Stream Restoration Series
W-Weir

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ALTERNATE NAMES:

double cross vane; double vortex weir

STRUCTURE TYPE:

rigid structure; grade control structure; river training structure

W-weirs are channel-spanning structures that provide grade control, dissipate energy, concentrate flows at two points within the channel cross section, and create pools (Figure 1). A grade control structure stabilizes the stream channel by preventing changes in bed elevation at that point. It can also protect a streambank from undesirable erosion or migration when the erosion is caused by flows impacting the bank face. By protecting the bank from fluvial erosion, this structure promotes the overall stability of the stream cross-section. Typically installed in larger streams (width > 40 ft.), it is also used to create pools, to direct flows to the center of culverts or bridge spans upstream of road crossings, or to stablilize the confluence of two channels.

The w-weir is configured such that four vane arms span the channel in a "W" formation (see plan view diagram, Figure 1). Thus, the w-weir is a stream-spanning structure. Depending on the desired configuration of the scour pools, the middle two vane arms may be a different length than the outer arms that are keyed into the bank. The w-weir provides grade control in two ways. First, the footer rocks extend below the expected scour depth to prevent upstream migration of knickpoints. A knickpoint is point along the channel where there is a sharp change in the stream bed elevation, which creates a small waterfall that can erode upstream. Second, the weir creates an elevation change in the channel longitudinal profile, which allows lower bed slopes

upstream and downstream of the weir, which in turn decreases the forces driving channel erosion.

Where applicable, the w-weir is a more ecologically beneficial alternative to traditional bank armor, such as riprap, or traditional grade control methods, such as check dams. The outer arms of the w-weir act as single-arm vanes, deflecting flows away from the bank and creating turbulence, which dissipates energy and thus lowers the applied shear stress near the bank. The flow deflection and resulting drop in applied shear stress improves the establishment of protective vegetation on bare or newly regraded banks.

W-weirs can also increase flow diversity in uniform channels. Water ponded upstream of the weir induces gravel deposition. By forcing the flow over a drop and concentrating at two points in the channel, w-weirs cause the formation of two scour pools downstream of the weir, further increasing flow diversity.

CAUTION: W-weirs are costly and have a relatively high risk of structural failure due to their position within the stream itself, so they should be installed only to protect infrastructure or to provide grade control.

Application

The w-weir is effective for stream reaches which…

- are slightly-to-moderately meandering/sinuous;

- have bankfull widths greater than 40 ft.;

- are actively incising;

- would naturally possess a riffle-pool sequence (i.e. Rosgen stream types B3-B4, C3-C4, and F3-F4 as described in Rosgen's 1996 text Applied River Morphology);

- have a moderate to high gradient;

- have coarse bed material (small boulders/cobbles to coarse sand), which is mobile enough for scour pool formation; and,

- have few or no regions of stagnant water or backwater.

In streams with steep bed slopes and/or knickpoints, w-weirs can be used to safely reduce the bed elevation and to prevent streambank erosion. W-weirs can also be used to improve aquatic habitat.

Consider use of the w-weir carefully for stream reaches which…

- have no site constraints which require the stream to remain stationary and not naturally migrate across the floodplain;

- are deeply incised or have a low width to depth ratio, as the arm slope may exceed recommended values;

- are experiencing substantial change in their cross-sectional geometry, as additional structural stabilization measures may be required; or,

- have beds of very fine, mobile material (fine sands and/or silt), which increases the risk of structural failure by undercutting.

CAUTION: Do NOT install a w-weir for streams which…

- are composed of exposed bedrock;

- regularly experience heavy loads of very large sediment (cobbles and larger) or other large debris (i.e. large logs) or,

- otherwise have little justification for preventing natural lateral channel migration.

General Design Guidelines

The numerical guidance listed below represents rules-of-thumb that may not be strictly followed on a site-by-site basis and should not be substituted for actual design calculations and/or modeling. Please see the references section for a list of useful documents from which these numbers were obtained, most notably the Maryland Waterway Construction Guidelines (2000), Sotiropoulis and Diplas (2014), and Gordon et al. (2016).

Design Flow

It is important to consider a range of low and high flows in stream restoration design. At low flows, structures should concentrate flows to maintain sufficient depth for fish passage and survival of aquatic organisms. Stability analysis at high flows should be conducted to ensure the weir remains in place for flows up to a given recurrance interval (return period). The magnitude of the design flows will depend on project goals, as well as physical (site and valley), budget, regulatory, and other constraints.

One consideration in the selection of a high design flow is the desired structure design life (SDL). Inherently, the SDL indicates the likelihood that, in any given year, the weir might experience a flood event of greater magnitude than the design storm. The SDL is often determined by client needs or permitting requirements. In an urban watershed, in which structure failure may cause damage to nearby infrastructure or adjoining property, the acceptable level of risk is important to consider.

If the acceptable level of risk is provided in the form of a given recurrence interval, T, for the flow to be withstood by the structure, the SDL will be equivalent to that recurrence interval. For example, if local regulations require that all in-stream structures be designed to withstand a 50-yr flood event, then the SDL will be 50 years, and the design flow will be the 50-yr flood discharge. The probability of the design flood occurring in any given year is $P = 1/T * 100\%$. Thus, there is a 2% probability of the 50-year flood occurring in any given year.

The risk, R, of the structure experiencing a flow equivalent to the design flood during a given time period, m, is determined using the formula $R = 1-(1- 1/T)^{m}$, where m is the time period of interest in years. Thus, a w-weir designed for an SDL of 50

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years will have a failure risk of 18% over a 10-year period.

Alternatively, the SDL can be determined by calculating the flow that will produce an applied shear stress or other hydraulic parameter that the weir must resist and then determining the recurrence interval of the associated flow.

Material Sizing

Material used for a w-weir must remain structurally sound during the design flow. To size boulders for the w-weir, the minimum size rock which will remain in place during the design flow must be determined. The flow exerts a shear stress on any material in the channel; this is called the applied shear stress. The critical shear stress of a particle (boulder) is the shear stress at which it will likely be displaced. Because different channel cross section geometries can produce the same average flow velocity, it is import-

ant to assess the stability of the materials using shear stress, rather than an allowable velocity. Technical Supplement 14C Stone Sizing Criteria of the NRCS Stream Restoration Design Handbook (NRCS, 2007a) describes these calculations in greater detail. Designers should recognize that techniques used to size riprap may underestimate the size stone needed for in-stream structures because the weir rocks are more exposed to the flow than riprap. Once a material size is calculated, a factor of safety of 1.1-1.5 is commonly used. Rocks used in w-weirs are typically 2-4 ft. (60-120 cm) in diameter. Designers should also consider using stones which are large enough to prevent movement by vandals.

Vane rocks of the middle arms should be large enough to remain secure in the streambed. These rocks will bear the brunt of the hydraulic force, as the outer two arms will deflect high flows away from the banks and toward the midsec-

tion. Footer rocks used in the midsection should larger than the midsection vane rocks.

Choose rocks which have flat, rather than round, surfaces to allow the weir rocks to sit securely on the footer rocks and to line up with adjacent rocks. In general, larger rocks will produce more turbulence, leading to deeper scour pools. Also be sure to consider rock mineral composition, as rocks such as sandstone can have lower density and some minerals can experience high rates of weathering or chemical leaching. Use native stone when possible.

CAUTION: If the channel substrate has a high sand content, use the Wilcock-Kenworthy modification of the Shields number, as described in Wilcock et al. (2008) to determine the critical shear stress.
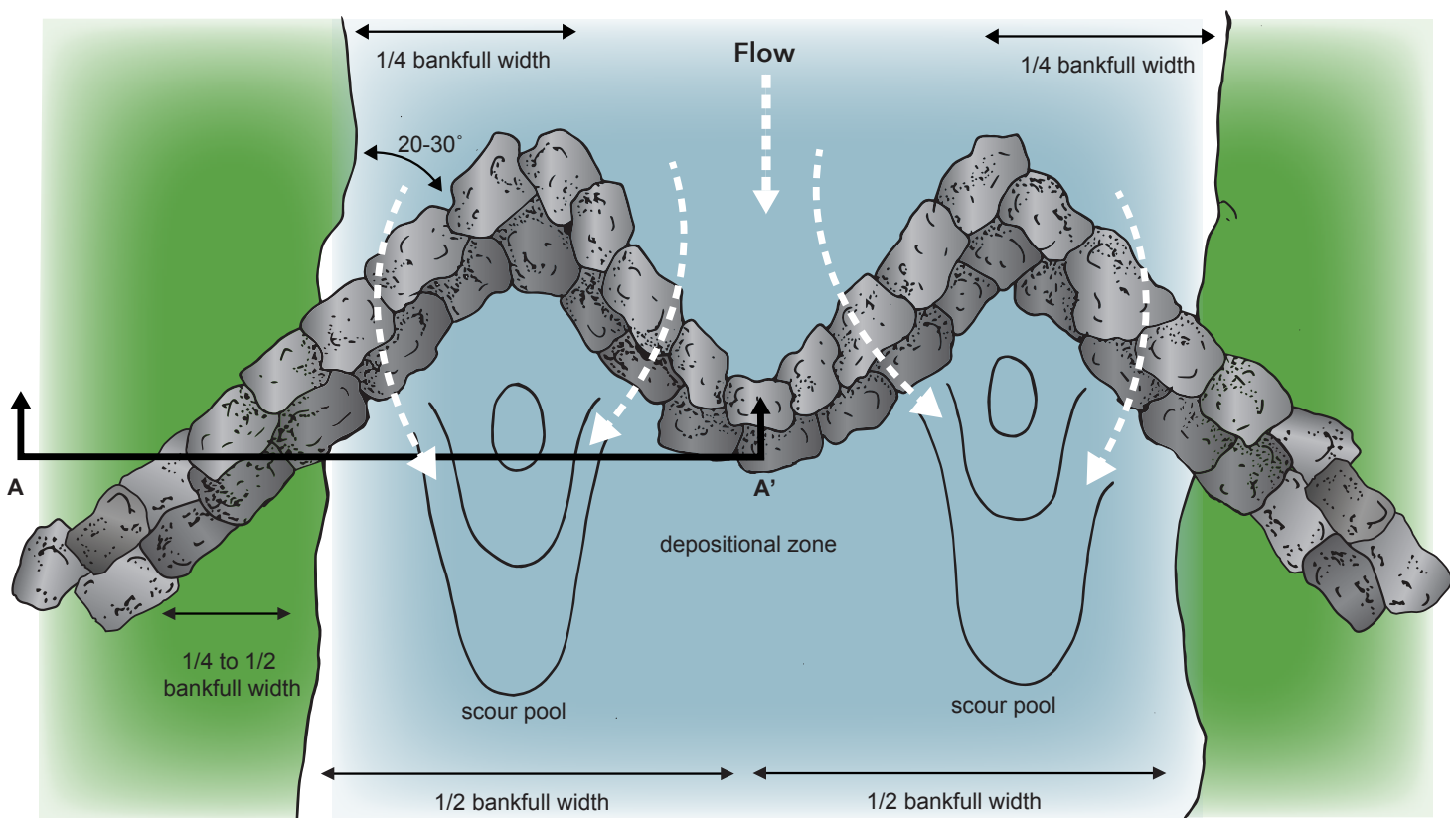

Figure 1. W-weir plan view.

Footer Depth

As water crosses over the vane arms, it will drop and impinge on the channel bed, causing a scour hole (plunge pool) to form. While this scour hole increases bedform and flow diversity, if it becomes deeper than the footer materials, the structure can be undermined. Therefore, it is critical to estimate the scour depth downstream of the structure over a range of flows to ensure the footer rocks extend below the maximum predicted scour depth. The expected scour depth can be determined using the methods described in Technical Supplement 14B ("Scour Calculations") of the NRCS Stream Restoration Design Handbook (NRCS, 2007b) and in Gordon et al. (2016). These methods frequently require knowledge of both the headwater and tailwater depths at multiple stream discharges; therefore, the design reach should be modeled using software such as HEC-RAS, as described in Gordon et al. (2016).

In designing structure footers, it is important to realize that the greatest scour will occur where there is the greatest drop height. Because the vane arms are sloped up, the greatest drop will occur along the vane arms, closest to the bank. However, this is also the area with the lowest footer depth (assuming the footers are parallel to the vane arms.) To provide greater support along the arms, the footer depth can be extended or larger rocks can be used under the vane arms.

If the w-weir is being used to prevent the migration of a downstream knickpoint, it is important to estimate the maximum bed degradation that could occur at the structure due to the knickpoint. Footer depth should then be based on the greater of either the scour pool depth or the bed degradation due to the knickpoint. Once the maximum bed degradation is estimated, the footer depth should extend 1.5-3.0 times this expected depth, or until a resistant layer, such as bedrock, is reached.

Placement within Stream Cross-Section

Install the vane arms at a 20° to 25° horizontal angle from the bank, such that the weir points upstream. Measure the angle between the vane arm and the upstream bank (see plan view diagram, Figure 1). The whole structure should form a "W" shape with the apices pointed upstream. The angles between the midstream arms should be about 40 degrees to prevent a hydraulic jump from forming. A larger angle between the outer arms and the banks can protect greater lengths of bank against erosion, but also results in more intense bed scour and greater risk of failure.

The outside vane arms should be keyed into the bank so that the vertical slopes of the arms do not exceed 5%. As the angle of the vane arm increases, so does the distance between the top of the vane arm and the bed, increasing the water drop height and the amount of scour that will
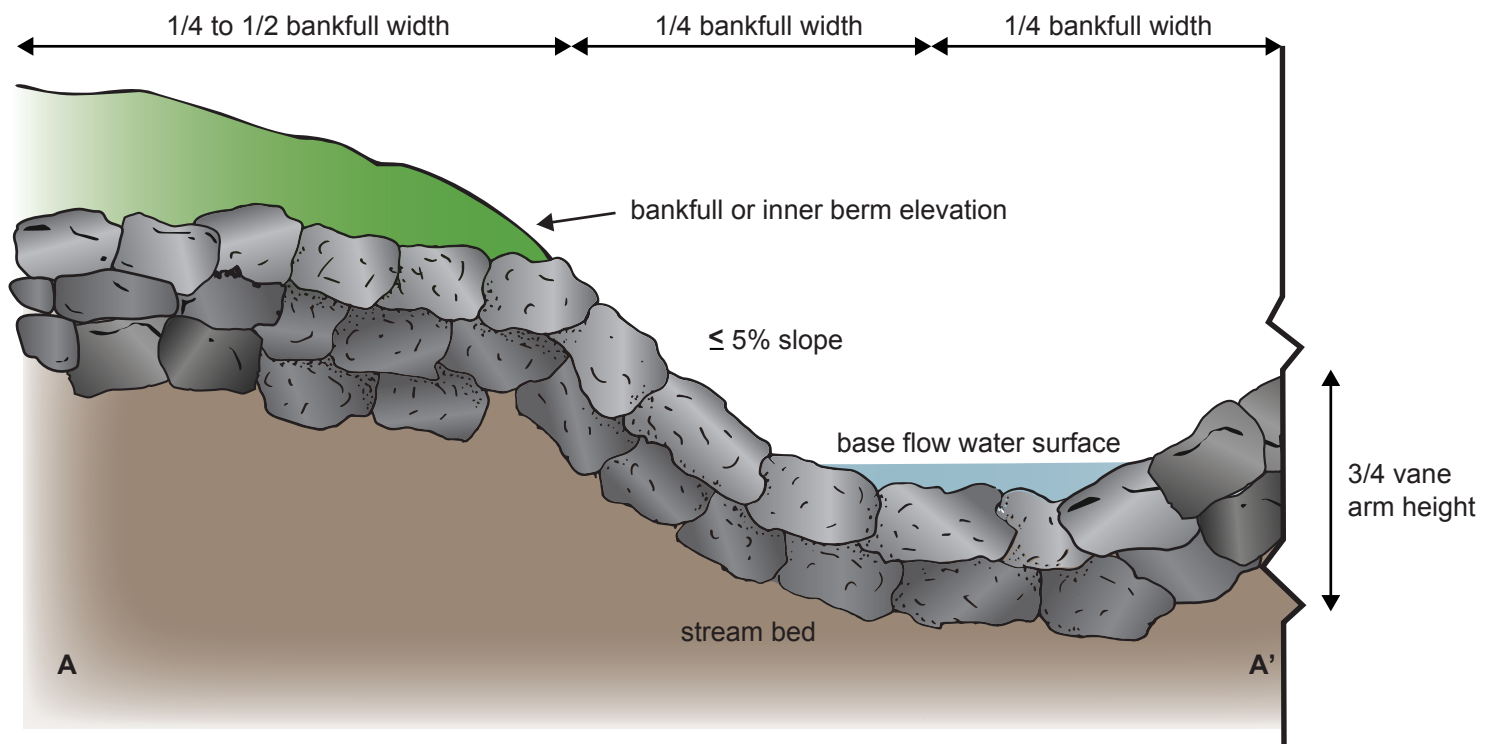

Figure 2. W-weir cross section.

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occur. Although prior design guidance (Rosgen, 1996) indicated the weir should be keyed in at bankfull height, this will not be appropriate for every stream (B.A. Doll, personal communication, April 11, 2016). The rocks at the upstream apices (not just the footer materials) should be buried in the stream bed at approximately thalweg elevation to allow sediment transport and fish passage.

Each vane arm should extend over no more than 1/4 of bankfull width (outer or midsection). The midstream section covers the middle 1/2 of bankfull width in the stream center. While the vane arms are traditionally symmetric (i.e. same horizontal angle and length), asymmetric vane arms may be used to provide additional protection along one bank or to redirect flows. Keep in mind the water will flow perpendicular to the vane arms: it is important to ensure the arms do not direct flows into a downstream bank and cause erosion.

CAUTION: The greater the vertical slope of the outer arms, the shorter the length of bank protected by the weir.

Placement within Stream Planform

Not only will a w-weir prevent stream bed incision, it will also prevent natural migration of the channel across the floodplain. If natural channel migration cannot be allowed, such as to protect infrastructure, a similarly confined reference reach can be used to inform structure spacing along the channel. In undisturbed meandering streams, pools commonly occur every 5 to 7 bankfull widths apart along the stream channel. If infrastructure protection or grade control is not a project goal and the stream can be allowed to migrate naturally, w-weirs should not used.

Because bed material will deposit upstream of a w-weir and two scour pools will form downstream, w-weirs should be placed in a run on meandering channels. W-weirs placed in a meander bend tend to fail due to structure flanking as the meander bend migrates.

When a w-weir is used to redirect flows upstream of a bridge or multiple culverts, care should be taken to ensure the result-ing scour does not impact the bridge/culvert foundation. As described in Johnson et al. (2002), placing the most downstream point of the central weir apex a distance of 1/3 of the bankfull width upstream of the upstream face of the bridge pier/culvert will minimize scour and encourage sediment deposition at the pier. Ideally, the hydraulic behavior of the existing bridge or culvert should also be evaluated as part of the design.

Note that no individual w-weir should produce a bed elevation change of more than 2 ft. (0.6 m), to ensure the developed scour pool does not undermine the vane footers, as scour depth increases with increasing step height. If fish passage is a design goal, the bed elevation change should also be limited to 0.5 ft. (0.15 m).

Construction

The most common failure modes for w-weirs are undermining of the structure, structure flanking, and loss of vane rocks.

Footer rocks are used to prevent scour from undermining the vane. One or more tiers of footer rocks may be used, depending on the susceptibility of the vane to structural failure by undercutting. During construction, slightly offset vane rocks into the flow (in the upstream direction), such that the footer rock is partially exposed on the downstream vane face. This offset prevents the creation of a scour hole directly on the downstream face of the vane which would undermine the structure, perhaps even causing vane rocks to collapse into the scour hole.

To prevent bank erosion where the vane is attached to the bank, it is important to "key in" the vane arms. Anchor the bank end of each arm into the bank a distance 1/4 to 1/2 bankfull width. Large boulders can be placed on the downstream side of the vane arms to increase structural stability (Figure 2). This increased support is provided along the downstream face where the vane is anchored into the bank.

Even though rocks may be sized correctly for the design flow, individual rocks may be dislodged due to turbulence around exposed rocks or flow between rocks. All rocks used in a w-weir should fit together snugly (Figure 3). Offset vane rocks from footer rocks such that each vane rock is

Figure 3. Rocks should fit snugly together and be chinked with smaller rock with a wide range of sizes. (Design by Wetland Studies and Solutions, Inc.)

centered on the intersection of two footer rocks, resting on half of each. To prevent sediment from eroding through gaps in the footer rocks, hand-chink any gaps that exist between rocks with gravel with a wide range of particle sizes and wrap the footer in geotextile fabric.

Post-Construction Monitoring

The function of most structures can be assessed using repeated visual observations and photographs. Some additional monitoring activities to evaluate vane function include the following:

- measure scour pool depth to ensure two pools are forming and the pool depth does not exceed the footer rock depth;

- regularly examine the adjacent streambanks for erosion or a lack of vegetation establishment;

- examine the weir for rock displacement after storm events of a similar magnitude as the design storm, where displacement is defined as complete removal of the rock from its place, rather than minor shifting;

- regularly examine the weir for aggradation or bed degradation upstream of the structure; and

- ensure that the weir is not creating tailwater depths greater than upstream structure elevations (i.e. upstream structures are flooded at baseflow).

If visual assessment of the structure indicates undermining, lateral erosion, or aggradation of the structure, additional assessments, such as cross section and longitudinal surveys, can be conducted to determine what corrective action may be needed.

Consider requesting help from local conservation or volunteer-based organizations for monitoring work that can be performed by laypeople, if resources for monitoring are unavailable or limited.

Illustrations by Sarah Cisneros and Layout by Tim Poff

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