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The Use of Log and Boulder Weirs in Stream Habitat Restoration

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Arch-shaped boulder weirs produce diverse hydraulics across the crest while concentrating flow towards the channel center. Photo credit: Rob Sampson.

This Fish Bulletin is dedicated to Marjorie (Margie) Caisley who, since 2006, served with distinction as an engineer with the California Department of Fish and Wildlife 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 four days shy of 46 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

This Fish Bulletin describes the methodology for the use of log and boulder weirs in California rivers and streams. This report does not replace Part XII Fish Passage Design and Implementation of the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 2010). The intent of this report is to supplement Part XII and describe the use of log and boulder weirs to improve instream habitat, beyond the need for fish passage. This report provides a review of current literature on the subject, combined with input from California Department of Fish and Wildlife scientists and engineers, and others with experience and expertise in the subject.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Log and boulder weirs are low-elevation structures that span the entire width of the channel to create a short drop or step in the channel bed and water surface elevation at the downstream side of the structure. There are numerous designs and variations of log and boulder weirs depending on the desired habitat modification to achieve the project goal. This report describes the planning process and provides design guidance and information on construction techniques that will help to facilitate a successful log or boulder weir project.

Log and boulder channel spanning elements occur naturally in streams and can play an important role in stream hydraulics and salmonid habitat. Naturally occurring elements in a stream control channel grade, induce pool scour, provide instream habitat, and facilitate sediment sorting redistribution and deposition. Designed to mimic these naturally occurring structures, constructed log and boulder weirs can facilitate the restoration of physical and biological processes in a stream channel. Log and boulder weir projects can be designed to achieve several goals, including:

- Improve fish passage over artificial barriers by backwatering the stream reach.
- Control connection to off-channel and side-channel habitat features.
- Raise the bed of an incised stream to reconnect it with its floodplain.
- Maintain existing salmonid habitat by arresting the upstream migration of a head-cut.
- Provide fish cover from predators.
- Provide thermal refugia.
- Increase invertebrate production.
- Increase dissolved oxygen saturation.
- Provide low velocity resting areas.
- Create spawning habitat.
- Increase connectivity to the hyporheic zone, the area beneath the streambed where there is a mixing of shallow groundwater and surface water.
- Capture and store alluvium in channels lacking sediment. Alluvium is material transported by flowing water.

Constructed log and boulder weirs are designed to set the channel bed or water surface at an elevation determined necessary to meet a specific restoration goal. The weirs flatten out the water surface profile upstream and facilitate gravel deposition. These gravel deposits often provide good spawning habitat. In addition, as water flows over the top of a weir, it scours out a pool. The plunging flow winnows out fine sediments, increases oxygen saturation, and enhances invertebrate production.

Pools provide low velocity resting areas for juvenile and adult salmonids and cover from predators. Weirs facilitate connectivity to the hyporheic zone. This connectivity creates thermal refugia during hot summer months.

Log and boulder weirs are also used to provide fish passage at stream crossings and low head dams. They can also be used in the place of low head dams for irrigation diversions. These applications are covered in Part XII of the California Salmonid Stream Habitat Restoration Manual, hereinafter referred to as the Manual (Flosi et al. 2010). Regardless of the objective, all log and boulder weir projects must comply with the California Department of Fish and Wildlife (CDFW) and National Oceanic and Atmospheric Administration (NOAA) fish passage criteria. The CDFW Culvert Criteria for Fish Passage are provided in the Manual, Appendix IX-A. The NOAA National Marine Fisheries Service West Coast Region Guidelines for Salmonid Passage at Stream Crossings in California are available from their website http://www.westcoast.fisheries.noaa.gov/. The Manual, Part XII has specific criteria relating to flow range, maximum drop heights, minimum depths, and maximum velocities for fish passage.

Several studies investigating the effectiveness of instream structures, including log and boulder weirs, have shown an improvement in salmonid habitat and salmonid density. A meta-data analysis of 211 stream restoration projects showed significant increases in pool area, average depth, large woody debris, and percent cover. The same study also showed a significant increase in salmonid density, with Rainbow Trout (*Oncorhynchus mykiss*) showing the largest increase (Whiteway et al. 2010). Boulder weir placement in 13 paired treatment reaches in seven bedrock streams in southwest Oregon increased the pool area in the treated reaches. Both Coho Salmon (*O. kisutch*) and trout (*O. spp.*) response were positively correlated with the increase in pool area (Roni et al. 2006). In addition, species that prefer pools, Coho Salmon, and trout (>100mm), were positively correlated with an increase in pool area.

RISK FACTORS AND CONSIDERATIONS

The U.S. Bureau of Reclamation (USBR 2016) states, "Rivers are dynamic in nature, and all structures within a river channel are exposed to risks associated with fluvial processes." Some degree of failure is not unusual with both boulder and log weir structures. A U.S. Bureau of Reclamation research team evaluated 127 boulder weir structures and reported over 70 percent had at least partially failed (USBR 2009). If the goal of the weir is to create fish habitat this may not be a significant problem as even a partially failed structure may continue to provide fish habitat. If the goal of the project is to control the channel profile, other types of boulder structures (i.e., roughened channels) discussed in the Manual, Part XII may be more reliable.

Consider all risk factors before any log or boulder weir project is proposed. Since every stream and location is unique, there is no 'cookbook' to follow to ensure a successful project. It is important to note that log and boulder weirs, like all restoration tools, can have negative effects on riverine and biotic communities. Specifically, log and boulder weir structures attempt to lock the channel in place. This prevents the channel from moving laterally. Due to this, the channel is unable to adapt and respond to natural watershed processes. Therefore, it is essential that these practices be supported by an analysis that identifies why, how, and where to put the structures on the landscape to increase the chance of benefitting aquatic communities, fish populations, and riverine conditions they are intended to bolster.

A licensed civil engineer must design and stamp a project in a site with potential risk to public safety, infrastructure, or private property (Professional Engineers Act, Business and Professions Code 6700-6799). This would include most fish passage projects. A professional with expertise in open channel hydraulics and fluvial geomorphology may design a log or boulder weir project in an area where there is no risk to public safety, infrastructure, or property. An example of this is a project to improve fish habitat in a low-risk site. The professional must have prior experience with successful implementation of similar projects using like materials. The civil engineer or professional should work closely with a multidisciplinary team of physical and biological scientists on project design.

Log and boulder weirs are often used to raise water surface elevations. In some cases, this change in water surface elevation can result in flooding of property and structures. Hydraulic modeling of the channel capacity and flood flows, including the 100-year recurrence interval flood flow, can help to determine the potential increase in water surface elevations. Furthermore, modeling can be used to inform modifications to the design if necessary and lower the risk of flooding. It is important that the design team understand and adhere to all applicable local, state, and federal regulations concerning flood risk and protection requirements.

Depending on site conditions, raising the water surface may lead to channel avulsion. An avulsion is the rapid abandonment of the existing stream channel resulting in the stream forming a new channel on a floodplain or enlarging an existing side channel. Although this can sometimes be the goal of the project, unintended channel avulsion can lead to property damage and result in a new channel that may lack habitat value. An unintended avulsion can contribute to water turbidity, known to increase stress in fish, and may also cause damage to habitat, including smothering salmonid redds. Stream channels that are well connected to their floodplain or have wide inset benches (i.e., with an entrenchment ratio greater than 2.2) (Figure 1), have the greatest risk of channel migration, avulsion, and flanking (Beavers 2010).

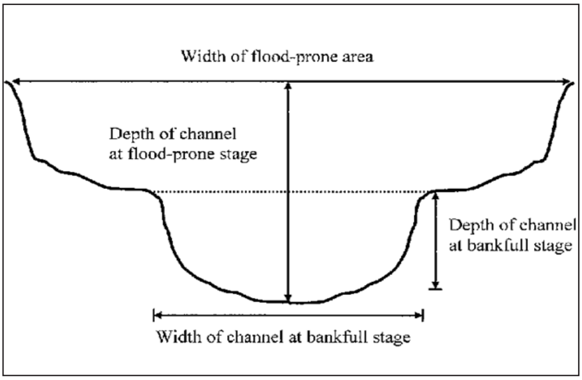

Figure 1. Illustration of how to determine the entrenchment ratio. Entrenchment ratio equals flood-prone area divided by width at bankfull stage. Flood-prone area equals the water level at two times depth of channel at bankfull stage (Rosgen 1996).

Log and boulder weirs can expose utilities, such as underground power and water lines, through erosion and scouring of the streambed and bank. It is important to place these features so that underground utilities are at low risk of being exposed. Even at remote sites, local utility survey services and the landowner or manager should be consulted before the site characterization portion of the design phase, and again immediately before construction, to avoid damaging utilities.

There is also the potential for a log or boulder weir to create a barrier to fish passage. Log and boulder weirs may form a vertical drop that can impede fish passage, especially for juveniles at low flow conditions. To lessen the possibility of creating a barrier to fish migrations, build log and boulder weirs in a series, with the downstream weir set below the existing streambed. A careful evaluation of the risk of creating fish passage problems within the stream channel reach or segment is part of the project planning process. Additionally, the drops between the structures must comply with CDFW and NOAA fish passage criteria.

Heavy equipment is typically required to construct most channel spanning structures. The need for a skilled and experienced heavy equipment operator with the right equipment to complete the project cannot be understated. An excavator with a thumb, and a bucket that rotates or spins helps improve boulder placement. The operator must follow the project design drawings and construction notes that were submitted. Even the most experienced heavy equipment operator may be challenged when dealing with natural materials. In some cases, it may be impractical to use boulders that meet the required symmetry to create structures according to design (UDOT 2009). The precision and patience with which the operator places the boulders at the proper elevation and positions them so they have a minimum of three contact points with adjacent boulders will also have a significant impact on the success of the project. The project manager should be on site to oversee boulder selection and placement and should have the right to request an alternate equipment operator if necessary.

A variety of federal, state, or local permits may be required to complete an instream project. Part VI of the Manual describes permits that may be required. The Department's Cutting the Green Tape Program[1] is leading efforts to develop and implement improvements to the way the department issues permits. All projects carried out by an "entity" as defined in Fish and Game Code Section 1601 that alter the streambed or bank require a Notification of Lake or Streambed Alteration, which may be obtained from the CDFW (see below). The resulting Lake or Streambed Alteration Agreement will require species protection measures, oil spill protection and reporting requirements, and several other conditions that must be followed. Follow heavy equipment decontamination protocols prior to any heavy equipment entering a stream. For general information, see CDFW's Invasive Species Program web page.[2] For field guidance and decontamination protocols, see CDFW's Aquatic Invasive Species Decontamination Protocol (2022) and Technical Memorandum No. 86-68220-07-05 Inspection and Cleaning Manual for Equipment and Vehicles to Prevent the Spread of Invasive Species (DiVittorio et al. 2012).

When working in a flowing stream, short-term negative impacts from construction work to the stream are inevitable. These include, but are not limited to, increased turbidity and temporary loss of habitat as flow is directed around the project site. The increase in turbidity is generally short lived. Isolating the work zone during most of the instream work will limit impacts. Sediment generated by the project must be confined to as small an area as possible to reduce impacts downstream to fish, invertebrates, and vertebrate life. Care must be taken when entering the stream with heavy equipment to minimize disturbance to riparian vegetation. For additional information, see the CDFW's Lake and Streambed Alteration (LSA) Program web page.[3] When dewatering the site and relocating the fish and amphibian species, all efforts must be made to minimize any impacts to aquatic life. See, Measures to Minimize Injury and Mortality of Fish and Amphibian Species during Dewatering, found in the Manual, Part IX on pages 52 and 53. If there is the possibility special-status species will be encountered during the project, California Endangered Species Act measures may be required.

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

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

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

PROJECT PLANNING

The need for a log or boulder weir project should be based on the findings of a watershed assessment, fish passage assessment, or individual stream habitat inventory. Watershed assessments are discussed in the Manual, Part II. Watershed assessments for several California coastal areas have been completed by the CDFW Coastal Watershed Planning and Assessment Program (CWPAP). The products listed include watershed assessment reports with background information, findings, limiting factor analysis, and improvement recommendations. Some watersheds may not have a complete watershed assessment. In that case, individual stream habitat inventories using the methodologies described in the Manual, Part III or fish passage evaluations described in the Manual, Part IX may have been completed. If no inventory or evaluation exists, this must be completed prior to moving forward. Contact the local CDFW regional office to receive the most recent information on a stream of interest. Also, search the CDFW Document Library for the watershed assessments and the stream inventory reports.

Log and boulder weirs may be used to enhance instream fish habitat. The National Marine Fisheries Service Final Southern Oregon/Northern California Coast (SONCC) Coho Salmon Recovery Plan (2014) lists thresholds for good or very good indicators of aquatic habitat suitability for Coho Salmon (Table 1).

In the National Marine Fisheries Service Coastal Multispecies Final Recovery Plan: California Coastal Chinook Salmon ESU, Northern California Steelhead DPS and Central California Coastal Steelhead DPS, October 2016, the key habitat attributes were divided into four categories, determined by percentage of the intrinsic potential (IP) of the stream per kilometer (Table 2).

TABLE 1. Indicators of aquatic habitat suitability for Coho Salmon populations (modified from National Marine Fisheries Service 2014).

Indicators	Good	Very Good
Pool Depths	3-3.3 ft	>3.3 ft
Pool Frequency (length)	41–50%	>50%
Pool Frequency (area)	21–35%	>35%

TABLE 2. Evaluation of key habitat attribute, habitat complexity (modified from National Marine Fisheries Service 2016).

Indicator	Poor	Fair	Good	Very Good
Pool/Riffle/ Flatwater Ratio†	<50% of streams IP-Km	50% to 75% of streams IP-Km	75% to 90% of streams IP-Km	>90% of streams IP-Km

† >30% pools: >20% riffles

A stream enhancement project involving the placing of log or boulder weirs may be considered in streams where the indicators of habitat suitability fall below good or very good stress thresholds. Log and boulder weir projects for stream enhancement may be designed to increase pool depth, frequency, and area.

In some instances, it may be more appropriate to use other restoration techniques, such as large wood projects (Flosi et al., in press) or boulder cluster projects (discussed later in this report), that may meet the same objectives, but with less detrimental impact to the stream (Saldi-Caromile et al. 2004).

The decision to design and construct a log or boulder weir project should be based on specific project goals and clearly stated objectives, identified in a watershed plan or stream inventory report. A fish passage project may require the analysis of just one site (Manual, Part IX) or reach of stream. Projects which are undertaken to enhance instream habitat must be consistent with overall watershed priorities and should be integrated with other restoration techniques (Cramer 2012).

GEOMORPHIC STUDY

A geomorphic study should be performed to determine if log or boulder weirs are the appropriate technique to address the project objectives. A geomorphic study characterizes the physical features of the stream in relationship to geologic features, sediment characteristics and transport, hydrology, flood recurrence, hydraulic geometry of the channel, riparian vegetation, and human influences. The following information should be gathered as part of the study:

Bed and bank material. One of the first steps of the geomorphic study is to make a visual observation of the bed and bank material in the project reach. Weirs are most effective in gravel or cobble bed channels (NRCS 2000). Sand bed streams are inappropriate for boulder weirs because the sand is easily scoured away from under the boulders (NRCS 2000). This can cause failure as the boulders shift and bury themselves in the sand or lose structural integrity. In addition, in sand bed streams it is difficult to seal the gaps between the boulders, as the particles are too small and lack cohesiveness to prevent piping between the boulders. Sand bed streams are also inappropriate for placing log weirs, as the sand is easily scoured away downstream of the weir leaving a hole under the log. When water flows under the log weir, the structure no longer holds the bed or water surface at the elevation set in the design. Methods to seal log and boulder weirs are discussed later in this report. The presence of bedrock in the streambed also makes it difficult to construct boulder and log weirs. It can be challenging to excavate in bedrock and difficult to seal weirs on or near bedrock (Saldi-Caromile et al. 2004).

If the log and boulder weirs are being installed to encourage sediment deposition over exposed bedrock, 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. The design team should look for gravel bar deposits in these reaches, not just isolated patches of gravel. In addition, the gravel bar deposits should look like they are regularly reworked by the stream, i.e., they lack mature vegetation, and the surface gravel is loose. In incised or narrow channels, the design team may not see gravel bars, but instead see gravel deposition at large wood accumulations or abrupt changes in channel width.

The design team should also make observations of the streambank material in the project reach. Loose unconsolidated alluvium is problematic for keying log and boulders weirs into the streambank. Consolidated material that can maintain a bank slope steeper than a 1:1 is necessary. Additionally, the bank should support established riparian vegetation. Most log and boulder weir projects will incorporate riparian plantings between the weirs and around the bank keys, both to provide improved bank stability and to reduce velocities and shear stresses along the bank.

Stream slope. Log or boulder weirs are suitable for installing in streams with slopes between 1–3%. Log and boulder weirs are generally inappropriate in streams with gradients less than 1%, where step-pool morphology is naturally uncommon (Saldi-Caromile et al. 2004). NRCS (2000) states that boulder weirs are most suitable in slopes less than 3%. The steeper the bed slope, the higher the flow velocity, thus the greater the scouring potential becomes over the structure (USBR 2009). However, the goal of the project also has some bearing on what stream gradient is appropriate. For example, if floodplain connectivity is the goal of the project, then weirs can be used on streams with gradients less than 1%, if the channel bed is composed of gravel and the channel form is a pool-riffle sequence.

Reach stability. It is important to determine where the stream is on the aggradation/degradation cycle. If the stream reach is in the process of aggrading, the log or boulder weirs could become buried and ineffective. Also, weir structures are frequently observed to fill with deposited sediment, often through lateral channel migration (USBR 2007). If the stream reach is degrading, or there is a head cut located downstream, then the most downstream structure may fail, possibly creating a barrier to fish passage. To aid in determining where the stream is on the aggradation/

degradation cycle, the design team should review historical and current aerial photographs, looking for increasing or decreasing channel sinuosity. In the field, the team should note the occurrence of recent sediment deposits, channel braiding, bank erosion due to increased sinuosity and bare vertical bank toes as a sign of incision. For further information on determining vertical channel stability see Castro (2003) and Castro and Beavers (2016).

Characterization of the bed material is necessary to anticipate the length and depth of scour and the potential for the boulders comprising the weir to settle. In some cases, a geotechnical investigation may be necessary. Geotechnical investigations provide information on the physical properties of subsurface soil and rock around and within a site. This information also aids in designing foundations for proposed structures. Geotechnical investigations are necessary when there is evidence of bedrock near the elevation of the bed. Depending on the competency of the bedrock, it can be difficult to excavate the channel to place footer boulders for the weirs. It may also be difficult to seal weirs when they are resting on bedrock, and bedrock can limit pool depth, which may result in inadequate depth for fish passage. If bedrock is exposed by scour downstream of a weir, this may increase pool length and affect the sealing of the next weir downstream. Bedrock present in the banks may affect the ability to key weirs into the bank and increase the mobility of the boulders next to the bank.

Other site constraints. Other site constraints may determine whether log and boulder weirs are appropriate. For example, dams within the watershed affect stream flow and sediment supply and transport. The resulting lack of sediment makes it difficult to seal the weirs. The design should consider any existing infrastructure in the bed and on the banks. The locations and depths of underground utilities may influence the placement of log or boulder weirs regarding pool scour and adequate cover. Any existing infrastructure will also affect whether floodplain connectivity is appropriate. Access to the site and general location can have a big impact on cost. Transportation costs can be prohibitive if access to the site is difficult for delivery trucks and if the site is far from the equipment and materials.

Moving heavy equipment in and out of the stream channel is another consideration. Some projects require a crane to lower equipment into the channel, while others require removing mature riparian vegetation and building access roads to move equipment into the channel. In some cases, it may be more practical to use on-site materials to build the weirs. However, often the challenges of gathering construction materials on-site, together with unanticipated environmental impacts, may result in higher costs than importing the materials, thus negating the use of on-site materials. Regardless of the source, the construction materials must be of appropriate size, density and strength to meet the design specifications for all projects.

After determining that a log or boulder weir project is appropriate based on geomorphic conditions, the next step is to conduct a topographic survey. The survey is integral to both hydraulic modeling and developing designs. The Pre-Design Site Assessment in the Manual, Part XII gives valuable guidance on the features to include in a topographic survey.

HYDROLOGIC ANALYSES

Hydrologic analyses determining recurrence interval flows, bankfull flow, and high and low fish passage flows are important when designing boulder and log weir projects. Use recurrence interval flows to determine the channel capacity in the hydraulic model. The recurrence interval is based on the probability that the given event will be equaled or exceeded in any given year (Recurrence Interval[4]). 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. In addition, use these flows to size the boulders in the boulder weirs and to determine the amount of ballast for log weirs. If using the weirs to reconnect the channel to a floodplain, use hydraulic modeling of the bankfull and recurrence interval flows to determine the elevations of the weirs. High and low fish passage flows are necessary for assessing fish passage depths and velocities over the weirs for adult and juvenile fish. Techniques for determining these flows are presented in the Manual, Part IX.

HYDRAULIC MODELING

Use hydraulic modeling to assess fish passage, flooding, and floodplain connectivity, to perform log weir stability calculations and to size boulders. Use one- or two-dimensional steady state hydraulic modeling, such as Hydrologic Engineering Centers' River Analysis System (HEC-RAS), to calculate depths and velocities to ensure fish passage conditions are being met throughout the range of fish passage flows. Additionally, using the recurrence interval flows developed in the hydrologic analysis, hydraulic modeling will show impacts to flood profiles from the design. This can also be used for boulder sizing for boulder weirs and for ballast calculations for log weirs. Model lower recurrence interval flows, such as the 2-year and 5-year flows, for designing floodplain connectivity.

Increased floodplain connectivity and decreased shear stress are necessary when installing log and boulder weirs to induce gravel deposition over bedrock. It is important that the gravel remains in the treated reach during storm events so that spawning salmonids can make use of it, and eggs and alevins[5] are able to survive. Use several approaches to ensure that most of the gravel is stable. One approach would

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[4] https://water.usgs.gov/edu/100yearflood.html

[5] Juvenile salmonids recently emerged from the egg stage and characterized by the presence of a yolk sac attached to the body.

be to design the weirs such that flows above the 1.5 to 2-year recurrence interval flows start to spread out onto the floodplain. Other approaches outside the purview of this report involve evaluating shear stresses, incipient motion of particle sizes, and sediment transport modeling.

Hydraulic modeling of lower recurrence interval flows can also be helpful in determining the risk of avulsion. Channel avulsion may be a greater risk during two and five-year recurrence interval flows when more flow is out on the floodplain than in the channel. The avulsion risk is based on professional judgement, with a range of geomorphic factors being considered. As such, hydraulic modeling is just one tool in assessing the avulsion risk. Water surface profiles, depths, and velocities over a wide range of flows should be included in the Basis of Design Report (see below) to show that a project would meet hydraulic criteria for fish passage, flood levels, and other project objectives.

When designing a floodplain connectivity project, the design should have the weirs spaced such that excessive flows do not return to the channel between weirs. Flow re-entering the channel can cause bank erosion and flanking of the weir bank keys. As such, it is necessary to examine the model output for evidence that the flow split between the main channel and the floodplain remains constant throughout the project reach. If it is not, then the weir spacing should be adjusted. Finally, in many projects all the flow re-enters the main channel at the downstream end of the project reach. As mentioned above, this re-entry can cause bank erosion and weir flanking. Additional calculations may be necessary to determine the velocity of the flow re-entering the main channel and the necessary bank protection designed accordingly. It is often desirable to spread the flow re-entering the main channel over a greater longitudinal distance to minimize the bank erosion potential.

PLANNING COSTS

Even after conducting the recommended planning procedures, the failure rate of boulder weirs over a 10-year period is generally high (USBR 2016). In addition, the cost to complete these basic planning steps may exceed the cost of implementing the project. Therefore, it is necessary to balance the cost of planning against the cost of failure, potential impacts to public safety, infrastructure and property, and the cost of ongoing project maintenance.

BASIS OF DESIGN REPORT

The planning exercise should result in a detailed basis of design report. A basis of design report details the decisions made in the design process and provides a narrative to accompany and explain the design plans. This report should include analysis outputs and a set of design drawings showing site topography, control points, structural dimensions, elevations, longitudinal profiles, and cross-sectional views, along with important component details, including construction notes on the placement of bed materials.

DESIGN METHODOLOGY

SITING CONSIDERATIONS FOR LOG AND BOULDER WEIRS

Locate log and boulder weirs in straight reaches of the stream. When studying boulder weir failures, USBR (2009) found that all the structures located on bends that failed were flanked due to general bank migration. Additionally, point bars often form at bends and are not suitable for keying in log or boulder weirs to the stream banks. Structure tie-in (keying in) to the banks is critical to sustaining the intended structure's function. Structures tied into point bars rather than into the bank are susceptible to flanking by downstream migration of the gravel bar (USBR 2007).

Log weirs are more suitable than boulder weirs in low energy systems or in channels already dominated with wood. Some examples of appropriate settings for log weirs include developing connectivity to off-channel ponds on the floodplain or in creeks primarily fed by springs. Log weirs in high-energy systems are prone to problems with sealing, scouring, and flanking.

Material selection and placement. The decision to build weirs out of boulders or logs is dependent on several factors. There are advantages and disadvantages for each. Logs of the appropriate length, diameter, and tree species to build weirs are sometimes available near the project site and may be obtained for the cost of delivering the material to the site. However, consider the labor and equipment costs to bring these logs to the project. Logs are less durable than boulders, although weirs built using tight-grained redwood, Douglas fir, or cedar logs can last for decades in a stream and are easy to work with. Tight grain conifer logs with minimal sapwood are expected to last 25 years (Cederholm et al. 1997; Johnson and Stypula 1993). It is important to consult with CDFW before proposing to use logs other than tight-grained conifer logs to construct log weirs in order to discuss limitations or restrictions on using that material. Log weirs are most appropriate in streams less than 30 ft wide at bankfull discharge (Saldi-Caromile et al. 2004). Another disadvantage of wood is buoyancy. Details of a force balance analyses and anchoring techniques to counteract the tendency of a log to float are described in Fish Bulletin 184 (Flosi et al., in press).

Boulder weirs are better suited than log weirs to withstand downstream channel adjustments because they can withstand small deformations and continue to function as designed. Build boulder weirs on a well-constructed foundation of bottom boulders, referred to as the footing boulders. Bury the footing boulders sufficiently into the bottom of the channel, such that the bottom of the footing boulders is at least a foot below the calculated scour depth. This can prevent undermining caused by scour, the most common mode of failure for boulder weirs (USBR 2009). Construct the weir footing with two rows of footing boulders (Figure 2). Using two rows of footing boulders provides a stable platform for placement of the top boulders at the design elevation. The footing boulders should extend into the bank at least the distance of two boulder diameters. Additional rows of footing boulders below the typical two rows of footing boulders may be necessary to ensure the bottom of the weir footing to be at least 1 ft below the calculated scour depth.

Planform and cross-section shapes of boulder and log weirs. The maximum structure height at the streambank should not be higher than the elevation of the bankfull flow, except if the goal of the project is floodplain connectivity. This bankfull elevation is often not the top of the bank, especially in incised channels. In these cases, rebuild the bank above the keyed in portion of the structure using bioengineering techniques. All weirs should have a positive slope down towards the center of the channel. The drop-in water surface over a weir influences the depth of scour. Generally, the greater the drop, the greater the depth of scour.

Boulder weirs. Generally, boulder weirs are in the shape of a U (arch weirs) with the apex pointing upstream (Figures 3 and 4). The throat of a U-shaped boulder weir should be in-line with the thalweg of the stream and the arms constructed with an open angle between 90 and 120 degrees (Beavers 2010). The thalweg is the maximum depth or deepest portion of the channel. Slope the weir down vertically from the banks toward the center of the channel. The side slopes should be between 3 and 7 degrees (Beavers 2010). Note: 3 degrees is approximately 5% slope; 7 degrees is approximately 12% slope. This shape concentrates low flow into depths acceptable for fish passage and directs high flows away from the banks and towards the center of the channel. Directing high flows away from the banks reduces the risk of the structure being flanked. USBR (2009) found that the more perpendicular the structure arms are to the flow, the more likely the weir is to fail. They also found that structures with wider throats (U-shape) failed less frequently than weirs with narrower throats (V-shape).

There are several variations to the standard design of boulder weirs. To span a wide stream or river, those with a bankfull channel width greater than 100 ft, may require the use of W-shaped weirs, also referred to as labyrinth weirs (NRCS 2000).These are composed of two or more V or Chevron shaped weirs placed together to span the channel. The weir shape will create a diverse streambed in the downstream channel rather than a uniform, flat one. The weir crests at the apex of each V cycle in a labyrinth weir, when placed at different elevations, concentrate flows into a single low flow notch rather than splitting it between multiple low flow notches.

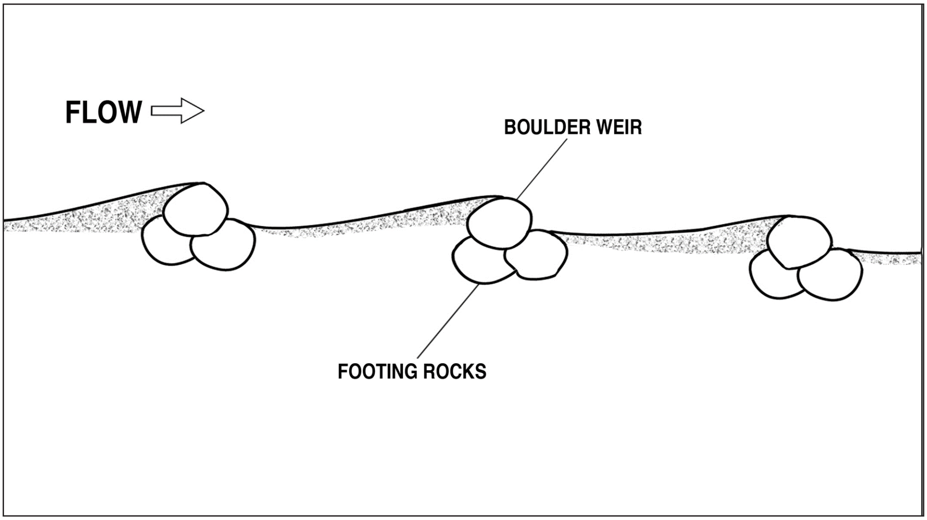


Figure 2. Boulder weirs using two rows of footing boulders.

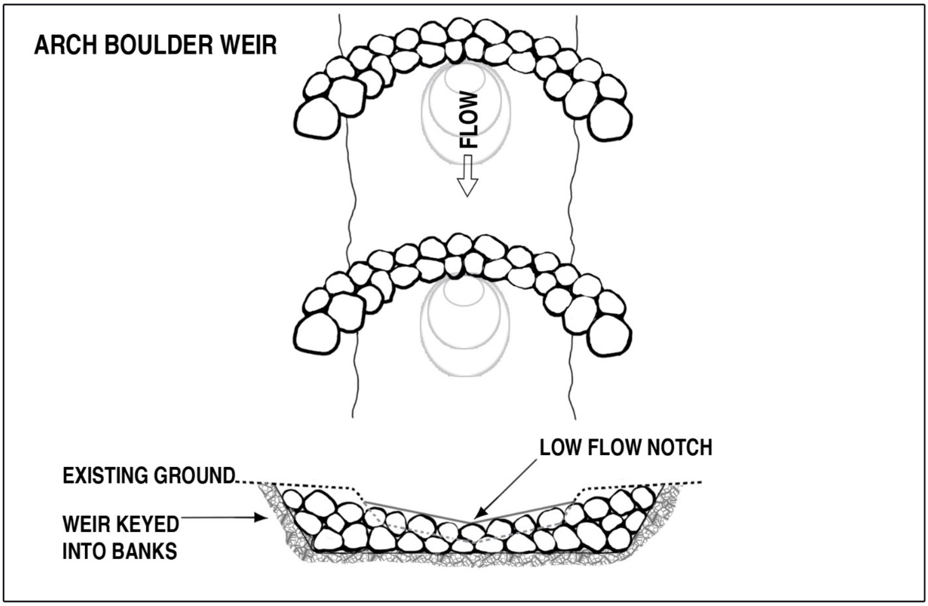


Figure 3. Examples of arch shaped boulder weir in planform and cross section.

Figure 4. Arch-shaped boulder weirs produce diverse hydraulics across the crest while concentrating flow towards the channel center. Photo credit: Rob Sampson.

Boulder clusters. Boulder clusters are a stream enhancement technique that generate structural and hydraulic diversity in uniform channels, induce scour and sediment deposition, and help maintain pool habitat features (Cramer 2012). Boulder clusters enhance fish habitat, without completely spanning the channel (Figure 5). Since the boulders are spaced apart, boulder clusters are not suitable for grade control or fish passage projects.

When constructing boulder clusters, Saldi-Caromile (2004) recommend placing the boulders in random patterns, keeping the boulders relatively low in the channel profile, and limiting bankfull area blockage to 20 to 30%. Boulders placed in the bottom half of riffle habitat are more stable than those placed near the riffle crest. Fischenich and Seal (2000) additionally recommend not placing boulder clusters in sand bed streams, avoiding placement in braided or unstable channel sections, and concentrating the boulders near the channel thalweg.

Log weirs. Logs may be used to construct different configurations and variations of straight or diagonal weirs. Construct all log weirs in series. Any exposed portions of the logs will deteriorate more quickly than if they are entirely and permanently submerged. Figure 6 illustrates an example of a log weir designed to create scour pools and to sort spawning gravel for improved habitat. The sill log is placed level with the stream grade and guide logs are angled to narrow the channel and provide stability.

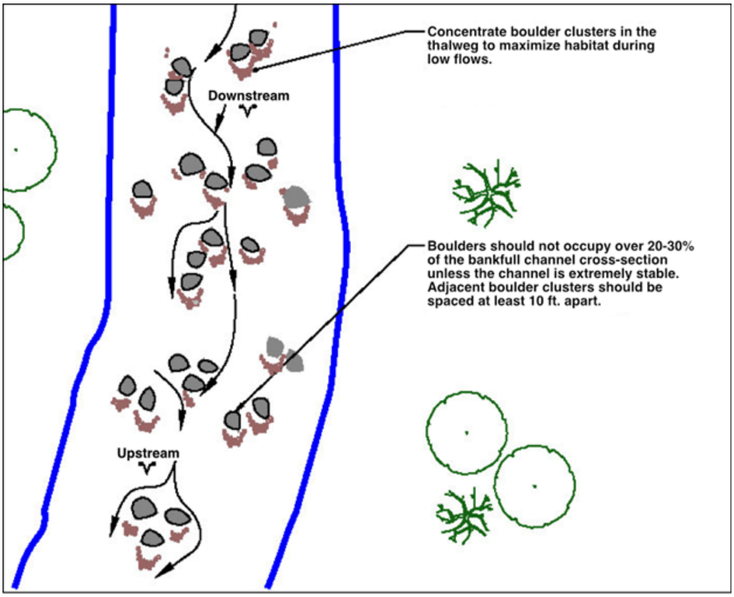


Figure 5. Illustration of placement and configuration of boulder clusters (modified from Saldi-Caromile 2004).

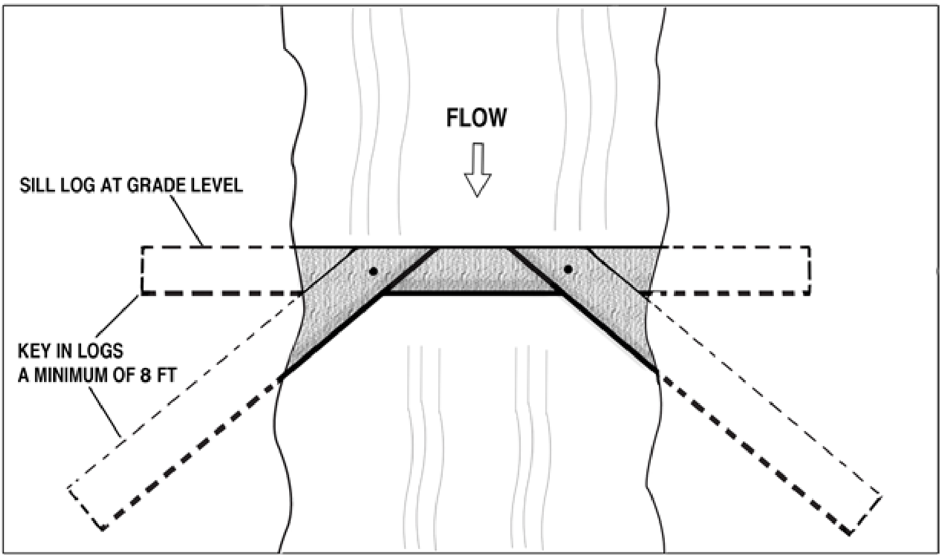


Figure 6. Log weir set at stream grade with angled guide logs.

Straight log weirs spanning the entire width of the channel are easy to build and set at exact elevations. Straight, level, log weirs dissipate the stream energy over the entire distance of the structure. Since the energy is not concentrated towards the middle of the channel, this style of weir can put increased stress on the banks and lead to bank failure unless the bank is properly protected. Straight horizontal log weirs stay submerged at most flows giving the log greater longevity. However, at low flow horizontal logs have a thin uniform sheet spill, which could cause a fish passage issue. To avoid this, a sloped low flow notch cut into the log allows for refinement of the drop height at low flows (Figures 7 and 8). Without a notch, straight log weirs can block fish passage at low flow.

Log weirs can have numerous variations depending on the desired effect. A variation of a log weir, used to maintain the stream at a set elevation, is a horizontal log weir with guide logs upstream directing the low flow to the center of the channel (Figures 9 and 10). The guide logs give some measure of protection from flanking. To direct the flow towards one bank instead of the middle of the channel, angle and pitch the step log toward one of the banks. This technique requires no low flow notch (Figure 11).

Figure 7. Straight log weir with low flow notch. Photo credit: Trevor Tollefson.

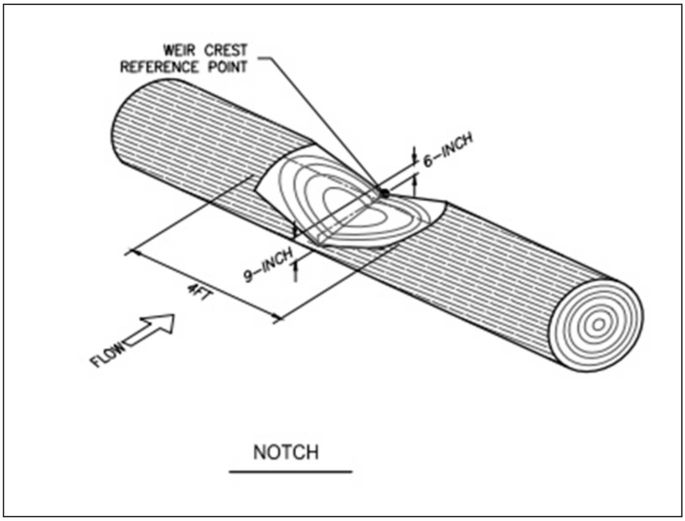


Figure 8. Weir log with low flow notch (Love et al. 2014).

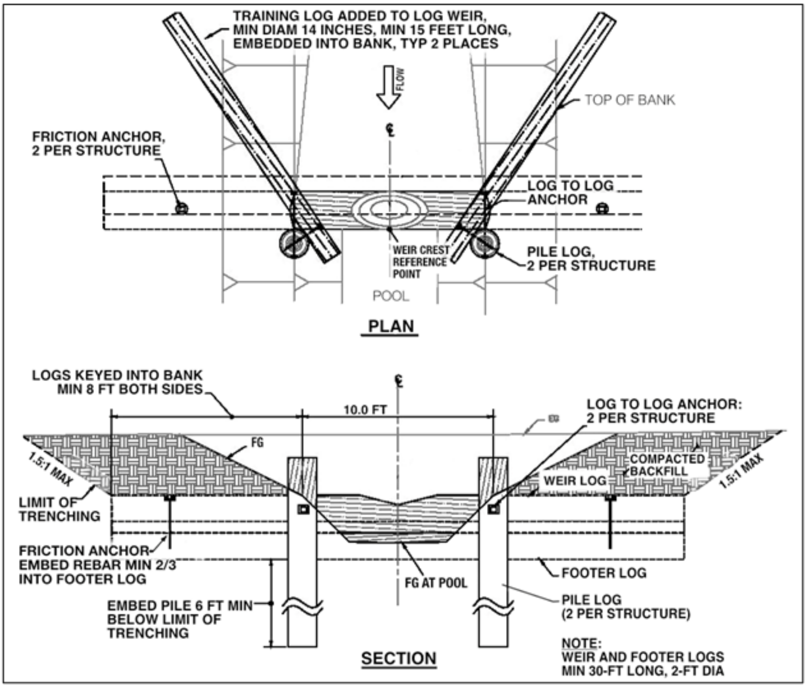


Figure 9. Diagram of horizontal log weir with upstream guide logs (Love et al. 2014).

Figure 10. Horizontal log weirs with guide logs in series. Photo credit: CDFW.

Figure 11. Pitched log weir. Photo credit: Michael Love.

Another variation is the diagonal log weir (Figure 12). Place diagonal log weirs crossways to stream flow and span the full channel width. One end of a diagonal log weir is set at a lower elevation than the other. The side slope of the log should be about 5%. Diagonal log weirs cause stream flow to adjust direction, so flow comes off the log at a right angle. Diagonal log weirs are good for collecting sediment as well as adjusting the direction of the stream. Since the diagonal weir is often directing flow into the bank where the next downstream weir will be keyed, it is necessary to consider the effect of scour on the receiving bank. Bioengineered streambank protection should be included in the design to protect against the flow eroding the receiving bank. Seal the upstream side of diagonal log weirs designed to hold grade. This requires a footer log to keep the flow from undercutting the structure.

Single log diagonal log weirs, with no footer log, are effective as habitat structures (Figure 13). Even with the water flowing under the log, the weir remains a hydraulic control at higher flows. The flow going under the log will create a scour hole. Upstream from the structure gravel will be retained from the backwater created by the log. With the water going under the log, fish passage is not an issue while the structure still retains sediment.

Figure 12. Diagonal log weirs in series. Photo credit: Sanctuary Forest.

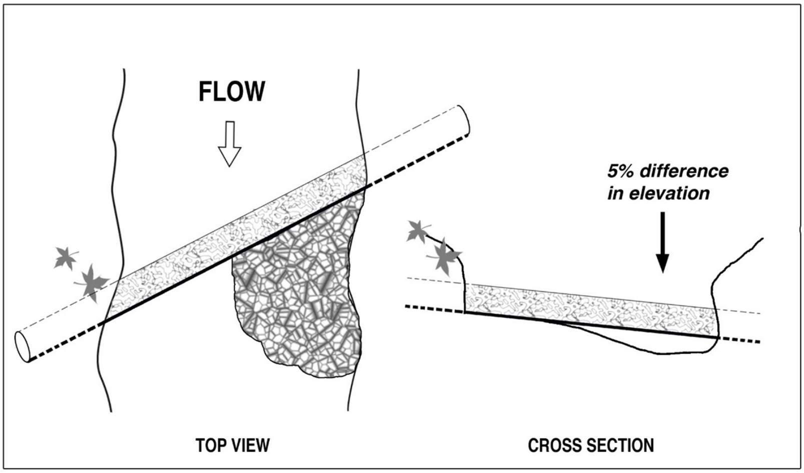


Figure 13. Single log diagonal weir.

PROJECT IMPLEMENTATION

BOULDER WEIRS

The construction of boulder weirs and other types of boulder structures requires a skilled equipment operator and attention to detail. The designer should be on site during construction and regularly check the elevation of placed boulders and adjust boulder position to achieve the design elevation. All large boulders used in structures and in the channel should be individually placed and secured in the desired position by machine tamping of boulders and surrounding support material. Place the boulders forming the boulder weir tightly together to minimize gaps. Footer boulders should have a minimum of three contact points with adjacent boulders. Top boulders should have a minimum of six-point contact (Mike Love, Michael Love and Associates, Inc. pers. communication). When constructing, it is useful to hand select individual boulders that fit best. Budget adequate time and money to construct weirs according to the plans and specifications.

Boulder weirs are best if constructed with large angular boulders to lock tightly with the other boulders and resist movement. If rounded boulders are necessary, increase the size to reduce movement and chance of structure failure. Boulder weirs constructed with rounded boulders are difficult to seal; therefore, avoid using rounded boulders if possible. Larger boulders resist movement by high flows, are less prone to failure due to scour, and take less time to install; however, the size of any boulder should not be disproportionately large relative to the channel width. Avoid using any individual boulder that is greater than one-third the channel width

(Beavers 2010). The weir should be comprised of several boulders to ensure that they interlock, and the voids filled with smaller rock to accomplish tight and integrated sections, thus increasing stability, and decreasing permeability.

Measure boulder size as the average of the three dimensions (length, width, thickness). The least dimension of an individual boulder should not be less than one-third the greatest dimension. Boulder sizing calculations assume a density of 165 pounds/cubic foot. If the available boulders are less dense, then increase the boulder sizes in proportion to the relative density. Boulders used in weirs should be uniformly sound, hard, and durable. The boulders should be free from cracks, seams, and other defects that can increase their deterioration from chemical dissolution as well as cycles of freezing and thawing.

NRCS (2000) recommends sizing boulders for boulder weirs by first computing the stable median rock size using the Far West States (FWS) Lane Method riprap sizing method (NRCS 1996) and then increasing the results by scaling factors to obtain an appropriate size of boulder for the weirs. This method is described in the Manual, Part XII. NRCS (2000) also recommends that the boulders be well graded between the D_{50} and D_{100} sizes, with the larger boulders forming the surface of the weir and the smaller rock filling the voids between the larger boulders.

Some designers have found that the above method gives too wide of a range of boulder sizes and instead use the Manual, Part XII equations for D84 and D100 for engineered streambed material as guidance for acceptable stable boulder sizes. It is important to keep in mind that boulders must be of adequate size so the two rows of footer boulders extend below the anticipated scour depth. For example, if the drop over the weir is 1 ft with an anticipated residual scour depth of 3 ft, then two rows of stacked 3-ft boulders would be necessary. The two rows of 3-ft footer boulders would likely account for 5 ft in actual height after accounting for overlap of the boulders. A D50 boulder has a diameter for which the cumulative weight of all boulders with smaller diameters equals 50% of the total boulder mixture weight.

Straight boulder weirs lack the inherent strength provided by the arch shape. Therefore, the boulders may need to be larger to remain stable. Additionally, achieving good boulder placement during construction of straight boulder weirs is essential, including ensuring excellent boulder-to-boulder contact.

LOG WEIRS

Elements of a log weir design, in addition to those described for weirs in general, are to use a minimum of two stacked logs with diameters of 16 to 30 inches embedded in the channel so the bottom log is deeper than the expected scour hole. Use logs long enough to key the structure 8 ft into both channel banks. The logs must fit tightly together to minimize the gap between the two logs. If necessary, cut any protrusions off the face of the log to create a better contact between the bottom and top log. Pin the logs together with the upper log downstream of the lower one creating an overhang. This way the water spills clear of the lower log (Figure 14). Notch the straight log weir to create a chute to direct flow for low flow conditions. The notch should slope to create deeper water upstream from the weir crest (Figure 8). Dig a pool at the downstream apex to allow fish to jump over the logs until high flows can create a scour pool.

A preferred method is to ballast the logs from below by cabling to a buried boulder rather than by depending on boulder riprap stacked on the ends of the logs. Attach the ballast boulder to the step log using cable and threaded rebar. Attach the cable to the boulder using polyester resin adhesive. See the Manual, Part VII for details of

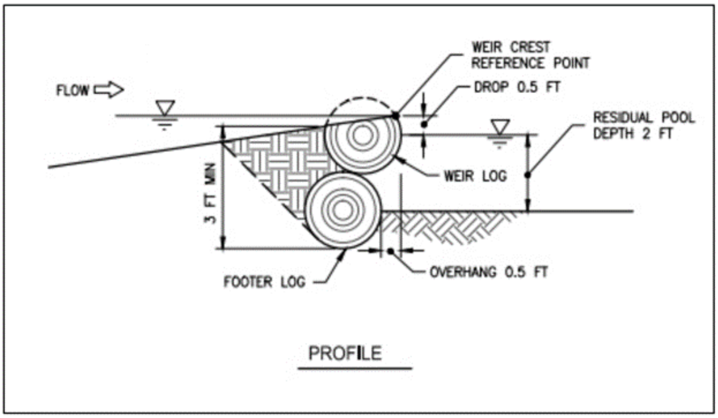
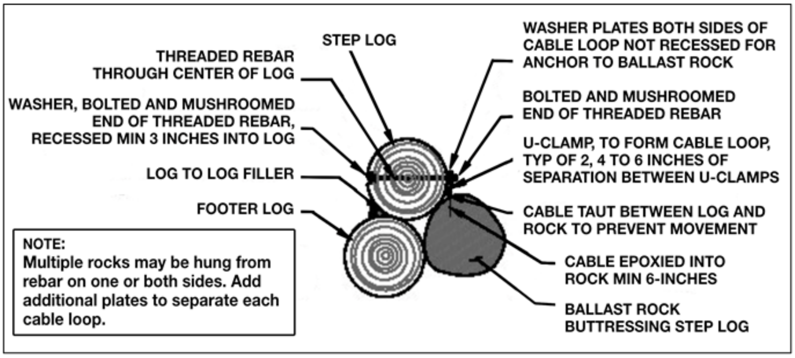


Figure 14. Detail of proper log overhang construction (Love et al. 2014).



NOTE:
Multiple rocks may be hung from rebar on one or both sides. Add additional plates to separate each cable loop.

Figure 15. Cabling log to ballast (modified from Gulch C design project by Michael Love and Associates Inc. 2018).

this anchoring technique. The buried ballast will allow the key ends of the logs to be protected using bioengineering techniques on the banks rather than boulder riprap. Place the ballast as close to the bottom log as possible (Figure 15).

Commercially available soil anchors provide another option for anchoring the ends of log weirs (Figure 16). To use a soil anchor, drive the anchor into the soil then activate it by providing tension on the anchor. Soil anchors are best used in cohesive soils (Cramer 2012). These anchors are available in different configurations and sizes, with various holding capacities. Always follow the manufacturer's specifications for commercial anchor systems. A useful reference is NRCS Technical Supplement 14E, August 2007.

Another anchoring technique is to secure the step log to a log piling with threaded rebar (Figures 17 and 18). Pile and buoyancy calculations are necessary to show that the log weirs are stable under all anticipated conditions. See Bulletin 184 for a detailed discussion of using pilings as anchors.

An alternate method is to use a raked log pile, angled upstream 20-30 degrees from vertical, on each bank end of log weir (Figure 19). Drive the pile log into the substrate a minimum of 6 ft below the limit of the trenching. The depth does not include the shaped tip of the pile or the depth of a pilot hole. An 18 to 24-inch uniform diameter, rot resistant log is desirable for the piling. Pile and buoyancy calculations are necessary to show that the log weirs are stable under all anticipated conditions. A variation of the raked pile method is to use two raked piles, one upstream and one downstream. Using this method requires no threaded rebar anchor (Figure 20).

FLANKING CONSIDERATIONS

Flanking (erosion around the side) is a common failure mechanism for both log and boulder weir structures. This occurs when structures are inadequately keyed into the streambanks. For log weirs, key the ends of the sill and footer logs at least 8 ft into the bank, if the banks consist of consolidated material. In locations with unconsolidated bank material, key the logs further into the bank and include bank protection. The preferred method for bank protection is the use of bioengineering techniques that rely on vegetation and root structure to protect the banks from scour. Typically, boulder riprap is used on the bank where the logs are keyed in to protect against bank erosion. Only install riprap to stabilize the streambanks when velocities and shear stresses are more than published acceptable limits for use of bioengineering bank stabilization techniques (Fischenich 2001; NRCS 2007a).

When using boulder riprap, fill the voids in the riprap to minimize interstitial flow and piping of the bank material and plant the riprap with live willow stakes. Placing root wads flush with the banks at each end of the log will help protect against flanking.

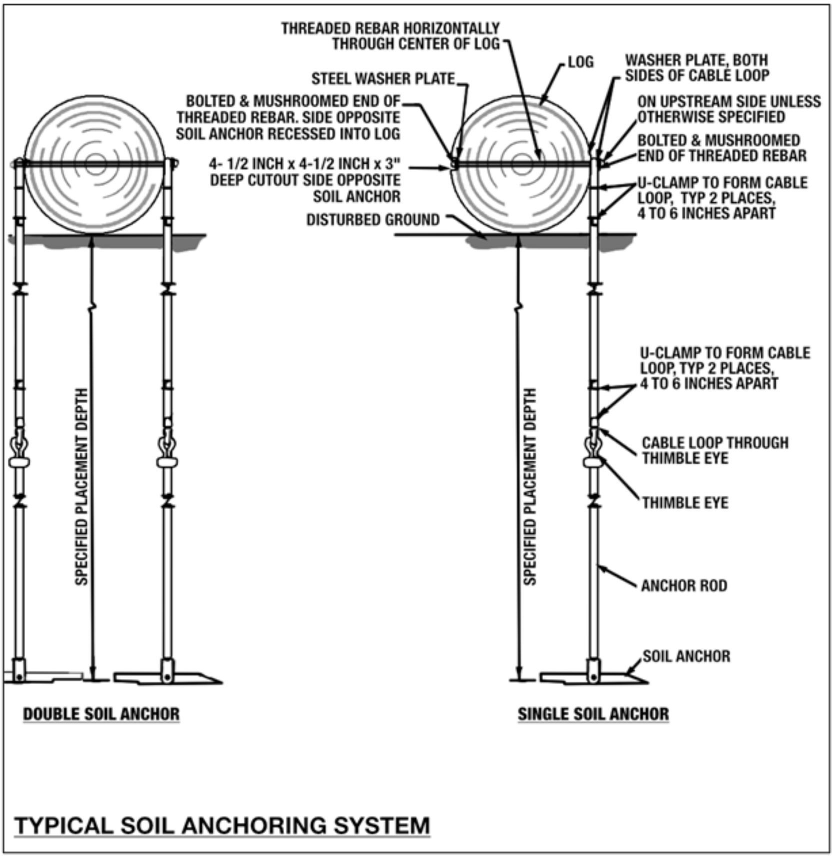


Figure 16. Soil anchoring system (Michael Love and Associates Inc. 2015). NOTE: (1) Soil anchors shall be placed on the upstream side of logs unless otherwise specified. (2) Two anchors, when required, shall be secured to a shared piece of rebar at the specified anchor location (3) Three anchors, when required, shall be secured to the log with two anchors sharing one rebar and third anchor secured to a second rebar. In this case the rebar shall be placed 2-ft on either side of the specified placement with the double anchor being closest to the exposed log end or root wad and the third anchor being placed on the upstream side of the log. (4) Four anchors, if used, shall be secured to each end of two lengths of rebar placed 1-ft on either side of the specified anchor location.

Figure 17. Series of log weirs with pilings as anchors. Photo credit: Mitch Farro.

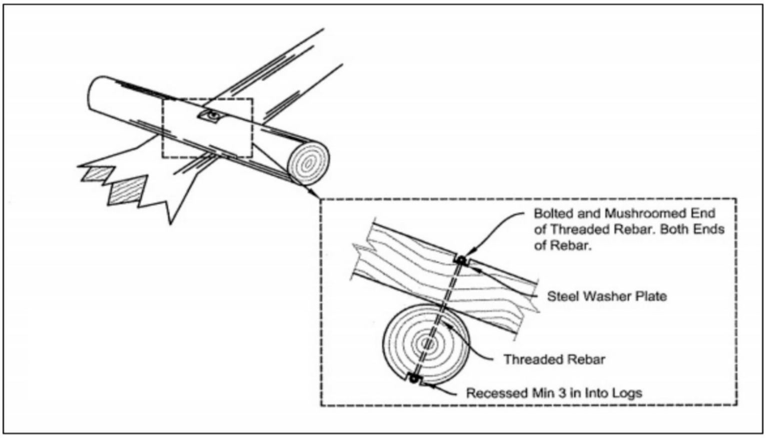


Figure 18. The use of threaded rebar, steel washers, and nuts to anchor logs together (Love and Shea 2012).

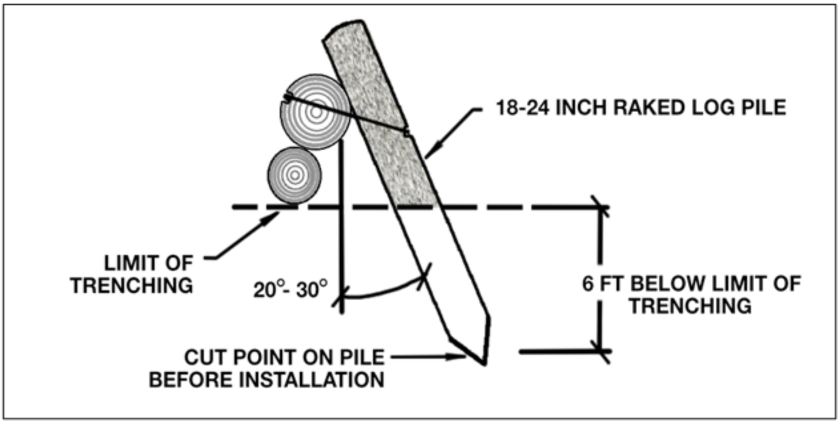


Figure 19. A raked log (Love and Shea 2012).

For boulder weirs, the ends of the weir should be keyed sufficiently into the banks to prevent flanking. NRCS (2000) recommends that the boulders extend at least four times the D_{100} boulder size into each streambank. Beavers (2010) provides updated recommendations that boulder weir arms should extend into the streambanks: (1) as far as the banks are tall, (2) two-footer boulder diameters, (3) 4 times the channel D_{100}, (4) a minimum of 8 ft, (5) whichever is greater. Exposed boulders keyed into the bank, uncovered due to bank scour, may become an active part of the boulder weir. For this reason, the boulders keyed into the banks should have footing boulders and be roughly the same size as the boulder used in the channel portion of the weir. Key the footer boulders into the bank the same distance as header boulders. Bank-keyed footers should extend below the predicted scour depth for the channel. If there is substantial over-bank flow during extreme high flows, the key may need to extend further. Including roughness elements on the floodplain as an element of the project can also reduce the risk of channel avulsion. Preferred methods for adding roughness includes riparian planting or placing large woody debris.

SCOUR CONSIDERATIONS

Scour pools generally develop downstream of weir structures in response to plunging flow over the top of the weir. If the structure is too high, the substrate is too small, or the footings too shallow, the scour pool may undermine the structure. In boulder structures, this may cause boulders from the weir to shift making the feature ineffective or the boulders to dislodge into the pool. In log structures, the logs may become exposed and suspend over the channel.

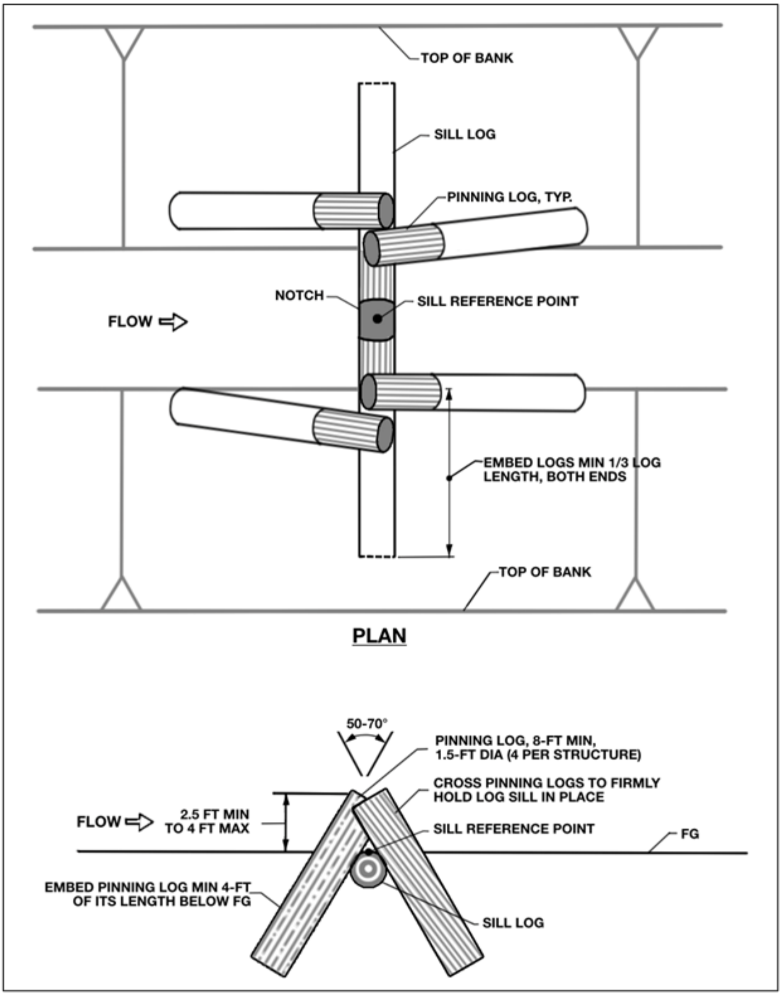


Figure 20. Logs installed at angles to pin logs down (Love et al. 2014).

USBR (2007a) noted that the most common failure mechanism for boulder weirs was growth of the scour pool and subsequent slumping of the footer boulders. The study identified that the most successful installation and design technique was the presence of a deep foundation for the structure. Saldi-Caromile et al. (2004) and NRCS (2000) state that the depth of scour in gravel and cobble bed streams is about 2.5 times the drop height over the weir. Ideally, the depth of scour should be calculated directly. Scour is dependent on bed material size, water depth, and velocity in three dimensions. There is no straightforward equation accounting for all these factors. Based on the U.S. Bureau of Reclamation study, the general rule of thumb for scour depth being 2.5 times the drop height underestimates actual scour depth in many situations.

More recently, Beavers (2010) suggests that the minimum scour depth considered in the design of boulder weirs should be 2.5 - 3 times the drop height or the size of the D_{100} boulder, whichever is greater. However, when designing U-shaped weirs in narrow, deeply incised channels or placing weirs in a bed that is more gravel than cobble, an additional layer of footer boulders or logs may be necessary.

Frequently, scour and footer slumping occur along the structure arms close to the bank (USBR 2009). The reason for this is that, typically, boulder weirs are constructed with the footer boulders sloping upward, toward the bank, along the arms of the weir. This leaves the location on the weir with the greatest height, and the least amount of foundation depth, susceptible to undermining during high flows. Beavers (2010) identified these areas as problematic for the structure because the deepest scour occurs where head drop is greatest and footer protection is the least. To accommodate this issue with the inclusion of a safety factor, the footer boulders should be below the calculated scour depth along the entire length of the weir arms, in a wedge shape (Figure 21).

Recent physical model studies (Scurlock et al. 2012; Marion et al. 2006) have attempted to develop equations for predicting scour downstream of drop structures. Marion et al. (2006) developed an equation to estimate scour downstream of straight horizontal drop structures (Equation 1):

Eq. 1 $$\frac{y_s}{H_s} = 3.0\left(\frac{a_1}{H_s}\right)^{0.6} SI^{-0.19}\left(1 - e^{-0.25\frac{L}{H_s}}\right)$$

Where

y_S = scour depth

H_S = energy head upstream of drop at 100-year flow

a_1 = drop height

L = spacing between drops

SI = $$\frac{\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}}}{2}$$

The equation is valid for $0.07 \leq \frac{a_1}{H_s} \leq 1.87$ with $R^2 = 0.86$. See Figure 22 for a graphical depiction of the variables. The calculation should use the calculated parameters (H_S, a_1) at the maximum design flow such as the 100-year recurrence-interval flood flow.

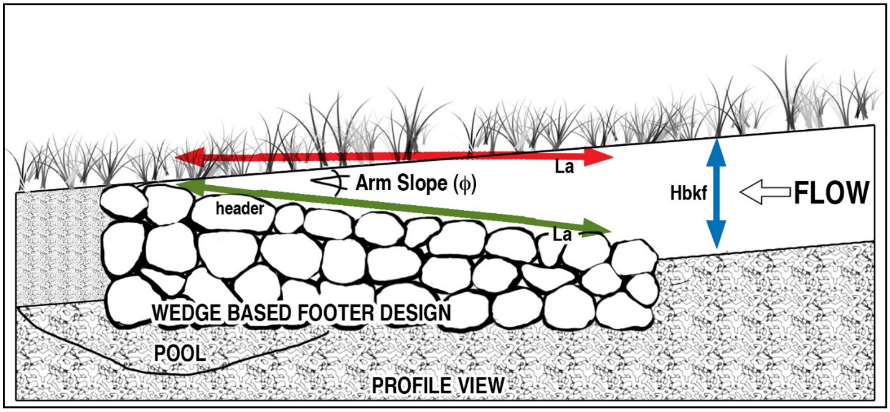


Figure 21. Illustration of proposed wedge-based footer design (modified from Reclamation 2016).

The portion of the data set used to produce Equation 1 from Scurlock et al. (2012) were from A, U, and W shaped weirs in a laboratory flume. In this experiment the range of conditions of their trial runs were too narrow to extend their use to much larger scales, such as those typical of stream channels in California. As a result, the scour predictions using those trial data are not reasonable in most natural conditions. For this reason, check scour predictions that are 2.5 - 3 times the drop height against the Equation 2 predictions regardless of weir shape. If the Equation 2 predicts scour greater than three times the drop height, then the design should place the footers below scour depth predicted by the equation.

Beavers (2010) recommends that the header boulders should rest upstream of the footer boulders at a 45-degree angle (Figure 23). USBR (2009) reached a similar conclusion and found that the likelihood of structure failure increased as maximum scour depth neared the structure crest. Do not set boulders at an angle upstream less than 45 degrees because fish initiate their leaping behavior in the depths of the pool.

CHANNEL SLOPE AND SPACING OF LOG AND BOULDER WEIRS

Build log and boulder weirs in a sequence of two or more. USBR (2007a, 2009) found that structures placed in series increased the sustainability of the project over time. Place the downstream-most weir at or below the elevation of a stable stream element, such as a natural pool tail out. Generally, for fish passage CDFW has accepted no greater than 5% finished gradient for these types of projects. Saldi-Caromile et al. (2004) recommend constructing most log or boulder weirs in series at slopes of 3% or less as providing the best assurances against failures. Bates et al. (2003) suggests a maximum overall grade (measured from crest to crest) of 3% for

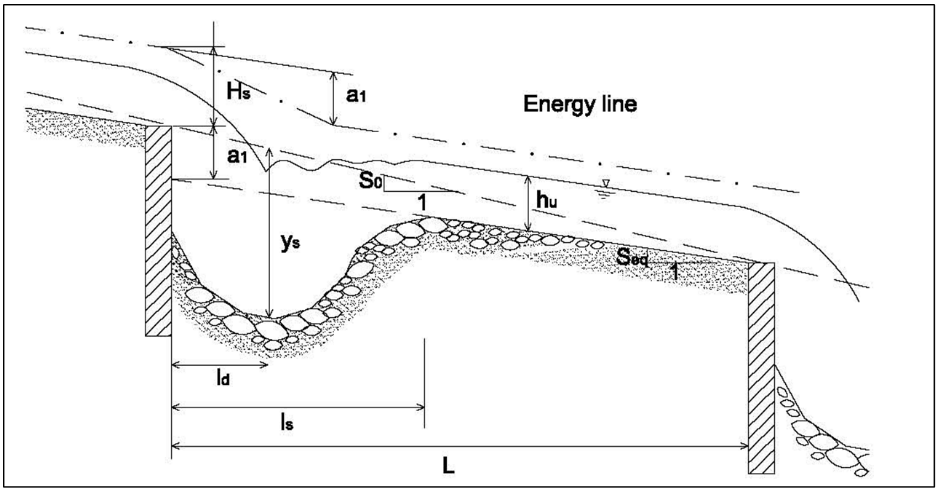


Figure 22. Graphical description of the variables (Marion 2006).

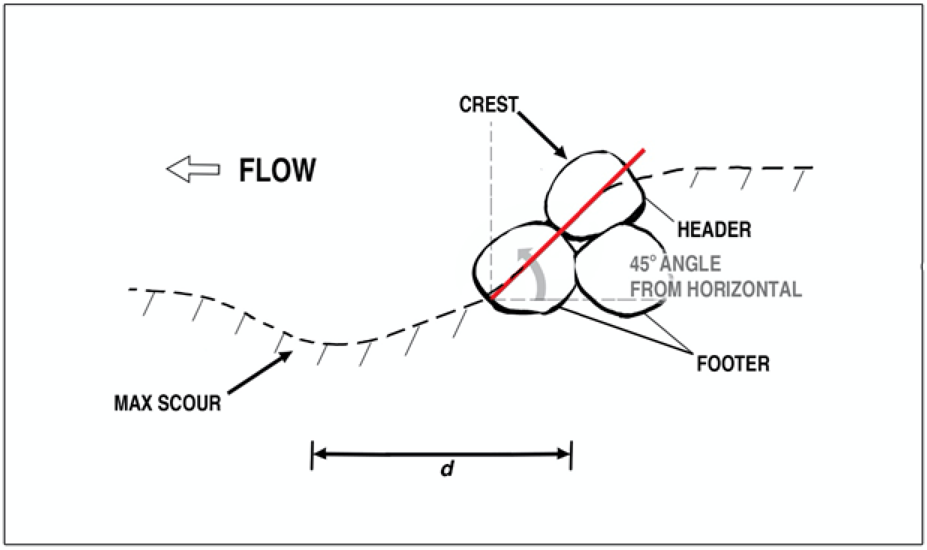


Figure 23. Header boulder at a 45% angle to the footer boulder.

U-shaped weirs. The scour pools formed downstream of U-shaped weirs tend to be longer and deeper, and thus it takes a longer distance for the pool tail out to naturally form. Without enough tail out the next weir downstream may not stay sealed and can fail. Therefore, build the next weir downstream at the natural pool tail out or further downstream.

Straight boulder weirs with level crests can be placed at closer spacing than U-shaped weirs because their scour pools are generally shorter in length. Bates et al. (2003) suggests a maximum overall grade (measured from crest to crest) of 5% for straight boulder weirs. However, due to the size of the boulders necessary in higher energy streams, a 5% slope does not provide enough length for a tail out to form. For cases where a steeper slope is desired, a step pool roughened channel approach is recommended (see Manual, Part XII).

Log weirs should be spaced such that the drop between weirs is 0.5 ft or less to ensure fish passage for juvenile salmonids. CDFW recommends maximum of one-foot design drops over boulder weirs for juvenile salmonid passage. This is due to variability in the form of the construction materials and the difficulty of precision placement. Also inherent with boulder weirs is a more natural hydraulic diversity over the crest of the weir that allows juvenile fish to seek and swim through lower velocity areas for passage upstream as compared to log weirs with simpler hydraulic geometry. The plunge pool that forms downstream of the log or boulder weir provides energy dissipation and must be of adequate depth to provide for fishpassage. A minimum plunge pool depth of 1.25 times the height of the drop, or 2 ft, whichever is greater provides for fish passage. During construction, a pool of at least 2 ft deep by 6 ft long should be excavated immediately downstream of the log or boulder weir to allow the plunge pool to develop and provide fish passage prior to the pool formation that the initial high flow will facilitate.

Marion et al. (2006) also provides an equation for estimating the length of scour, which can prove useful in spacing of structures (Equation 2):

Eq. 2 $$\frac{l_s}{a_1} = 7\left(\frac{H_s}{a_1}\right)^{0.86}$$

Where l_S = length of scour and the other variables are defined above. This equation is valid for $0.84 \le \frac{H_s}{a_1} \le 14.1$ with an $R^2 = 0.94$.

Log or boulder structures are often used for fish passage and grade control at culvert retrofits and replacements (Figure 24). Most culverts influence stream hydraulics by creating a constriction, either laterally, vertically, or both. The hydraulics are often quite complex and can result in scour at the inlet and outlet of the culvert. Log or boulder weirs placed near the inlet or outlet can exacerbate scour or not function properly due to scour induced by the culvert. For these reasons, log or boulder weirs should be located at least 35 ft upstream of a culvert inlet and below the outlet scour pool tail out, but no closer than 20 ft downstream of the culvert outlet (Beavers 2010).

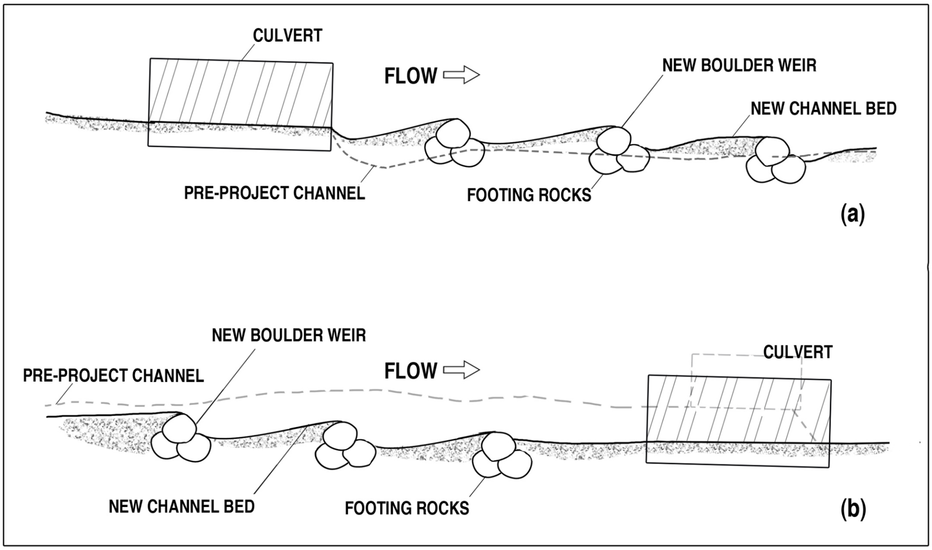


Figure 24. (a) Placement of boulder weirs below culvert. (b) Placement of boulder weirs above culvert.

Figure 25. Water flowing through gaps in a boulder weir (Questa Engineering Corp 2009).

SEALING OF WEIRS

Sealing weirs so that low flows pass over the top of the weir rather than through voids or gaps between boulders in boulder weirs (Figure 25) or under log weirs is an important part of design and construction. Improperly sealed weirs can create failure issues such as becoming a barrier to fish passage, initiating down cutting in the channel, or causing unwanted lateral erosion (Figures 26 and 27). If weirs are adequately spaced and incoming sediment is of the right size and quantity, deposition against the upstream face of the weir will keep the weir sealed; however, this can take more than a single rainy season to occur. As such, seal weirs and, where practical, test the seal as part of the initial construction. Log and boulder weirs are not appropriate on systems where there is insufficient bedload to maintain a seal long term.

To seal boulder weirs, place the boulders close together to minimize the size and number of voids. Fill the voids with native material and smaller rock specifically selected to fill the niches during construction. Tamp and wash the native bed material in place. Then use a water hose with a spray nozzle to force smaller sediment material into the voids to complete the seal. If necessary, pack clay into the spaces between the boulders to help seal the weir. This may be warranted in projects where the weirs are being used to induce alluvial material to deposit such as on an exposed bedrock bed. Fabric is not an acceptable material for sealing boulder weirs. An alternative method for sealing boulder weirs is to fill the voids between the boulders with small rock and if there is still significant leakage, fill the gaps with coir fiber to trap and hold the fines (Questa Engineering Corp 2009).

Log weirs used for grade control in low velocity areas can usually be sealed with compacted native material if the native material consists of small gravel, silt, and clay. Before backfilling the logs, any gap between the logs must be sealed. One technique is to fill the gap between the logs with manila rope and then attach a 2" x 4" redwood board using galvanized wood screws (Figure 28). When backfilling the log weir with native material excavated from the site, compact the material in six-inch lifts. Only where necessary, add clay to the native material to help seal the structure.

In areas where the substrate is gravel or cobble, attaching biodegradable small mesh coir blanket material upstream of the face of a log weir to help seal it is sometimes required. If the material is not sufficiently buried to prevent the substrate from scouring, the fabric may become exposed during high flows. When using coir blanket, attach the material from the top of the structure to a minimum depth of 2 ft below the streambed and upstream at least 5 ft. To completely seal the structure, extend the coir blanket into the key trenches (Figure 29).

Figure 26. Log weir with a failed seal. The weir is leaking under the step near the left bank. Photo credit: CDFW.

Figure 27. Log weir where the seal is broken and the flow is going under the log. Photo credit: Trevor Tollefson.

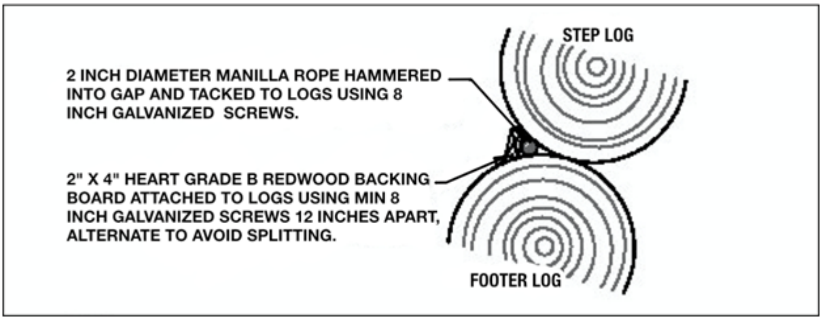


Figure 28. Illustration of a log weir seal between the footer and step log (Michael Love and Associates, Inc. 2018).

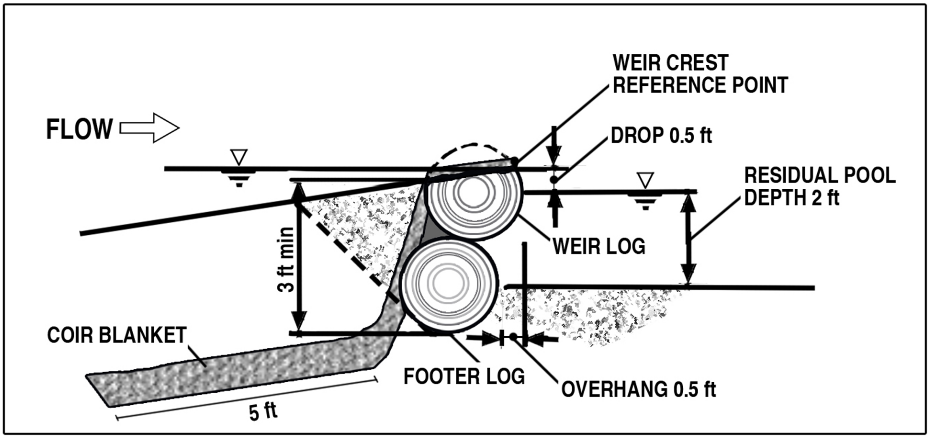


Figure 29. Diagram of log weir with attached coir blanket.

EVALUATION PLAN

At the conclusion of every log or boulder weir project, complete an as-built survey that includes all the constructed elements based on the final design drawings. Use the as-built survey to compare the actual construction to the design drawings. Repeat this level of survey after bankfull flow events to determine if the structure has shifted creating an issue with fish passage and to determine if the structure is performing as intended. Establish photo points pre-construction to monitor before, during and after project changes. Repeat the photo points after bankfull storm events for an established time to ensure functionality of the structures.

MAINTENANCE

Due the propensity of boulder and log weirs to fail, the entity responsible for the project is responsible for maintaining projects that do not meet project objectives or are creating unintended problems. Prior to modifying a structure, conduct an evaluation to determine why the project needs maintenance or has failed. Maintenance of a log or boulder weir project may include one or more fixes such as re-positioning of the structure; replacement or removal of individual boulders or logs; removal of wood that has racked up on the structure creating unintended backwater effects or bank erosion; or resealing of log or boulder weirs. In some cases, it may be necessary to remove the structure entirely because it is causing unintended consequences.

REFERENCES

Bates, K., Barnard, B., Heiner, B., Kalavas, P., and Powers, P. D. 2003. Design of road culverts for fish passage. Washington Department of Fish and Wildlife, Olympia, WA.

Beavers, A. 2010. Fish passage design for boulder weirs. NOAA Fisheries Service.

California Department of Fish and Wildlife. 2022. California Department of Fish and Wildlife Aquatic Invasive Species Decontamination Protocol. California Department of Fish and Wildlife, Fisheries Branch, West Sacramento, CA, USA. Available from: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=43333

Castro, J. 2003. Geomorphic impacts of culvert replacement and removal: avoiding channel incision. USFWS, Oregon Fish and Wildlife Office, Portland, OR. Version 2.0

Castro, J. and Beavers, A. 2016. Providing aquatic organism passage in vertically unstable streams. Water 8(4):133. Available from: https://doi.org/10.3390/w8040133

Cederholm, C. J., Dominquez, L. G., and Bumstead, T. W. 1997. Rehabilitating stream channels and fish habitat using large woody debris. *In* Slaney, P.A., and Zaldakas, D. (editors) Fish Habitat Procedures. Watershed Restoration Program, Ministry of Environment, Lands and Parks, Vancouver, BC, Canada.

Cramer, M. L. (editor). 2012. Stream habitat restoration guidelines. Co-published by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service. Olympia, WA.

DiVittorio, J., Grodowitz, M., and Snow, J. 2012. Inspection and Cleaning Manual for Equipment and Vehicles to Prevent the Spread of Invasive Species. U.S. Department of the Interior, Bureau of Reclamation, Technical Memorandum No. 86-68220-07-05.

Fischenich, C. 2001. Stability thresholds for stream restoration materials. ERDC TN-EMRRP-SR-29. USACE Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Fischenich, C., and Seal, R. 2000. Boulder clusters. ERDC TN-EMRRP-SR-11. USACE Research and Development Center. Environmental Laboratory, Vicksburg, MS.

Flosi, G., Downie, S., Hopelain, J., Bird, M., Coey, R., and Collins, B. 2010. California salmonid stream habitat restoration manual. Fourth Edition, State of California, Resources Agency, California Department of Fish and Game, Sacramento, CA.

Flosi, G., Caisley, M., and Smelser, M. In press. The Use of Large Wood in Stream Habitat Restoration. California Department of Fish and Wildlife, Fish Bulletin 184.

Fripp, J., Fischenich, C., and Biedenham, D. 1998. Low head stone weirs draft, Technical Note EMSR 4-XX. U.S. Army Corps of Engineers.

Johnson, A. W., and Stypula, J. M. (editors) 1993. Guidelines for bank stabilization projects in the riverine environments of King County. King County Department of Public Works, Surface Water Management Division. Seattle, WA.

Love, M., and Shea, R. 2012. Strawberry Creek restoration project at Redwood National Park, final basis of design report. Prepared by Michael Love & Associates, Arcata, CA.

Love, M., Llanos, A., and Shea, R. 2014. Jacoby creek off-channel habitat restoration, basis of design report. Prepared by Michael Love & Associates, Arcata, CA.

Marion, A., Tregnahi, M., and Tait, S. 2006. Sediment supply and local scouring of bed sills in high gradient streams. Water Resources Research 42(6). Available from: https://doi.org/10.1029/2005WR004124

Michael Love and Associates, Inc. 2015. Fish access restoration to Manly Gulch in Mendocino Woodlands State Park. FRGP Grant # P1410555.

Michael Love and Associates, Inc. 2018. Gulch C salmon barrier removal design project. For Trout Unlimited, Fort Bragg, CA.

National Marine Fisheries Service. 2014. Final Recovery Plan for the Southern Oregon/Northern California Coast Evolutionary Significant Unit of Coho Salmon (*Oncorhynchus kisutch*). National Marine Fisheries Service. Arcata, CA.

National Marine Fisheries Service. 2016. Coastal Multispecies Final Recovery Plan: California Coastal Chinook Salmon ESU, Northern California Steelhead DPS and Central California Coastal Steelhead DPS. National Marine Fisheries Service, West Coast Region, Santa Rosa, CA.

Natural Resource Conservation Service (NRCS). 1996. National engineering field handbook, Part 650, Chapter 16 – Streambank and shoreline protection. U.S. Department of Agriculture, Natural Resources Conservation Service. Available from: http://directives. sc.egov.usda.gov/17553.wba

Natural Resources Conservation Service (NRCS). 2000. Technical notes – design of rock weirs. Engineering - No. 24, U.S. Department of Agriculture, Portland, OR.

Natural Resource Conservation Service (NRCS). 2007a. Streambank soil bioengineering. Technical Supplement 141. Part 654 National Engineering Handbook. Available from: https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17818.wba

National Resource Conservation Service (NRCS). 2007. Use and design of soil anchors. Technical Supplement 14E. Part 654 National Engineering Handbook. 201-VI-NEH.

Questa Engineering Corp. 2009. Sealing rock weirs with COIR (coconut fiber stuffing).

Roni, P., Bennett, T., Morley, S., Pess, G. R., Hanson, K., Van Slyke, D., and Olmstead, P. 2006. Rehabilitation of bedrock stream channels: the effects of boulder weir placement on aquatic habitat and biota. River Research and Applications 22(9):967-980. Available from: https://doi.org/10.1002/rra.954

Rosgen, D. L. 1996. Applied river morphology. Second edition. Wildland Hydrology, Pagosa Springs, CO.

Saldi-Caromile, K., Bates, K., Skidmore, J., and Pineo, D. 2004. Stream habitat restoration guidelines: final draft. Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. Olympia, WA.

Scurlock, M. S., Thorton, C. I., and Abt, S. R. 2012. Equilibrium scour downstream of three dimensional grad-control structures. ASCE Journal of Hydraulic Engineering 138:167-176.

U.S. Bureau of Reclamation (USBR). 2007. Qualitative evaluation of rock weir field performance and failure mechanisms. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center. Denver, CO.

U.S. Bureau of Reclamation (USBR). 2009. Qualitative evaluation of the field performance of rock weirs. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center. Denver, CO.

U.S. Bureau of Reclamation (USBR). 2016. Rock weir design guidance. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO.

Utah Department of Transportation. 2009. Evaluating shallow-flow rock structures as scour countermeasures at bridges. Report No. UT-08.24. Prepared for Utah Department of Transportation Research Division. Salt Lake City, UT.

Whiteway, S. L., Biron, P. M., Zimmermann, A., Venter, O., and Grant, J. W. A. 2010. Do instream restoration structures enhance salmonid abundance? A meta-analysis. Canadian Journal of Fish and Aquatic Science. 67:831-84112.