desire to use materials on-site to build the large wood structures. However, the challenges of gathering the material on-site can result in higher costs than importing the materials and may result in unanticipated environmental impacts, negating the use of on-site materials. Materials used must be of appropriate size, strength, and species, regardless of the source. Combining large wood projects with other projects, such as upslope sediment reduction projects, may offer opportunities to reduce costs and equipment impacts.

SITE CHARACTERIZATION FOR HIGH-RISK PROJECTS

The site characterization for high-risk projects requires additional assessments, such as a geomorphic study, topographic mapping, and hydrologic and hydraulic analyses. Low-risk projects that include apex bar jams, posts, or piles also require hydrologic and hydraulic analyses. In addition to all the geomorphic considerations for low-risk projects, high-risk projects should include the geomorphic data and observations described below.

Bed material. One of the first steps of the geomorphic study is to make a quantitative assessment of the bed material gradation in the project reach. The size of bed material gives input to the project design. Pebble counts (Wolman 1954; Harrelson et al. 1994) are necessary to determine the grain size distribution of the bed material for scour calculations. If a goal of the project is to develop scour pools, it is important to determine if there is adequate depth of alluvial material by boring or trenching into the streambed. A geotechnical investigation, with logged borings or trenches, analyzed by a licensed Geotechnical Engineer or Professional Geologist, is required for projects that will rely on piles or posts to anchor wood structures. Subsurface conditions will determine installation criteria for the piles. It is particularly important to know if bedrock or boulders are present when installing piles.

Streambank and floodplain stability. The geomorphic assessment should include a qualitative assessment of streambank and floodplain stability. When planning a project near infrastructure, or one intended to induce meandering or re-establish floodplain connectivity, it is important to evaluate the potential for erosion of the streambanks as well as addressing whether mass wasting, or channel avulsion, are concerns.

Topographic survey. The topographic survey supports both hydraulic modeling and design development. The Pre-Design Site Assessment in the California Salmonid Stream Habitat Restoration Manual, Part XII (Love et al. 2009) gives valuable guidance on the features to include in a topographic survey, e.g., riparian trees designated for anchoring or wedging logs. In addition, it is helpful to survey in other anchor points, potential structure sites, or habitat to enhance or avoid. A scaled topographic map should show survey points, cross-sections, and longitudinal profiles from the survey data. It is helpful to put the maps onto an aerial photograph. The longitudinal profile should extend at least five bankfull widths upstream of the most upstream large wood structure and at least five bankfull widths downstream of the farthest downstream large wood structure, far enough above and below the project to capture any potential effects of the proposed structure on the stream. At a minimum, scaled cross-sections should be included near each intended structure location. Cross-sections can be added as needed for hydraulic modeling or to document changes in the channel and floodplain that occur away from the structure. Cross-sections should be extended beyond the active channel to include the floodplain. The cross-section plot should include an estimate of the bankfull depth. Finally, data should be sufficient to estimate channel roughness for use in Manning's equation (Chow 1964), an essential component in hydraulic models. Channel roughness estimates should be supported by photographs of the bed material and riparian vegetation at each cross-section.

Hydrology and hydraulics. Hydrologic analyses that determine recurrence interval flows and bankfull flows are important in analyzing numerous aspects when designing large wood structures in high-risk settings. The recurrence interval is based on the probability that the given event will be equaled or exceeded in any given year. For example, a 100-year recurrence interval flow has a 1% chance of being equaled or exceeded in any given year, while a 2-year recurrence interval flow has a 50% chance of being equaled or exceeded in any given year. Recurrence interval flows are mostly determined using the U.S. Geological Survey Streamstats Tool[3]. Recurrence interval flows are utilized to determine channel capacity in a hydraulic model. Modeling these flows provides depths and velocities for scour and stability calculations. These calculations inform the design of ballast, piles, or posts for structures requiring stabilization. For structures designed to reconnect the channel to a floodplain, hydraulic modeling of the bankfull and recurrence interval flows is used to determine the frequency at which the channel currently spills out onto its floodplain.

CONSTRUCTION CONSIDERATIONS

SPECIFICATIONS OF LARGE WOOD

High-flow events flush sediment, nutrients, and large wood downstream. The downstream transport of large wood is facilitated by the fact that wood is buoyant. For an unanchored log to remain in a stream and withstand high-flow events, it must be of sufficient length, relative to the bankfull width, and ample diameter, relative

[3] https://streamstats.usgs.gov/ss/

to bankfull discharge, to stay stabilized in the streambed or streambank. Logs that include branches and a root wad are considered "rougher" and tend to be more stable than logs without. Residence time in the channel is directly related to the species of tree and its resistance to decay. The definition of a key piece includes metrics used to scale a structure to a stream. Key pieces of wood serve to stabilize the log structure within the streambed. Non-key logs usually require some form of stabilization to remain within the stream channel. To qualify as a key piece, a given log must meet length, diameter, log durability, and resistance to decay criteria.

Length and diameter. Logs must meet a minimum relative length and diameter respective to stream size to be considered a key piece. For logs with root wads attached, the length of a key piece must be 1.5 times the bankfull width of the stream (ODF and ODFW 2010). If no root wad is attached, the length of the log must be two times the bankfull width. The diameter for a key piece should be equal to or greater than half the bankfull discharge depth of the stream (USBR and USACE 2015). As an alternative, guidance on the minimum log diameter for a key piece can be determined relative to bankfull width (Table 2). Two or more key logs at a site increases structure stability and complexity.

Utilizing whole trees that meet the length and diameter criteria is desirable whenever possible. The root wad increases stability and provides exceptional cover for salmonids at all life stages, so logs with root wads should be placed with root wads in the channel. Leaving limbs and branches on the logs also increases stability and adds cover, though the limbs on some species of trees are brittle and prone to sheering off during high flow. Cutting the limbs to a length of between 18 and 24 in can prevent breakage, enable the limbs to trap smaller wood, and help stabilize the tree to the channel. Still, leaving limbs on the logs may present a safety hazard in high-risk areas.

TABLE 2. Minimum log diameter for key log pieces (modified from ODF and ODFW 2010).

Bankfull Width (ft)	Minimum Diameter (in)
<10	12
10 to <20	16
20 to <32	18
>32	22

Log durability and decay resistance. The maximum design life of a large wood project is dependent on the durability of the wood used (Table 3). In coastal northern California, the preferred wood species are old growth redwood, western red cedar, or Douglas fir. Using these species in the stream increases the life expectancy of a structure as compared to using other types of wood.

TABLE 3. Desirability of various tree species for stream structures (modified from USBR and USACE 2015).

Species	Durability*	Source
Cottonwood (*Populus* spp.)	Poor	Johnson and Stypula (1993)
Alder (*Alnus* spp.)	Poor	Johnson and Stypula (1993), Cederholm et al. (1997)
Maple (*Acer* spp.)	Fair (will survive 5–10 years)	Johnson and Stypula (1993)
Hemlock (*Tsuga* spp.)	Least of conifers	Johnson and Stypula (1993)
Sitka spruce (*Picea sitchensis*)	Excellent	Johnson and Stypula (1993)
Douglas fir (*Pseudotsuga* spp.)	Excellent, will survive 25–50 years/ 32–56 years	Johnson and Stypula (1993) Harmon et al. (1986)
Western red cedar (*Thuja plicata*)	Most desirable, will survive 50–100 years	Johnson and Stypula (1993)
Yellow-poplar (*Liriodendron tulipifera*)	0.4 years	Harmon et al. (1986)
Aspen (*Populus tremuloides*)	5 years	Harmon et al. (1986)
White fir (*Abies concolor*)	4 years	Harmon et al. (1986)
Norway spruce (*Picea abies*)	~30 years	Kruys et al. (2002)
Conifers (*Picea sitchensis, Tsuga heterophylla, Pseudotsuga menziesii, Thuja Plicata*)	~20 years	Hyatt and Naiman (2001)
Black locust (*Robinia pseudoacacia*), red mulberry (*Morus rubra*), Osage orange (*Maclura pomifera*), Pacific yew (*Taxus brevifolia*)	Exceptionally high heartwood decay resistance	Simpson and TenWolde (1999)

Species	Durability*	Source
Young growth bald cypress (*Taxodium distichum*), western larch (*Larix occidentalis*), longleaf old growth pine (*Pinus palustris*), old growth slash pine (*Pinus elliottii*), young growth redwood (*Sequoia sempervirens*), tamarack (*Larix laricina*), old growth eastern white pine (*Pinus strobus*)	Moderately resistant to heartwood decay	Simpson and TenWolde (1999)
Red alder (*Alnus rubra*), ashes (*Fraxinus* spp.), aspens (*Populus tremuloides*), beech (*Fagus* spp.), birches (*Betula* spp.), buckeye (*Aesculus glabra*), butternut (*Juglans cinerea*), cottonwood (*Populus* spp.), elms (*Ulmus* spp.), basswood (*Tilia Americana*), true firs (*Abies* spp.), hackberry (*Celtis occidentalis*), hemlocks (*Tsuga* spp.), hickories (*Carya* spp.), magnolia (*Magnolia grandiflora*), maples (*Acer* spp.), pines (*Pinus* spp.), spruces (*Picea* spp.), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), tanoak (*Notholithocarpus densiflorus*), willows (*Salix* spp.), yellowpoplar (*Liriodendron tulipifera*)	Slightly or nonresistant to heartwood decay	Simpson and TenWolde (1999)

*assuming wetting and drying

It is important that the wood used for any instream project is structurally sound. Fresh cut logs from near the project reach, a current logging operation, upslope restoration project, or recent windfalls are good sources of logs. Logs salvaged from the forest floor should be checked for soundness before use as they may have decayed, making them structurally unsound. The resistance of large wood to decay is dependent on the diameter, density, and species of the piece of wood. Large conifer logs, such as old growth redwood and Douglas fir, decay much more slowly than hardwood trees, such as alder, willow, and tan oak. In general, decay rates are lowest for species with high-density wood (USBR and USACE 2015). Sapwood in second growth conifer logs will decay rather quickly; thus, the longevity of second growth logs is less than old growth logs of the same species. Decay rates for logs vary with wetting frequency, ambient temperatures, and humidity. Conifers have the potential to last seven times longer than hardwoods, given the same diameter and conditions (ODF and ODFW 2010). Therefore, due to their resistance to decay, conifer logs are preferred for large wood projects. Hardwoods may be combined with conifers to increase complexity at the site. Wood completely submerged retains its structural integrity for a much longer time than wood subjected to repeated wetting and drying (USBR and USACE 2015).

STRUCTURE LOCATIONS AND CONFIGURATIONS

Areas with unstable streambanks, riparian roads, or landslide activity should be avoided unless the log structure is part of a larger effort to address those specific issues. In small streams, (less than 30 ft bankfull width) logs can be placed in any orientation (Cramer 2012). Depending on the goal of the project, logs placed at different angles will have different outcomes. Combining or joining multiple logs into a complex structure to add stability is a common practice. In small streams, logs may span the channel or protrude partway into the channel in any orientation. Logs with one end placed on the streambank and angled downstream are less obstructive, making them more stable than logs oriented upstream or perpendicular to flow. Wood structures designed to significantly affect channel planform, profile, or flow distribution, or provide geomorphic complexity, typically must obstruct streamflow to some degree.

For projects that aim to reconnect floodplains or re-engage side channels, different configurations of logs are appropriate. Key logs placed from both streambanks to constrict the channel help divert high flow above bankfull to access the floodplain. Channel spanning logs with two points of contact may similarly divert or force stream flow onto adjacent floodplains. Logs arranged to catch floating logs and small wood, thus reducing channel capacity, facilitate flow to re-engage with the floodplain. Logs placed adjacent to benches, or downstream of side channel connections, increase flow into high elevation side channels. If the project goal is to maintain connectivity to side channel inlets or outlets, and alcove outlets, one option is to place logs from one streambank, tucked closer to the streambank than logs placed for inducing meanders. Logs placed close to the streambed encourage the formation of a scour pool and limit deposition when overtopped. Wood placed at an upstream angle are more obstructive, promoting scour and collecting additional large and small wood (Carah et al. 2014; Figures 6 and 7).

Logs placed from one streambank induce streambank scour and meandering, especially logs with a root wad to break up the flow. Alternatively, logs placed so that they are angled with the streambank end high in the water column, or logs that are arranged to catch floating logs, will also induce streambank scour and stream meandering (Figure 8). Adding small wood from conifer or hardwood trees to fill in interstitial spaces will help trap additional small wood and increase complexity and the scour potential of the structure.

Figure 6. Logs placed at an upstream angle against the banks of a dry stream channel. Photo credit: Alan Ader, California Conservation Corps.

Figure 7. Additional woody debris collected by the structure shown in Figure 6 after the first winter in an active stream channel. Photo credit: Alan Ader, California Conservation Corps.

Figure 8. Logs trapping additional large and small wood. Photo credit: Trevor Lucas, Pacific States Marine Fisheries Commission.

Logs arranged from one or both streambanks, with the logs placed low in the channel, facilitate pool scour and sediment sorting. This configuration can be used to break up long glides or to enhance existing features. Aggraded pools or pools with little existing shelter, flatwater habitat types, and backwater eddy areas along the channel margins are some of the better locations for the large wood structures. Wood placed perpendicular to the channel will facilitate gravel sorting and storage. Wood angled downstream will deflect flow and increase velocities directly downstream, resulting in bed scour (Carah et al. 2014).

PROJECT DESIGN

PURPOSE AND NEEDS STATEMENT

Based on the findings of the watershed assessment or stream inventory, and the opportunities and constraints found in the site characterization, the design team can finalize one or more objectives for the large wood project. Typical objectives include providing summer rearing habitat, high-flow refugia for adult and juvenile salmonids, floodplain reconnection, or sorting and stabilization of spawning substrate. The project goal should consider not just the immediate problems for salmonids, but the processes that led to those problems. To the extent possible, the project goal should address the cause of the problem, rather than just seek to remediate the symptoms. It is unlikely that a large wood project alone will be able to restore the stream back to conditions found prior to channel and riparian alterations, but there are often opportunities to establish meanders, or connectivity to side channels or the floodplain. Along with guiding project design, project objectives are necessary to have a metric against which to evaluate project effectiveness (Tear et al. 2005; Roni and Beechie 2013).

DESIGN PROCESS FOR LOW-RISK SMALL STREAMS (LESS THAN 30 FT BANKFULL WIDTH)

Most of the design work for low-risk projects in small streams takes place in the field. Design methodology for high-risk projects in small streams is presented below. Based on the type of structures used to achieve the project goal, the project design team needs to determine where to place the structures and how to orient the logs. It is important to find the best locations for achieving the project goal. This iterative process involves numerous steps, including identifying the number and length of logs needed and determining the source of the logs. Logs can be acquired by felling on-site trees from within or near the riparian zone if the tree canopy is dense enough to fell trees without reducing too much shade canopy. Logs can also be obtained near the project using downed wood of the appropriate length, diameter, soundness, and species (identified in preliminary site characterization). Prior to harvesting any trees or downed logs, the landowner or land manager must be informed and grant permission. A third option is importing logs from off-site by purchasing logs or securing logs from logging operations or upslope restoration sites. However, the maximum length that a log truck can haul is approximately 40 ft. Additionally, since most imported logs do not have root wads, to qualify as a key log, the recipient stream must be 20 ft or less bankfull width. No stabilization is necessary if the logs are of suitable length and diameter to qualify as key pieces. If the logs are not key pieces, then techniques should be used for adding stability, for example wedging or anchoring the logs. If the project involves heavy equipment, the need for equipment access should be evaluated. The ease or difficulty of getting equipment to the site influences the type of project possible, along with the scale, design, and cost of the overall project.

The final step is to produce sketches of each structure, organized by longitudinal stationing along the project reach. Each sketch should be in plan-view with the stabilization scheme or anchoring techniques described. Additional cross-section or detail views should be provided where necessary. Designs should include a listing of the diameter at breast height, together with the length and source for each of the logs used in the structure. Finally, the specific goal of each structure and how the structure contributes to achieving the reach scale goal should be described (Figure 9).

Stream Name: Cobble Garden Creek — Reach Station: 930′

Site Access: forestry road on right bank — Bankfull Width: 20′

Materials: Push over the 22″ diameter Douglas fir tree on right bank with an excavator to maintain the root wad. Minimum length of the log will be 30′ to be a key sized piece. Select one redwood tree from the clump on left bank. Cut the tree into two 25′ lengths that are at least 12″ in diameter to qualify as large wood.

Structure Goal: This structure will work with the rest of the proposed structures to aggrade the streambed. Local effects will be pool formation, sediment sorting, and cover.

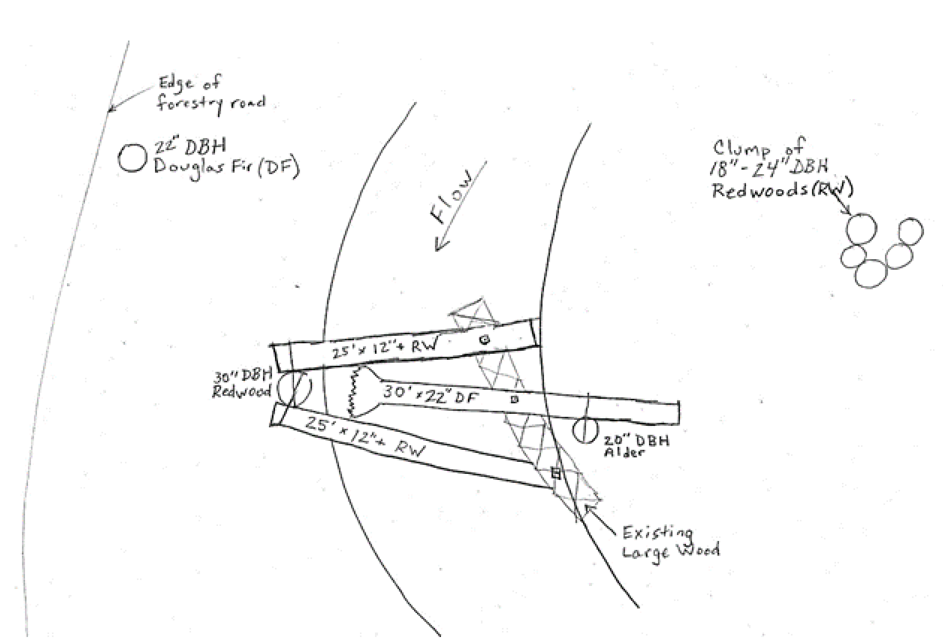

Figure 9. Sketch of a low-risk project with design details included.

DESIGN PROCESS FOR LOW-RISK LARGE STREAMS (GREATER THAN 30 FT BANKFULL WIDTH)

On large streams, structures with multiple logs are typically placed at the outside of meander bends, along the streambanks of a straight reach of stream, or mid-channel, such as apex bar jams. A large wood structure placed in a meander can enhance pool habitat in ways similar to the large wood structures on small streams, by providing cover and by inducing scour. The logs should lie within the active channel or intrude into it. Full channel spanning structures are discouraged due to their vulnerability to flood damage (Cramer 2012). Often the goal of a multi-log meander structure is to redirect flow away from an eroding streambank that is producing excessive sediment detrimental to aquatic habitat (Figure 10).

Figure 10. Large wood structures redirecting the flow from an eroding streambank. Photo credit: Joey Howard, Cascade Stream Solutions.

On larger streams, in reaches straightened either by human actions or channel incision, complex large wood structures should be used to initiate meanders by redirecting flow towards the streambank.

Apex bar jams are multi-log large wood structures placed at the head of a gravel bar, or mid-stream with the intention of creating a mid-channel bar, reinforcing an existing mid-channel bar, or redirecting a portion of the flow into one or more side channels (Figures 11–13). Regardless of the risk, construction of this type of structure requires scour and stability calculations based on the results of hydrologic and hydraulic analyses.

In streams larger than 30 ft bankfull width, stream power can be significant, and stabilizing structures becomes more complex. In many cases, additional stabilization beyond anchoring to live trees and bedrock in the bed or streambanks will be necessary. Additional stabilization typically consists of boulder ballast, keying logs into streambanks, or securing logs to piles or posts. These stabilization techniques require scour and stability calculations based on the results of hydrologic and hydraulic analyses.

Figure 11. Apex bar jam redirecting flow into a side channel. Photo credit: David Bandrowski, Yurok Tribe.

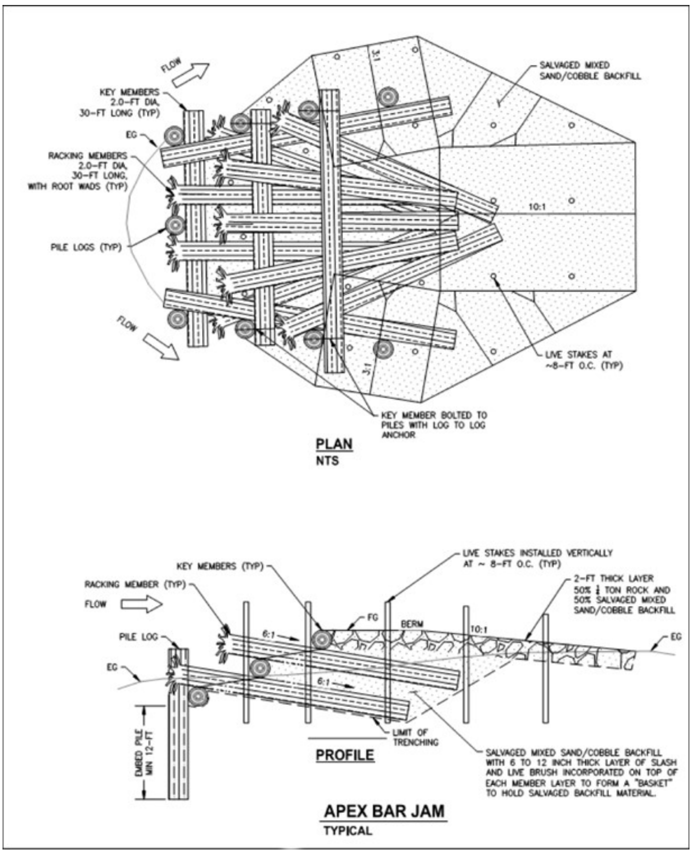

Figure 12. Construction details of a typical apex bar jam (Michael Love & Associates 2016).

Figure 13. Apex bar jam. Photo credit: Rocco Fiori, Fiori GeoSciences.

Hydrologic and hydraulic analyses can range from straightforward web-based tools, such as StreamStats and Manning's equation normal depth calculators, to one- or two-dimensional hydraulic models. Site complexity, such as being in a tight bend, structure complexity (i.e., apex bar jam), or having the goal of inducing meanders or splitting flow into a side channel, may necessitate using a two-dimensional hydraulic model. For relatively straight reaches with the goal of increasing floodplain connectivity, normal depth calculations or one-dimensional hydraulic modeling may be adequate.

In general, the design process for more complex large wood structures is as follows. A topographic map from ground surveys or Light Detection and Ranging (LIDAR)[4] is used to determine locations where structures are likely to accomplish the project goal. One- or two-dimensional hydraulic modeling is then used to determine the size of the wood structure and fine-tune the placement of the structure to achieve the objectives of the project. For design refinement, the model should consider flows that are significant to the project objectives, such as frequent winter storm flows or bankfull flow. Modeling higher flows, such as the 10-, 25-, and 100-year recurrence interval flows, will determine depths and velocities for scour and stability calculations. For complex large wood structures in a low-risk environment, designing for the 25-year recurrence interval is recommended (USBR and USACE 2015).

[4] LIDAR is a surveying method that measures distance to a target by illuminating the target with laser light and measuring the reflected light with a sensor

After the design is refined and the hydraulic analysis is complete, the next step is to conduct scour calculations. Abbe and Brooks (2011) report that damage to large wood structures is primarily associated with scour and turbulence along the flanks of the structure. Scour in streams is generally considered to be caused by four different mechanisms:

- plunging scour - flow over a weir
- contraction scour - accelerated flow through a channel constriction
- abutment scour - water piling up against an obstruction
- pier scour - water piling up against and flowing around both sides of an obstruction

Typically, scour analyses rely on empirical coefficients developed from laboratory experimentation. Consequently, results can vary between methods. Abbe and Brooks (2011) warn that clear assumptions and substantial professional judgement are necessary to achieve the best outcomes. Streambed scour analysis should be performed before stability calculations to be able to develop conservative estimates of embedment for those calculations. The design team should spend considerable time in the project reach investigating residual pool depths and alluvial cover thickness to best estimate actual (minimum) depths of scour and the mechanics responsible for that scour. CDFW recommends the design team use HEC 18 – Evaluating Scour at Bridges (Arneson et al. 2012) to understand the types of scour and their related analyses.

After the scour analysis is completed, stability calculations can be performed. Forces acting upon large wood include net buoyancy, friction between the wood structure and the bed, fluid drag and lift, and geotechnical forces on buried members (USBR and USACE 2015). Three specific force balance stability analyses are required. For all force balance stability calculations, it is necessary to use the design flow water depth from the hydraulic analysis to determine the buoyancy of the materials in the structures. The first of the stability calculations is the force balance analysis that resolves differences in vertical forces (buoyancy of wood elements versus gravity of the structure). Second is the force balance analysis that resolves the difference of horizontal forces (impinging water versus friction force of the structure). Third are the force moment analyses (the rotation of the wood about an axis) to resolve lever arm and rotational forces. It is beyond the scope of this report to provide an in-depth discussion of the physics, mathematics, and methods of these analyses. Comprehensive discussions are provided in Abbe and Brooks (2011), Knutson and Fealko (2014), USBR and USACE (2015) and Rafferty (2017). However, Rafferty (2017) is exclusive to the force balance and moment analyses and does not address scour analysis. Rafferty (2017) is available free online and includes spreadsheet templates to assist in the analyses.

Within each of the three stability calculations, there is a variable called factor of safety (FOS). The FOS is the ratio of the forces resisting the movement of the structure to the forces trying to move the structure (Knutson and Fealko 2014). The FOS ratio is used to reduce the uncertainty in the modeling of the forces affecting the structure, and to help ensure the structure does not move in an unanticipated way. FOS ratios less than or equal to one are less stable than ratios greater than one. For low-risk projects, CDFW suggests the lowest FOS recommended by Knutson and Fealko (2014), which is 1.5 for the vertical, buoyant forces and 1.25 for both the horizontal, sliding forces and the rotation and overturning forces.

HIGH-RISK PROJECTS

In high-risk situations where human life, property, or infrastructure are at risk, it is necessary to design the structures to stay intact for the design flow of the project. A licensed civil engineer must design, approve, and stamp a project for a site with potential risk to public safety, infrastructure, or private property. For high-risk projects, two-dimensional hydraulic modeling is necessary (Knutson and Fealko 2014). If flooding is of concern, water surface profiles of existing and proposed conditions should be compared for a range of recurrence interval flows between the channel capacity flow and the 100-year flow. High-risk projects should be designed to withstand the 100-year recurrence interval flow (USBR and USACE 2015). Since it is impossible to predict when a 100-year recurrence interval flow will occur, this level of design is necessary to protect downstream infrastructure.

High-risk structures require a higher FOS. For high-risk settings, CDFW suggests the highest FOS recommendations from Knutson and Fealko (2014), which is 2.0 for vertical, buoyant forces and 1.75 for both horizontal, sliding forces and the rotation and overturning forces. If streambank erosion is a concern, maximum velocities and shear stresses should be compared against the ability of the streambank material to withstand velocities and shear stresses (Fischenich 2001). For high-risk projects, two-dimensional modeling should be used to predict streambank erosion locations and modify the design to reduce the impact. If boat recreation is a public safety concern for the project reach, two-dimensional modeling should be used to fine-tune the design to guide boaters away from the wood structures.

A licensed engineer must design a project where an eroding streambank may be problematic for private property or infrastructure interests. Designing and installing a multi-log meander structure to redirect flow away from an eroding streambank may be counter to the natural stream process but more desirable than traditional hard streambank stabilization techniques, such as boulder riprap.

LARGE WOOD PROJECT IMPLEMENTATION

PERMITTING

Avariety of permits may be required to complete a large wood project. A discussion of potential permits is included in Flosi et al. (2010). Projects that alter the streambed or streambank or divert or obstruct natural streamflow may require an LSA Notification. Any subsequent LSA Agreement will contain species protection measures, oil spill protection and reporting requirements, and several other conditions that must be followed. If there is the possibility that special-status species will be encountered during the project, California Endangered Species Act[5] measures may be required. Alternately, the Habitat Restoration and Enhancement Act of 2014 (Fish & G. Code §§ 1650-1657) established a permitting process with CDFW for landowners, state and local governments, and conservation organizations seeking to implement small-scale, voluntary habitat restoration projects throughout California. Restoration and enhancement projects approved by CDFW, pursuant to the Habitat Restoration and Enhancement Act, do not require additional permits from CDFW, such as an LSA Agreement or California Endangered Species Act permit. The Cutting the Green Tape[6] program at CDFW is leading efforts to develop and implement improvements to the way permits are used.

In addition to acquiring all necessary permits and adhering to their requirements, it is important to be aware of some best management practices when working in and around streams. Heavy equipment decontamination protocols must be followed prior to any heavy equipment entering a stream. Resources include CDFW's Aquatic Invasive Species Decontamination Protocol[7] and the U.S. Bureau of Reclamation's Inspection and Cleaning Manual for Equipment and Vehicles to Prevent the Spread of Invasive Species (DiVittorio et al. 2012). For general information, see the CDFW Invasive Species Program website[8]. Short-term negative impacts from construction work to the stream are inevitable. These include, but are not limited to, increased turbidity, temporary loss of habitat if flow is directed around the project site, and disturbance of riparian vegetation. To minimize impacts, projects should be implemented when the reach is dry or at its lowest summer flow, and equipment should stay on the streambank when installing logs (Figure 14). Sediment generated by the project must be confined to as small an area as possible to reduce downstream impacts to fauna. If dewatering is necessary, care must be taken to minimize impacts when relocating fish. Guidelines can be found under the section, "Measures to Minimize Injury and Mortality of Fish and Amphibian Species During Dewatering" in the California Salmonid Stream Habitat Restoration Manual, Part IX (Taylor and Love 2004).

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[5] https://wildlife.ca.gov/Conservation/CESA/Permitting

[6] https://wildlife.ca.gov/Conservation/Watersheds/Cutting-Green-Tape

[7] https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=43333

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

Figure 14. Placement of logs from the streambank using a rubber-tired grapple skidder. Photo credit: Derek Acomb, CDFW.

HAND-CREW PROJECTS

Many large wood projects are constructed by hand-crews using tools, such as portable lever operated hoists and chainsaws. Sources of wood include trees within the riparian corridor, trees that have fallen, logs left behind from past logging, or trees generated during upslope restoration projects. Whole trees with root wads and branches are the most desirable. The California Conservation Corps and other restoration practitioners use portable lever operated hoists and hand labor to move trees from hillsides into the stream (Figure 15). These practitioners also use chainsaws to cut trees on hillsides or trees spanning the channel, due to windfall, in a way that they fall into the stream. If the project involves falling on-site trees, for safety reasons, a licensed timber operator with experience in timber falling is required to conduct the felling. If the trees or logs are of key piece size, then they require no stabilization or anchoring. Non-key logs must be anchored to live trees on the streambank, to bedrock or existing instream boulders, and to each other to increase their stability.

HEAVY EQUIPMENT

Heavy equipment is used to construct many large wood structures. Placing wood with heavy equipment is very efficient, unless the sites are in a remote location or the logs are small enough to move using hand tools, such as portable lever operated hoists.

Figure 15. California Conservation Corps member moving a log with a portable lever operated hoist. Photo credit: Derek Acomb, CDFW.

Figure 16. Log being positioned with a rubber-tired backhoe. Photo credit: Derek Acomb, CDFW.

Placement of large wood using heavy equipment is usually accomplished using an excavator, a rubber-tired backhoe (Figure 16), or a rubber-tired grapple skidder. This technique is limited to areas of relatively flat ground where the stream channel can be accessed using existing roads or skid trails. In some cases, windfall trees spanning the channel above bankfull height are pulled into the stream channel, using a winch to move the log into the desired location. With proper cable rigging, a skidder or similar machinery equipped with a hydraulic winch can be used to manipulate and move logs from up to 200 ft away.

When using heavy equipment to position logs, or bring logs in from outside the riparian zone, it is best to use existing roads and trails whenever possible. Using a rubber-tired skidder or backhoe will help minimize ground disturbance (Figure 17). On completed projects, all roads and skid trails should be treated with locally generated logging debris (slash). The slash should be track-walked and compacted into the ground. If using mulch, only weed free mulch should be used in order to reduce the possibility of importing invasive weeds to the area.

The need for a skilled and experienced heavy equipment operator cannot be overstated. The operator must follow the project design drawings and construction notes as submitted. However, even the most experienced heavy equipment operator may be challenged when dealing with natural materials. The precision and patience

Figure 17. Rubber-tired skidder moving a log. Photo credit: Derek Acomb, CDFW.

with which the operator can place the logs at the proper elevation and position will have a significant impact on the success of the project. It may be difficult to secure the identified length and diameter logs required to meet the design specifications of the structure. The designer should be on-site to accept materials and oversee construction so adjustments and modifications may be made in the field during project implementation.

PLACEMENT USING A HELICOPTER

Helicopters are used to place large wood when access for ground-based equipment is difficult, where the project calls for a large volume of wood, or where whole trees are available or required. Using a helicopter can be highly efficient, and a good pilot and ground crew can position the large wood precisely (Figure 18). However, helicopter time is very expensive and requires extensive planning. Aircraft selection is an important consideration, as there are many models with different capabilities and specifications regarding maximum weight, flight range, fuel capacity, and speed. A suitably large area near the project site with vehicle access is required for the extensive team of mechanics, fuel trucks, boom trucks, and support staff that are required. The large wood must be staged as close to the project reach as possible and

Figure 18. Wood being placed by a helicopter. Photo credit: Mattole Salmon Group.

be prepared for immediate pick-up and release to minimize turnaround times. Wood placement locations should be clearly identified and communicated to the pilot and ground crew prior to flying. Helicopters flying close to the ground with whole trees are noisy, attract curious bystanders, and may require the closure of roads to ensure public safety beneath flight paths. Formal outreach to the local community is a critical component of project planning and execution. While a helicopter can be an excellent tool to accomplish instream wood placement, the logistics of such an operation are considerable and a detailed plan that includes a flexible schedule is essential.

STABILIZATION METHODS

There are numerous methods and techniques for stabilizing instream wood. Site characteristics determine the need for stabilization, taking into consideration the wood material available, the likely forces the structure will need to withstand, and the level of risk to infrastructure and public safety. Often, a large wood structure will incorporate several different stabilization techniques into the same structure.

NO ADDED STABILITY

The most natural method of adding large wood to a stream is to introduce wood that is free to mobilize and adjust. This placement technique is referred to in various ways in the literature, including "directional falling of riparian trees into stream channels" (Carah et al. 2014), "no added stability" (Cramer 2012), and "wind throw emulation" (ODF and ODFW 2010). Regardless of how this method is termed, this approach works best on key pieces. This technique should only be used in low-risk locations, such as public lands or large timber holdings, or with cooperative large private landowners that understand the risks involved with this technique.

Directional felling of large riparian trees to create instream habitat is a cost-effective method to increase the volume of large wood in a stream (Figure 19). If the project includes extensive directional felling, care needs to be taken to minimize the amount of green or fine material in the wetted channel. Directional felling of riparian trees can be challenging. For example, felling trees into a topographically diverse channel versus flat ground greatly increases the potential for breakage. It is beyond the scope of this document to discuss strategies for addressing these procedural and technical complexities. Carah et al. (2014) summarize challenges associated with felling large trees effectively and safely into channels. The Forest Practice Rules (CAL FIRE 2015) and the CAL FIRE management guide for riparian zones (VTAC 2012) can be consulted for more information. Due to the procedural and technical complexities, large wood projects that rely on directional falling should be planned and executed under the responsible charge of a forester licensed in the State of California. A licensed professional forester should provide input on which trees may be felled, taking into consideration the impacts on non-target species and habitats.

Figure 19. Felled key piece capturing woody debris with no added stability. Photo credit: Chris Blencowe, Blencowe Watershed Management.

It is unnecessary to fell larger older trees leaning toward the stream that are likely to recruit naturally. It is common for several trees to grow from the stump of a previously harvested redwood. By felling one or more of these stump sprouts, the remaining trees will grow larger and potentially become naturally recruited large wood in the future. Removing one of the stump sprouts will have little effect on the overall canopy closure at the site. Felling trees is not advised in areas where the riparian zone is impaired, as this will leave gaps in the riparian canopy. A licensed professional forester must determine which trees may be felled.

WEDGING

To increase stability, logs can be wedged between existing roughness elements, such as stumps, live trees, or large boulders, with the intent to minimize wood movement during winter flows (Carah et al. 2014; Figure 20). Wedged logs are vulnerable to buoyancy, resulting in logs pivoting or unanticipated mobilization during high flows. Heavy equipment, or in some cases portable lever operated hoists, can be used to manipulate the logs in place to create a pivot and stop point.

Figure 20. Logs wedged between trees and pinned at the apex for stability. Photo credit: Brett Leonard, California Conservation Corps.

PINNING LOGS

Threaded rebar or all-thread can be used to pin logs together (Figures 20 and 21), pin a log to a piling, or pin a log to a live tree. Anchoring to live trees requires trees to be of sufficient size and root strength to secure the log structure during high flows. Anchoring to trees that are leaning toward the stream is a poor choice, as they are likely to fall in. To pin logs with threaded rebar, the logs should be touching each other, and once aligned, a hole can be drilled through both logs using an auger. To form a flat surface for the washer, the logs should be notched with bark removed. The threaded rebar inserted should leave just enough length for the washer and the nut. The rebar pounded through the holes should be capped on the ends with a steel-plate washer and nut, with the nuts tightened to secure the logs. The ends of the rebar should be flared or mushroomed to prevent the nuts from backing out (Figure 22).

Figure 21. Logs pinned using threaded rebar. Photo credit: Chris Blencowe, Blencowe Watershed Management.

Figure 22. Finished end of threaded rebar used to secure logs together. Photo credit: Scott Monday, CDFW.

BALLAST

Ballast is a material used to provide necessary counterweight against driving forces, as determined by the stability calculations. Options for ballast include native streambank material, gravel, boulders, or logs. There are several considerations when determining which material to use as ballast, including the availability and cost of materials, along with the location of the structure. The purchase and transportation of boulders adds to the cost of the project.

Streambank material is commonly used as ballast when keying into the streambank (Figure 23). The streambank material should be composed of cohesive soil capable of supporting vegetation, not sand or silt. Topsoil should be salvaged for separate storage and replacement on top of the backfilled surface to facilitate post-project riparian planting. Native material excavated from the trench in lifts should be replaced and compacted as backfill over logs placed in the streambank trenches. The site should be replanted with live willow cuttings and other native vegetation. If necessary, biodegradable erosion control fabric can help stabilize the site.

Gravel is sometimes used as ballast in complex woven wood structures; however, it should be used with caution, as gravel is easily mobilized. For structures using gravel as ballast, the top of the structure must be high enough that it is not submerged during the design event (Cramer 2012). Water jets supplied by pumps and hoses can fill interstitial spaces of wood structures with fine grain alluvium. This improves consolidation, increases the ballast weight, and provides a better planting medium (USBR and USACE 2015). Incorporating vegetation and slash into the structure is essential to stabilize the gravel ballast.

Boulders are frequently used as ballast for large wood structures, including logs trenched into the streambanks, single to multiple log structures, or woven log structures. Boulders can be advantageous in large woven structures because they leave interstitial spaces that fish can utilize. In small streams in low-risk settings, boulders may just be set on top of logs in a position anticipated to be stable. In large streams or high-risk settings, it may be necessary to anchor the logs to the boulders with polyester resin and cable (see "Anchoring to Bedrock and Boulder" section below).

Stacking logs on top of a structure is another method of ballasting (Cramer 2012). Large diameter logs have the greatest weight and buoyancy and should be reserved for use as top ballasting logs. When comparing the buoyancy of two logs of equal length, one with twice the diameter of the smaller log has four times the buoyancy force (Cramer 2012). There must be enough wood above the design water surface elevation to weigh down the buoyant wood under water. The dry weight of the wood is used to calculate the weight of the wood above water.

To stabilize a structure, practitioners commonly use a combination of ballast. Figure 24 shows an example of placing native streambank material, gravel, and boulders within a matrix of logs to provide ballast to the structure.

Figure 23. Log keyed into the streambank. Photo credit: Mark Elfgen, CDFW.

Figure 24. Combination of native streambank material, boulders, and logs used as ballast. Photo credit: Clackamas Soil and Water Conservation District.

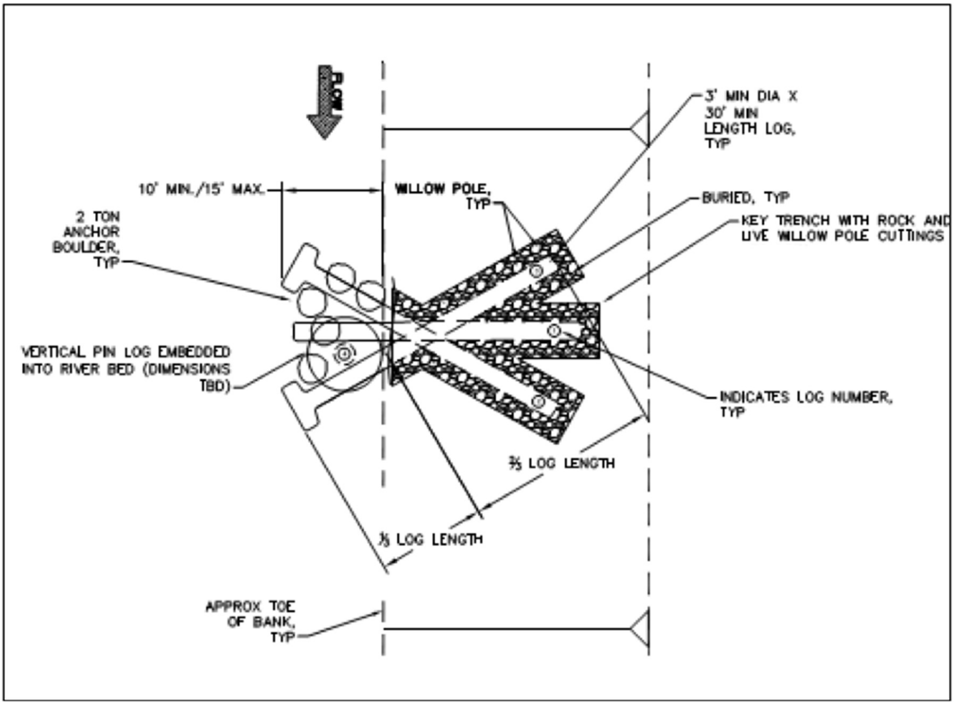
PILINGS AND POSTS

Pilings and posts are used to stabilize complex large wood structures. Pilings are structures made of logs, or piles, driven into the substrate. Posts are installed by digging a hole, installing a log (preferably with a root wad), and then filling the hole back in. The depth and diameter of the piles and posts are determined from the stability calculations. A geotechnical investigation is necessary to provide the parameters for pile and post calculations.

Pilings are most appropriate in streams with moderate to fine grained bed materials and are not suitable for boulder or bedrock channels (Cramer 2012; Figure 25). The substrate must be of adequate depth to drive the piling deep enough to resist pullout due to buoyancy. Piles can be installed using a diesel hammer, a hydraulic hammer, a vibratory impact driver, or by using an excavator mounted vibrator. In fine gravel and finer materials, a large excavator can drive the pile with its bucket. Sharpening one end of the log may help in driving the pile to the desired depth.

Several factors determine the longevity of log pilings. Log pilings lose strength due to impact, abrasion, and decay, which may cause breakage and risk the integrity of the structure. The diameter of the log used as a pile will affect stability. Larger diameter logs are more resistant to pullout due to skin friction but are more buoyant. Therefore, unless the piling can be driven deep into the substrate, smaller diameter logs are preferred. Pile pullout resistance due to skin friction is a function of pile

Figure 25. Large wood project using a piling for stabilization. Photo credit: Greg Andrew, Marin Municipal Water District.



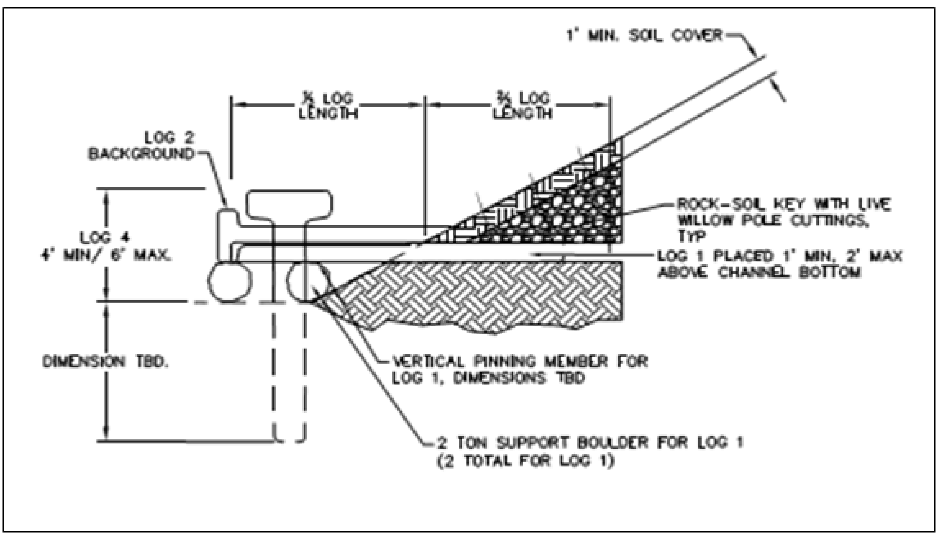


Figure 26. Diagrams showing logs with root wads holding other logs in place (Philip Williams & Associates 2010).

diameter and length, density of the wood, submerged length, depth, and the internal friction angle, unit weight, and relative density (loose or dense) of the soil substrate (Cramer 2012). A recommended reference is the U.S. Army Corps of Engineers' Design of Pile Foundations manual (USACE 1991).

To install posts, a large hole is excavated, a log is placed into the hole vertically, and the hole is backfilled with native substrate. Posts are more likely to pull out than piles because they lack the skin friction created through being driven into the substrate. Posts are most suitable for project locations where the primary forces are horizontal rather than vertical. Burying the root wad end of a log with the root wad attached increases the stability of the post and increases its resistance to pullout. The backfill of the post should be compacted effectively and in lifts. Some projects have used logs with root wads as piles, with the root wad on top of the other logs holding them in place (Figure 26). Similarly, log piles may be installed at an angle to pin down the log with the root wad (Figure 27).

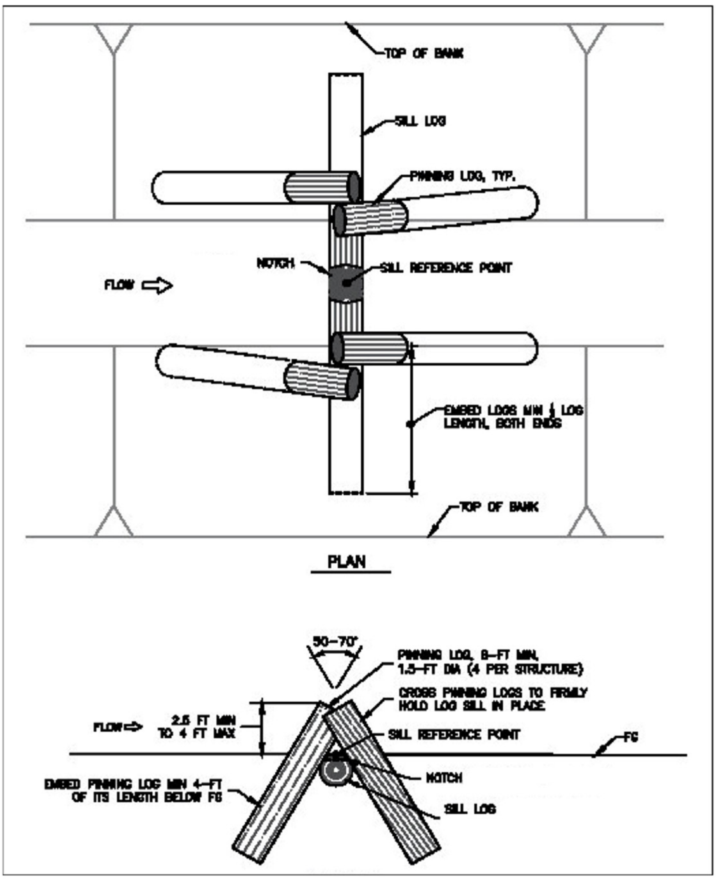


Figure 27. Diagrams showing logs installed at angles pinning down other logs (Michael Love & Associates 2014).

Figure 28. Vertical logs used for weaving angled logs rather than for structural stability. Photo credit: Clackamas Soil and Water Conservation District.

Vertical logs can also be used as pins to help hold the structure together. In Figure 28, logs are added into the matrix of horizontal logs and vegetative slash. The vertical logs help keep the structure from disassembling, but do not counteract buoyant forces unless much of the length of the logs is above the water surface. The pictured example demonstrates that the buoyant forces are counteracted with weight from the boulders and streambank material.

SOIL ANCHORS

Commercially available soil anchors provide another option for anchoring log structures (Figure 29). To use a soil anchor, the anchor is driven into the soil and then activated by providing tension on the anchor. Soil anchors should only be used in cohesive soils (Cramer 2012). When used to anchor a large wood structure, the cables should be tightened so that the logs are unable to move. The movement of the logs will destabilize the soil anchor, causing erosion of the streambed or streambank. At least three anchors should be placed to minimize the potential for movement (USBR and USACE 2015). Anchors are available in different configurations and sizes with various holding capacities. Commercial anchor systems should always be used according to the manufacturer's specifications. A useful reference is the Natural Resources Conservation Service's technical supplement, Use and Design of Soil Anchors (NRCS 2007).

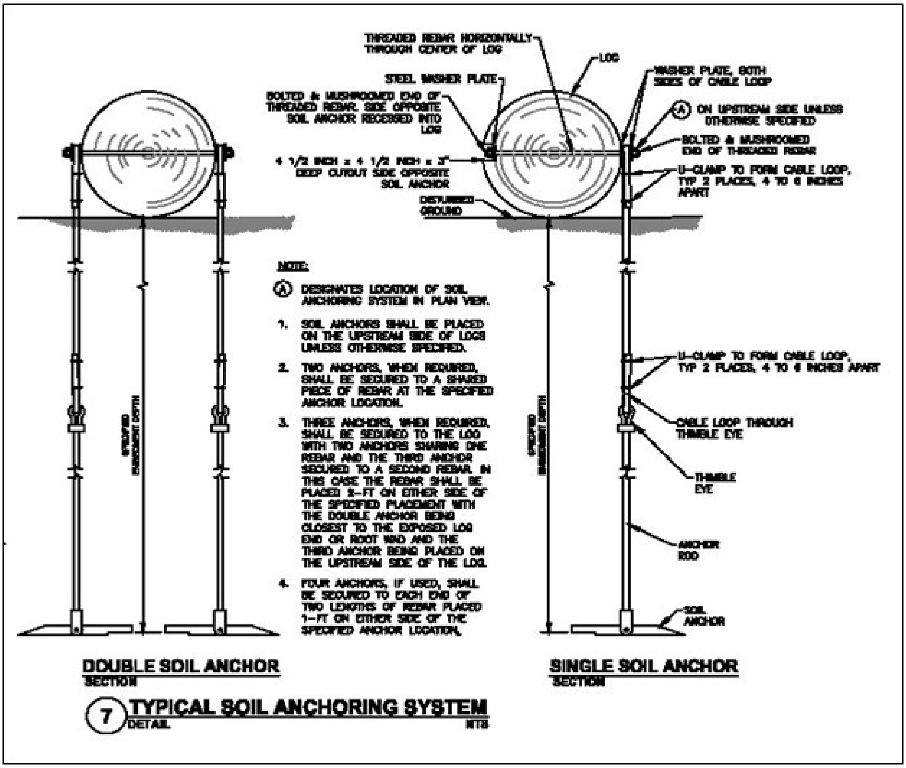


Figure 29. Diagram of a soil anchor system (Michael Love & Associates 2015).

ANCHORING TO BEDROCK OR BOULDER

Polyester resin and cable should be used to anchor logs to boulders or to secure two small boulders together to increase their weight. This technique is described in detail in Flosi et al. (2010).

To pin a log to competent bedrock, a technique using threaded rebar, cable, and polyester resin adhesive should be utilized (Figure 30). The cable should be secured to the bedrock or boulder using polyester resin adhesive as per the manufacturer's recommendations. Competent bedrock is sound, resistant to abrasion, free from cracks, seams, and other defects that would tend to increase their ability to scour, dissolution by water, and disintegration by frost action.

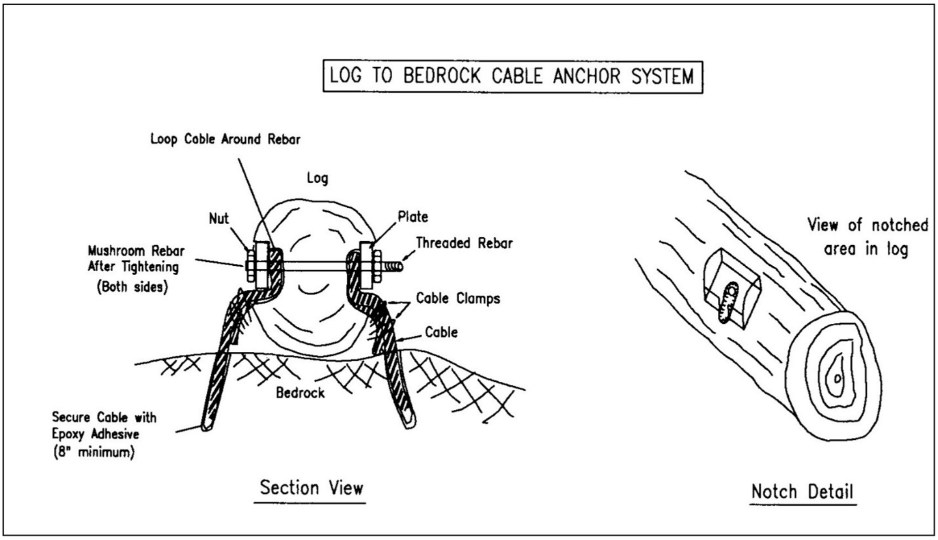


Figure 30. Diagram showing log anchored to bedrock using threaded rebar and cable.

EVALUATION PLAN

For most large wood projects, it is not important if the wood structures adjust or even if some of the logs move downstream. Large wood projects should be evaluated by determining if the objectives of the project were met. The geomorphological changes in the stream are what should be evaluated. Did the large wood structures trap additional wood and sediment? Are there more and deeper pools within the project reach? Is the flow accessing the floodplain in areas it was not before the project? If the project objectives were not met or only partially met, would the addition of more large wood move the project closer to achieving the stated objectives?

Photo points should be established pre-construction to monitor before, during, and after project changes. Photos should be repeated after bankfull storm events for an established length of time to document changes in the project reach.

At the end of a large wood project located in high-risk reaches, an as-built survey should be completed that includes all the constructed elements in the final design drawings. The as-built survey can be used to compare the actual construction to the design drawings. This level of survey should be repeated after bankfull flow events to determine if the structure has adjusted and if it is performing as intended.

INSPECTION AND MAINTENANCE

The inspection and maintenance of structures may not be necessary in low-risk reaches, but it is more important in high-risk settings. Structures located in high-risk settings should be inspected on a regular basis and after each major storm event. A commitment to inspections and maintenance is necessary for structures where infrastructure is located within the influence of the project.

Prior to constructing the project, it must be determined who will be responsible for project inspection and maintenance if project objectives are not met or unintended problems are created. Generally, responsibility falls on the entity who initiated the project, such as a landowner or land manager. Prior to modifying a structure, an evaluation should be conducted to determine why the project requires maintenance. Maintenance can be as simple as readjusting the logs to increase the effectiveness of the structure. In other cases, the total removal of a structure may be deemed necessary if it is causing unintended streambank erosion, blocking a culvert, or lodging against a bridge piling. Anchored structures may need to have the anchors replaced or updated on a periodic basis, or in some cases, totally removed to prevent a safety hazard.

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