POROUS WEIRS

1 DESCRIPTION

Porous weirs are low-profile structures typically comprised of boulders that span the width of the channel. Collectively, the boulders within a porous weir redirect flow by concentrating water between individual rocks. Porous weirs are typically arranged to form an upstream-pointing arch in plan view, with their lowest point located at the apex of the arch. They can be utilized to redirect the channel thalweg, control channel alignment in confined areas or in proximity to infrastructure, alter and maintain the width to depth ratio of the channel, protect an eroding or sensitive streambank, create and maintain a scour pool for fish habitat, concentrate low flow into a deeper, narrower channel to improve fish passage in otherwise flat-bottomed channels, backwater the upstream channel (to increase riffle water depth, provide fish passage over barrier drops, provide water to diversions, or other uses), and encourage natural sorting of sediment at the pool tailout[1 2]. Porous weirs may also be designed to provide grade control in addition to other applications. However, they are not typically used to significantly raise the channel bed enough to steepen its profile. Although similar to drop structures in appearance, porous weirs are designed with spaces between boulders that allow water, sediment, fish, and other aquatic organisms to move through the structure. Conversely, drop structures are typically continuous, solid structures without gaps or openings that retain sediment and direct water over them. As a result, porous weirs are less likely than drop structures to present a passage barrier to fish and other aquatic species. The principal purpose of a drop structure is to control channel-bed grade, while porous weirs are used primarily for flow redirection and to increase channel complexity through scour and sorting of sediment.

Three popular variations of porous weirs developed by Rosgen[3] include cross-vane, W-weirs, and J-hook vane structures. They are defined primarily by their shape in plan view (refer to **Porous Weir Figures 1, 2, and 3**). Cross-vanes are full spanning boulder structures arranged in a "V"- or "U"-shape that points upstream; W-weirs are two cross-vanes side by side to span a wider channel; J-hooks are similar in shape and function to cross-vanes but do not fully span the channel. J-hooks typically consist of a double row of boulders or other natural materials angled upstream with a "hook" at the end that focuses flow through a pocket. Scour occurs in the pocket of the "hook" and, to some extent, along the downstream edge of the entire structure. J-hook structures are primarily used to protect streambanks by redirecting the flow away from the bank and toward the center of the channel.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Porous weirs direct and constrict flow within the channel. When water flows through or over a porous weir, it turns to an angle perpendicular to the structure's downstream face The typical upstream pointing "U", "J", or "V" pattern of a porous weir concentrates flow into the center of the arch, away from the stream bank. As a result, the shear stress and stream power near the banks are reduced, encouraging sedimentation and reduced erosion along streambanks. Those in the middle of the-channel are increased, encouraging development of a deeper, narrower channel thalweg and a lower channel width to depth ratio[2 3]. A scour pool typically develops immediately downstream of the structure, providing energy dissipation. The effects of porous weirs on the direction and definition of the downstream channel thalweg typically extend for 100 to 200 feet. Although redirection of flow will occur immediately following porous weir construction, scour and the resulting redistribution of sediment may not occur until the first high flow events.

Constriction of flow created by the porous weir results in two hydraulic conditions: 1) backwater upstream of the structure, and 2) accelerated flow through the structure.
Backwater that occurs upstream of the porous weir will reduce velocity and increase depth at a variety of flows. As porous weirs typically lie low in the channel profile and angle down toward the center of the channel, backwater effects associated with them are generally localized and occur only in the near-bank region, typically resulting in increased sedimentation along streambanks. However, if the structure (either alone or in combination with debris that it traps) causes a significant reduction in channel cross-sectional area or a series of porous weirs 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. Ultimately, water quality may also be impacted by increased turbidity and temperature.

Accelerated flow through porous weirs typically creates scour between and around boulders and velocity gradients through the resultant scour pool. The velocity gradients that occur at the pool tailout and along the channel thalweg naturally sort sediments to improve aeration and further diversify stream habitat.

The seasonal occurrence of scour and deposition maintains pool depth and provides cleaning, sorting, and retention of gravels. Many aquatic species native to the Pacific Northwest rely upon this seasonal disturbance of bed materials to produce optimal habitat conditions. For example, various salmonids depend on the scour-inducing sorting that creates gravel beds of the appropriate size and location for spawning; tailed frogs depend on the cleaning aspect of scour for suitable oviposition sites among the interstices of selected coarse rocky substrates. Another key aspect of the habitat value of scouring on the streambed is regular renewal of surfaces suitable for primary producers to adhere to (especially diatoms and other algal groups). This process is critically important in illuminated streambeds of higher velocity streams where grazers (e.g., caddis flies, catostomid fishes, tailed frog larvae) depend on the algal production on rock surfaces or thin algal film ("aufwuchs").

Porous weirs produce a variety of water depth, velocity, and sediment conditions in a relatively predictable pattern. The value of this habitat varies seasonally among species. The structure provides interstitial hiding areas, particularly near the bank (those incorporating large wood will offer additional cover). Surface turbulence creates hiding cover. Gravels deposited downstream of the structure may be utilized by spawning fish and other aquatic species. Scour pools offer good holding and feeding stations for many fish during low to moderate flows. However, turbulence may prevent the structure from being very useful for refuge during high flow events.

As with all in-channel construction, the placement of boulders will result in considerable disturbance in the form of increased turbidity and rearranging of bed material. Access and staging areas will probably experience short-term impacts and will require reclamation or mitigation. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. Consideration should also be given to the potential habitat impacts to source areas for boulders, access to and from the source area, and to and from the installation site.

3 Biological Considerations

3.1 Mitigation Requirements for the Technique

Placement of porous weirs in the channel will alter the thalweg alignment. Existing fish spawning areas and pools may be impacted by new scour patterns that result from the redirected thalweg. 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 fish rearing habitat, especially those with wood in them and cover from the overhanging bank. Furthermore, the control that porous weirs have on channel alignment, especially when applied in series on a reach scale, reduces the opportunity for natural channel migration that can introduce sediment and wood to a stream and create new and diverse habitat. Porous weirs, however, allow flow and sediment to pass through the structure, which may result in establishment of new spawning areas and scour pools, possibly avoiding the need for mitigation. Adding wood to the affected or nearby reach or floodplain may further increase the habitat value of the project (see Section 6.6, *Incorporating Large Wood into Porous Weir Structures)*.

Refer to the Integrated Streambank Protection Guidelines[4], Chapter 4, *Considerations for a Solution* and the matrices in Chapter 5, *Identify and Select Solutions* for additional guidance concerning mitigation requirements.

3.2 Mitigation Benefits Provided by the Technique

Porous weirs can increase the habitat diversity of otherwise homogenous reaches. They can create and maintain pools that provide holding and rearing habitat for fish, deepen the thalweg to improve fish passage, and sort sediment at the pool tailout and along the channel thalweg to improve habitat for spawning fish and other aquatic organisms. These and other habitat benefits provided by porous weirs are further described in Section 2, *Physical and Biological Effects*.

4 Application

Porous weirs are effective tools for enhancing habitat variability, stabilizing banks, controlling channel alignment, and altering or maintaining the width to depth ratio of both new and existing stream channels. They may be applied individually at a site scale or in series to affect the pool/riffle sequence of the channel at a reach scale. However, due to concerns regarding the lost opportunity for future channel migration and habitat development when applying this technique on a reach scale, series of porous weirs are only recommended where the channel alignment is permanently confined due to close proximity of infrastructure or in channelized streams where there is no opportunity to restore a natural meander pattern and wood (or other structural element) recruitment to provide habitat diversity.

Porous weirs are most effective in gravel and cobble-bed streams with slopes less than three percent. At higher slopes, step pools created by drop structures may be more appropriate than porous weirs (refer to the *Drop Structures* technique). The relatively large depth of scour associated with porous weirs placed in sand, silt, and other fine-grained material leaves them prone to being undermined or simply sinking into the substrate. Porous weirs are only applicable in free flowing reaches. They are not applicable in backwatered reaches and pools as they will be ineffective at redirecting flow or creating scour. They may be used in surface-water dominated or groundwater dominated streams. However, effects may be limited to redirection of flow if flows are inadequate to redistribute sediment.

Porous weirs should be placed so that their scour pools occur in areas where pools would naturally form. They are typically located in straight channel reaches (near the downstream end of a riffle) and at the entrance of channel bends. If placed at the head of a riffle, the riffle will be scoured out. Avoid placing porous weirs directly in a channel meander bend. 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 the structure very susceptible to being flanked. The other reason to avoid channel meander bends is that the pattern of sediment scour and deposition created by the structure on a bend will not coincide with natural patterns of scour and deposition. Pools naturally form along the outside of meander bends and create a pool tailout comprised of sorted sediment deposits downstream. Porous weirs create pools downstream and may retain sediment upstream. When used to redirect flow away from an eroding bank, porous weirs should be located upstream from, or directly adjacent to, the eroding bank.

Because porous weirs are essentially immobile objects within the stream channel, they are typically constructed using medium to large boulders; the size of boulders employed should be roughly proportional to the size and slope of the channel. As a result, application of porous weirs on large rivers may encounter practical design and construction limitations imposed by the size of available material, equipment, and impacts that cannot be effectively mitigated. Access limitations may place additional constraints on where porous weir construction is feasible. W-shaped weirs are recommended over "V"- or "U"-shaped weirs in channels over 100 feet wide. A minimum channel width of 40 feet is desirable to facilitate construction of "W"-shaped weirs[5].

Porous weirs are not recommended in aggrading channel reaches unless the aggradation results from an unnaturally large channel width-to-depth ratio (an over-wide stream) caused, for instance, by the removal of riparian vegetation or the presence of a stream crossing (for cattle, vehicles, etc). A porous weir can restore the natural width to depth ratio of the over-widened channel and, thus, its sediment transport capacity. In such situations, porous weirs are best used in combination with riparian restoration and management. If aggradation is caused by something other than an over-widened stream, the effects of porous weir placement are likely to be short-term. Sediment that accretes along depositional reaches will tend to fill scour holes and the channel thalweg and will ultimately bury the porous weir. Consider also that porous weirs inherently create backwater effects that may exacerbate aggradation.

Caution should be exercised when installing drop structures in laterally dynamic channels where there is the potential for an avulsion that could bypass the structure. It should also be exercised 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[6].

Porous weirs should be located at least 20 feet downstream of the outlet of a culvert[7] 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 structure. Porous weirs should be located at least 35 feet (50 feet where possible) from the inlet of the culvert to prevent the bed of the culvert from being scoured out. Based on a series of flume studies, Johnson et al. recommend that the apex of a cross vane be placed upstream from a bridge abutment 1.5 to 2 times the bankfull channel width to direct flow through the bridge span and away from bridge abutments. They further recommend that the downstream end of a W-weir be positioned 0.3 times the bankfull channel width upstream of a bridge pier to protect the pier.

4.1 Habitat Restoration and Enhancement

Porous weirs should only be applied for habitat restoration and enhancement purposes where a biologic need has been identified. They can be used to restore habitat diversity and improve fish passage to plane bed streams from which boulders have been removed, or to restore the natural width to depth ratio of a stream that has been over-widened (by livestock access or vegetation removal, for example). Porous weirs may also be used as an enhancement technique to increase habitat diversity and improve fish passage in new channels, naturally plane bed channels, and altered plane bed channels that were historically dominated by wood. However, if creating scour pools and increasing habitat diversity are the sole objectives for porous weir construction, boulder clusters or large wood and log jams should be considered as alternative or supplemental techniques. Boulder clusters and wood are less likely to permanently influence the alignment and cross-section of the channel and so reduce concerns regarding the lost opportunity for future channel migration and habitat development.

4.2 Grade Control

Full-spanning structures that incorporate a solid continuous row of footer rocks below those that protrude above the streambed will control the grade of the stream. The bed elevation will be established at the elevation of the lowest point in the row of footer rocks. J-hook vanes do not fully span the channel and, therefore, are inappropriate where grade control is an objective. Although porous weirs can be used to raise the channel bed, drop structures are more appropriate where significant changes to the channel profile are necessary. Users of this technique should note that porous weirs and drop structures typically address only the symptoms of channel incision, not the cause. They 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 Incised Channels* in the Stream Habitat Restoration Guidelines for further discussion on potential causes and treatments for channel incision.

4.3 Streambank Protection

Porous weirs protect streambanks through flow realignment and energy dissipation as a result of local scour and increased channel roughness (when used in series). When being used for these purposes, the advantage of using porous weirs to direct channel flow, as opposed to other river training techniques (riprap, groins, barbs, walls) is that they can be designed to provide benefits to fish and other aquatic species as well. These benefits were previously discussed in Section 2, *Physical and Biological Effects*. Note that while porous weirs do a reasonable job of providing bed roughness, other techniques, such as boulder clusters or large wood placement could be used as a complement or an alternative to porous weirs where increased channel roughness is desired.

When using porous weirs to protect an eroding bank, it is important to determine whether porous weirs are the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Integrated Streambank Protection Guidelines, Chapter 2, *Site Assessment*, Chapter 3, *Reach Assessment*, and the selection matrices in Chapter 5, *Identify and Select Solutions* for guidance). Porous weirs are appropriate for sites where the mechanism of failure is toe erosion. Porous weirs can be used alone or, more typically, in conjunction with other bank protection treatments. They can add to the integrity of downstream bank protection practices by realigning the low-flow channel.
Porous weirs are not good candidates for emergency streambank protection. They completely span the stream channel and usually require instream construction, which may not be possible during an emergency situation.

5 RISK AND UNCERTAINTY

The effects of porous weirs on habitat, streambanks, and the channel are fairly predictable as long as the relative locations and elevations of the channel and boulders remain constant. However, the possibility of unwanted effects and impacts, such as increased backwater or redirection of flow into banks supporting critical infrastructure must be considered. In addition, because weirs are typically designed as relatively rigid features, their long-term impacts are unpredictable and uncertain in dynamic systems where the channel alignment or profile is likely to change.

5.1 Risk to Habitat

Porous weirs will cause the bed and thalweg to shift. Existing spawning areas may be impacted by scour patterns that result from the redirected thalweg. Existing pools along the old thalweg alignment may be lost or minimized. This loss in pool habitat may be compensated by new pool habitat created through scour induced by the weir. However, pool habitat associated with weirs will have different velocity characteristics (turbulent, jet and/or plunging flow) than that formed along a bend (helical flow).

Depending upon the channel size, bedload movement and particle size, it may take time for the channel to adjust to this structure. During the adjustment period, spawning areas may scour or accrete and any eggs or alevins in the bed could be damaged.

Porous weirs that cause significant backwater or rise in the channel bed may create a barrier to fish passage. Fish passage barriers may also occur as a result of upstream migration of channel incision. For this reason, porous weirs typically lie low in the channel profile and do not raise the bed of the stream. If the spacing between header rocks is maintained and the head differential across the structure is minimized, fish passage should not be a problem.

5.2 Risk to Infrastructure and Property

The risk to infrastructure situated on the streambanks is relatively low. Properly designed porous weirs focus stream energy towards the center of the channel and away from the banks. However, improperly aligned weirs and weirs that trap large wood can erode nearby banks. In addition, large wood incorporated into porous weirs can become mobile posing a threat to downstream structures. Porous weirs should not be implemented at or immediately upstream of piers, culverts, or other in-channel structures, as resulting scour may undermine structure footings.

Risks to infrastructure and property and the risk of structural failure of the weir itself are often amplified in the urban environment, where channels are typically constricted or incised and culverts and bridges are relatively numerous. Hydraulic forces also tend to be more concentrated in constrained or incised urban channels than in natural streams. Porous weirs in urban streams should be designed with these factors in mind.

5.3 Risk to Public Safety

Risk to public safety is generally low. Porous weirs are typically low profile structures that provide only a small increase in elevation and generally do not create hydraulic conditions dangerous to the public. Porous weirs have been used in some instances to enhance recreational boating opportunities.

5.4 Uncertainty of Technique

Most of the design criteria are based primarily on gravel-bed streams. The Natural Resources Conservation Service (NRCS) design guidance was developed from project examples in OR, WA, and ID[8]. Design processes will be refined as more research is done for Washington stream systems, including habitat needs. The greatest degree of uncertainty lies in the depth of analysis conducted in the design process. The risk of structural failure increases with the size, slope, and degree of confinement of the channel.

6 METHODS AND DESIGN

6.1 Data and Assessment Requirements

Many considerations and analyses that are relevant to the design of porous weirs are the same as those for most or all structures within stream channels. The following are minimum assessment requirements. Many of these are further discussed in *General Design and Selection Considerations for In-Stream Structures*.

- *What is the objective of porous weir placement?* The elevation, configuration, and number of structures will vary with the objective. Are porous weirs the best alternative to meet those objectives?
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of a porous weir (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 the lowermost structure.
  - Does the channel carry a relatively high bed or debris load? Limiting the potential backwater effects of a porous weir 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, the pool: riffle ratio of the channel reach, 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 size of material will be necessary to meet those 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, structure elevation, and the degree of allowable backwater.
- *Conduct a biological assessment*. What species of fish and wildlife require passage over and through the structure (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 minimum spacing between rocks within the structure necessary 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*, of the Stream Habitat Restoration Guidelines.

- *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?

The most common unintended impacts of porous weirs are bank erosion, backwatering, and upstream sedimentation in excess of project goals. Bank erosion can result from flanking of structures, inadequate protection of banks near structures, inadequate keying of structures into streambanks, upstream sedimentation, and misdirection of stream flow. All of these factors can be controlled and/or avoided, for the most part, by careful planning and analysis. Backwatering and associated upstream sedimentation can be predicted by employing hydraulic analyses, and therefore minimized or avoided. Because porous weirs 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.

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, selection of design discharges, analysis of backwatering effects, sediment transport, and calculation of scour. These aspects of design are discussed in detail in the *General Design Considerations for In-Stream Structures*. Where design considerations are specific to porous weirs, they are presented below.

The primary function of porous weirs is to direct or concentrate flow. As such, hydraulic modeling of design conditions will be essential to project design. Hydraulic modeling will quantify the extent and magnitude of increased water levels upstream (backwatering), changes in flow velocities, and bed shear stresses. These hydraulic parameters will be required for sizing boulders, determining boulder spacing and configuration, and quantifying impacts to sediment transport. The secondary function of porous weirs is to induce scour. It is for most practical purposes inseparable from the primary function, and deserves equal evaluation and consideration in design. Predicting scour depth at varying flows will quantify flow conditions that would be expected to fill or deepen the scour pools as well as equilibrium depths. These characteristics will provide insight to the anticipated benefit of porous weirs to habitat as well as the stability of the structure. The footer rocks of porous weirs must extend to or below the estimated depth of scour in order to prevent the structure from being undermined. Hydraulic modeling and methods used to conduct various hydraulic analyses are described in the *Hydraulics* appendix.

Sediment transport characteristics, such as deposition and erosion rates, govern structure effectiveness in terms of scour pool development and maintenance, depositional bar formation, and substrate size and sorting. 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 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.

6.2 Structure Spacing

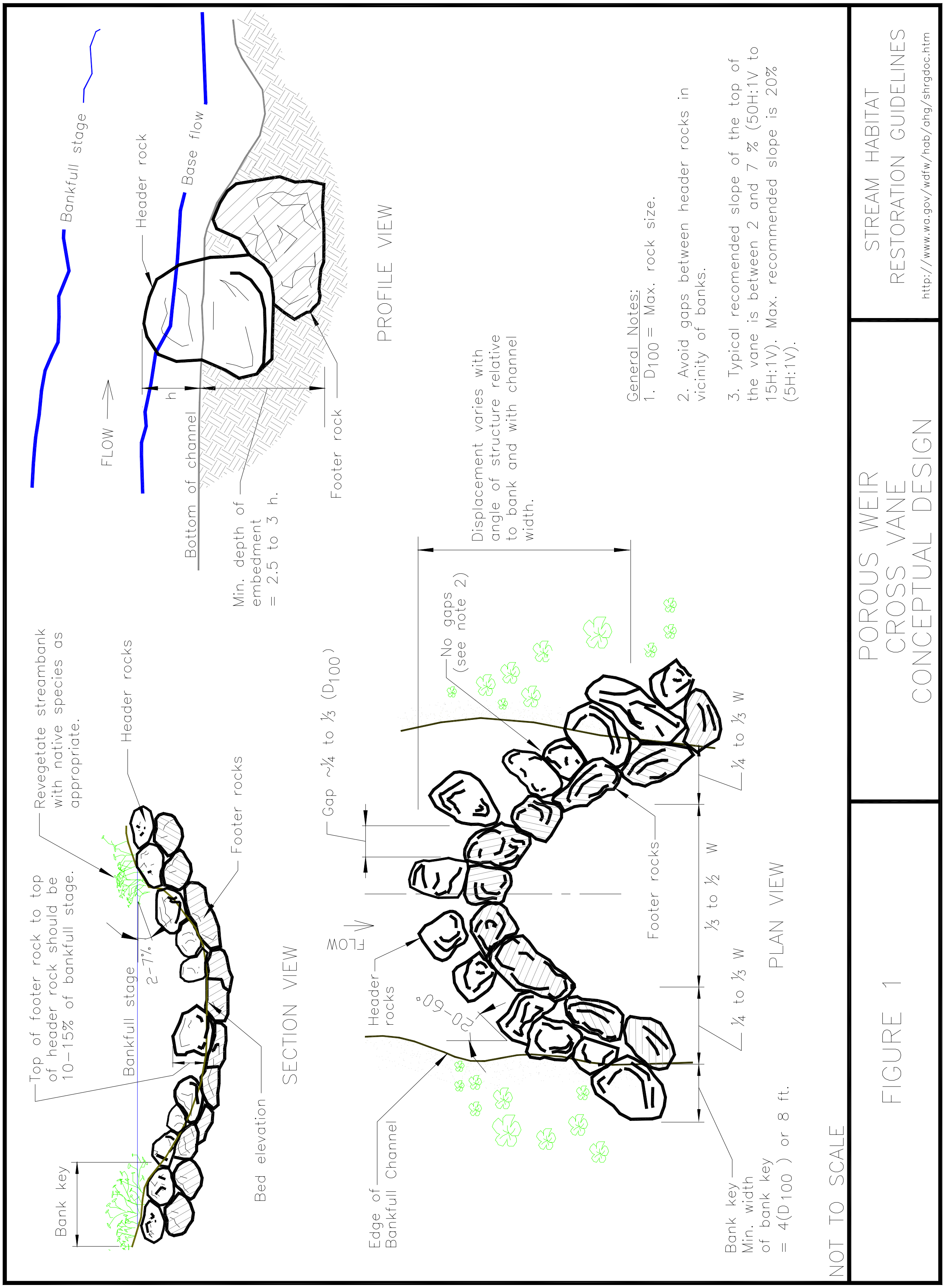
Geomorphic characteristics such as pool frequency and location (e.g. from an analog stream reach) lend information on appropriate spacing, frequency, and locations of porous weirs. In order to be effective in the short and long term, porous weirs should work in concert with these natural bedform characteristics. Typical alluvial channels with slopes between 1 and 3 percent generally have pool spacing between 3 and 10 channel widths and average about six channel widths[9], although closer spacing has been observed in wood-dominated channels[10]. At slopes steeper than about three percent, step-pools created by drop structures may be more appropriate. Refer to the *Drop Structures* technique for guidance on drop structure design and application. Additional guidance on typical spacing of natural pool-riffle sequences for various stream types can be found in the *Fluvial Geomorphology* appendix.

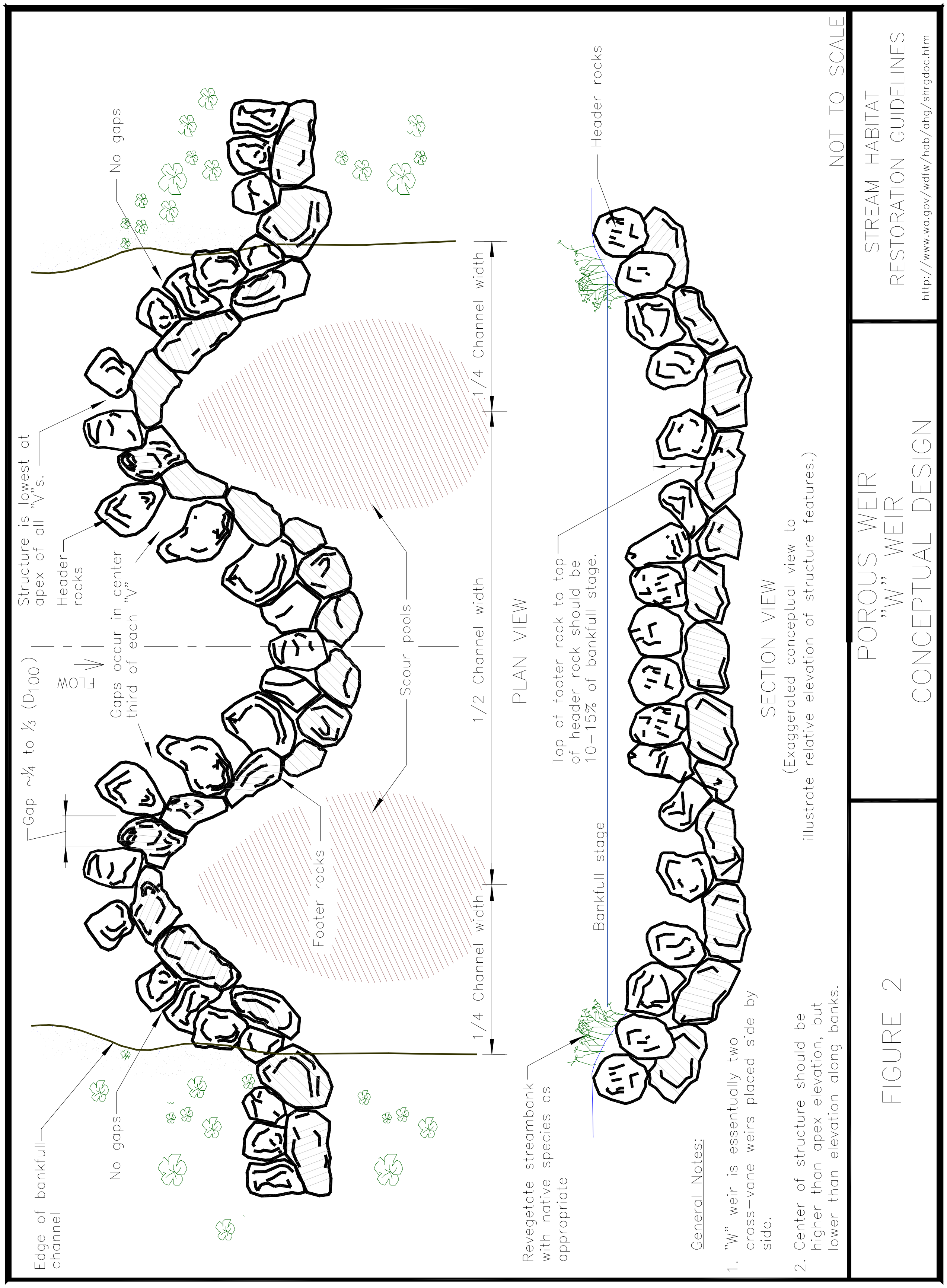
To ensure fish passage through a series of porous weirs, channel slope, maximum allowable head drop, length and depth of backwater, and length of thalweg created downstream should also be considered. For grade control, the minimum spacing should equal the maximum allowable head drop over the weir divided by the proposed channel slope. For example, the minimum spacing between 8-inch high weirs in a stream with a 2 percent slope will be 0.67 ft/ 0.02 = 33.5 feet. In general, the slope between the weir crests should not be flatter than that of the pre-project, low-flow water surface.

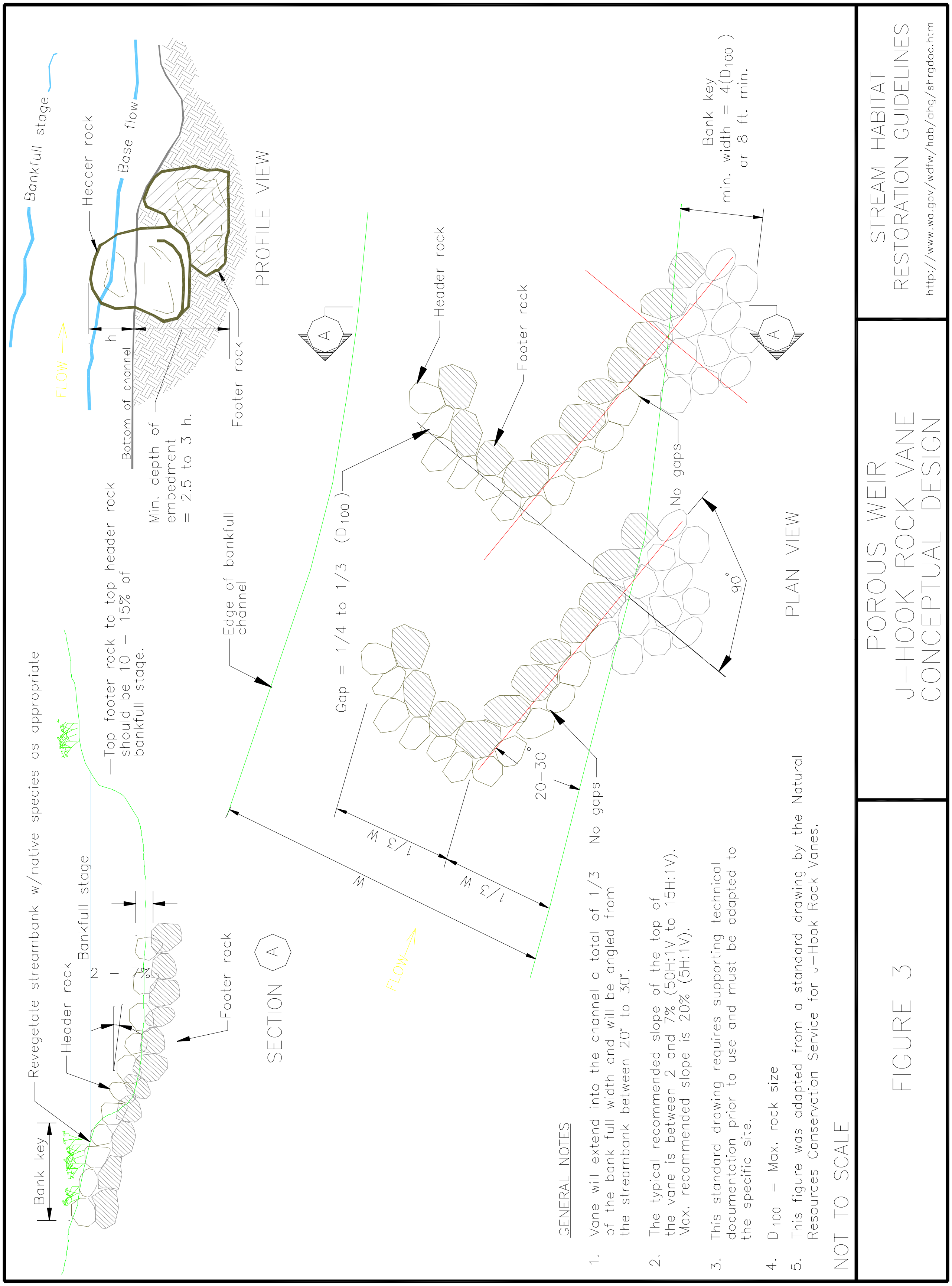
6.3 Shape and Configuration

Porous weirs should be installed with a relatively low profile, such that the tops of the boulders are exposed at low to average flows but submerged by higher flows. Cross-vanes and “W”-weirs span the entire width of the channel while rock “J”-hooks extend approximately 2/3 of the way across the channel width (see **Porous Weir Figures 1, 2, and 3**). Each is typically arranged to form an upstream-pointing arch in plan view, with the lowest point at the apex of the arch. Each arm of the arch of full-spanning porous weirs can have either equal or different lengths, depending upon the thalweg alignment as it approaches the weir and the desired thalweg alignment immediately downstream. The lowest point of the weir occurs at the apex of the arch and should be located far enough from the streambank so that the scour pool that develops will not undermine the bank; it is typically located in the center third of the channel. Note that the two apexes of a W-weir can be set at different elevations to accommodate different channel bed elevations or to increase flow through the one span. Locating the lower apex further upstream than the higher apex can further increase flow through that span.

Design guidelines provided by Rosgen and the NRCS both promote the use of a solid continuous row of footer rocks below and slightly in front of a top layer of “header” rocks that protrude from the streambed into the flow. Header rocks are responsible for creating the hydraulic effects of the weir, inducing scour, backwater, and redirection of flow. The primary function of footer rocks is to support the header rocks and prevent undermining of the structure. Footer rocks of full-spanning structures (not J-hooks) also provide grade control; their top elevation should be designed to correspond with the desired elevation of the channel bed. Note that a single row of rocks, rather than a double row of footer and header rocks, may be sufficient provided they are stable and extend deep enough into the bed to prevent them from being undermined.


Bankfull stage
Header rock
Base flow
FLOW
h
Bottom of channel
Min. depth of embedment = 2.5 to 3 h.
Footer rock
PROFILE VIEW
Displacement varies with angle of structure relative to bank and with channel width.
General Notes:
1. D100 = Max. rock size.
2. Avoid gaps between header rocks in vicinity of banks.
3. Typical recomended slope of the top of the vane is between 2 and 7 % (50H:1V to 15H:1V). Max. recommended slope is 20% (5H:1V).
Top of footer rock to top of header rock should be 10-15% of bankfull stage.
Revegetate streambank with native species as appropriate.
Header rocks
Footer rocks
Bankfull stage
2-7%
Bank key
Bed elevation
SECTION VIEW
Gap ~¼ to ⅓ (D100)
No gaps (see note 2)
FLOW
Header rocks
20-60°
Edge of Bankfull Channel
Footer rocks
¼ to ⅓ W
⅓ to ½ W
¼ to ⅓ W
PLAN VIEW
Bank key Min. width of bank key = 4(D100) or 8 ft.
NOT TO SCALE
POROUS WEIR CROSS VANE CONCEPTUAL DESIGN
FIGURE 1
STREAM HABITAT RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm


Edge of bankfull channel
No gaps
Gap ~1/4 to 1/3 (D_{100})
FLOW
Gaps occur in center third of each "V"
Structure is lowest at apex of all "V"s.
Header rocks
No gaps
Footer rocks
Scour pools
1/4 Channel width
1/2 Channel width
1/4 Channel width
PLAN VIEW
Revegetate streambank with native species as appropriate
Bankfull stage
Top of footer rock to top of header rock should be 10-15% of bankfull stage.
Header rocks
SECTION VIEW
(Exaggerated conceptual view to illustrate relative elevation of structure features.)
General Notes:
1. "W" weir is essentially two cross-vane weirs placed side by side.
2. Center of structure should be higher than apex elevation, but lower than elevation along banks.
NOT TO SCALE
STREAM HABITAT RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm
POROUS WEIR
"W" WEIR
CONCEPTUAL DESIGN
FIGURE 2


Bank key
Revegetate streambank w/native species as appropriate
Header rock
Bankfull stage
2 - 7%
Footer rock
SECTION
A
Top footer rock to top header rock should be 10 - 15% of bankfull stage.
Edge of bankfull channel
Gap = 1/4 to 1/3 (D 100)
W
1/3 W
1/3 W
FLOW
20-30°
No gaps
No gaps
90°
PLAN VIEW
Header rock
Footer rock
Bank key min. width = 4(D 100) or 8 ft. min.
A
A
Bankfull stage
Header rock
Base flow
FLOW
h
Bottom of channel
Min. depth of embedment = 2.5 to 3 h.
Footer rock
PROFILE VIEW
GENERAL NOTES
1. Vane will extend into the channel a total of 1/3 of the bank full width and will be angled from the streambank between 20° to 30°.
2. The typical recommended slope of the top of the vane is between 2 and 7% (50H:1V to 15H:1V). Max. recommended slope is 20% (5H:1V).
3. This standard drawing requires supporting technical documentation prior to use and must be adapted to the specific site.
4. D 100 = Max. rock size
5. This figure was adapted from a standard drawing by the Natural Resources Conservation Service for J-Hook Rock Vanes.
NOT TO SCALE
FIGURE 3
POROUS WEIR
J-HOOK ROCK VANE
CONCEPTUAL DESIGN
STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm

Weir angle.

The distance that the structure projects upstream varies with the angle of its alignment relative to a line tangent to the bank. Weirs with smaller angles are longer and project further upstream than those with larger angles. Therefore, more of the bank is protected and the discharge per unit length of weir is less. The later may benefit fish passage by providing a greater range of water depths and lower velocities to swim through. But the designer should also consider that weirs with smaller angles redirect flow more sharply towards the center of the channel creating deeper scour pools. This scour depth will need to be accounted for in footer rock design to ensure the structure is not undermined. Cross vanes and W-weirs typically project upstream at an angle ranging from 20 to 60 degrees. NRCS recommends that a hydraulic analysis be conducted for angles approaching 60 degrees. For J-hook vanes, a narrower range of 20 to 30 degrees is recommended. In a series of flume experiments, Johnson et al. found that structures with angles of less than 25 degrees were less effective at moving scour away from the bank.

Height of structure.

It is important to configure the porous weir such that it does not significantly backwater upstream reaches, particularly during flows that result in scour and habitat development. Excessive height can cause structural failure, trigger upstream aggradation and bank erosion, trap debris, and create a barrier to fish passage. To minimize backwater and to allow bedload to move through the porous weir with minimal restriction, the low point of the weir (situated at the apex) should not be placed higher than 15 percent of the bankfull channel height. This height is measured at the thalweg from the surface of the bed (or the top of the footer rock if it is higher than the bed) to the top of the header rock. From the apex, the crest of the porous weir should gradually but continuously slope up towards the bank such that the boulders nearest the bank are the last to be submerged as stage increases. Rosgen recommends a slope of 2 to 7% (50H:1V to 15H:1V). Due to the difficulty of achieving this relatively low slope in the field, especially for small streams, NRCS recommends the slope not exceed 20% (5H:1V). As the slope increases, so does the degree of channel confinement as more water is directed through the apex. Upstream backwater effects and downstream scour may increase in response. Guidance by NRCS and Rosgen suggest that the height of the porous weir near the bank should approach but not exceed the bankfull stage elevation. The relatively flat portion of the weir typically transitions into the bank at an angle of 1V:1.5H to 1V:2H. Hydraulic modeling can be used to quantify the degree of backwatering for a particular configuration. Excessive backwater effects will occur where the depth of bankfull flow over the weir is more than 120% of the average depth of bankfull flow. Fish passage may be obstructed at lower levels of backwater.

In fish bearing waters it is a requirement that any 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. To provide passage for adult steelhead and chinook, coho, and sockeye salmon, a 12-inch maximum difference in water surface elevation above and below the porous weir applies. But to allow passage for the weaker swimming fish, such as pink or chum salmon or adult trout, the difference in water surface elevations above and below the porous weir should not exceed 0.8 feet. If upstream juvenile salmonid passage is critical, the drop should not exceed six inches. Passage of other fish and wildlife species may require lesser drops.

Typically, the hydraulic drop over a weir placed in series is equal to the elevation drop between the tops of the footer rocks 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. For this reason, it is recommended that individual weirs within a series have similar configurations. The hydraulic drop over an individual weir or the lowest structure within a series is governed by the amount of backwater created by the weir. The maximum allowable hydraulic drop 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. The top elevation of the footer rocks may be installed below the elevation of the channel bed. However, if grade control is an additional objective, the elevation of the row of footer rocks should be designed to correspond with the desired elevation of the channel bed.

Gaps between rocks.
The location and size of the gaps between header rocks influence the hydraulic effects of the weir. Too large a gap will not create sufficiently high velocities through the gap needed to move bedload and dissipate energy. Too small a gap will constrict flows, trap sediment and debris, and may cause backwater conditions or impede fish passage. Guidance by Rosgen suggests that the gap between header rocks near the apex of the porous weirs (generally within the central third of channel width) should be between ¼ and 1/3 of the rock diameter. No gaps are recommended along the arm of the weir, as they tend to produce back-eddy erosion during large flood events that can erode the banks and compromise the integrity of the structure. Limiting gaps to the apex of the structure further concentrates water and may be desirable in areas with low base flows. The gaps in the weir can be modeled in HEC-RAS with the in-line weir option. For flows that overtop the rocks it may be necessary to use the velocity distribution option to determine flow velocities through the gaps. Using an iterative approach, the gap spacing can be designed to provide the desired hydraulic and scour conditions at design flows.

Depth of structure.
Boulders will "sink" into the bed as scour removes material from around their bases. To prevent the structure from being undermined, the bottom of the structure should extend below the estimated depth of scour. Numerous equations to estimate scour depth are provided in the *Hydraulics* appendix. These equations are often based on flume experiments and will provide an approximation. The depth of the scour pool increases with increasing degree of flow confinement, drop height, or channel slope, and with decreasing substrate size (e.g., from boulder to cobble, or from to gravel to sand).

Field measurements of similar scour conditions should be used to verify estimates of scour depth. (Be cautious that maximum scour depths occur at the peak of the hydrograph with infilling occurring on the receding limb of the hydrograph. Scour depths observed during low flows will be less then the maximum depth.) As a rule of thumb for gravel or cobble bed streams, NRCS guidance suggests that the expected scour depth associated with porous weirs may be estimated by:

$$\text{Scour Depth} = 2.5 * h$$

Where h is the height of exposed rock relative to the bed elevation. In sand bed streams, the depth of scour will be greater. NRCS suggests that estimated depth of scour in sand bed streams will be 3 to 3.5 *h. Rosgen recommends that footer rocks extend to a depth of 3*h in cobble and gravel bed streams and 6*h for sand bed streams. As a result, boulder placement in sand bed streams may be inappropriate.

6.4 Bank Key

Porous weirs (including footer rocks) should be keyed into the channel banks to prevent flanking of the weir at high flows. The key provides protection from scour associated with overbank flow spilling back into the channel. The bank key should be at least as high as the exposed portion of the porous weir at the bank. The extent to which the structure is keyed into the banks will depend upon bank, channel, and flow characteristics. Hydraulic modeling will indicate the flow depths and limits likely to occur for the expected range of flows. With this information the extent and height of the key can be determined for the specific site conditions. . The minimum recommended length for the bank key is four times the D_{100}, 1.5 times the height to the top of the bank, or eight feet (whichever is greater). However, in very stable channel systems with non-erodible banks, lesser keys may be appropriate. Longer keys may be necessary where banks are frequently overtopped.

For small streams, the key typically extends into the bank at the same angle as weir. On large streams, however, keys are often constructed perpendicular to the bank. The designer is encouraged to consider the hydraulic effects associated with the angle of the bank key should it become exposed. Material comprising the key should have the same dimensions as that used for the exposed portion of structure within the channel. Buried large wood can be incorporated into the bank key.

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

6.5 Materials

Most porous weirs can be constructed wholly, or in large part, of stone. In general, the designer should strive to use natural materials as much as possible, and to use materials appropriate to the location and stream type. Porous weir structures should be designed to be rigid non-deformable features for flows up to some maximum design flow (a minimum of a 20-year flow is recommended). Flows that exceed the design condition may move some of the individual boulders or undermine the structure and cause it to deform. Material sizing guidance given in the *Drop Structure* technique also applies to porous weirs. Calculated rock sizes should be verified against those observed in the field.

Rock used in porous weirs should be sound, 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. The smallest dimension of an individual rock used in a porous weir should be greater than one-third its largest dimension[11]. 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.

6.6 Incorporating Large Wood into Porous Weir Structures

Large wood can be incorporated into porous weir designs for added habitat benefit, additional roughness, and flow realignment. It is sometimes incorporated directly into the structure itself by replacing header rock(s) near the bankline with tree trunks and attached rootwads or situated parallel to the bankline as added bank protection. However, the designer should note that placement of wood within the structure increases the risk of structure failure by creating voids in the rock fill, poor foundation conditions, and increased uplift forces. In addition, when adding wood in the vicinity of 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 infrastructure. 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 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 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 structures (the later two options pose the least risk of compromising the structure). Refer to the *Anchoring and Placement of Large Wood* appendix and the *Large Wood and Log Jams* technique for further guidance on wood placement.

7 Permitting

As installation of porous weirs involves in-channel work, stream bed 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 Section 404 Permit). A Clearing and Grading Permit, Washington Department of Natural Resources Use Authorization, 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 porous weirs will result in considerable in-stream disturbance in the form of increased turbidity and rearranging of bed and bank material. General construction considerations relevant to all in-channel work, and ways to reduce them, are detailed in the *Construction Considerations* appendix. Principle construction issues relevant to porous weir construction include locating, transporting and installing boulders. Permit restrictions may require that additional factors be considered.

Construction of porous weirs requires careful excavation and placement of material within the stream channel and banks. Rock should never be dumped into the stream. Two types of equipment are typically used for placing boulders: 1) a hydraulic excavator fitted with a thumb and capable of excavating streambed materials and placing the largest rock size required for the project; and, 2) a loader to shuttle materials at the site. The equipment should be capable of placing rocks to insure that the rocks are interlocked and stable. Note that motorized wheel barrows, rock bars, winches, and other hand tools may be required where heavy equipment access is limited and to fine-tune boulder placement. Pre-construction planning in the field with the equipment operator during installation is very important to facilitate construction and achieve the desired results. Presence of the designer, or an inspector experienced in these structures, during construction is critical. Site specific conditions may arise that simply cannot be forecast and will require adjustment on the part of both the designer and the operator.

Except under special circumstances, construction will not be permitted to occur in flowing water due to the potential impacts to in-stream habitat and biota. To facilitate construction and meet regulatory restrictions the work area will need to be isolated from flowing water during construction using a diversion dike, flow bypass, or similar technique. Fish will need to be removed and excluded from the work area. Depending on site conditions, dewatering of the work area may be necessary during excavation of streambed materials and placement of footer rocks. Dewatering facilitates installation, prevents siltation of the stream during construction, and minimizes trampling and disturbance of aquatic life.

The number and location of access points must be selected to minimize damage to the existing riparian vegetation. At project completion, disturbed areas, including staging and access areas, will need to be graded smooth, seeded, and planted to repair damage and restore the riparian zone.

Construction should be conducted during a period where impacts to critical life stages of fish and wildlife are avoided and when dewatering for construction is possible (if necessary). Low-flow conditions are ideal for the placement of boulders and may be essential for dewatering efforts. In-stream work windows vary among fish species, other aquatic organisms, and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows.

Porous weirs on small streams may be best contracted as time and materials contracts, as they will require considerable detail work. 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. Use of an experienced contractor with a proven track record for constructing in-stream projects with minimal impacts to the environment can facilitate installation.

8.1 Cost Estimation

Porous-weir structures can be a relatively low-cost approach to improving habitat or reducing erosive energy along a streambank. The greatest cost factor is the size of the channel. Weir structures range in cost from approximately $75 per linear foot to $200 per linear foot. The cost will be determined primarily by the cost of available rock, the proximity of the source of material to the construction site, and equipment and operator rates. Rock materials typically range in cost from $25 to $80 per cubic yard. Typical costs for installing rock range from $50 to $100 per cubic yard depending on source and access. However, it is not uncommon to have higher unit costs for very difficult sites. Dewatering, if required, may greatly increase the cost of the treatment. Additionally, access for large equipment may require either temporary access road construction or the use of specialized equipment, such as a spider hoe and tracked dump trucks, to cross riparian areas for channel access and materials delivery. Refer to the Integrated Streambank Protection Guidelines, *Cost of Techniques* appendix for further discussion of materials costs and construction costs.

9 MONITORING

Monitoring methods employed depend on project and monitoring objectives. At a minimum, monitoring should include annual evaluations of porous weir integrity and their ability to provide unobstructed fish passage to determine if maintenance is required. Inspections should note if there is any debris accumulation that may require clearing or more frequent inspection to ensure it does not become a problem. It should also note if infrastructure, public safety, or habitat is compromised or at risk as a result of the structure.

Long-term monitoring of other parameters (such as the impacts a porous weir has on the channel, bank stability, the abundance and favorability of stream habitat available to fish and other aquatic life, fish production, infrastructure, and water levels) will probably require both pre-project and post-project surveys. The level and frequency of monitoring required vary with monitoring objectives and the risks to habitat, infrastructure, and public safety that are associated with the presence or failure of the structure. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding bank erosion, flow characteristics, scour and deposition patterns, fish use, and the configuration and stability of header and footer rocks. On the other hand, projects that pose a relatively high risk to infrastructure, property, public safety, or habitat may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include photo documentation from fixed photo points, detailed surveys of boulder dimensions, locations and bed and bank topography (including multiple cross-sections at, upstream, and downstream of the structure and spaced approximately one channel width apart) to document changes over time, pre- and post-construction snorkeling of the site and a reference reach to document fish use, or pre- and post-construction water level recording at multiple stream flows to document changes in flood elevations. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

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 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[12].

10 Maintenance

Regular monitoring of the site after high flow events will identify any maintenance requirements. Maintenance of a porous weir project should not be required except in a few situations where the project is no longer meeting project objectives or unintended consequences have occurred and are unacceptable. Maintenance, when needed, may include re-positioning, replacement, or removal of individual boulders, removal of wood that has racked up against the boulders, or supplemental treatments of eroding banks. However, keep in mind that repositioning and replacement of boulders is only recommended after careful evaluation to determine what went wrong to avoid repeating the mistake. Note that any mitigation measures, such as the placement of large wood, may also require maintenance. This could include replacement or re-anchoring of large wood that was removed or loosened by high flows.

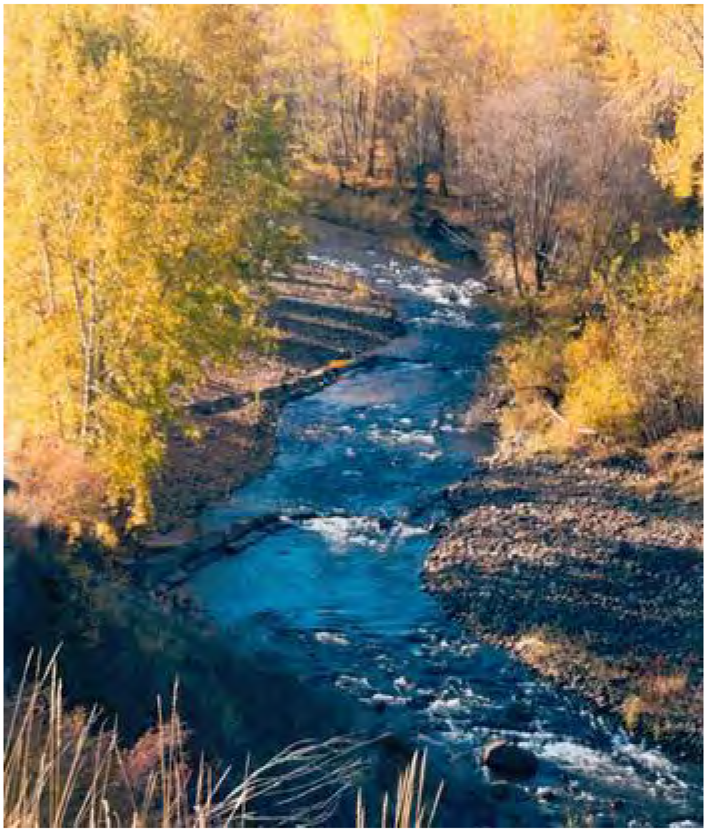
11 Examples

Porous Weirs Figure 4: Porous Cross Vane on Cedar Creek, Clark County, Washington.

Porous Weirs Figure 5: Porous Cross Vane on stream in southeastern Washington.

Porous Weirs Figure 6: J-Hook Rock Vane on Omak Creek, Okanogan County. Photo provided courtesy of the Natural Resources Conservation Service.

Porous Weirs Figure 7: J-Hook Rock Vane on stream in southeastern Washington.



Porous Weirs Figure 8: Series of J-Hook Rock Vanes on the Tucannon River, Columbia County, Washington.

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