DROP STRUCTURES

1 DESCRIPTION OF TECHNIQUE

Drop structures (also known as grade controls, sills, or weirs) are low-elevation structures that span the entire width of the channel, creating an abrupt drop in channel bed and water surface elevation in a downstream direction. Drop structures have been used extensively in Washington State to stabilize channel grades, improve fish passage, and to reduce erosion. Generally speaking, in fish bearing waters, vertical drops must not exceed 1 foot [WAC 220-110-070]; lesser drops are often required to accommodate certain species and age classes of fish.

Drop Structures are designed to spill and direct flow such that there is a distinct drop in water surface elevation at normal low flows. The purpose of drop structures may include but is not limited to:

- redistribute or dissipate energy;
- stabilize the channel bed;
- restore a step pool morphology to an altered channel
- limit channel incision;
- limit bank erosion by directing flow away from an eroding bank;
- modify the channel bed profile and form by promoting collection, sorting and deposition of sediment;
- create structural and hydraulic diversity in uniform channels;
- improve fish passage over natural and artificial barriers by backwatering the upstream reach;
- scour the channel bed, creating holding pools for fish and other aquatic life;
- provide backwater (depth) in groundwater fed side channels; or
- raise the bed of an incised stream to reconnect it with its floodplain.

Drop structures may resemble porous weirs in appearance. But while drop structures direct water over the structure and are applied primarily to modify the profile of a channel, porous weirs allow water to flow through the structure and are applied primarily to redirect or concentrate flow. Like porous weirs, their longevity is limited by their structural integrity and the lateral and vertical stability of the channel. Drop structures can be constructed to be either deformable or non-deformable. They are commonly constructed with natural materials (rock or logs), but timber planks, sheet pile, concrete, and other rigid artificial materials have also been used.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Drop structures alter the velocity, flow hydraulics, and sediment transport characteristics upstream and immediately downstream of the structure. The common characteristic of all forms of drop structures is that they create a distinct drop in the channel bed and in the low-flow water surface profile, producing backwater effects upstream and a plunge pool immediately below the structure.

Drop structures create low velocity backwater conditions upstream by raising the effective bed elevation, thereby reducing channel slope. Backwatering commonly induces sediment deposition and increases the water surface elevation upstream of the structure at low to moderate flows. Typically, at high flows, no backwatering effect of the structure is evident provided the structure lies low in the channel profile and does not significantly reduce the channel cross-section. Deposition upstream of a drop structure is particularly common in moderate to high bedload channels. Sediment deposition upstream of the structure is not as likely for low bedload or incising channels due to limited sediment availability. The upstream extent of backwater depends upon the scale of the structure and the slope of the channel. Backwater effects extend much further on low-gradient streams than on high gradient streams. As drop structures typically lie low in the channel profile, backwater effects associated with them are generally localized. However, if the structure causes a significant reduction in channel cross-sectional area or a series of structures collectively increase the hydraulic roughness of the channel, backwater effects may be more far reaching. Effects of large-scale backwatering can include increased flood levels and frequency of floodplain inundation, an adjustment of the elevation of streamside vegetation as lower-growing plants are drowned out, potential change in riparian species composition and distribution in response to changing inundation patterns and water table elevations, and reduced reach transport of sediment. Other effects associated with reduced sediment transport include channel aggradation and associated channel widening, bank erosion, increased channel meandering, and decreased channel depth.

As flow passes over a drop structure, it is directed perpendicular to the structure’s alignment. It is also funneled towards any low spots that occur on the structure. Thus, drop structures may redirect, concentrate, or disperse flow depending on their shape in both plan view and cross-section. This, in turn, may alter the patterns of scour and deposition in the downstream channel. Depending upon its shape, drop structures may also affect the channel cross section. Drop structures that are flat and straight across the channel tend to create a channel cross-section that is flat and uniform. The pool created in this case is at the base of the structure and spans the entire channel. Drop structures that have a “V” cross-section geometry create a thalweg in the pool and generate more diversity. The pool is longer but narrower and may not span the channel.

An important benefit of drop structures is the habitat they can provide. Drop structures may increase habitat complexity by breaking up a long glide or riffle into a series of step/pools. They create surface turbulence and bubbles that provide hiding cover, and a diversity of plunge pools, eddies, velocity chutes, and interstitial hiding areas that can benefit a host of fish and other aquatic organisms. They also catch debris, provide aeration, and collect and sort gravel in the tailout of associated scour pools. The scour pool formed by plunging flow over the structure provides energy dissipation and holding habitat for fish[1]. However, drop structures also pose a risk of becoming barriers to fish passage. This is most likely to occur if the downstream channel incises over time, if it or an adjacent structure fails such that the drop becomes too high. Or if the plunge pool is obstructed or of inadequate depth, if the depth of flow over the weir is too shallow, or if the head differential during fish passage flows is higher than predicted. For this reason, periodic monitoring is essential. However, keep in mind that even properly functioning drop structures create a distinct drop in water elevation that may pose a barrier or impede the upstream or downstream passage of non-target fish and wildlife species.

The impact of drop structures on channel grade and flow redirection is immediate. However, scour and the resulting redistribution of sediment may not occur until the first high flow events following construction. The physical and biological benefits and impacts drop structures provide may extend upstream and downstream of their application, particularly along low gradient streams.

3 Biological Considerations

3.1 Mitigation Requirements for the Technique

Placement of drop structures in the channel will fix the bed profile and prompt adjustments in the thalweg alignment and pattern of sediment scour and deposition. Existing fish spawning areas and pools may be impacted by these changes unless the structure is specifically designed to maintain them. In addition, the opportunity for future development of near-bank pool habitat may be lost. These near-bank pools provide some of the best types of rearing habitat, especially when they contain wood and cover from the overhanging bank. Loss of near-bank pool habitat may be mitigated by the scour pool that will develop on the downstream side of the structure and by adding wood to the affected or nearby reach. Refer to Section 6.2.9, *Incorporating Large Wood into Drop Structure Design*.

In addition to direct habitat loss, natural channel evolution, including dynamic erosion and deposition processes such as channel migration, will be reduced. This represents a lost opportunity for future development of habitat complexity resulting from periodic inputs of gravel and wood and side channel development. Placing large wood in the channel or floodplain can mitigate some negative impacts to habitat as discussed above. The drop structure itself may also provide mitigation, at least in part, if it restores fish access to historically available upstream habitat.

Refer to the Integrated Streambank Protection Guidelines[2], Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5, *Identify and Select Solutions* for additional guidance concerning mitigation requirements when used as a bank protection technique.

3.2 Mitigation Benefits Provided by the Technique

Drop structures can increase the habitat diversity of otherwise homogenous reaches. They can create and maintain pools that provide holding and rearing habitat for fish, improve fish passage, and sort and capture sediment to improve fish spawning habitat. These and other habitat benefits provided by drop structures are further described in Section 2, *Physical and Biological Effects*. Refer to Matrix 3 in Chapter 5 of the Integrated Streambank Protection Guidelines[2], for more detail on the mitigation benefits of this technique.

4 APPLICATION

Drop structures can be applied as a stand-alone technique, or in concert with other techniques. They can be applied at a site or reach scale. Though they can be applied individually, many project objectives require that multiple drop structures be installed in series, throughout a stream reach. For example, when replacing an undersized culvert that has a high outlet drop, it may be necessary to install several drop structures to incrementally step up the channel grade to provide fish passage through the new culvert.

Despite the potential benefits of drop structure placement (e.g., target fish passage, habitat complexity, floodplain reconnection), drop structures are an “unnatural anomaly in the fluvial system”[3] and may have serious negative impacts on the stream ecosystem. For instance, drop structures prevent the channel from moving laterally or adjusting vertically to maintain itself, to respond to changing watershed conditions, and to create and maintain new habitats and habitat diversity. Drop structures may exclude passage of non-target fish and wildlife species; and they may become barriers to target fish passage if the downstream channel incises or a downstream structure fails. Therefore, drop structures should only be applied where necessary, and only where they will be monitored regularly to ensure they do not become barriers to fish passage. Assurances should be in place for future access in case maintenance is needed. Drop structures should be discouraged solely for the purpose of habitat enhancement such as scour pool development or sorting of sediments. Other structural techniques (e.g., porous weirs, large wood and log jams, or boulder clusters, all of which are discussed in this document) or non-structural techniques (e.g., channel modification or removal or modification of infrastructure) may meet the same objectives with less detrimental impact to the ecosystem.

Siting of structures is a critical component of the design process. Drop structures should be located in straight channel sections and at the entrance and exits of channel bends; they should not be installed in the bends themselves. One reason for this is that flow is directed along the outside bank as it enters and moves through a channel bend. If a structure is located on the bend, it is difficult to redirect the flow if that is the objective. Flow will naturally tend to stay along the outside bank, making it very susceptible to an end run as the plunge pool forms downstream. The other reason why channel bends should be avoided is that the pattern of sediment scour and deposition created by the drop structure does not coincide with natural patterns of scour and deposition near a meander bend. Pools naturally form along the outside of meander bends and create a pool tailout comprised of sorted sediment deposits downstream. In channels that carry a sediment load, sediment is expected to deposit upstream of a drop structure and a pool to form immediately downstream.

Channel Width: Drop structures have been installed in channels up to 400 feet wide. Their use in systems above that threshold may be limited depending on project goals and objectives and the influence of other factors limiting their success. Application of drop structures on large rivers may encounter practical design and construction limitations imposed by the size of available rock or wood, equipment, and impacts that cannot be effectively mitigated. The scale of the structure should be roughly proportional to the size and slope of the channel.

Channel Gradient: The applicable channel gradient varies with the type of drop structure and the energy of the stream. The Washington Department of Fish and Wildlife (WDFW)[4] recommends a maximum finished gradient of 5 percent for straight log weirs placed in series in streams with typical rainfall-dominated hydrology. In small, spring-fed streams that don't experience extreme high flows, higher gradients may be possible (up to 7 percent). The recommended maximum final gradient of boulder weirs and other configurations of log weirs is 3 percent. California Department of Fish and Game[5] recommends limiting the use of log weirs to gradients of 1.5 to 4 percent in moderately entrenched channels. In steeper channels, the relatively close spacing of drop structures necessary to meet the maximum allowable vertical drop criteria for fish passage may cause the scour pool of one structure to collide with the next structure downstream and potentially undermine it or prevent it from sealing. (Drop structures that contain spaces between individual structural elements, such as double log or boulder weirs, rely upon upstream deposition of material to form an effective seal.) Interception of the scour pool with the next downstream structure also prevents total dissipation of energy between structures and, instead, transfers the energy downstream where it will likely scour the channel bed or banks. Therefore, the maximum recommended finished gradient for a series of solid (non-porous) drop structures, such as concrete or sheet pile weirs, is also 5 percent. As a result, it is difficult to steepen a rainfall-dominated channel with a natural slope greater than about 3 percent.

Drop structures are generally inappropriate in low-gradient (less than 1%) reaches where a step-pool morphology is uncommon in nature. Low gradient channels are typically characterized by plane-bed, pool-riffle or dune-ripple morphology. An exception to this is the incorporation of drop structures in constructed groundwater-fed side channels that are often at a level grade and the drop structures are used to maintain an optimal water depth for rearing and spawning.

Channel Stability: Drop structures are inappropriate in aggrading reaches. Aggrading reaches will deposit sediment above, around and over the drop structure burying it, thereby counteracting their intended function. Structures that create large backwater effects should be used with caution in flood-prone developed areas and streams that carry high bedload due to the potential for causing upstream aggradation and increased flooding. Caution should also be exercised when installing drop structures in laterally dynamic channels where there is the potential for an avulsion that could bypass the structure.

When applying drop structures to raise the bed of an incised channel, care is needed to ensure downstream incision is not exacerbated. The sediment-storage capacity of a drop structure can be enough to exacerbate downstream incision. This is especially true if the cause of channel incision is due to a decrease in sediment supply. Users of this technique should note that drop structures typically address only the symptoms of channel incision, not the cause. Drop structures may not be appropriate in actively incising reaches unless the root cause of vertical instability is also addressed. Refer to Chapter 4.5.5, Restoring an Incised/Incising Stream for further discussion on potential causes and treatments for channel incision.

Channel Bed: Drop structures are best applied to channels with gravel or cobble beds[6]. Securing drop structures into bedrock channels presents a challenge, but log weir drop structures have been successfully bolted to bedrock using rock bolts. Sand, silt, and other fine-grained material are easily erodible and can compromise the structural integrity of the structure if subject to high flow events. However, this becomes less of a concern in groundwater streams with stable flows and in small, low-gradient (<0.12%[6]) streams provided the banks are well vegetated. Boulder weirs are inappropriate in sand or other fine-grained bed streams.

Bank Protection: When using drop structures to protect streambanks, it is important to determine whether drop structures are the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Integrated Streambank Protection Guidelines[2], Chapter 2, *Site Assessment*, Chapter 3, *Reach Assessment*, and Chapter 5, *Identify and Select Solutions* for guidance).

Drop structures are not useful in emergency streambank protection. They completely span the stream channel and usually require construction from within the channel, which may not be possible during an emergency. However, on smaller channels that are actively degrading or headcutting, rock may be placed as a grade-control measure during emergency conditions to arrest formation or progression of a nickpoint.

Other Siting Considerations: Drop structures may not be appropriate if navigation or recreation is a concern as they can create hazardous hydraulic conditions that trap objects. Drop structures should be located at least 20 feet downstream of the outlet of a culvert[4] to prevent scour at the culvert outlet from undermining the structure and to limit the amount of debris trapped within the culvert as a result of the drop structure. Drop structures should be located at least 35 feet (50 feet where possible) from the inlet of the culvert[4]. When placed in closer proximity to its upstream end, turbulence created by the drop tends to scour out the inlet of the culvert and occasionally its entire bed. The proximity of drop structures to other in-stream structures, such as bridge piers, should be similarly limited.

Use caution when locating drop structures in streams that carry a high debris load as debris may become trapped on the structure and increase the degree of backwatering caused by the structure or redirect flow[7].

5 Risk and Uncertainty

5.1 Risk to Habitat

Drop structures have the potential to adversely impact existing habitat by altering channel processes such as sediment transport, scour, and deposition. Depending upon the channel size, bedload movement, and particle size, it may take time for the channel to adjust to a new structure. In the adjustment period, spawning areas may scour or accrete, and any eggs or alevins in the bed could be damaged. Relative to other habitat-enhancement options, traditional drop structures tend to provide uniform habitat features with little diversity if placed in a series. However, drop structures can be installed to provide complex and variable flow and scour conditions, which may benefit habitat in the long term.

Drop structures can create a barrier to upstream migration of non-target species or age classes of fish and other aquatic organisms. Where drop structures enable fish species to gain access to areas they don't currently inhabit, they could significantly alter predator, prey, and competition relationships among resident fish species upstream. These effects should be given careful consideration.

Installation of drop structures typically requires significant channel disturbance, which must be minimized with sediment control and dewatering. As such, there will be short-term negative impacts to the stream environment and its inhabitants in the form of either increased turbidity, temporary loss of habitat as flow is diverted around a construction site, and loss or disturbance of vegetative, invertebrate, and vertebrate life forms within the disturbed channel reach. In addition, access and staging areas will probably experience short-term impacts and will require temporary erosion and sediment control and best management practices to minimize impacts, followed by reclamation and restoration measures. Refer to the Section 8, *Construction Considerations* and the *Construction Considerations* appendix for further discussion of construction impacts and ways to reduce them. Consideration should also be given to the potential habitat impacts to source areas for boulders, logs, and other materials.

Potential impacts to habitat are further discussed in the Section 2, *Physical and Biological Effects*.

5.2 Risk to Infrastructure and Property

Improperly designed and/or poorly constructed drop structures endanger habitat and public safety. The risk to infrastructure is typically low, but is dependent upon the configuration of the drop structure and its influence on channel scour and flow hydraulics. Drop structures have the potential to greatly increase channel scour within the channel bed and along channel banks. For example, drop structures should not be placed immediately upstream of bridge piers, as the downstream scour may undermine the piers. Similarly, structures placed across the channel may redirect the channel thalweg toward a channel bank, thereby increasing risk to streamside infrastructure.

Drop structures that create significant upstream backwater can place upstream property and structures at increased risk of flooding and erosion. Drop structures that are constructed too high across the channel or that direct flow toward the channel banks rather than toward the center of the channel can result in significant bank erosion and potential loss of property.

5.3 Risk to Public Safety

Risk to public safety is generally lower on smaller streams. Drop structures discussed here typically provide a small increase in elevation and generally do not create hydraulic conditions dangerous to the public. There is some risk of debris becoming lodged on the structure and creating a public safety hazard. On the other hand, larger channel spanning structures can create hazardous hydraulic conditions that trap objects and prevent flushing downstream. Kayakers, canoeist, inner tubers, swimmers and boaters should use caution when navigating through these structures. It is best to scope out your route ahead of time, since these low-head dam situations often create a hydraulic jump that may trap a boat or person[8].

5.4 Uncertainty of Technique

Drop structures can be designed and constructed with a high degree of certainty for structural integrity and longevity. Log controls built in accordance with Washington Department of Fish and Wildlife standard details as early as 1984 are still in good condition today (2003). If properly constructed and maintained, it is reasonable to expect that drop structures will serve the intended function for many years. Certain functions of drops structures are immediate and virtually guaranteed provided they are properly designed and installed (e.g., grade control, water level control, flow redirection). However, scour and deposition patterns resulting from drop structures may prove difficult to predict or achieve as intended, depending upon the substrate, sediment transport characteristics, and the accuracy of hydrologic and hydraulic estimates.

6 METHODS AND DESIGN

As part of the design process, site, reach, and watershed assessment should be performed, as necessary. The extent of assessment will depend on the objectives of the project, and the factors the project is intended to address. For example, installation of a single or short series of drop structures to provide upstream passage in proximity to a culvert may not warrant a watershed assessment. Conversely, a drop structure project intended to trap sediment or otherwise affect sediment transport may require a comprehensive assessment of sediment supply and transport, which generally involves watershed scale assessment. Refer to Chapter 3, *Stream Habitat Assessment* for further discussion. Because drop structures create backwater conditions that may impact channel processes upstream and downstream of the structure, a reach assessment will likely be necessary to evaluate potential influences on structure performance and impacts resulting from the structure itself.

Additional information on structures that alter the channel profile is available in the Washington Department of Fish and Wildlife's <u>Design of Road Culverts for Fish Passage</u>[4] (http://wdfw.wa.gov/hab/engineer/cm/).

6.1 Data and Assessment Requirements

The following are minimum assessment requirements for drop structures. Many of these are further discussed in *General Design and Selection Considerations for In-Stream Structures*.

- *What is the objective of drop structure placement?* The elevation, configuration, and number of drop structures will vary with the objective. Are drop structures the best alternative to meet those objectives?
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of a Drop Structure (refer to Section 4, *Application*)? Develop plan, profile, and cross-section drawings of the site and reach, as appropriate. An analysis of baseline conditions may include:
    - General characteristics of bed material. What is the dominant substrate?
    - Channel width.
    - Channel gradient.
    - Cross-section survey(s)
    - Condition of the banks. Are they relatively stable or actively eroding?
    - Degree of channel entrenchment. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of entrenchment. This increases the potential for boulder transport and bed and bank scour because velocity and depth have increased along with the ability to move larger and greater sediment volumes.
    - General assessment of the lateral and vertical stability of the channel and the overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? If the channel is actively incising, has the cause of channel incision been identified and addressed? If not, the channel may continue to incise downstream and undermine or create a fish passage barrier at the lowermost drop structure.
    - Does the channel carry a relatively high bed or debris load? High gradient, high bedload channels can wear away log weirs at a relatively rapid rate. Limiting the potential backwater effects of a drop structure may be desirable in channels with high debris loads where wood accumulations could compromise the project or adjacent infrastructure.
    - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. It may include, but is not limited to, documentation of fish presence and abundance upstream of the structure, the extent and nature of eroding banks, or the frequency, extent, and depth of over bank flows.
- *Evaluate structure stability.* What is the necessary design life or design flow of the structure? What kind and size of material will be necessary to meet that design criteria?
- *Evaluate access and materials availability.* What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type of material, that can be utilized? What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will in-stream and riparian site conditions permit construction? Will the cost or availability of materials limit the design?
- *Document the location and nature of in-stream and nearby infrastructure that may benefit or be harmed by the proposed structure.* This is best done in

conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection, drop structure elevation, and the degree of allowable backwater.

- *Conduct a biological assessment*. What species of fish and wildlife require passage over the drop structures (refer to *Fish Passage Table 1* in the *Fish Passage Restoration* technique for a list of migratory fish species native to Washington State)? What is the maximum allowable hydraulic drop over the structure to accommodate these species? What is the current distribution of habitat, including spawning, rearing, high flow refuge, cover, and pool habitat, within, upstream, and downstream of the site that may be impacted by the structure? The local WDFW Area Habitat Biologist should be consulted for additional information on local aquatic fauna. Contact the WDFW Habitat program at (360) 902-2534 to find a WDFW Habitat Biologist in your project area. Further information regarding biological assessments is provided in Chapter 3, *Stream Habitat Assessment*.
- *Will the placement adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure, and public safety during and following construction if the project succeeds or if it fails structurally*? What is the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection, structure configuration)? What can be done to minimize the risk? Are the costs acceptable?

In relatively small, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design may be based on reference site conditions. For instance, the necessary size of material, structure configuration, and the anticipated depth of scour can be estimated by observing stable structures located in similar channel reaches operating under similar conditions. However, high risk projects, high cost projects, and projects conducted on larger streams (greater than 20’ wide) and steeper or more confined channels may have additional data collection and assessment requirements. These could include, but are not limited to:

- *Hydrologic analysis*. Hydrologic analysis may be necessary to generate discharge values used in design and to evaluate potential impacts to the channel or property. Common design discharges applied to drop structures include:
  - Low fish passage -flow
  - High fish passage flow
  - Ordinary High Water flow
  - Structural integrity and maximum design discharge. Specific design flow recommendations are provided in Section 6.2, *Design*.
  - Flood discharge - 100-year discharge for determining impacts on regulatory flood flows

  It is recommended that non-deformable drop structures be designed to be stable for all flows up to and including the 50-year flow event. In locations where infrastructure may be at risk, a higher design discharge (e.g., 100-year flow recurrence interval) may be required. Further discussion of hydrologic statistics and their derivation is available in the *Hydrology* appendix.

- *Scour analysis*. The integrity of drop structures depends, to some extent, on the depth of installation relative to the depth of scour. Critical flow conditions can occur at the crest of the structure with supercritical flow possibly occurring along the face of the structure at some flows. These conditions create a hydraulic jump downstream of the drop structure that can create scour and bank erosion. The *Hydraulic* appendix defines varying types of scour under various site conditions, and how to estimate depth of scour. Data required for scour analysis depends on the type of scour evaluated. While scour can be evaluated empirically in some instances, analysis usually requires a minimum of three cross-sections (one at each structure plus upstream and downstream of the structure), a channel profile survey (extending upstream and downstream of the project for a distance of at least 200-ft above and below the last structure or 10 bank full channel widths), and an evaluation of the bed substrate distribution. At a minimum, one representative substrate sample should be taken at each structure location. Significant changes in substrate composition along the project reach should be noted.
- *Sediment transport*. Sediment transport analysis may be necessary where large-scale backwatering effects are likely or where the project is intended to trap sediment or otherwise affect sediment transport (alter channel width, depth, or slope). Such effects are more likely to occur when a series of drop structures are installed. Local, individual structures will most likely affect scour and sorting without impacting general sediment transport characteristics through a reach. The evaluation of sediment transport is detailed in the *Sediment Transport* appendix.
- *Hydraulic analysis*. Channel hydraulics must be analyzed for fish passage at low flows and for stability at flood flows. Hydraulic parameters for design include flow depth, velocity and bed shear. These parameters should be estimated for a range of flows for existing and post-project conditions. These parameters will be used to size rock, wood, and other materials, and demonstrate fish passage conditions are met. An analysis of the hydraulic effects of backwatering is also recommended and can be accomplished using computer programs such as HEC-RAS. Hydraulic design in a natural environment, using natural materials, necessarily involves a significant degree of uncertainty. Equations and methods presented in the *Hydraulic* appendix are useful in the analysis and design of in-stream structures. These tools should be employed with an understanding of the variability in natural stream systems and sound professional judgment.

The above parameters are further discussed in *General Design and Selection Considerations for In-Stream Structures.*

6.2 Design

Dozens of various drop structure designs have been applied to stream channels; many have proven successful in multiple applications, while others have prematurely failed or never achieved the desired results. The most common instances of premature failure include:

- Structure undermining from scour or channel incision
- Water flowing around the structure, making an "end run"
- Water flowing subsurface through the structure rather than over it, preventing fish passage
- Materials comprising the structure becoming mobile or breaking, and
- Fish passage over the structure being inhibited by inadequate depth of flow over the weir, or an excessively shallow or obstructed plunge pool

The following text provides guidance to increase the success of any drop structure design.

6.2.1 Preventing Structure Undermining

A common and intended characteristic of all drop structures is that a scour pool develops downstream of the structure in response to plunging flow. The volume of the pool increases with increasing drop height or channel slope (which is directly related to shear stress), and with decreasing substrate size (e.g., from boulder to cobble, or from to gravel to sand). The scour pool has the potential to undermine the structure, causing loose rock and other material to fall into the scour pool and leaving rigid structural elements that fully span the pool (e.g., logs, concrete blocks) exposed and suspended over the channel bed.

Several techniques can be employed individually or collectively to prevent the structure from becoming undermined. One technique is to ensure that the depth of the structure meets or exceeds the anticipated depth of scour. For example, WDFW's standard log weir design uses two logs, placed one on top of the other (at approximately a 15 degree angle from the vertical), to prevent scour from compromising the integrity of the structure. Scour by flows over a drop can be estimated using jet or sill scour equations[9] [10]. The *Hydraulics* appendix presents equations for estimating scour depths for flow pouring over both vertical and sloping drop structures. Additional scour may occur if the structure forms a constriction to flow. Scour conditions at constrictions can be estimated using abutment or contraction scour methods, also detailed in the *Hydraulics* appendix. A series of flow conditions, representing the full range of design flows, should be considered in the scour analysis to determine worst-case scour conditions (there is not necessarily a linear relationship between scour and discharge). Depth of scour can also be estimated from field conditions by measuring the depth of scour associated with similar drops under similar site conditions. However, the reader should consider such measurements to indicate a minimum depth of scour. Scour measurement taken during high flow events will be higher than those taken during low flow. As a rule of thumb, expect the depth of scour to be 2-1/2 to 3 times the height of the drop in gravel or cobble bed streams. The depth of scour will be greater in sand bed streams.

Woven geotextile fabric is typically installed on the upstream face of wood drop structures to help "seal" them and minimize subsurface flow. Properly installed, this fabric also provides a factor of safety against structure undermining by preventing upstream bed material from eroding out from underneath the structure should it become undermined. The capacity of the material to provide this service is limited by its strength and durability.

Another method to minimize the risk of undermining the drop structure is to line the plunge pool with immobile material to limit the extent of its formation. This method was employed in the Goldsborough Dam Removal project on Goldsborough Creek in Mason County. At that site, the plunge pool downstream of each weir was lined with a 12" layer of riprap below a design scour depth of 6 feet. Lining the plunge pools is less desirable than other methods to prevent structure undermining due to the risk of forcing the plunge pool to extend horizontally into the banks or longitudinally into the next downstream structure in order to achieve the pool volume necessary to fully dissipate the energy over the drop. Any excess energy due to inadequate pool volume will be transferred downstream where it may scour the channel bed or banks.

In addition to energy dissipation, adequate plunge pool depth is necessary to enable fish to leap over a drop. Stuart[11] (as cited by Powers and Orsborn[12]) suggests that the minimum plunge pool depth should be 1.25 times height of the drop to provide the best standing wave for leaping salmonids. Aaserude[13] (also cited by Powers and Orsborn[12]) reported that optimal leaping conditions for coho and chum salmon in a test fishway at Johns Creek Fish Hatchery near Shelton, Washington occurred when the plunge pool depth exceeded the depth of penetration of the falling water. And the depth of the plunge pool was equal to or greater than the length of the fish trying to pass. It is recommended that a pool at least two feet deep by six feet long be excavated immediately downstream of each drop structure during construction in preparation for the plunge pool that will develop[4]. Otherwise, there is an increased risk that fish passage will be impeded prior to plunge pool formation and that initial high flows will stream over the structure such that energy is not fully dissipated and the downstream channel erodes.

There is a risk that if a lower drop structure of a series fails, those above it will be undermined and fail in a chain reaction. To limit the extent of any chain reaction, it's recommended that, if a number of drop structures are placed in a series, deeper structures should be placed at intervals (for instance, every fifth structure)[4]. These deeper structures should be designed as independent dams, assuming the downstream controls do not maintain a backwater.

Although typically placed above the existing grade of the channel, drop structures can be constructed at or below grade to account for and limit future changes to the channel profile that could create a barrier to fish passage over the weir or ultimately undermine the weir and cause it to fail. Subsurface drop structures are especially useful in newly constructed channels and at the lower end of a series of drop structures. Energy is often not fully dissipated over a drop structure series during peak floods[4]. The downstream channel is, therefore scoured and lowered in the vicinity of the logs.

6.2.2 Preventing structure end run

End runs, or flanking of a structure, are most likely to occur when the structure or the next upstream structure directs flow towards the bank, when the downstream plunge pool extends laterally to the banks and erodes the bank toe, or when overbank flow spilling into the channel scours the bank creating a headcut around the structure. The risk of an end run can be minimized by configuring the weir such that water is directed towards the center of the channel rather than toward the banks during all flows and by keying the structure into the banks. The extent to which the structure is keyed into the banks will depend upon bank characteristics and the stability of the channel. The key should extend from the bank line into the bank at a slope of 1.5H:1V or flatter. The minimum recommended length for a rock drop structure bank key is four times the D_{100} diameter of the header rocks[14] or six feet[6]. The minimum recommended length for a log drop structure bank key is five feet. In laterally dynamic channels that have a high probability of frequent or impending channel shifts, it may be appropriate to install structures to the full width of the floodplain. The above recommended bank key lengths are measured perpendicular to the bank line, even if the key itself is at an angle. Materials keyed into the bank should be of the same dimensions as those used within the wetted channel.

Armor is often placed on the banks near the structure (generally 3 feet upstream and far enough downstream to reach the beginning of the pool tailout). An exception may be when the weir is configured to concentrate and direct flow into the center of the channel at all flows. Though riprap is most commonly used, other materials can be utilized such as logs, coir, or root wads. Armor placed downstream of the structure should extend to the anticipated depth of scour. Otherwise, it will simply fall into the scour pool as it develops alongside it. Alternatively, bank armoring can be placed along the bank as launchable material (see the Integrated Streambank Protection Guideline's[2] *Riprap* technique for more information on launchable rock. When using riprap, care should be taken to fill the voids in the riprap as much as possible to minimize interstitial flow and piping of bank material.

It is important to minimize bank disturbance and vegetation removal during construction. Revegetating the bank at both keys is necessary for added structural strength cover, shade and habitat needs.

6.2.3 Minimizing Subsurface Flow

It is critical in small streams to minimize the occurrence of subsurface flow where the potential exists for a substantial portion, if not the entire amount, of low flow to go subsurface through the structure and thus prevent fish passage. Subsurface flow may occur through any porous elements of the structure (e.g., between the logs of a double log weir, between the boulders of a boulder weir, or through the riprap armoring the banks adjacent to the weir). Sealing of the voids in the structure is most often achieved by installing a well-graded mix of sediment (including at least 10 to 15 percent fines) upstream of the structure and within the voids of any rock (e.g., boulders, riprap) utilized in the design. Woven geotextile fabric is typically placed between the structure and the added sediment mix to prevent piping of material. This fabric should extend from the top of the drop structure, down its upstream face to a depth at least two feet below the streambed, and upstream at least five feet. The sides of the fabric along the banks should be at least as high as the top of the weir and should extend into the key trenches to completely seal the structure. Installing the fabric in this manner minimizes the risk of fabric exposure which often occurs as a result of installing the fabric too close to the bed surface such that it becomes subject to abrasion, tearing, and photodecomposition.

Geotextile fabric used in drop structure construction should have a tensile strength of at least 600 lbs and a burst strength of at least 1,200 lbs[4]. It is sometimes underlain by wire fencing for reinforcement, as necessary. Geotextile fabric has the advantages of longevity, availability, and flexibility for ease of construction. It is easier to install than impermeable material, which tends to billow in the stream current during installation and is extremely vulnerable to punctures. Impermeable liners may, however, be necessary at sites with a limited source of sediment (e.g., downstream of pond or reservoir, or within a groundwater-fed channel). Consult the liner manufacturer for installation recommendations.

Once sealed, the drop structure should remain sealed provided that the sealant material is not transported downstream (e.g., in a low energy groundwater-fed side channel not subject to storm flows). If it is, the seal will be maintained only if hydraulic conditions allow a fresh supply of bed material transported from upstream during high flow events to accumulate and protect the upstream face of the structure. For the latter to occur, the stream must carry an adequate supply of sediment, including fines, to replenish the lost material. Any upstream structures (including other drop structures, wood, or boulders) must be located sufficiently far enough upstream such that their associated scour pools do not extend to the drop structure in question.

Note that subsurface flow may occur at newly constructed drop structures, but they should seal after the first high flow events.

6.2.4 Material Selection

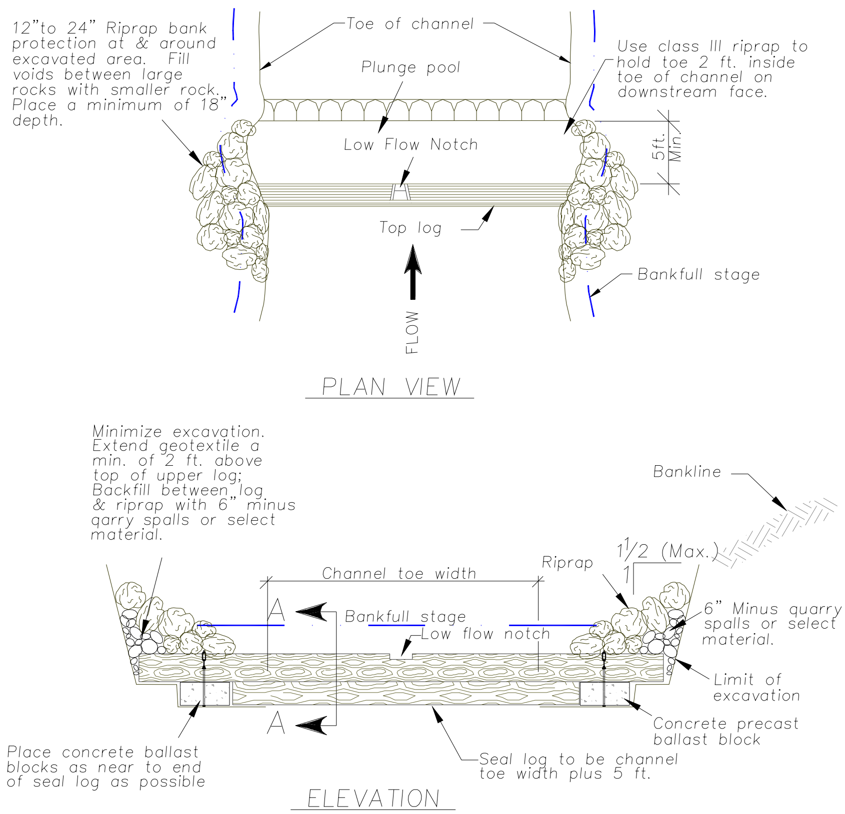
Drop structures are typically constructed using rock, wood planks or logs, although sheet pile, concrete, and other artificial material may also be used. The selection of material should be based, in part, on the required durability and deformability to meet design criteria. Drop structures installed to provide fish passage over or through a man-made obstruction must persist, or be replaced, so as to provide fish passage as long as the obstruction exists. In other settings, drop structures may only be required to provide temporary stability and hydraulic effects and so may deform over time. Another potential design criterion is aesthetics. Drop structures constructed in a stream dominated by large wood should be comprised primarily of wood, while those in a boulder dominated stream should be comprised of rock in order to blend with their surroundings. Similarly, the species of wood, and type of rock, should be selected to replicate the naturally occurring materials. Limitations on equipment, access, cost, and available materials will also influence material selection.

Drop Structure Table 1: General comparison of drop structure types.

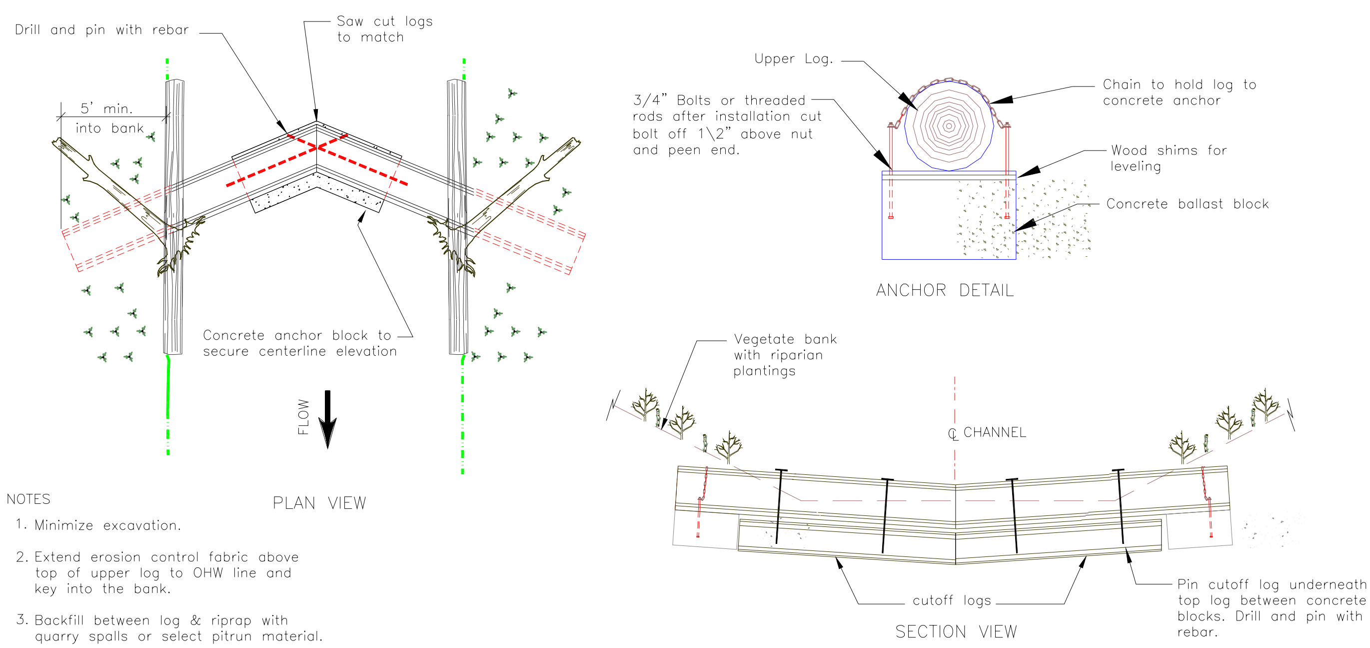
Type of Drop Structure	Advantages	Disadvantages
Log Weirs	Low cost; durable	Limited to ~30' max channel toe width; Max recommended final grade is 5% for straight weirs and 3% for up-stream pointing arch or chevron weirs; Wood will decompose over time if exposed to drying and wetting; Wood must be securely anchored to counteract its buoyancy
Boulder Weirs	Deformable; Due to uneven nature of boulders, provides greater diversity of water depths and velocities over the weir; May be installed in relatively wide channels	Greater uncertainty of long-term durability; Difficult to maintain a specific water surface elevation; Inappropriate in sandy and other fine-grained streams; 9" max recommended drop
Plank Weirs	May be installed by hand; Well-suited to streams with sandy beds; Low cost	Less durability; Limited to small or groundwater-fed streams with regular flow
Concrete or Sheet Pile Weirs	Self-ballasting; Impermeable Deep cutoff wall	Aesthetics; Large equipment required to place heavy, pre-cast concrete units and drive sheet pile

Wood

Wooden drop structures may be comprised of entire logs or wooden planks. Log weirs can be built into the streambed to span the entire channel width. They are a low-cost and durable means of fish passage for streams with natural gradients of less than about three percent and channel toe widths of less than about 30 feet. Adequately sized material for wider streams may be relatively difficult to find, costly, and have higher environmental impacts on the source area. A variety of designs have been employed, including single logs, multiple logs, straight weirs, angled weirs, V-weirs, and K-dams. Design of simple, straight, double-log weirs is detailed in the Design of Road Culverts for Fish Passage[4] and illustrated in **Drop Structure Figure 1**. Refer to **Drop Structure Figure 2** for an example of a chevron weir design.



Drop Structure Figure 1

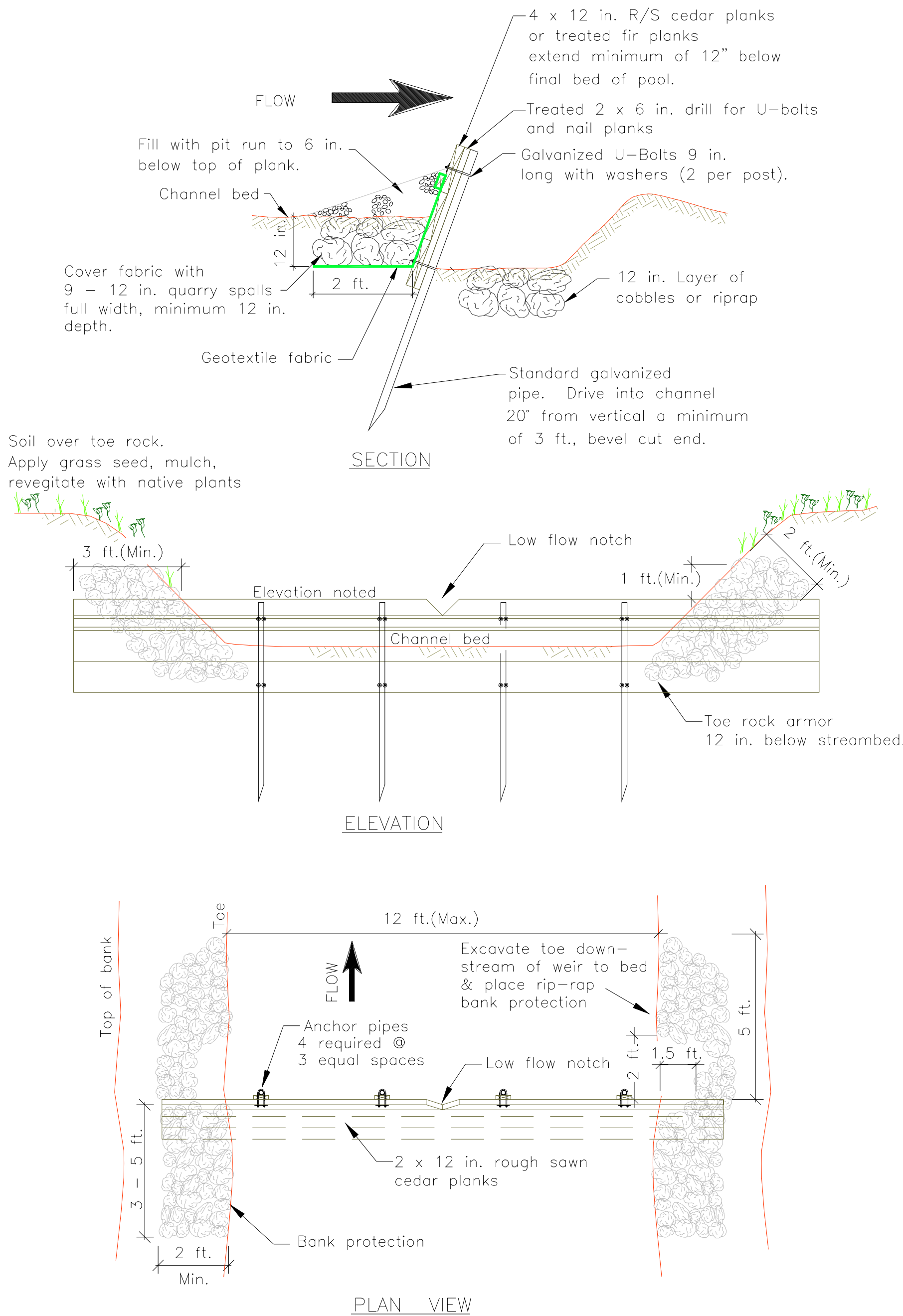


Drop Structure Figure 2

Disadvantages of log weirs include their eventual decomposition and the common requirement for anchoring logs with rock, concrete blocks, or other ballast to counteract their buoyancy (refer to the *Anchoring and Placement of Large Wood* appendix). Slow-decaying species such as cedar, fir, and pine are recommended to maximize the design life of the drop structure. Use of deciduous species such as alder or maple is discouraged, as their decomposition rates are relatively high. However, if the log remains submerged year round, their life expectancy is greatly increased[15].

Although log weirs are by far the most common form of wooden drop structure, wooden plank weirs have their application. Being thinner than entire logs, they are less strong and subject to decay that is more rapid. As a result, plank weirs are typically used in very small streams or ground water channels where stream energy, debris load, and sediment load are low. Plank weirs are especially useful for providing upstream juvenile salmonid passage in small streams and creating a backwater for placing and retaining spawning gravel. They are well suited for streams with sandy beds.

A benefit of plank weirs is that they can be constructed entirely by hand, thereby reducing construction impacts to the riparian zone and access areas. Plank weirs are comprised of rough-cut, milled timbers. Untreated fir timbers are used in perennial streams where the wood will always be submerged. Cedar is used in intermittent streams. Straight plank weirs have an application limited to channel toe widths of about 10 feet. (The maximum standard timber length available is 16 feet; each end is embedded three feet into the bank.) Plank weirs have been constructed in wider channels using zigzag and spider-weir designs to shorten the span lengths of individual members. Design of Road Culverts for Fish Passage[4] provides further details on plank weir design. A typical plank weir design is illustrated in **Drop Structure Figure 3**.



Drop Structure Figure 3: Conceptual plank weir design.

Rock:
The size, shape, and placement of rocks that comprise a drop structure are chief factors governing its longevity. Individual rocks must remain relatively immobile up to the selected design flow, with the knowledge that some shifting and settling may occur. Forces acting on the rock include stabilizing gravitational forces and destabilizing forces related to the momentum of flow impinging on the rock and hydrodynamic lift forces

from flows over the top of the rock[16]. Additional force may be exerted on the rock by wood, debris, or ice.

Riprap sizing methods are based on a blanket of stone, placed roughly parallel to flow, and rely on interlocking for a degree of stability. As a result, the size of rock determined by standard riprap-sizing procedures will be too small for drop structures unless allowances have been made to account for impinging flow, such as those described in EM 1110-2-1601[17]. The NRCS suggests using standard riprap sizing criteria at the design flow, but modifying it in the following manner:

$$D_{50\text{-weir}} = 2 \times D_{50\text{-riprap}}$$
$$D_{100\text{-weir}} = 2 \times D_{50\text{-weir}}$$
$$D_{min\text{-weir}} = 0.75 \times D_{50\text{-riprap}}$$

Incipient motion equations for coarse boulder movement may be more applicable to drop structure design than riprap sizing equations as they do not rely on inter-stone contact. Two such equations, developed independently by Isbash[18] and Costa[19], are included below.

Isbash conducted hydraulic investigations concerning the phenomena that occur when constructing rock dams in running water. The minimum velocity necessary to remove loose stones lying in a channel on top of rock fill was documented to be:

$$V_{min} = 0.86 \{2\ g\ [(SG_s - SG_w)/SG_w]\}^{.5}\ D^{.5} \qquad \text{[Isbash, 1936 [18]]}$$

where: V_{min} = minimum velocity
g = gravity = 32.2 ft/s^2 = 9.81 m/s^2
SG_s = specific gravity of stone, varies with the type of stone—generally ranges from 2.2 to 3.2
SG_w = specific gravity of water, generally assumed = 1.0
D = diameter of the stone (assuming a spherical shape)

Rearranged to solve for the minimum diameter of stone (D_{min}) necessary to withstand a given design velocity (V), Isbash's equation becomes:

$$\mathbf{D_{min} = V^2/\{1.479\ g\ [(SG_s - SG_w)/SG_w]\}} \qquad \text{[Equ. 1]}$$

Costa studied nine steep bedrock channels in the Colorado Front Range to test the accuracy of velocity and depth estimates for historic peak floods based on the size of boulders transported during the flood event. He developed the following equation by taking the arithmetic average of four commonly used methods for computing stream velocity.

$$V_{avg} = 9.571\ D^{.487} \qquad \text{[Costa, 1983 [19]]}$$

where: V_{avg} = average velocity (ft/s)
D = diameter of the stone (ft)

Rearranging to solve for D:

$$\mathbf{D_{min} = (V_{avg}/9.571)^{2.05}} \qquad \text{[Equ. 2]}$$

Note that D_{min} represents the maximum rock size likely to move for a given velocity and, therefore, a minimum rock size to be utilized within an in-stream structure subject to direct flow. As a factor of safety, it is recommended that D_{50} of the structure be at least 2 times D_{min}. D_{100} of the structure should be approximately 1.5 times D_{50}.

Drop Structures Table 2 includes rock specifications developed by Allan and Lowe[6] for in-stream structures. They suggest that rock from the next lowest velocity column may be applied to bank armor and keys as they do not lie within the channel. However, because the bank keys may become exposed at some time, this document recommends that the key be comprised of the same size of material as that used within the channel. For comparison, minimum stone diameters calculated using Equations 1 and 2 are also provided.

Drop Structures Table 2: Specifications for rock for in-stream structures. (Modified from Allan and Lowe[6])

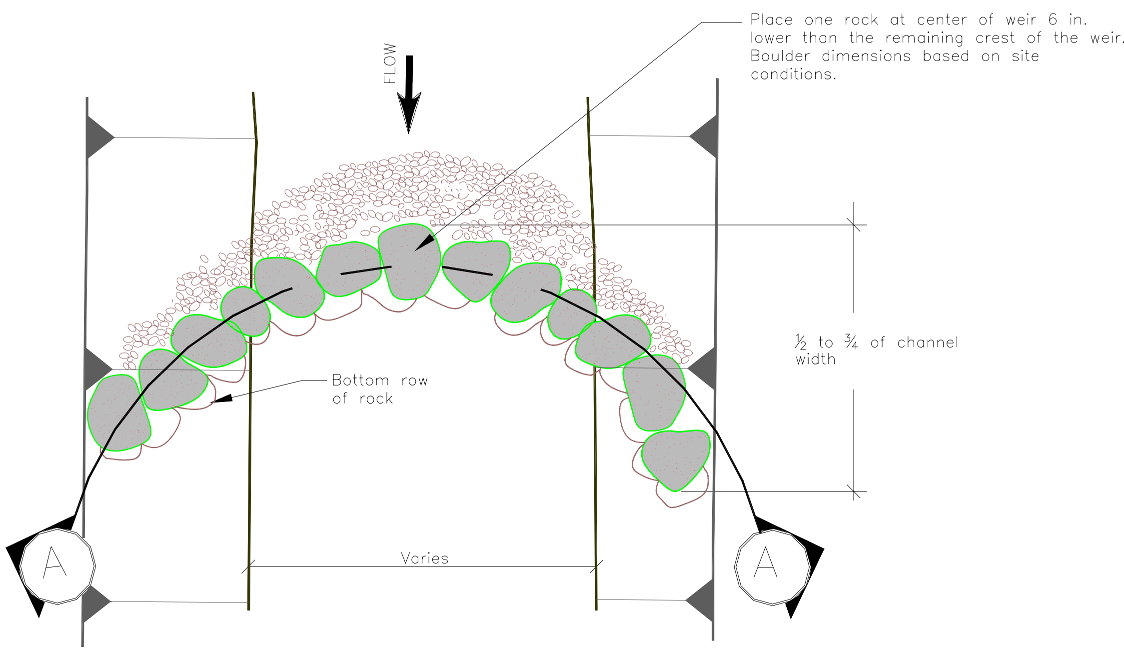
	Design Velocity			
Nominal Rock Diameter	<7.5 ft /s	<9.8 ft /s	<12.5 ft /s	<15.4 ft/s
D_{max}	2.6 ft (1540 lb)	3.9 ft (5290 lb)	5.9 ft (17600 lb)	8.8 ft (59500 lb)
D80	2.0 ft (660 lb)	3.0 ft (2200 lb)	4.9 ft (10400 lb)	7.2 ft (33100 lb)
D50	1.6 ft (440 lb)	2.6 ft (1540 lb)	3.9 ft (5290 lb)	5.9 ft (17600 lb)
D20	1.0 ft (90 lb)	1.6 ft 440 lb)	2.6 ft (1540 lb)	3.9 ft (5290 lb)
Isbash[18] (Equ. 1)[a]				
D_{min}	0.7 ft	1.1 ft	1.8 ft	2.7 ft
Costa[19] (Equ. 2)				
D_{min}	0.6 ft	1.1 ft	1.8 ft	2.7 ft

[a] Specific gravity of stone assumed equal to 2.85.

Rock sizes should be verified by engineering judgment and comparison to field conditions as hydraulic models can be limited in their ability to accurately predict rapidly varied hydraulic conditions that occur at the crest and along the profile of the drop structure. The minimum required rock size for drop structures should be at least as large as naturally occurring rocks in the channel under similar conditions; twice the D_{100} is recommended[4]. As a rule of thumb, drop structures in small, lower-gradient streams should use a minimum two-foot mean-dimension rock. Larger, higher-gradient streams require rock as large as four to six feet.

Rock should be sound, durable, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular rock is preferred over rounded rock for its ability to lock tightly together to prevent movement during high flows and the fact that it is also less likely to roll. Its greatest dimension should be no greater than three times the least dimension[20]. The diameter of rounded rock, if used, will have to be greater than the mean dimension of angular rock to provide the same resistance to entrainment.

Boulder weirs are typically placed in an upstream-pointing configuration to maximize their stability, although other configurations can be used. Careful attention must be paid to ensure that rocks are stable and gaps between rocks are reduced to a minimum. Place rock at a stable angle of repose so that it will remain in place once the plunge pool forms. Care must be taken to ensure that rock placed near the plunge pool does not obstruct plunging flow over the weir or block fish passage. Further guidance on boulder weir design is provided in the Design of Road Culverts for Fish Passage[4] and illustrated in **Drop Structure Figure 4**.



Drop Structure Figure 4: Conceptual boulder weir design.

6.2.5 Ensuring unobstructed fish passage

Even if fish passage is not the primary goal, in fish bearing waters it is a requirement that any human-made obstruction across or in a stream must freely pass fish [RCW77.55.060]. For fish passage to be achieved, the hydraulic drop over the structure must not exceed maximum criteria for fishways given in WAC220-110-070 and summarized below in **Drop Structure Table 2.**

Drop Structure Table 2: Maximum allowable hydraulic drop in fishways [WAC220-110-070]

Adult Trout >6” (150 mm)	Adult Pink, Chum Salmon	Adult Chinook, Coho, Sockeye Salmon, Steelhead
0.8 ft	0.8 ft	1.0 ft

If upstream passage of juvenile salmonids is critical, the drop is dependent on structure type and flow profile but should be a maximum of 0.7 feet. Other fish and wildlife species may require lesser drops. Note that, due to the deformability and mixed success of boulder weirs, it’s recommended that their use be limited to a maximum drop of 9 inches (0.75 feet). Improvements in design and construction of this technique may eventually expand their recommended application.

Hydraulic drop is the difference in elevation between the water surface upstream and downstream of the structure. Typically, the maximum hydraulic drop is equal to the elevation drop between the tops of two successive weirs, provided the conditions at each weir are the same. However, conditions may differ significantly if the degree of backwater upstream of the uppermost weir is higher than that for the lower weir, causing a greater drop to form over the structure. The maximum allowable hydraulic drop in Table 2 must be satisfied at all flows between the low and high fish-passage design flow. The low fish passage design flow is the two-year, seven-day, low-flow discharge or 95-percent exceedance flow during the migration months for the species of concern. The high fish passage design flow is the flow that is not exceeded for more than 10 percent of the time during the months of fish migration. The two-year peak flow may be used as the high fish passage flow when stream-discharge data is unavailable.

To maximize the depth of flow over the structure during low summer flow, and thus improve fish passage, flow should be concentrated through a low point on the structure. This may be accomplished by cutting a notch in the log or plank or having the structure slope to one low spot, usually in the middle third of the channel. The notch should be cut during low flow after the structure is installed to ensure that it isn’t so big that the rest of the log is dewatered. If it becomes dewatered, the likelihood is it will decay more quickly. Notches should be sloped down in the direction of flow so that fish don’t have to struggle across a long flat weir crest.

The nappe of flow plunging over the structure and the plunge pool should both be kept free of rock and debris to facilitate fish passage.

6.2.6 Structure Configuration

A drop structure’s configuration in plan form and cross-section influences its hydraulic effect on the stream and the shape of the channel bed. Drop structures can be built in a number of different configurations. The effects of typical configurations are described and illustrated below. Desired habitat modifications and other project objectives dictate the type of structure selected.

Channel-spanning structures that are straight, level, and placed perpendicular to flow evenly spread water and energy out across the stream and encourage a relatively flat cross-section upstream. They have limited backwater effect once bed material fills in to the top of the weir. The plunge pool created at the base of the structure tends to be wide and shallow and spans the entire channel. Such weirs generate a minimum degree of bedform complexity. They can also contribute to bank erosion by directing energy towards channel margins rather than concentrating it in the center of the channel. As a result, such structures are not recommended where bank protection or habitat enhancement within the altered reach is one of the primary objectives. They are more applicable where a short series of drop structures are intended to provide fish passage over or through a man-made obstruction to gain access to habitat upstream. Level weirs should include a low-flow notch to facilitate fish passage (see Section 6.2.5, *Ensuring Unobstructed Fish Passage* for guidance).

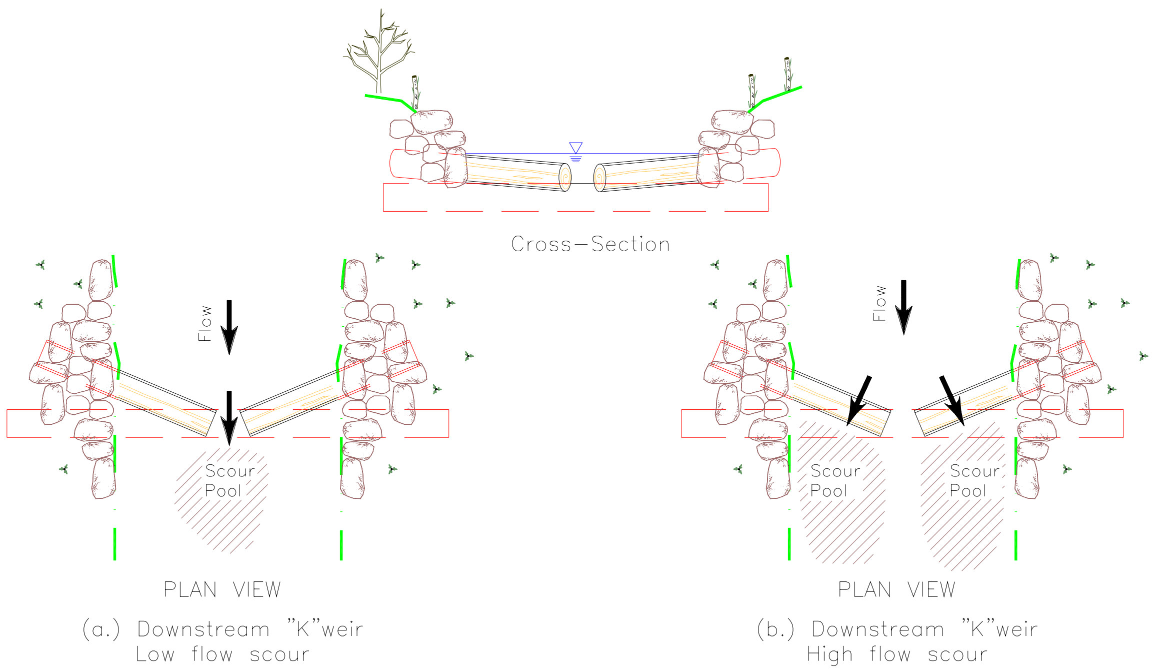
Flow over a drop structure moves roughly perpendicular to its alignment in planform and is funneled towards any low spots that occur on the structure. Thus, drop structures may redirect, concentrate, or disperse flow depending on their shape. Straight weirs oriented diagonally to flow can be used to redirect flow towards or away from channel features. Typically installed such that the upstream end is lower than the downstream end (California Fish and Game recommends a drop in elevation of 6 inches for every 10 feet of weir length[21]), diagonal weirs, also known as sloped log weirs, are effective at collecting sediment along the bank at the higher end of the log.

Arch or chevron ("V" shaped) weirs in plan view concentrate flow through their apex when pointing upstream, and direct flow to the outside of the channel when pointing downstream. Chevron drop structures are hydraulically very similar to barbs (see the Integrated Streambank Protection Guidelines[2], Chapter 6); they are basically two barbs that extend from opposite banks toward one another and connect at the center of the channel. Upstream-pointing structures create longer and deeper, but narrower plunge pools than straight weirs and avoid potential impacts to adjacent streambanks. They have the strength inherent in an arch design[6]; the thrust of streamflow and bedload is transferred through the weir into the banks making them more stable than straight or downstream-pointing weirs. Downstream-pointing weirs are more effective at dissipating energy as they spread scour over a wider area, creating shallower pools. They are frequently used to collect gravel to create spawning habitat[21]. Their application, however, is limited to areas with good bank stability.

The recommended angle of the apex of upstream and downstream-pointing weirs ranges from 90^{o} [22] to 120^{o} [7]. As the angle of the apex decreases (the point gets sharper), the scale of effects resulting from flow redirection increases such that more and more flow is directed to the center of the channel at upstream-pointing weirs, deepening the pool and increasing the risk of undermining, and more and more flow is directed into the banks at downstream-pointing weirs.

Arch and chevron drop structures can be symmetrical or asymmetrical, depending upon the thalweg alignment as it approaches the structure and the desired thalweg alignment immediately downstream. Typically, the apex is located within the center third of the channel. A meandering thalweg can provide additional channel complexity and should be taken into account in positioning the apex. WDFW recommends that upstream-pointing weirs be limited to a final grade of 3 percent whereas straight weirs can be placed at a final grade of 5 percent. Chevron weirs concentrate flow energy toward the center of the channel at the thalweg. Straight weirs spread the energy across the channel and are therefore more efficient at energy dissipation, which allows them to be placed in steeper streams.

Drop structures can be designed and constructed to appear relatively random in configuration to promote maximum hydraulic complexity and natural appearance, similar to natural step-pool structures. Natural step pools and drops within the same or similar streams provide excellent analogs for arrangement and orientation of drop structures. However, the proximity to infrastructure may place limitations on the orientation of redirected flow or the degree of allowable backwatering. Flow should not be directed into structure footings or bridge pilings as it may undermine the structure. When designing drop structures, consider how water will interact with the structure at various flows. A structure that funnels flow to the center of the channel during low flow events may direct water to the banks during high flow events (see **Drop Structure Figure 5**). This will need to be accounted for in the design.

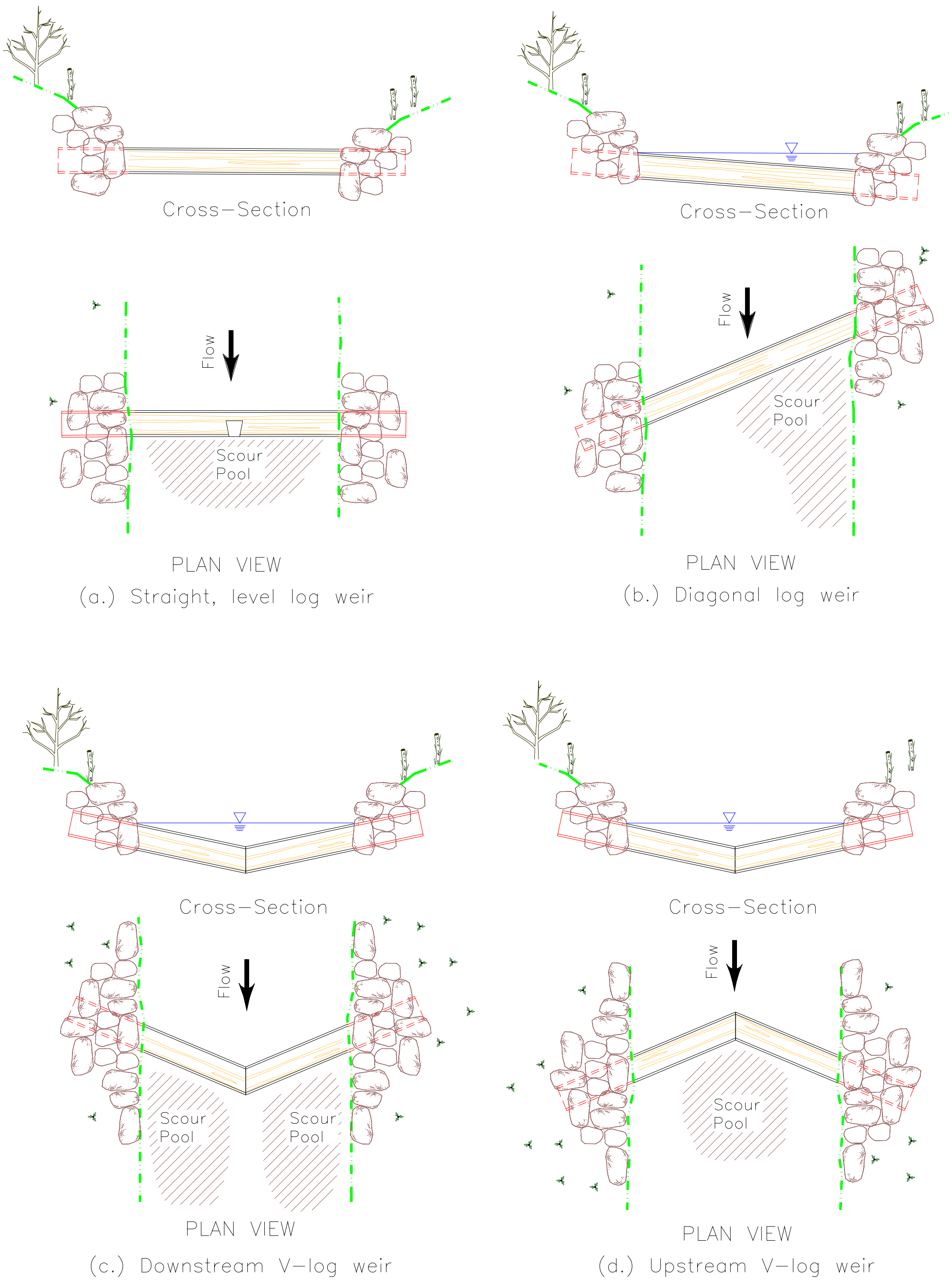


Drop Structure Figure 5: "K"-weir with side logs resting on top of main log during (a) low flow, and (b) high flow events where flow overtops the side logs.

Drop structures that are sloped down from the banks will maintain a concentrated low flow channel thalweg and have increased backwater effects over a level weir. Generally, the horizontal-to-vertical ratio for this slope should not exceed 5H:1V. At the bank line, the top of the structure should not exceed the elevation of the ordinary high water mark.

The lowest point in the structure should coincide with the elevation of the desired thalweg. The bigger the difference between the low and high elevation on the weir, the greater the backwater effect and the higher likelihood that wood or other objects will become trapped on the structure. For example, K weirs in the configuration illustrated above create significantly higher backwater than a level weir. Potential backwater effects include deeper water, gravel accumulation, and increased risk of upstream flooding, aggradation, and bank erosion, among others (see Section 2, *Physical and Biological Effects* for further information). These effects may be positive or negative depending on their magnitude, extent, and on site conditions and limitations. Significant backwater will likely need to be avoided where it may put nearby infrastructure or developed property at risk of flooding. A typical rule of thumb provided by Fripp et al.[7] is that backwater effects of a structure will be negligible at water depths over five times its height. Therefore, provided the height of the structure remains less than twenty percent of the height of the bank, no noticeable increase in out of bank flow should occur. However, patterns of sediment scour and deposition may still be affected. Possible affects of backwater should be considered on a case-by-case basis.

It is recommended that the configuration of structures placed in series be similar in order to produce uniform hydraulics during high flows[4]. The water depth over a weir varies with its configuration. Where structures with differing configuration are used, there is a greater risk of creating hydraulic drops that exceed fish passage criteria.



Drop Structure Figure 6: Typical Patterns of Scour Associated with Common Drop Structure Configurations.

6.2.7 Structure Elevation

The desired upstream water stage, allowable head differential between drop structures, and desired hydraulic effects will help dictate the height of the drop structure. The presence of infrastructure may also dictate the desired elevation of the structure, such as if the bed needs to be raised or maintained to cover an upstream pipeline.

Although typically placed above the existing grade of the channel, drop structures can be constructed at or below grade to limit future changes to the channel profile. This is especially useful in newly constructed channels and at the lower end of a series of drop structures.

6.2.8 Structure Spacing.

Drop-structure spacing is based primarily on project objectives, channel gradient, maximum allowable hydraulic drop, and plunge pool characteristics at the design flow, although access limitations may also be a factor. Generally, steeper channels will require more frequent structure placement. Consider a natural step-pool system, where each step backwaters the channel upstream such that each upstream step spills water into a backwatered pool. Step-pool channels are most common on slopes between 4 and 8 percent[23]. Steps are commonly spaced between 2 and 4 channel widths[24]. However, experience has found that man-made drop structures installed at gradients higher than 5% for straight weirs and 3% for upstream-pointing weirs and boulder weirs are subject to higher rates of failure and unintended project impacts (see Section 4, *Application* and Section 6.2.6, *Structure Configuration*). These limiting slope criteria can be used to determine the minimum recommended spacing between weirs for a given hydraulic drop.

Min spacing = Max hydraulic drop/ Max final channel gradient

Slope criteria may be revised, as drop structure design is refined over time. Where constructing a long series of structures over an entire reach, the designer may want to consider breaking them up into smaller groups with resting areas in between.

6.2.9 Incorporating large wood into drop structure design

Large wood can be incorporated into the drop structure for added habitat benefit, additional roughness, and flow realignment. When adding wood near drop structures, consideration must be given to the scour, deposition, and flow patterns that are likely to develop. Care should be taken to ensure that flow is not directed to bypass or flank the next downstream structure and that the scour pool does not undermine adjacent drop structures or prevent them from sealing. Consideration should also be given to the fact that wood can create a constriction and additional backwater that may or may not be desirable. Wood may also recruit additional wood and other material moving downstream which can exacerbate constriction and backwater effects, impede fish passage over the weirs, and can cause unexpected shifts in flow direction or scour and deposition patterns. For this reason, wood is most often placed in or along the fringe of the plunge pool created by the drop structure where it can provide critical in-stream cover, in the adjacent floodplain to provide floodplain refuge, or in the upstream or downstream channel away from the drop structures (the later two options pose the least risk of compromising the structure). Structures low in profile that don’t constrict a significant percentage of the channel will be less likely to trap material and create backwater. Refer to the *Anchoring and Placement of Large Wood* appendix and the *Large Wood and Log Jams* technique for further guidance on wood placement.

6.2.10 Deformable Drop Structures

When the situation allows (e.g., when a drop structure is installed purely to create channel complexity, provide temporary bed stability, or slow channel regrade), drop structures may be designed to deform over time through undermining, end scour, or entrainment of structural components. Deformation generally occurs during high flow events that exceed the design flow, or because of channel incision or other changing watershed conditions. Deformation differs from design life and ultimate failure – deformation implies that the function of a structure may evolve or diminish over time through gradual mobility of materials rather than catastrophic and sudden failure. For instance, the function of a boulder weir may change from a drop structure to a low cascade and, eventually, to a short roughened channel as rocks roll and disperse before settling into the bed through natural scour and settling processes. In contrast, rigid structures (log, plank, concrete, or sheet pile weirs) cannot adjust to changing flows, stream profile, cross-section, or planform. For these reasons, rigid drop structures are not generally recommended in habitat enhancement projects except for the purpose of providing fish passage through man-made structures and other situations where long-term monitoring and maintenance can be guaranteed.

Rock lends itself best as a building material in deformable drop structures. However, any natural material may be used. Unnatural materials, such as rebar, wire rope, and concrete blocks should be avoided. Deformability may be achieved by sizing the rock to withstand relatively low design flows, or by minimizing the amount of structure keyed into the channel bed or banks to prevent undermining and end runs, respectively. Designers should note that there is a high degree of uncertainty in the final form of a deformable drop structure once it deforms. Deformable drop structures placed in series may create fish passage barriers due to uneven deterioration of weirs over time.

7 PERMITTING

The installation of drop structures involves in-channel work, streambed and bank excavation, and the placement of fill within the channel. Required permits and checklists may include, but are not limited to: State Environmental Policy Act (SEPA) and a Joint Aquatic Resource Permits Application (JARPA) (including a Hydraulic Project Approval and possibly a Shoreline Management Act Permit, Section 401 Certification, and a Section 404 Permit). A Clearing and Grading Permit and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Typical Permits Required for Work in and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

8 CONSTRUCTION CONSIDERATIONS

As with all in-channel construction, the installation of drop structures will result in considerable in-stream disturbance in the form of increased turbidity and rearranging of bed and bank material. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. In addition to in-stream habitat, consideration should be given to the potential riparian habitat impacts to access and staging areas for construction. Access and staging areas will probably experience short-term impacts and will require reclamation and revegetation.

Principle construction considerations that apply to drop structures include:

- Fish exclusion/removal
- Isolating the work site/dewatering. To facilitate construction and meet regulatory restrictions the work area will need to be isolated from stream flow during construction. This is most commonly achieved with a diversion dike or flow bypass[7]. A diversion dike can be used to neck down the stream width to allow work on one streambank at a time. Cofferdams can be used to bypass flow around the entire construction site using pumps or a bypass pipe or channel. It is important to note that constructing a by-pass channel may involve substantial disturbance to the riparian corridor. Measures should be in place to accommodate storm flows during construction.
- Dirty construction water handling
- Temporary Erosion and Sediment Control (TESC) for the banks
- Permit timing, anticipated allowable construction dates
- Access – proximity to site, disturbance of existing vegetation. Because series of drop structures are often constructed in sequence, generally starting from the upstream end and working downstream, access considerations are particularly important to minimize the need to access the channel at multiple points.
- Material size, volume, and availability.
- Restoration of disturbed areas, including staging and access areas, but especially banks affected by installation of structural keys or securing of log materials

Use of experienced contractors with a proven record of accomplishment for constructing in-stream projects with minimal impacts to the environment can facilitate installation. Drop structures will benefit greatly from significant experienced construction oversight and some degree of flexibility in contracting. Construction conducted without careful oversight and done with rigid contracting specifications will likely result in uniform structures that do not maximize the potential added value resulting from creative and variable placement of rock and wood components.

8.1 Equipment Required

Equipment require to install drop structures will depend on the following variables:

- Access limitations
- Size of materials used in construction
- Size of channel

Tracked excavators are typically the most appropriate type of equipment to perform the majority of the instream work, including excavation and installation. However, plank structures can be installed by hand labor and tools. Access or other restrictions may require the use of spider-hoe excavators. Material delivery may require street-legal dump trucks and 4-wheel drive loaders to move material from a stockpile to the project site.

8.2 Timing Considerations

Drop structures should be constructed during low-flow conditions to minimize instream disturbance. It is typically necessary to work within the stream channel to construct drop structures, which means it may be necessary to dewater the channel. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows. Further discussion of construction timing can also be found in the *Construction Considerations* appendix.

8.3 Cost Estimation

The total material and construction costs for drop structure installation ranges from approximately $1,500 to $3,000 per structure, assuming a channel width of 10 to 30 feet. This range excludes the cost of design and permitting. Installation cost will be determined primarily by the size of the channel, cost of materials, proximity of the construction site to the source of materials, equipment and operator rates, access limitations, and the need for dewatering. Rock materials typically range in cost from $25 to $80 per cubic yard. Typical costs for installed rock range from $50 to $100 per cubic yard depending on source and equipment access difficulty. Dewatering, if required, will greatly increase the cost of the treatment. Additionally, access for large equipment may require that either a temporary access road be constructed, or that specialized equipment such as a spider hoe and tracked dump trucks be used to cross riparian areas for channel access and materials delivery. Refer to the Integrated Streambank Protection Guidelines'[2] *Cost of Techniques* appendix for further discussion of material and construction costs.

Cost of logs for log control structures are becoming increasingly more expensive and reflect the current value of saw logs. This figure fluctuates and is often market driven as well as geographically driven. In 2003, a 40-foot long fir log that was 18"-24" in diameter and sound with no apparent rot cost just over $200 each. An extra fee was charged for delivering the logs to the site at a cost of $200 per load.

Complex drop structure designs and projects on small streams that will likely cause significant disturbance to the channel (e.g., a long series of drop structures) may be best contracted as time and materials contracts as they will require considerable detail work. Drop structures on larger streams (greater than 20 feet wide) may be contracted as lump sum contracts if sufficient detail is provided in construction plans and specifications. The amount of detail provided in plans and specifications should be considered when selecting a contract format, and vice-versa.

9 MONITORING

Drop structures may be installed for a number of different reasons and the risks to habitat and infrastructure associated with drop structure placement will vary between sites. Therefore, monitoring requirements to evaluate the effectiveness and impacts of drop structure placement will vary from project to project. At a minimum, monitoring should include annual evaluations of drop structure integrity and their ability to provide unobstructed fish passage to determine if maintenance is required. Conduct an as-built survey to document the location, elevation, and configuration of each structure. An inspection should be conducted early in the project life after a significant flood event, and in later years following flows greater than a 5- to 10-year flood event. The inspection should look for evidence of settling, movement, undercutting, flanking, and subsurface flow. Small movement of individual stones is acceptable but significant movement is probably indicative of a failure in design and may necessitate repair or replacement. Note if there is any exposed fabric. This may cause a break in seal and eventually lead to undermining of the structure. Is there undo wear on the structure resulting from high bed and debris load? Is there any debris accumulation that may require clearing? Should there be frequent inspection to ensure it does not become a problem? Is infrastructure, public safety, or habitat compromised or at risk because of the structure? Is there any evidence of any downstream channel incision that may require installation of additional drop structures to continue to meet fish passage criteria and to prevent undercutting of the weir? A general, qualitative description of the drop structure should also be recorded and may include such observations as its general effect on channel flow characteristics and a visual description of the drop structure. Photos and descriptions of observations made safely during low flow and flood events are particularly useful. Where wood and debris recruitment is likely to occur on or adjacent to drop structures such that fish passage may be impeded, multiple surveys should be conducted during critical periods of fish passage.

Long-term monitoring of other parameters (such as the impacts a drop structure has on the channel, bank stability, the abundance and favorability of habitat for fish and other aquatic species, fish production, infrastructure, and water levels) will probably require both pre-project and post-project surveys. The level and frequency of monitoring required will vary with monitoring objectives and project risk. Channel changes occurring following installation can be documented by reviewing annual cross-sections that were surveyed prior to installation and after construction. Patterns of sediment deposition or scour should be noted. The impact of drop structures on flood levels may require regular recording of water levels during the high flow season. Habitat and fish usage monitoring protocols will likely require more rigorous and comprehensive monitoring plans than those required to evaluate the integrity of the structure as many must be tailored to fish life cycles. For a comprehensive review of salmon habitat-monitoring protocols, refer to *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols and Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia*[25].

10 MAINTENANCE

Operation and maintenance of drop structures should be minimal. However, logs rot and become worn down from bed and debris loads, hydrology changes, and we live in a constantly changing environment, so designing with the expectation of some need for future maintenance is a good idea. The legal requirement to provide fish passage necessitates that any necessary repairs identified through regular monitoring be addressed. Such maintenance may involve clearing of accumulated debris, installation of additional drop structures, or replacement of geotextile fabric, logs, boulders, riprap, ballast, or other structural elements.

11 EXAMPLES

Drop structures of various size, materials, and configurations can be found throughout the state, especially in the vicinity of culverts. Photos of typical applications are provided below.

(a) K-weir. Longfellow Creek.

(b) "V" shaped boulder weir.

(c) Boulder weir. Cedar River.

(d) Plank Zig-zag weir. Lear Springs.

(e) Log weir grade controls. Hylebos Cr.

(f) Example of poorly installed and failing log weir.


(g) Log weirs. Aldon Creek.


(h) Log weirs. Aldon Creek.


(i) Plank weirs. Mosley Springs.

12 Glossary

Critical flow – The flow condition with the minimum specific energy (depth plus velocity head) and occurs at, or slightly upstream, of the crest of a weir or steepening in profile.
Launchable – refers to rock that is installed with the intent of falling into place when undermined by scour
Subcritical (tranquil) flow – One of two alternate depths with the same energy representing low velocity and deeper depth.
Supercritical (rapid) flow – One of two alternate depths with the same energy representing high velocity and shallow depth.
Thalweg – The longitudinal line of deepest water along a stream.
Weir – A small dam that causes water to back up behind it and flow over or through it.

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